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Arsenic Removal from Drinking Water by Iron Removal Plants

by

Keith Fields
Abraham Chen
Lili Wang

Battelle
Columbus, OH 43201-2693

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Thomas J. Sorg
Water Supply and Water Resources Division
National Risk Management Research Laboratory
Cincinnati, OH 45268

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, OH 45268

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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.

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E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Abstract

This report documents treatment plant information as well as results of sampling and analysis at two iron removal plants (referred to as Plants A and B). 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 chemical characteristics of 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, was initiated at Plant A in April 1998 and at Plant B in May 1998. This phase consisted of a four-week sampling period to refine procedures for subsequent events during the third phase. The third phase, long-term evaluation, consisted of weekly sample collection and analysis beginning in June 1998 and continuing through June 1999 at Plant A and through December 1998 at Plant B. Plant personnel conducted all sampling during the long-term evaluation phase and Battelle coordinated sampling logistics. Sludge samples also were collected at Plant A during a single sampling event from an outdoor settling pond in November 1998. Samples of supernatant discharge (Plant A) and recycle supernatant (Plant B) were collected monthly beginning in November 1998 and continuing until June 1999 at Plant A and until January 1999 at Plant B.

Results from the long-term evaluation phase were varied regarding the ability of the iron removal process to consistently achieve low-level arsenic concentrations (e.g., <5 µg/L in the finished water). The total arsenic concentrations at Plant A were reduced by an average of 87%, which represents a decrease in average arsenic concentration from 20.3 µg/L to 3.0 µg/L. Adsorption and coprecipitation with iron hydroxide precipitates are believed to be the primary arsenic removal mechanisms. The total arsenic concentrations at Plant B were reduced by an average of 74%, which represents a decrease in average arsenic concentration from 48.5 µg/L to 11.9 µg/L. At Plant B, it appeared that only the particulate arsenic in the source water was removed. This particulate arsenic was most likely associated with the oxidized iron particles present in the source water (i.e., arsenic sorbed onto iron particles). The primary difference in arsenic removal efficiency at Plants A and B is believed to be the amount of iron in the source water. Source water at Plant A averaged 2,284 µg/L of iron, while Plant B averaged 1,137 µg/L. Increasing the iron in the source water at Plant B using a coagulant, such as ferric chloride, would likely enable Plant B to consistently achieve lower levels of arsenic.

None of the sludge samples collected at Plant A qualified as a hazardous waste based on the Toxicity Characteristic Leaching Procedure (TCLP) test for metals. Therefore, nonhazardous waste landfills should be able to accept the sludge generated by this treatment facility. Stricter hazardous waste classification regulations in some states, such as California, on total arsenic concentrations in solid waste also were met at Plant A. Sludge samples were not collected at Plant B; however, analytical results were provided from a 1994 sludge sampling event.

Contents

Foreword iii
Abstract iv
Figures vii
Tables viii
Acronyms and Abbreviations ix

1.0 Introduction 1
  1.1 Background 1
    1.1.1 General Chemistry of Arsenic 1
    1.1.2 Determination of Arsenic Species 3
    1.1.3 Treatment Technologies for Arsenic Removal 3
    1.1.4 Data Gaps 4
  1.2 Objectives 4
  1.3 Report Organization 4

2.0 Conclusions 5

3.0 Materials and Methods 6
  3.1 General Project Approach 6
  3.2 Preparation of Sampling Kits and Sample Coolers 7
    3.2.1 Preparation of Arsenic Speciation Kits 7
    3.2.2 Preparation of Recycle Backwash Water/Supernatant Discharge Sampling Kits 8
    3.2.3 Preparation of Sample Coolers 8
  3.3 Sampling Procedures 9
    3.3.1 General Approach and Sampling Schedules 9
    3.3.2 Arsenic Field Speciation Procedure 10
    3.3.3 Recycle Supernatant/Supernatant Discharge Sampling Procedure 13
    3.3.4 Sampling Procedure for Other Water Quality Parameters 13
  3.4 Analytical Procedures 13

4.0 Results and Discussion 16
  4.1 Plant Selection 16
  4.2 Plant A 16
    4.2.1 Plant A Description 17
    4.2.2 Initial Source Water Sampling 17
    4.2.3 Preliminary Sampling 17
    4.2.4 Long-Term Sampling 22
      4.2.4.1 Arsenic 22
      4.2.4.2 Other Water Quality Parameters 24
      4.2.4.3 Supernatant Discharge 24
      4.2.4.4 Sludge 26

4.3 Plant B 28
4.3.1 Plant B Description 28
4.3.2 Initial Source Water Sampling 28
4.3.3 Preliminary Sampling 30
4.3.4 Long-Term Sampling 33
4.3.4.1 Arsenic 33
4.3.4.2 Other Water Quality Parameters 34
4.3.4.3 Recycle Supernatant 37
4.3.4.4 Sludge 37

5.0 Quality Assurance/Quality Control 39
5.1 Quality Assurance Objectives 39
5.2 Overall Assessment of Data Quality 39
5.2.1 Total Arsenic, Aluminum, Iron, and Manganese 39
5.2.2 Water Quality Parameters 40
5.2.3 TCLP Metals in Sludge 40

6.0 References 41

Appendices

Appendix A: Complete Analytical Results from Long-Term Sampling at Plant A 43
Appendix B: Complete Analytical Results from Long-Term Sampling at Plant B 57

Figures

Page

Figure 1-1. Solubility Diagrams for As(III) and As(V) 2
Figure 3-1. Example of Sample Bottle Label 9
Figure 3-2. Photographs of a Typical Sample Cooler (with Three Sample Compartments) and a Color-Coded Instruction Sheet 11
Figure 3-3. Instruction Sheet for Arsenic Field Speciation 12
Figure 3-4. Instruction Sheet for Recycle Supernatant/Supernatant Discharge Sampling 14
Figure 4-1. Schematic Diagram, Plant A 18
Figure 4-2. Process Flow Diagram and Sampling Locations at Plant A 20
Figure 4-3. Total Arsenic Analytical Results During Long-Term Sampling at Plant A 23
Figure 4-4. Arsenic Form and Species Analytical Results During Long-Term Sampling at Plant A 25
Figure 4-5. Inlet Turbidity, pH, Hardness, and Alkalinity Analytical Results at Plant A 27
Figure 4-6. Schematic Diagram, Plant B 29
Figure 4-7. Process Flow Diagram and Sampling Locations at Plant B 31
Figure 4-8. Total Arsenic Analytical Results During Long-Term Sampling at Plant B 34
Figure 4-9. Arsenic Form and Species Analytical Results During Long-Term Sampling at Plant B 35
Figure 4-10. Inlet Turbidity, pH, Hardness, and Alkalinity Analytical Results at Plant B 37

Tables

Page

Table 3-1. Sample Containers and Preservation Methods 8
Table 3-2. Summary of Sampling Activities at Plants A and B 10
Table 3-3. Summary of Sampling Schedule for Plants A and B.......................... 10
Table 3-4. Summary of Analytical Methods for Arsenic Treatment Study 15
Table 4-1. Initial List of Treatment Facilities Identified for the Study 16
Table 4-2. Source Water Analytical Results at Plant A (February 10, 1998)....... 19
Table 4-3. Analytical Results from Preliminary Sampling at Plant A (April 22 to May 13, 1998) 21
Table 4-4. Summary of Arsenic Analytical Results at Plant A 22
Table 4-5. Summary of Water Quality Parameter Analytical Results at Plant A .. 26
Table 4-6. Summary of Analytical Results from Supernatant Discharge Samples at Plant A.. 27
Table 4-7. Analytical Results of Sludge Sampling at Plant A............................. 28
Table 4-8. Source Water Analytical Results at Plant B (February 4, 1998)......... 30
Table 4-9. Analytical Results from Preliminary Sampling at Plant B (May 7 through May 28, 1998) 32
Table 4-10. Summary of Arsenic Analytical Results at Plant B 33
Table 4-11. Summary of Water Quality Parameter Analytical Results at Plant B .. 36
Table 4-12. Summary of Analytical Results from Recycle Supernatant Samples at Plant B 38

Acronyms and Abbreviations

AF	after filtration
As	arsenic
AS	after softening
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
cfs	cubic feet per second
DI	distilled
EDR	electrodialysis reversal
EPA	United States Environmental Protection Agency
GFAAS	graphite-furnace atomic-absorption spectrophotometer
GI	gastrointestinal
gpm	gallons per minute
GW	ground water
HCl	hydrochloric acid
HDPE	high-density polyethylene
ICP-MS	inductively coupled plasma/mass spectrometry
ID	identification
IN	inlet
$KMnO_4$	potassium permanganate
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
NS	not sampled
NTU	nephelometric turbidity units
PF	prefiltration
POC	point of contact
ppm	parts per million
psi	pounds per square inch

QA	quality assurance
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/Quality Control
RPD	relative percent difference
SDWA	Safe Drinking Water Act
SW	surface water
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
WA	work assignment
WAM	work assignment manager
%R	percent recovery

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Sincere appreciation is extended to the two 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 at Plant A and more than 6 months at Plant B. Their work on this project was uncompensated, making their superb efforts even more remarkable. Personnel from both plants are thanked for their hard work and dedication throughout the duration of this project.

1.0 Introduction

This project consists, in part, of a field study to collect drinking water samples from various locations throughout the treatment processes at two iron removal plants. These samples were analyzed and used to evaluate the effectiveness of conventional iron removal 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 the treatment processes. This report describes the design and operation of the two treatment plants and presents the analytical results of the water samples collected during the study.

1.1 Background

The Safe Drinking Water Act (SDWA) of 1974 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 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 remove arsenic to a level significantly lower than the current MCL. This study was conducted as part of an EPA Work Assignment (WA) 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 from [As(III)] normally is found in ground water (assuming anaerobic conditions) and the oxidized, pentavalent form [As(V)] is found in surface water (assuming aerobic conditions), although this rule 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: H_3AsO_4, $H_2AsO_4^-$, $HAsO_4^{2-}$, and AsO_4^{3-}. Similarly, arsenite exists in five forms: $H_4AsO_3^+$, H_3AsO_3, $H_2AsO_3^-$, $HAsO_3^{2-}$, and 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, and arsenite is neutral at pH <9 and ionic at pH >9. Conventional treatment technologies used for arsenic removal, such as iron removal, 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.

Although soluble arsenic species typically make up the majority of the total arsenic concentration in natural waters, some research indicates that arsenic can exist as particulate at significant concentrations. Studies by Cheng

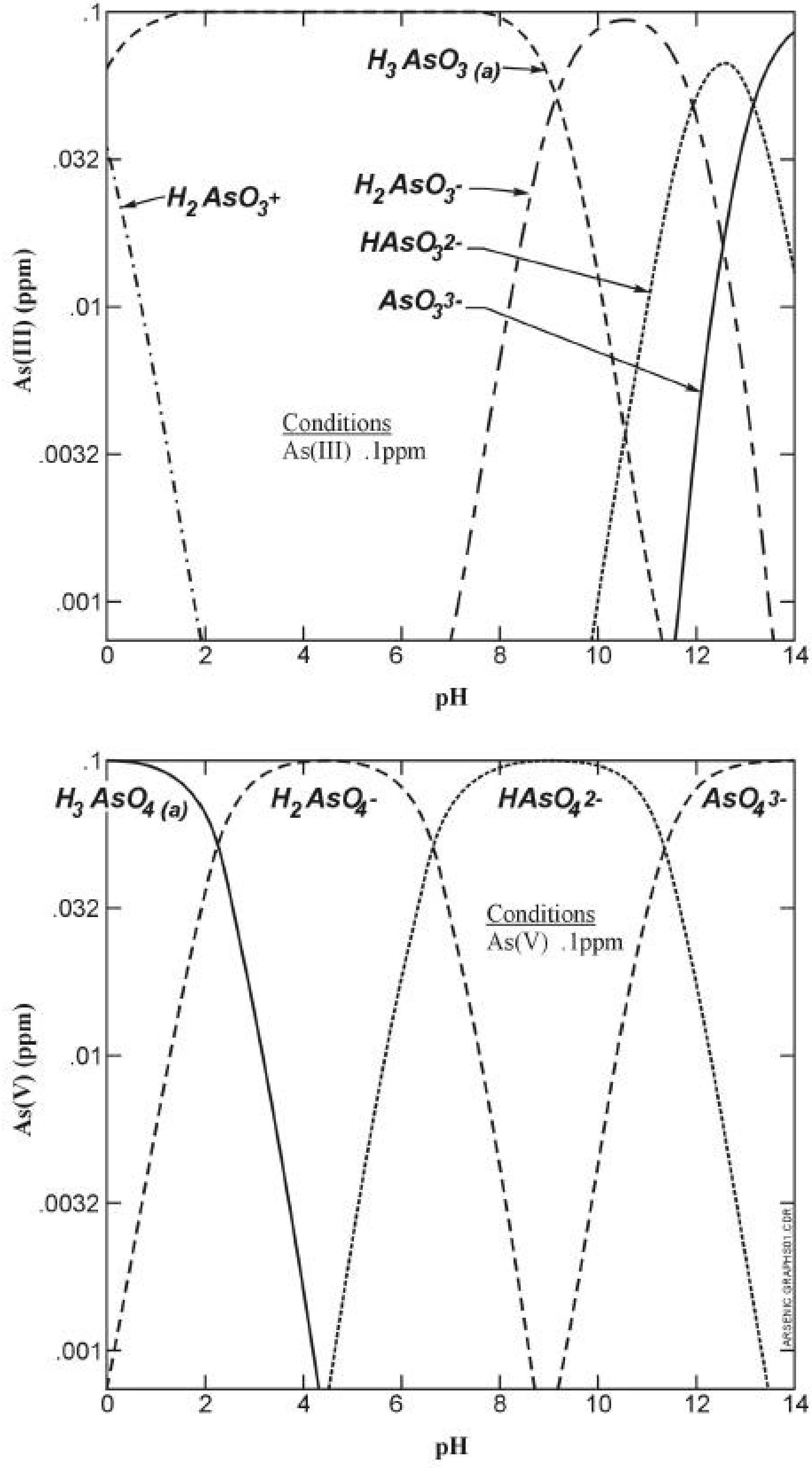


Figure 1-1. Solubility Diagrams for As(III) and As(V)

et al. (1994) and Hemond (1995) measured particulate arsenic at levels of 17 and 50% of the total arsenic concentration, respectively, in 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 pH <2 in the field. However, a high level of ambiguity exists when acids such as nitric acid (HNO_3) or hydrochloric acid (HCl) are used to preserve inorganic species of arsenic. Interconversion of As(III) and As(V) in samples preserved with 0.05 N 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 HCl; the study concluded that no effective method exists for preserving As(III) and 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 × 8, 100-200 mesh, acetate form) in a 10 cm × 7 mm glass column to separate As(III) from As(V) in water samples that had been filtered through a 0.45-µm membrane filter and acidified with 1% 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 As(III) from 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 50-100 mesh resin for the 100-200 mesh resin to allow faster sample flow. (2) Used 12 cm × 15 mm polypropylene columns to improve safety and speed of sample treatment. (3) Used 0.05% H_2SO_4 instead of 1% HCl to acidify samples prior to resin treatment. Edwards et al.'s use of H_2SO_4 helped to prevent potential problems associated with overacidification of the sample, and also helped to prevent Cl^- from interfering with the inductively coupled plasma/mass spectrometry (ICP-MS) analysis. The reported recoveries of As(III) and 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 the 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 filtration to remove arsenic. Chemical precipitation is another common, conventional treatment process used for water softening as well as iron and manganese removal 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 iron removal, a conventional treatment process used for arsenic removal at large-scale operations. Two additional reports have been developed for (1) coagulation/filtration and lime softening plants and (2) anion exchange and activated alumina plants.

Chemical precipitation/filtration commonly is used for removal of iron from source waters. This process, referred to in this document as iron removal, involves two major steps: (1) oxidation of reduced iron, Fe(II), to the relatively insoluble Fe(III) in order to form precipitates; and (2) filtration of the water to remove the precipitated iron hydroxides. The most common oxidants used to precipitate soluble iron are air, chlorine, and potassium permanganate.

Iron removal can be used to remove arsenic from drinking water. Two primary removal mechanisms exist: adsorption and coprecipitation (Benefield and Morgan, 1990). During the adsorption process, dissolved arsenic attaches to the surface of a particle or precipitate. And during the coprecipitation process, dissolved arsenic is adsorbed to a particle and entrapped as the particle continues to agglomerate. The following major steps occur when using iron removal for arsenic treatment: (1) the soluble iron and any As(III) are oxidized; (2) As(V) attaches to the iron hydroxides through adsorption and/or coprecipitation; and (3) the particle/precipitate subsequently is filtered from the water.

Several bench- and pilot-scale studies and some short-term full-scale evaluations have been conducted to evaluate arsenic removal during iron hydroxide precipitation. Most of the 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 be easily converted to As(V) using a strong oxidant such as chlorine (Hering et al., 1996; Sorg, 1993). McNeill and Edwards (1995) conducted a survey of full-scale treatment facilities and observed that arsenic removal efficiencies of 80 to 95 percent were obtained at facilities with greater than 1.5 mg/L Fe(II) in the source water. However, arsenic removal efficiency may be reduced in the presence of orthophosphate, natural organic matter (NOM), and silicate due to competition for sorptive sites on iron hydroxide precipitates (Edwards, 1994; Meng et al., 2000).

Previous studies also indicate that arsenic removal during iron hydroxide precipitation is directly correlated with the initial, or inlet, iron concentration (i.e., arsenic removal efficiency increases with increasing iron concentrations) (Sorg and Logsdon, 1978; Sorg, 1993; Hering et al., 1996; Gulledge 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; Cheng et al., 1994; Edwards, 1994). Other research indicates that As(V) removal is not pH-dependent between pH 5.5 and 8.5 for iron hydroxide precipitation (Sorg and Logsdon, 1978; Sorg, 1993; Hering et al., 1996).

1.1.4 Data Gaps

The removal of arsenic from drinking water by adsorption and coprecipitation with metal hydroxides has been extensively studied at the laboratory and pilot-scale level. Although some short-term full-scale evaluations have been performed for iron removal, little data exist on the capability of (natural) iron removal in full-scale applications to reduce arsenic on a sustained basis. Thus, a need exists to determine the effectiveness of the iron removal process to produce drinking water with low levels of arsenic on a long-term basis, under varying operational and seasonal conditions.

Another data gap is the generation and disposal of residuals from conventional drinking water treatment processes. Currently, little or no data exist on the amounts and the chemical composition of residuals generated by the arsenic removal processes and the environmental impacts of their disposal. Therefore, information needs to be collected on the quantity and the chemical characteristics of the wastes produced by iron removal plants.

1.2 Objectives

One objective of this study was to evaluate the effectiveness of conventional iron removal to consistently reduce arsenic concentrations in source water to low levels. This report presents the results of weekly monitoring for approximately one year and 6 months at Plants A and B, respectively.

Another objective of this study was to examine the residuals produced during treatment at iron removal plants. Information was collected on the 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 iron removal plants. 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 and B present the complete set of analytical data collected at Plants A and B, respectively, during long-term sampling.

2.0 Conclusions

The U.S. EPA has begun the process of revising the arsenic MCL. It is anticipated that the revised limit will be significantly lower than the current 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 study were to document arsenic removal at two iron removal plants, and to assess potential impacts of 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 sampling (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 four-week sampling period to refine the sampling approach before implementing the long-term sampling 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 collection and analysis of water samples at both water treatment plants. The long-term evaluation also included sludge sampling (November 1998 at Plant A only), supernatant discharge sampling (November 1998 through June 1999 at Plant A), and recycle supernatant sampling (November 1998 through January 1999 at Plant B). During the long-term sampling, plant personnel conducted sampling and Battelle coordinated sampling logistics.

The primary focus of this study was the long-term performance of the two iron removal plants. Total arsenic concentrations at Plant A were reduced from an average of 20.3 µg/L to 3.0 µg/L. Total arsenic concentrations at Plant B were reduced from an average of 48.5 µg/L to 11.9 µg/L. Adsorption and coprecipitation of As(V) with iron hydroxides precipitates are believed to be the primary arsenic removal mechanism at Plant A. Plant A oxidized As(III) in the source water to As(V) using chlorination. At Plant B, it appeared that only the particulate arsenic in the source water was removed. Particulate arsenic most likely represents the arsenic sorbed to oxidized iron particles. The primary difference in arsenic removal between Plants A and B is believed to be the amount of iron in the source water. Source water at Plant A averaged 2,284 µg/L of iron, while Plant B averaged 1,137 µg/L. Therefore, increasing the available iron at Plant B by using a coagulant such as ferric chloride would likely enable Plant B to consistently achieve lower levels of arsenic.

The secondary focus of this study was on the chemical characteristics of the residuals generated during the treatment processes. None of the sludge samples collected at Plant A qualified as a hazardous waste based on Toxicity Characteristic Leaching Procedure (TCLP) tests for metals. Therefore, sludge generated by this plant should be accepted by nonhazardous waste landfills. Sludge samples were not collected at Plant B; however, the plant did provide analytical results from a 1994 sampling event. TCLP tests were not performed on this sample, although the total arsenic concentration exceeded stricter requirements in California regarding hazardous waste classification. Supernatant water from the settling pond at Plant A was discharged to the sanitary sewer, whereas backwash water at Plant B was allowed to settle in a concrete vat then combined with the source water. The recycle supernatant at Plant B did not appear to adversely impact treatment plant operations.

3.0 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 iron removal plants. 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 study 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 up to one 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 on the following criteria: 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 iron removal plants (designated as Plants A and B) 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 and B 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 both plants over a four-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 from four sampling locations at Plant A: (1) the inlet to the treatment plant (IN); (2) before the filtration process (prefiltration [PF]); (3) after the filtration process (AF); and (4) after a final zeolite resin softening process (AS). Also, water samples were collected weekly from three sampling locations at Plant B: (1) the inlet to the treatment plant (IN); (2) before the filtration process (PF); (3) and after the filtration process at the plant outlet (AF). During the preliminary and long-term sampling phases, field arsenic speciation sampling was conducted once every four weeks. Starting from November 1998, samples of supernatant discharge (from a settling pond at Plant A) or recycle supernatant (from a concrete vat at Plant B) were collected once every four weeks from each plant. Finally, three sludge samples were collected from the settling pond at Plant A during one sampling event.

All sample containers and arsenic speciation kits were prepared 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 using an ICP-MS method. 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/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-µm screw-on disc filter to remove any particulate arsenic and collecting 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 H_3AsO_3, and As(V) was present in both ionic (i.e., $H_2AsO_4^-$) and protonated forms (i.e., H_3AsO_4) (see Figure 1-1). A portion of the acidified sample in bottle B was run through the resin column. The resin retained the As(V) and allowed As(III) (i.e., H_3AsO_3) to pass through the column. (Note that the resin will retain only $H_2AsO_4^-$ and that H_3AsO_4, when passing though the column, will be ionized to $H_2AsO_4^-$ due to elevated pH values in the column caused by the buffer capacity of acetate exchanged from the resin.) The eluate from 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 made up the total arsenic concentration of the resin-treated sample in bottle C. The 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:

- One anion exchange resin column
- Primary and duplicate A, B, and C bottles
- One 400-mL disposable beaker
- Two 60-mL disposable syringes
- Several 0.45-µm 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 for 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 × 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 µL, respectively, of concentrated ultra-pure HNO_3; and bottle B was spiked with 1.25 mL of 5% (volume/volume) ultra-pure sulfuric acid (H_2SO_4). H_2SO_4 was used to acidify the sample in bottle B because Cl^- in HCl could interfere with the ICP-MS arsenic detection and 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-µm 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, 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 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-µm screw-on disc filters
- Bottles provided by Wilson Environmental Laboratories used for pH analyses.

The sampling kit was prepared in a similar way as the arsenic speciation kit except that bottle B was preserved with HNO_3 instead of H_2SO_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

Table 3-1. Sample Containers and Preservation Methods

Container Size	Container Type	Preservation Method	Analyte	Hold Time
Arsenic Speciation Samples				
250 mL (A)	certified clean HDPE bottles	4°C HNO_3 for pH <2	Total As, Al, Fe, Mn	6 months
125 mL (B)	certified clean HDPE bottles	4°C 0.05 % H_2SO_4	Dissolved As, Al, Fe, Mn	6 months
125 mL (C)	certified clean HDPE bottles	4°C HNO_3 for pH <2	Dissolved As, Al, Fe, Mn	6 months
Recycle Backwash Water/Supernatant Discharge Samples				
250 mL (D)	plastic	4°C	pH	immediate
250 mL (A)	certified clean HDPE bottles	4°C HNO_3 for pH <2	Total As, Al, Fe, Mn	6 months
250 mL (B)	certified clean HDPE bottles	4°C HNO_3 for pH <2	Dissolved As, Al, Fe, Mn	6 months
Water Quality Parameter Samples				
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 HNO_3 for pH<2	Hardness	6 months
250 mL (F)	plastic	4°C H_2SO_4 for pH <2	NO_3^-/NO_2^-	28 days
500 mL (G)	glass	4°C H_2SO_4 for pH<2	TOC	14 days
Sludge Samples				
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.

(for water and sludge samples), sample preservation used, analysis to be performed, and holding time. All sample containers were labeled prior to shipment.

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.

AC-02/15/98-PF-B-DUP

Date: 02/15/98 **Time:** 11 a.m.
Collector’s Name: Sample Collector
Location: Any City WTP
Sample ID: AC-02/15/98-PF-B-DUP
Send to: Battelle
Analysis Required: Total As, Al, Fe, and Mn
Preservative: 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. When arsenic speciation or recycle supernatant/supernatant discharge samples were to be collected, arsenic speciation kits or recycle supernatant/supernatant discharge sampling kits also were included in the cooler. 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

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 (Plant A only) and the monthly collection of recycle supernatant or supernatant discharge, 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 both plants.

During the preliminary and long-term sampling, sample collection was conducted on a four-week cycle, with each week having unique sampling requirements. Table 3-3 summarizes the schedules for the initial source water, the preliminary, the long-term, and the sludge sampling at both plants.

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 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 on 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, and turbidity) were sent along with sample coolers or transmitted via facsimile to Battelle for information/ evaluation.

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

Sampling Activities	Sampling Frequency	Plant A	Plant B
Initial source water sampling	Once	02/10/98	02/4/98
Preliminary sampling	Weekly	4/22/98 through 5/13/98	5/7/98 through 5/28/98
Long-term sampling	Weekly[(a)]	6/24/98 through 06/16/99	6/11/98 through 12/8/98
Sludge sampling	Once	11/18/98	NS
Recycle water sampling	Weekly	11/11/98 through 06/16/99	11/10/98 through 1/15/99

(a) Except for the weeks of 11/23/98, 12/21/98, and 12/28/98.
NS = Not sampled.

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

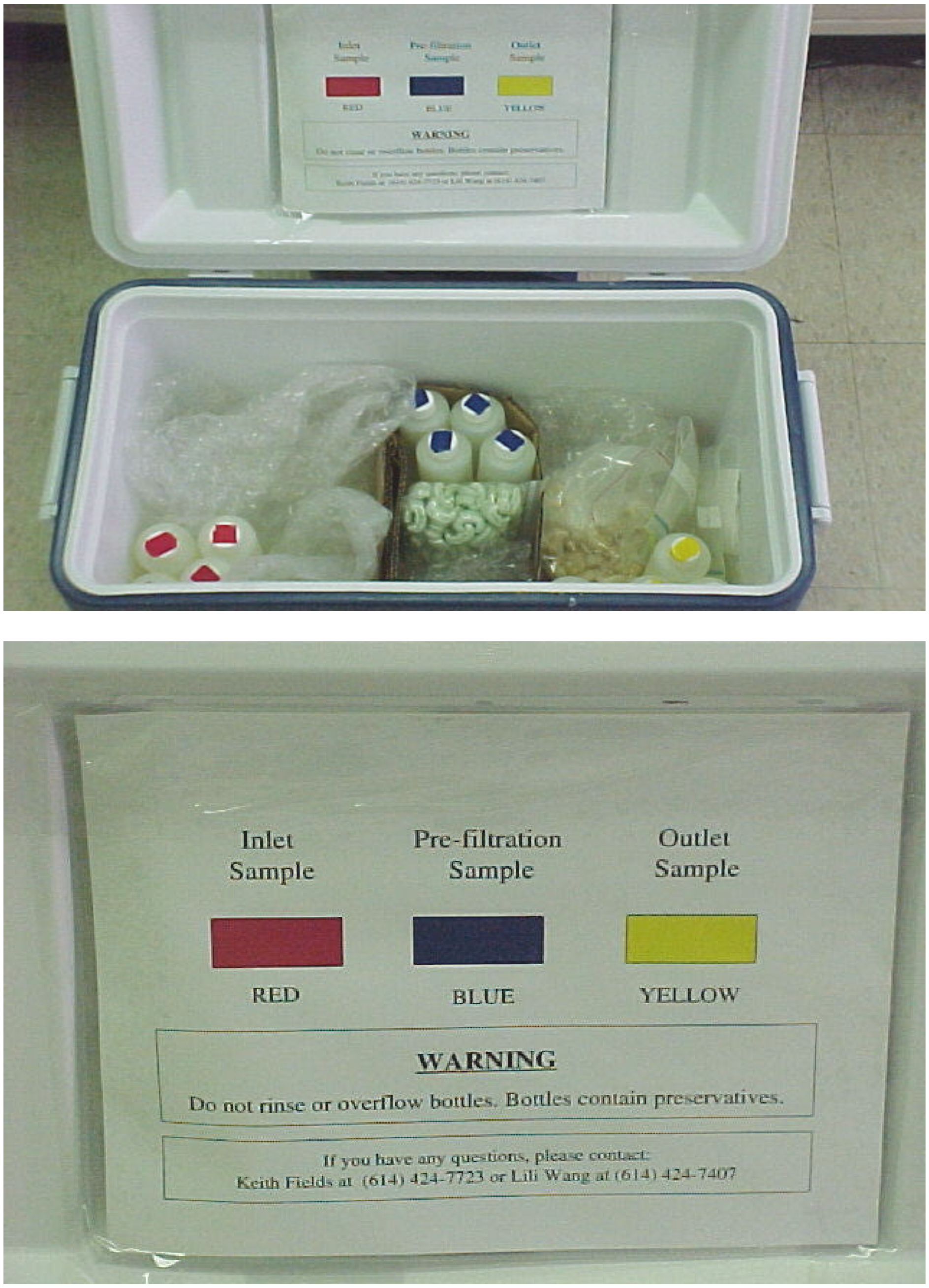
	Water Sampling									
	Initial Source Water Sampling	Preliminary Sampling Cycle				Long-Term Sampling Cycle				Sludge Sampling
Analyte	(Once)	Week 1	Week 2	Week 3	Week 4	Week 1	Week 2	Week 3	Week 4	(Once)
As (total)	W*	W*	W	W	W	W*	W	W, R*	W	
As (total soluble)	W*	W*				W*		R*		
As (particulate)	W*	W*				W*		R*		
As (III)	W*	W*				W*				
As (V)	W*	W*				W*				
Al (total)	W*	W*				W*	W	W, R*	W	
Fe (total)	W*	W*	W	W	W	W*	W	W, R*	W	
Mn (total)	W*	W*	W	W	W	W*	W	W, R*	W	
Al (dissolved)						W*		R*		
Fe (dissolved)						W*		R*		
Mn (dissolved)						W*		R*		
Alkalinity	W*	W*	W	W	W	W	W*	W	W	
Sulfate	W*									
NO_3-NO_2 (N)	W*									
TOC	W*									
Turbidity	W*	W*				W				
pH	W*	W*	W	W	W	W	W*	W, R*	W	
Hardness	W*	W*				W				
Ca Hardness	W*	W*				W				
Mg Hardness	W*	W*				W				
TCLP Metals										S
Percent Moisture										S
pH										S
As (total)										S
Fe (total)										S
Mn (total)										S

* = Duplicate samples collected and analyzed.
W = Water samples collected from the inlet, prefiltration, and after-filtration locations (Plants A and B) and from after-softening location (Plant A only).
R = Recycle supernatant sample collected at Plant B; supernatant discharge sample collected at Plant A.
S = Sludge samples collected at Plant A.
Empty cells indicate no samples taken.

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):

- **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-µm disc filter and wasting about 10 drops of the filtrate, the syringe was used to filter the water sample from



Inlet Sample	Pre-filtration Sample	Outlet Sample
🟥	🟦	🟨
RED	BLUE	YELLOW

WARNING

Do not rinse or overflow bottles. Bottles contain preservatives.

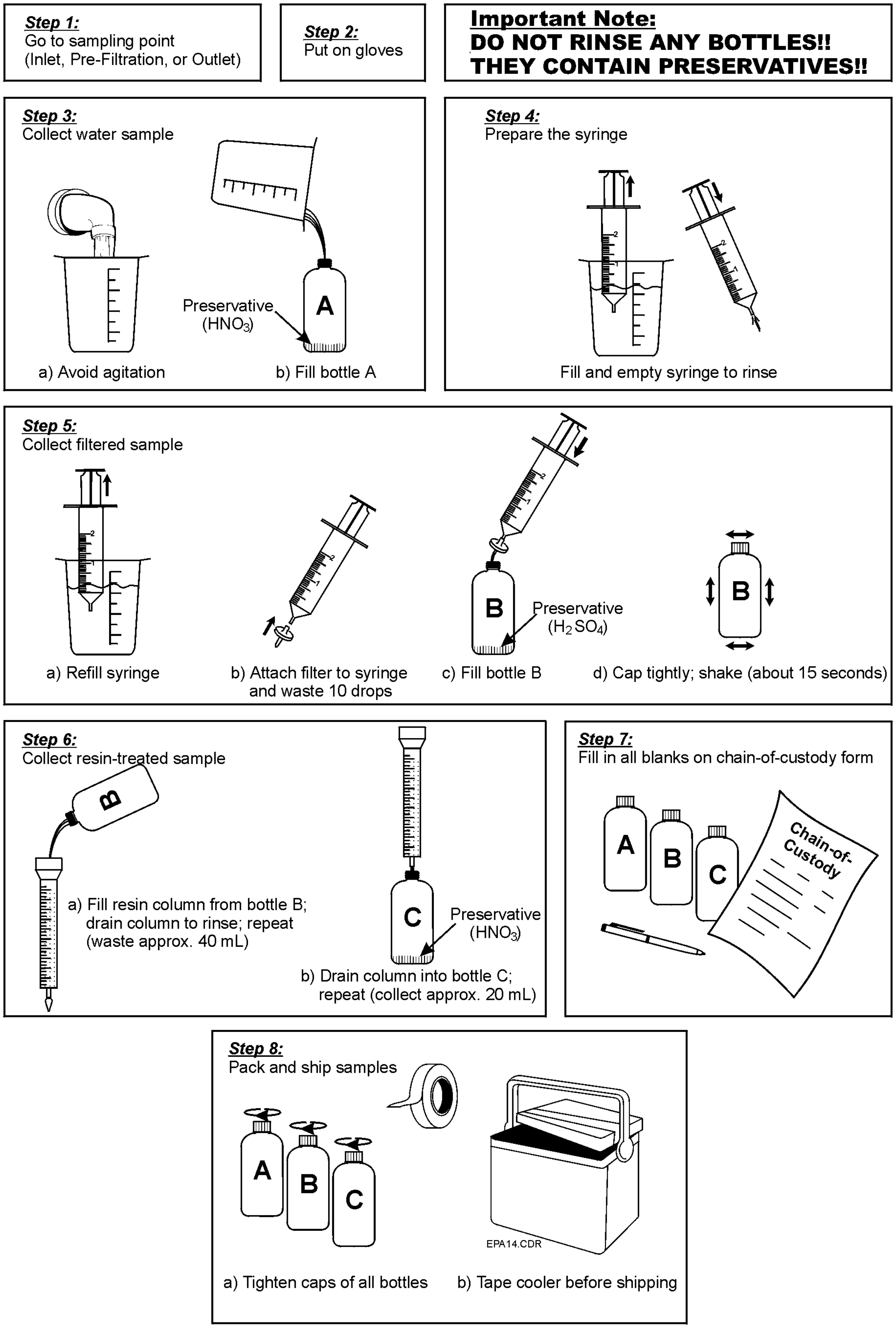
If you have any questions, please contact:
Keith Fields at (614) 424-7723 or Lili Wang at (614) 424-7407

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

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).

- **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.



Step 1:
Go to sampling point
(Inlet, Pre-Filtration, or Outlet)

Step 2:
Put on gloves

Important Note:
DO NOT RINSE ANY BOTTLES!!
THEY CONTAIN PRESERVATIVES!!

Step 3:
Collect water sample

Preservative (HNO_3)

a) Avoid agitation

b) Fill bottle A

Step 4:
Prepare the syringe

Fill and empty syringe to rinse

Step 5:
Collect filtered sample

Preservative (H_2SO_4)

a) Refill syringe

b) Attach filter to syringe and waste 10 drops

c) Fill bottle B

d) Cap tightly; shake (about 15 seconds)

Step 6:
Collect resin-treated sample

a) Fill resin column from bottle B; drain column to rinse; repeat (waste approx. 40 mL)

Preservative (HNO_3)

b) Drain column into bottle C; repeat (collect approx. 20 mL)

Step 7:
Fill in all blanks on chain-of-custody form

Step 8:
Pack and ship samples

a) Tighten caps of all bottles

b) Tape cooler before shipping

Figure 3-3. Instruction Sheet for Arsenic Field Speciation

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).

3.3.3 Recycle Supernatant/Supernatant Discharge Sampling Procedure

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

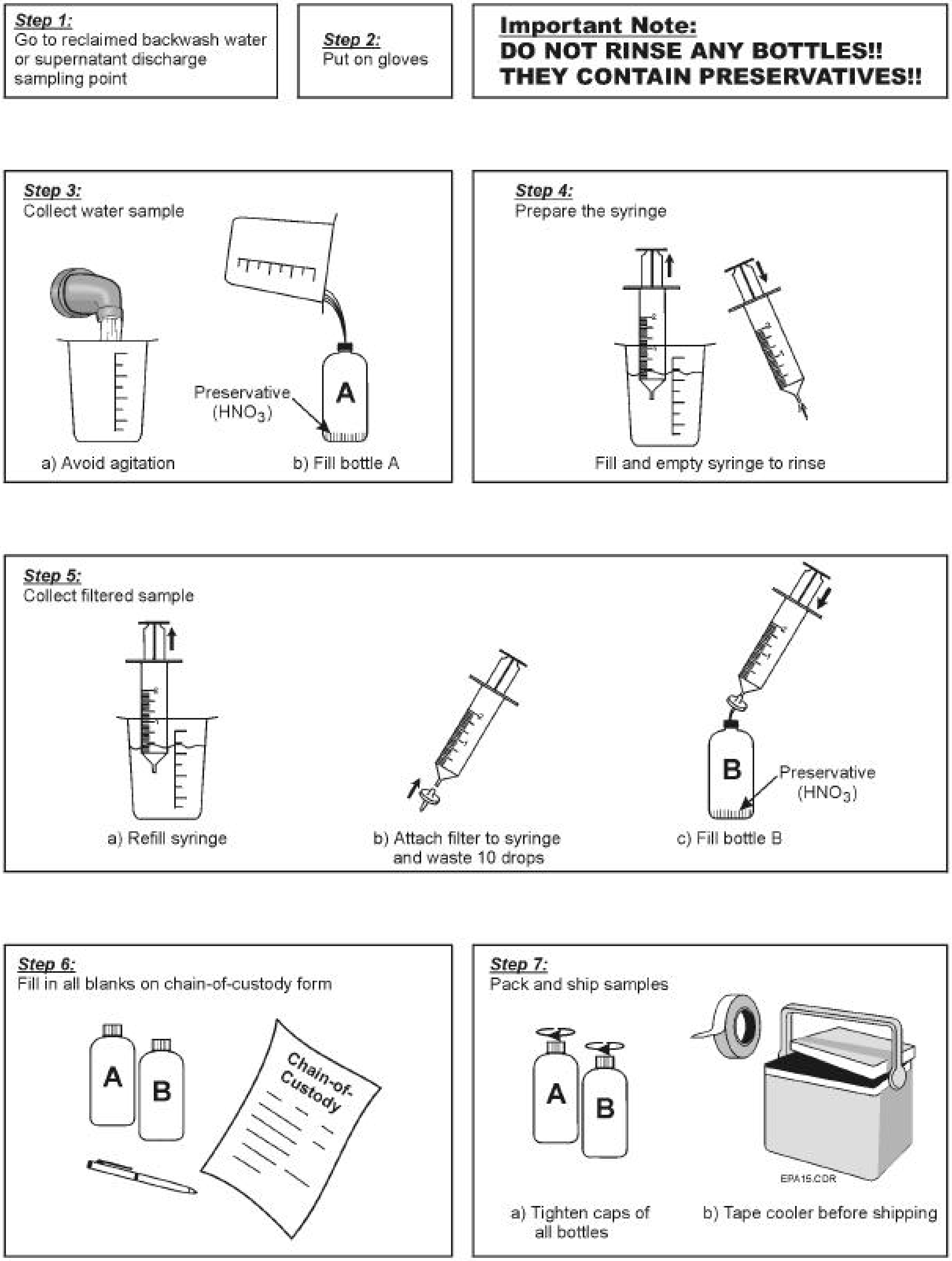
3.3.4 Sampling Procedure for Other Water Quality Parameters

All other water quality parameters identified in Table 3-3, 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 3-4 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 $35/sample). ICP-MS analyses were conducted on a Perkin Elmer Sciex Model 6000 equipped with a crossflow pneumatic nebulizer and an automatic sampler. Yttrium ($^{88.9}Y$) was added to all samples as an internal standard to correct for instrument drift. Because arsenic is monoisotopic, all measurements were made at a mass/charge ratio of 75. To eliminate an appreciable interference from a chloride molecular species ($^{40}Ar^{35}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 Environmental 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.

It should be noted that turbidity tests were not run on site. Relatively high levels of reduced iron in raw water samples may have oxidized during transportation of samples to the analytical laboratory, resulting in elevated turbidity readings. The turbidity might have been much lower if readings had been taken on site.



Step 1:
Go to reclaimed 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

a) Avoid agitation

b) Fill bottle A

Step 4:
Prepare the syringe

Fill and empty syringe to rinse

Step 5:
Collect filtered sample

a) Refill syringe

b) Attach filter to syringe and waste 10 drops

c) Fill bottle B

Step 6:
Fill in all blanks on chain-of-custody form

Step 7:
Pack and ship samples

a) Tighten caps of all bottles

b) Tape cooler before shipping

Preservative (HNO_3)
A
Preservative (HNO_3)
B
A
B
Chain-of-Custody
A
B
EPA15.CDR

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

Table 3-4. 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_4^{2-}	EPA 375.4	Wilson Environmental
	TOC	EPA 415.1	Wilson Environmental
	NO_3^-/NO_2^-	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

ASTM = American Society for Testing and Materials.

4.0 Results and Discussion

This section presents the results of the treatment plant selection process, which resulted in the selection of two iron removal plants, referred to as Plants A and B. In addition, results from water and residuals sampling and analysis at each plant are summarized and discussed. Complete analytical results from long-term water sampling at Plants A and B are presented in Appendices A and B, 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 eight potential iron removal treatment facilities. These 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 on the following criteria: source water arsenic concentrations, source water type, availability of manpower to conduct study, availability of historical 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 long-term 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 a mix of plants using ground water and/or surface water sources.

From the eight initial plants, two iron removal plants were selected for site visits and source water sampling (see 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 sampling at both facilities during each phase of the study are presented in the sections that follow.

4.2 Plant A

Water and residual samples were collected and analyzed at Plant A during three phases of the study. The first phase consisted of source water sampling, which was used to help determine if the plant should be considered for further evaluation. 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 four-week period in April and May 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 four locations throughout the treatment process. Also, arsenic speciation sampling was conducted every fourth week. The third phase of the study also included residual sample collection and analysis. Supernatant discharge samples from the settling pond were collected monthly beginning in November 1998, and three sludge samples were collected during a single sampling event from the settling pond.

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

Plant ID	Process	Source Water Arsenic Concentration, March 1995[a] (µg/L)	Source Water Arsenic Concentration, September 1997[a] (µg/L)	Population Served	Historical Data	Source Water Type
A	Iron removal	30.2	Not sampled	15,000	Yes	Ground water
B	Iron removal	Not sampled	65	Up to 20,000	Yes	Surface water

(a) Results provided by treatment facility.

4.2.1 Plant A Description

Plant A is one of three plants that provides water to a city with a population of approximately 15,000 (approximately 6,000 connections). Plant A was built in 1970 and treats ground water using an iron removal process followed by zeolite softening. The plant is capable of treating 1.6 million gallons per day (mgd). A schematic diagram of the Plant A treatment process is shown in Figure 4-1.

The treatment process consists of the following major elements:

- **Aeration**. Aeration is used to oxidize iron and manganese as well as remove H_2S, NH_3, SO_2, and CH_4.
- **Chlorination**. Approximately 5 mg/L total chlorine (1.5-2 mg/L free chlorine) is added to oxidize remaining iron and manganese and to disinfect filters and softeners.
- **Sedimentation.** Sedimentation occurs in a baffled basin with approximately 20 minutes retention time. After sedimentation, potassium permanganate ($KMnO_4$) is added to remove manganese, taste, and odor as well as to continuously regenerate the manganese greensand in the filter.
- **Filtration**. The filtering media consists of manganese greensand (top) and graded gravel (bottom). A water backwash occurs every 20 hours and an air backwash occurs every 72 hours.
- **Softening**. Approximately two thirds of the filtered water is sent through a zeolite resin softener (ion exchange) to reduce hardness. Regeneration occurs every 175,000 gal processed with 27% solution of NaCl. The regeneration takes approximately 1 hour and consists of a 12-minute backwash, 20-minute brine rinse, and a slow/fast rinse cycle.
- **Postchlorination.** Approximately 5 to 6 mg/L of total chlorine (<1 mg/L free chlorine) is added for distribution residual. Also, 0.9 to 1.2 mg/L of fluoride (H_2SiF_6) is added. No ammonia is added because the water contains NH_3 and about 0.8 to 1.0 mg/L of residual chloramines is maintained in the finished water.
- **Backwash.** Backwash water and regenerant waste is sent to an outdoor settling pond and supernatant is discharged to the sanitary sewer. Sludge is sent to wastewater plant drying beds and then to local farm fields. No arsenic sampling on sludge had been conducted prior to this study.

4.2.2 Initial Source Water Sampling

Plant A obtains source water from three ground water wells (Wells 5, 6, and 7). Each well is approximately 275 ft deep. An initial site visit to Plant A was conducted February 10, 1998 during which time source water samples were collected from the intake, which represents a combined sample from ground water Wells 5, 6, and 7.

The total arsenic concentration during the initial sampling event was 23.5 µg/L. Particulate arsenic accounted for 1.7 µg/L of the total arsenic concentration, and soluble arsenic accounted for the remaining 21.8 µg/L. Field arsenic speciation sampling indicated that the soluble arsenic consisted of 20.1 µg/L of As(III) and 1.7 µg/L of As(V), which was consistent with what would be expected for a ground water source. Also, as would be expected at an iron removal plant, the total iron concentration was relatively high, 2,700 µg/L. Table 4-2 presents the complete analytical results from the initial source water sampling event.

Due primarily to the relatively high source water arsenic concentrations and the availability of plant personnel to perform preliminary and long-term sampling, Plant A was selected for incorporation into the preliminary and long-term evaluation phases of this project.

4.2.3 Preliminary Sampling

During the preliminary sampling phase of this study, water samples were collected at four locations within the treatment plant: inlet (IN), before filtration (PF), after filtration (AF), and after softening (AS). The IN samples were collected from a tap located prior to treatment and represents combined water from Wells 5, 6, and 7. The PF samples were collected after the water had undergone aeration, chlorination, and sedimentation.

After filtration and prior to zeolite softening, the AF samples were collected. Finally, the AS samples were collected after softening and prior to final chlorination and H_2SiF_6 addition. 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, pH, total iron, total manganese, and total arsenic analyses were performed on samples collected at each of the four sampling locations each week. Turbidity, hardness, and arsenic speciation analyses were conducted once during the preliminary study on samples collected at each sampling location. Soluble and particulate arsenic were determined as part of the arsenic

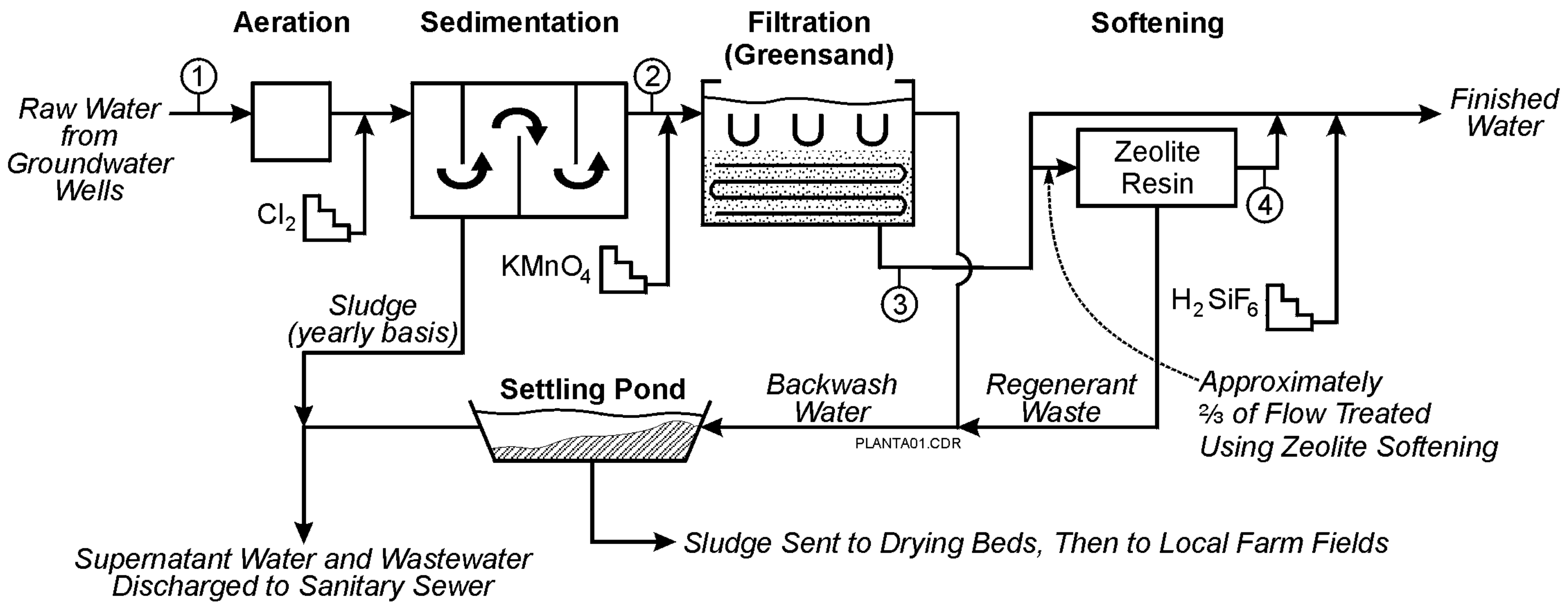

Aeration
Sedimentation
Filtration (Greensand)
Softening
①
②
③
④
Raw Water from Groundwater Wells
Cl_2
$KMnO_4$
Zeolite Resin
Finished Water
H_2SiF_6
Sludge (yearly basis)
Settling Pond
Backwash Water
Regenerant Waste
Approximately ⅔ of Flow Treated Using Zeolite Softening
PLANTA01.CDR
Supernatant Water and Wastewater Discharged to Sanitary Sewer
Sludge Sent to Drying Beds, Then to Local Farm Fields

Figure 4-1. Schematic Diagram, Plant A

Table 4-2. Source Water Analytical Results at Plant A (February 10, 1998)

Parameter	Unit	Primary Sample	Duplicate Sample	Average
Alkalinity	mg/L[(a)]	413	412	412.5
Sulfate	mg/L	<1	<1	<1
Turbidity	NTU	25	24	24.5
pH		7.6	7.6	7.6
Hardness	mg/L[(a)]	270	270	270
Ca Hardness	mg/L[(a)]	140	137	138.5
Mg Hardness	mg/L[(a)]	130	133	131.5
Total Al	µg/L	400	400	400
Total Fe	µg/L	2,640	2,760	2,700
Total Mn	µg/L	<20	<20	<20
NO_3–NO_2 (N)[(b)]	mg/L	<0.02	<0.02	<0.02
TOC	mg/L	6	7	6.5
As (total)	µg/L	23.5	23.4	23.5
As (total soluble)	µg/L	21.9	21.6	21.8
As (particulate)	µg/L	1.6	1.8	1.7
As (III)	µg/L	19.7	20.5	20.1
As (V)	µg/L	2.2	1.1	1.7

(a) As $CaCO_3$.
(b) Combined NO_3–N and NO_2–N.
ND = not detected.
TOC = total organic carbon.

speciation, as well as the species (arsenite and arsenate) making up the soluble fraction of the total arsenic concentration. Table 4-3 presents the results from the four-week preliminary sampling period.

Results from the preliminary sampling events indicated that inlet total arsenic concentrations ranged from approximately 23.7 to 18.6 µg/L. Consistent with the initial source water sampling, the source water contained primarily As(III) and minor concentrations of As(V) and particulate arsenic. As would be expected following chlorination and sedimentation, As(III) had been almost completely oxidized to As(V) at the PF sampling location. It appeared that, after the As(III) had been oxidized to As(V), it coprecipitated with the oxidized iron. Therefore, at the PF sampling location, arsenic was present primarily as particulate. The majority of the arsenic removal occurred during filtration. No significant removal occurred during sedimentation or softening.

The average total arsenic removal by Plant A was approximately 91% during the preliminary sampling, reducing the finished water total arsenic concentration to between 3.4 and 0.6 µg/L. McNeill and Edwards (1997) developed the following simplified model for predicting arsenic removal during metal hydroxide precipitation based on raw water Fe and Al concentrations:

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

where K = 78 mM^{-1}.

This model was based on data collected at more than 14 full-scale facilities, and was able to accurately predict arsenic removal within ±13% (90th percentile confidence interval). Applying this model to the preliminary results from Plant A, the predicted removal ranged from 77% to 79% compared to actual removal rate ranging from 84% to 97%. The maximum difference between the actual and predicted arsenic removal efficiencies was 10%. It should be noted that the calculation did not incorporate aluminum concentrations because they were not obtained during the preliminary sampling phase. Nevertheless, the simplified model appeared to approximate the arsenic removal at Plant A fairly well, and was used to evaluate long-term system performance.

Other water quality parameters were analyzed to support understanding of mechanisms of arsenic removal. During preliminary sampling, pH was relatively constant, at approximately 7.7 throughout the treatment process. This pH is in the range where no effect on arsenic removal efficiency using iron hydroxide precipitation has been observed in previous studies (Sorg and Logsdon, 1978; Sorg, 1993; Hering et al., 1996).

Oxidation of Fe(II) by chlorine may be described by the following chemical reaction:

$$2Fe^{2+} + Cl_2 + 6H_2O \Leftrightarrow 2Fe(OH)_3(s) + 2Cl^- + 6H^+ \qquad (2)$$

The slight decrease in alkalinity observed after oxidation of the iron (i.e., at the PF sampling location) is a result of stoichiometry of iron oxidation in which protons are produced and alkalinity is destroyed (Benefield and Morgan, 1990).

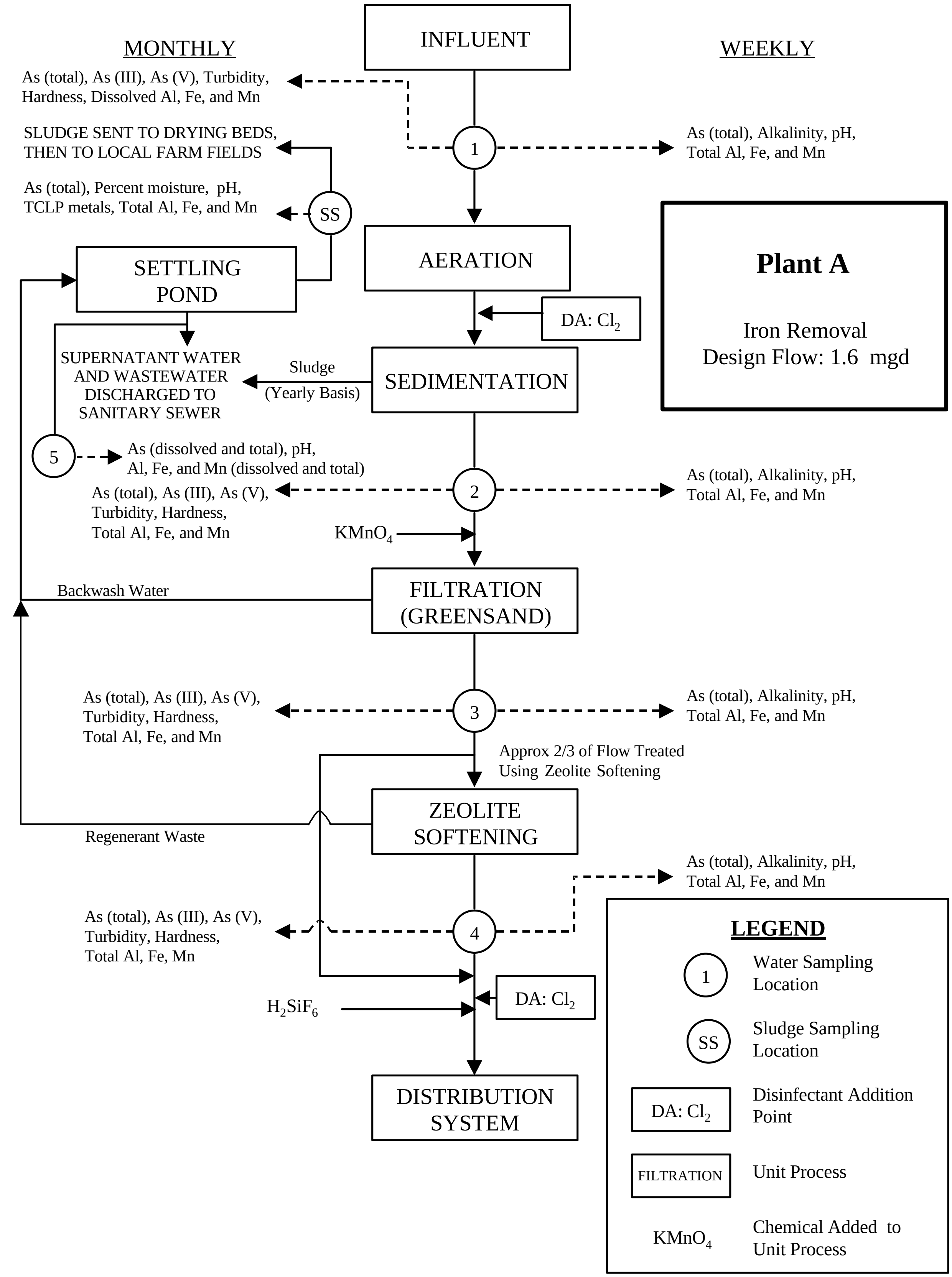

INFLUENT
MONTHLY
WEEKLY
As (total), As (III), As (V), Turbidity, Hardness, Dissolved Al, Fe, and Mn
SLUDGE SENT TO DRYING BEDS, THEN TO LOCAL FARM FIELDS
1
As (total), Alkalinity, pH, Total Al, Fe, and Mn
As (total), Percent moisture, pH, TCLP metals, Total Al, Fe, and Mn
SS
AERATION
Plant A
Iron Removal
Design Flow: 1.6 mgd
SETTLING POND
DA: Cl_2
SUPERNATANT WATER AND WASTEWATER DISCHARGED TO SANITARY SEWER
Sludge
(Yearly Basis)
SEDIMENTATION
5
As (dissolved and total), pH, Al, Fe, and Mn (dissolved and total)
As (total), As (III), As (V), Turbidity, Hardness, Total Al, Fe, and Mn
2
As (total), Alkalinity, pH, Total Al, Fe, and Mn
$KMnO_4$
Backwash Water
FILTRATION (GREENSAND)
As (total), As (III), As (V), Turbidity, Hardness, Total Al, Fe, and Mn
3
As (total), Alkalinity, pH, Total Al, Fe, and Mn
Approx 2/3 of Flow Treated Using Zeolite Softening
ZEOLITE SOFTENING
Regenerant Waste
As (total), Alkalinity, pH, Total Al, Fe, and Mn
As (total), As (III), As (V), Turbidity, Hardness, Total Al, Fe, Mn
4
DA: Cl_2
H_2SiF_6
DISTRIBUTION SYSTEM
LEGEND
1
Water Sampling Location
SS
Sludge Sampling Location
DA: Cl_2
Disinfectant Addition Point
FILTRATION
Unit Process
$KMnO_4$
Chemical Added to Unit Process

Figure 4-2. Process Flow Diagram and Sampling Locations at Plant A

Table 4-3. Analytical Results from Preliminary Sampling at Plant A (April 22–May 13, 1998)

Sampling Date		4/22/98(a)				4/29/98				5/6/98				5/13/98			
Sampling Location Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L(b)	411 410	387 385	382 381	387 387	409	385	381	387	407	391	387	389	413	375	382	374
Turbidity(c)	NTU	24 22	5.1 5.2	0.3 0.2	0.2 0.1												
pH	—	7.6 7.6	7.6 7.6	7.7 7.7	7.6 7.6	7.7	7.6	7.6	7.6	7.7	7.7	7.7	7.7	7.7	7.6	7.5	7.5
Hardness	mg/L(b)	306 302	297 306	292 296	13.1 7.9												
Ca Hardness	mg/L(b)	150 150	150 160	145 147	10.7 5.6												
Mg Hardness	mg/L(b)	157 152	147 146	147 148	2.5 2.3												
Total Fe	µg/L	2,650 2,620	2,540 2,530	50 50	<30 160	2,520	2,570	50	30	2,540	2,380	70	50	2,390	2,290	120	<30
Total Mn	µg/L	60 50	50 70	60 60	30 60	30	20	20	30	30	30	50	<20	50	50	<20	<20
As (total)	µg/L	21.4 21.6	20.0 18.8	3.1 2.4	3.3 3.5	23.7	22.1	3.2	2.7	18.6	20.3	2.1	1.3	20.2	21.3	2.0	0.6
As (total soluble)	µg/L	24.5 24.7	4.1 4.1	2.8 2.8	3.6 3.6												
As (particulate)	µg/L	ND ND	15.9 14.7	0.3 ND	ND ND												
As (III)	µg/L	19.6 22	0.2 0.1	0.1 0.2	0.1 0.2												
As (V)	µg/L	4.9 2.7	3.9 4.0	2.7 2.6	3.5 3.4												

(a) Duplicate samples were taken on 4/22/98.
(b) As $CaCO_3$.
(c) Inlet turbidity concentrations may be elevated due to oxidation of iron occurring after sample collection and prior to laboratory analysis.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.
ND = not detected.
NTU = nephelometric turbidity units.

The source water at Plant A would be classified as hard to very hard and the zeolite softening process effectively reduced hardness from approximately 304 mg/L (as $CaCO_3$) to 11 mg/L (as $CaCO_3$). As stated previously, approximately two-thirds of the water processed at Plant A is treated using zeolite softening. Turbidity also was effectively removed at Plant A with concentrations decreasing from approximately 23 NTU to 5.2 NTU following aeration, chlorination, and sedimentation. Relatively high turbidity concentrations at the inlet may be a result of iron oxidation after the sample was collected and prior to analysis. After filtration the turbidity decreased to approximately 0.3 NTU. Total manganese concentrations were relatively constant throughout the treatment process with concentrations ranging between 60 and <20 µg/L. Total iron concentrations ranged from 2,390 to 2,635 µg/L in the source water and <30 to 50 µg/L in the finished water. Total iron concentrations were relatively constant between the plant inlet and prior to filtration, with significant iron removal occurring as a result of filtration. It appears that the primary arsenic removal mechanism at Plant A is adsorption and coprecipitation of As(V) with the iron hydroxide precipitates.

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, except for the addition of aluminum. The 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 determined 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 four locations that were used during the preliminary sampling phase. Alkalinity, pH, total arsenic, total aluminum, total iron, and total manganese analyses were performed on sampled 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 supernatant discharge 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 at each location.

4.2.4.1 Arsenic

Table 4-4 provides a summary of the arsenic analytical results collected at the four treatment process locations. Total arsenic concentrations at the inlet ranged from 12.5 µg/L to 42.5 µg/L, with an average concentration of 20.7 µg/L. These concentrations were basically consistent with what had been observed during the preliminary phases of the study. Total arsenic concentrations at the

Table 4-4. Summary of Arsenic Analytical Results at Plant A (June 24, 1998–June 16, 1999)

Parameter	Sample Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	Inlet	µg/L	49	12.5	42.5	20.7	3.8
	Prefiltration	µg/L	49	3.8	23.8	19.3	4.0
	After filtration	µg/L	49	1.0	8.0	3.1	1.1
	After softening	µg/L	49	0.8	10.1	2.8	0.1
As (total soluble)	Inlet	µg/L	12	15.1	25.4	20.3	3.7
	Prefiltration	µg/L	12	3.1	10	5.3	2.3
	After filtration	µg/L	12	2.3	4.1	3.0	0.5
	After softening	µg/L	12	1.7	10.2	4.0	2.5
As (particulate)	Inlet	µg/L	12	<0.1	4.9	1.8	2.1
	Prefiltration	µg/L	12	10	17.9	14.3	2.4
	After filtration	µg/L	12	<0.1	5.1	0.8	1.5
	After softening	µg/L	12	<0.1	<0.1	<0.1	NA
As (III)	Inlet	µg/L	12	10.8	21.3	16.0	3.7
	Prefiltration	µg/L	12	0.1	4.8	0.9	1.3
	After filtration	µg/L	12	0.1	0.8	0.4	0.2
	After softening	µg/L	12	<0.1	0.8	0.5	0.3
As (V)	Inlet	µg/L	12	1.1	10.8	4.3	2.4
	Prefiltration	µg/L	12	2.7	5.4	4.0	0.8
	After filtration	µg/L	12	2.0	3.6	2.5	0.5
	After softening	µg/L	12	1.2	10.2	3.1	2.6

PF sampling location ranged from 3.8 µg/L to 23.8 µg/L, with an average of 19.3 µg/L. It should be noted that only three sampling events produced approximately 3 to 6 µg/L of arsenic at the PF location. Therefore, only minor arsenic removal occurred during the sedimentation process. Samples collected after filtration contained total arsenic concentrations ranging from 1.0 µg/L to 8.0 µg/L, with an average of 3.1 µg/L; and total arsenic concentrations averaged 2.8 µg/L in samples collected after the zeolite softening process. The data indicate that the majority of the arsenic removal occurred in the filters.

The average removal percentage of total arsenic between the IN and AF sampling locations was 85% and between the IN and AS locations was 87%. These data indicate that the vast majority of the arsenic was removed during filtration and that the softening process did little to improve removal efficiency. The average arsenic removal predicted by McNeill and Edwards (1997) sorption model was 76%, which is within the 90th percentile confidence interval of the model. Figure 4-3 is a graph showing the total arsenic concentration recorded at each sampling location throughout the study, as well as the removal percentage calculated for each sampling event. As shown in this figure, total arsenic concentrations at the IN and AF sampling locations remain relatively constant throughout the study with no seasonal effects noted. The three dips in the arsenic concentrations at the PF sampling location may have been a result of reduced process flow occurring during the winter months, resulting in longer retention times in the sedimentation basins.

Particulate arsenic concentrations averaged 1.8 µg/L at the inlet, 14.3 µg/L before filtration, 0.8 µg/L after filtration, and <0.1 after softening. The increase in particulate arsenic at the PF sampling location was due to sorption and coprecipitation of arsenic on/with iron hydroxide precipitates. This observation was supported by the decrease of particulate arsenic in the AF sampling location.

As(III) and As(V) make up the soluble portion of the total arsenic concentration. The average As(III) and As(V) concentrations in the source water were 16.0 and 4.3 µg/L, respectively. The As(III) was oxidized to As(V) by chlorination prior to the PF sampling location and the As(V) was sorbed to and coprecipitated with the iron hydroxide. Therefore, the majority of the total arsenic in the water prior to filtration was in particulate form (i.e., attached to the iron). Average As(III) concentrations remained low and relatively constant following oxidation and the average As(V) concentrations decreased slightly from 4.3 µg/L in the source water to 3.1 µg/L after softening.

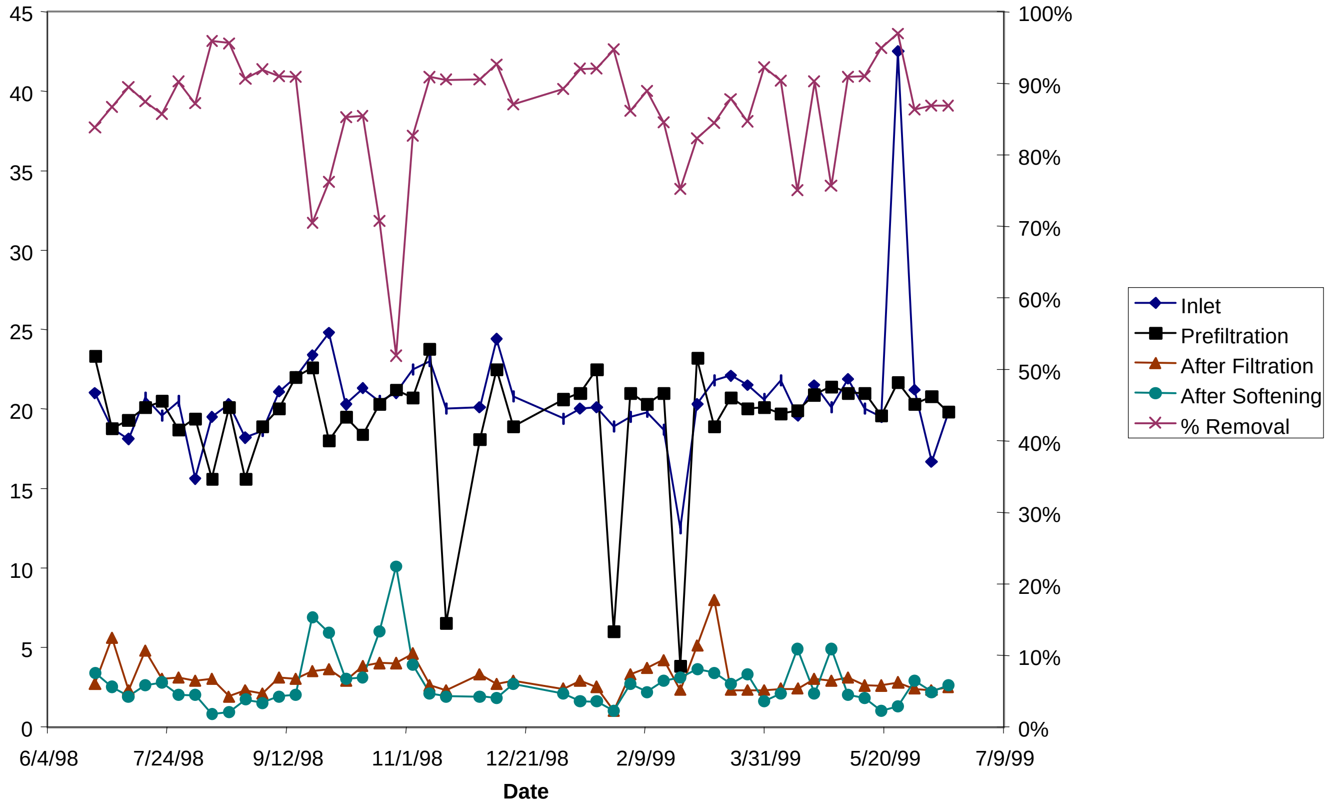


Figure 4-3. Total Arsenic Analytical Results During Long-Term Sampling at Plant A

Figure 4-4 shows As(III), As(V), and particulate arsenic concentrations measured during the long-term evaluation.

Plant A water treatment system was able to consistently remove arsenic to low levels (i.e., average treated water total arsenic concentration was 2.8 µg/L). The primary arsenic removal mechanism appears to be coprecipitation with iron hydroxide precipitates followed by filtration. The simplified sorption model developed by McNeill and Edwards (1997) appears to approximate the arsenic removal process at Plant A reasonably well, although the model consistently underestimated the removal by approximately 11%.

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 were relatively constant ranging between 347 mg/L and 415 mg/L (as $CaCO_3$) in the source water, with an average of 413 mg/L. As observed during the preliminary sampling, a slight decrease in average alkalinity to 398 mg/L was observed after oxidation of the iron due to the stoichiometry of iron oxidation process. Turbidity concentrations ranged from 13.8 NTU to 26 NTU, with an average of 19 NTU. Increased turbidity concentrations may have resulted from oxidation of iron occurring after the sample was collected and prior to analysis at the laboratory. The bulk of the turbidity was removed during sedimentation, reducing concentrations to an average of 5.1 NTU. The system effectively removed turbidity with an average finished water concentration of 0.1 NTU. Figure 4-5 plots inlet alkalinity, pH, and hardness concentrations observed throughout the duration of the study.

The pH was constant, averaging 7.6 or 7.7 at each sampling location within the treatment process. This pH is in the range (pH 5.5 to 8.5) where arsenic removal efficiency by iron oxides is not affected (Sorg and Longsdon, 1978; Sorg, 1993; Hering et al., 1996). Total hardness concentrations ranged from 286 mg/L to 432 mg/L (as $CaCO_3$) in the plant source water, with an average of 316 mg/L. These concentrations were relatively constant with the exception of the sample collected on September 30, 1998. Similar to alkalinity, a slight decrease in hardness was observed following oxidation of iron, resulting in an average hardness concentration of 291 mg/L. As would be expected, considerable removal of hardness was observed following zeolite softening, reducing total hardness to an average of 5.2 mg/L (as $CaCO_3$).

Total iron concentrations at the inlet sampling location ranged from 762 µg/L to 3,289 µg/L and averaged 2,284 µg/L. At the PF sampling location, total iron concentrations ranged from 267 µg/L to 3,026 µg/L and averaged 2,241 µg/L. Therefore, the total iron concentrations were relatively constant between the source and just prior to the filters. However, dissolved iron analytical results show that approximately half of the iron entering the plant was in the reduced form. The average dissolved iron concentration in source water was 953 µg/L. After aeration and chlorination, practically all iron was oxidized with concentrations of <30 µg/L at all other sampling locations throughout the study. The filtration process removed most of the iron, reducing average total iron concentrations to 71.5 µg/L. The zeolite softener filtered additional iron particles and the average total iron concentration after the softening process was <30 µg/L. 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.

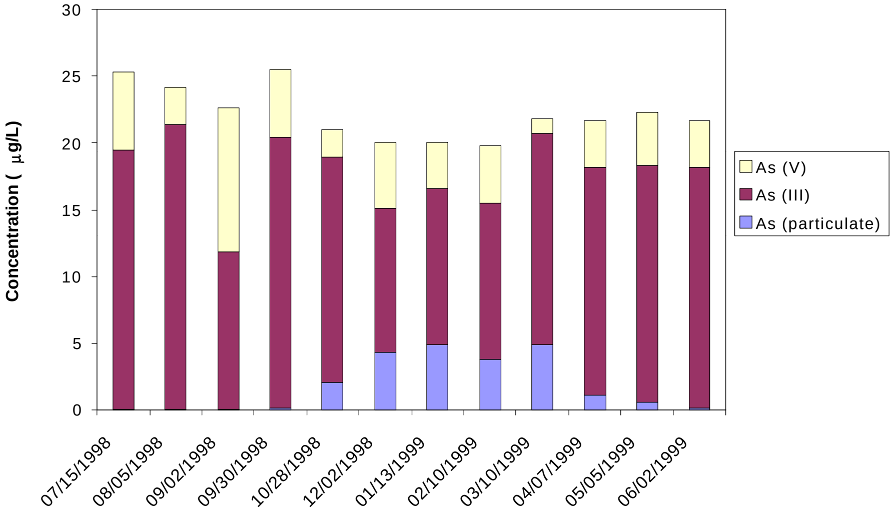
Total aluminum concentrations averaged 17.9 µg/L at the inlet and <11 µg/L at the other three sampling locations. Concentrations of dissolved aluminum averaged 20.4 µg/L in the source water and <11 µg/L at the other three sampling locations. It did not appear that coprecipitation with aluminum hydroxide was a significant factor in the removal of arsenic, because only minor concentrations were present.

Total and dissolved manganese concentrations were relatively low. Total manganese concentrations averaged 22.2 µg/L in the source water, 42.4 µg/L prior to filtration, 22.7 µg/L after filtration, and 5.1 µg/L after softening. The increase in manganese prior to filtration is most likely due to the addition of $KMnO_4$ for the greensand filters. Average dissolved manganese concentrations were 21.0 µg/L in the source water, 17.5 µg/L prior to filtration, 9.0 µg/L after filtration, and 2.5 µg/L after softening.

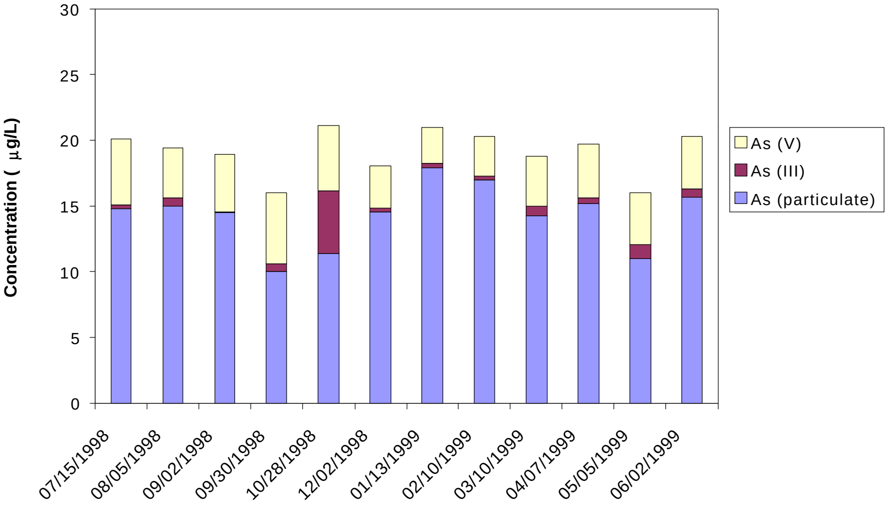
4.2.4.3 Supernatant Discharge

Backwash water is generated from backwashing the filtration units every 24 hours and from backwashing the zeolite resin softeners after every 275,000 gallons processed. All backwash water and regenerant waste at Plant A is sent to an outdoor settling pond and supernatant from the pond is discharged continuously to the sanitary sewer. Supernatant discharge samples were collected at the outfall of the settling pond into the sanitary sewer. Results of the supernatant discharge sampling are summarized in Table 4-6.

Inlet



Prefiltration



After Softening

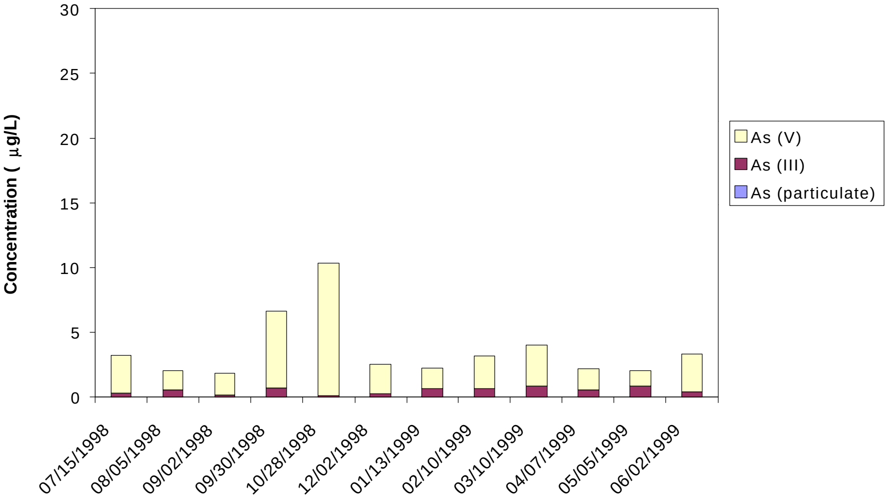


Figure 4-4. Arsenic Form and Species Analytical Results During Long-Term Sampling at Plant A

Table 4-5. Summary of Water Quality Parameter Analytical Results at Plant A (June 24, 1998–June 16, 1999)

Parameter	Sample Location	Units	Number of Samples	Minimum	Maximum	Average	Standard Deviation
Alkalinity	Inlet	mg/L	49	347	415	413	12.9
	Prefiltration	mg/L	49	380	415	398	6.2
	After filtration	mg/L	49	378	409	393	6.6
	After softening	mg/L	49	377	414	394	6.7
Turbidity(a)	Inlet	NTU	12	13.8	26	19	3.4
	Prefiltration	NTU	12	3.0	7.2	5.1	0.9
	After filtration	NTU	12	0.1	2.3	0.5	0.6
	After softening	NTU	12	0.05	0.3	0.1	0.08
pH	Inlet	–	49	7.5	7.8	7.6	0.05
	Prefiltration	–	49	7.6	8.0	7.7	0.09
	After filtration	–	49	7.5	8.0	7.6	0.09
	After softening	–	49	7.5	8.1	7.7	0.14
Total Hardness	Inlet	mg/L	11	286	432	316	41.3
	Prefiltration	mg/L	12	270	308	291	11.9
	After filtration	mg/L	12	165	317	280	38.9
	After softening	mg/L	12	3.0	11.4	5.2	2.5
Total Al	Inlet	µg/L	49	<11	324	17.9	45.4
	Prefiltration	µg/L	49	<11	35.9	<11	6.5
	After filtration	µg/L	49	<11	22.8	<11	5.4
	After softening	µg/L	49	<11	34.4	<11	6.6
Total Fe	Inlet	µg/L	49	762	3,289	2,284	424
	Prefiltration	µg/L	49	267	3,026	2,241	565
	After filtration	µg/L	49	<30	440	71.5	96.4
	After softening	µg/L	49	<30	128	<30	22.3
Total Mn	Inlet	µg/L	49	14.5	57.3	22.2	7.1
	Prefiltration	µg/L	49	14.9	694	42.4	103
	After filtration	µg/L	49	4.8	95.8	22.7	16.2
	After softening	µg/L	49	1.2	24.3	5.1	5.6
Dissolved Al	Inlet	µg/L	12	<11	121	20.4	33.3
	Prefiltration	µg/L	12	<11	24.1	<11	7.5
	After filtration	µg/L	12	<11	51.8	<11	13.6
	After softening	µg/L	12	<11	68.6	<11	18.2
Dissolved Fe	Inlet	µg/L	12	<30	1,943	953	720
	Prefiltration	µg/L	12	<30	<30	<30	NA
	After filtration	µg/L	12	<30	<30	<30	NA
	After softening	µg/L	12	<30	<30	<30	NA
Dissolved Mn	Inlet	µg/L	12	17.4	24.1	21.0	2.2
	Prefiltration	µg/L	12	13.9	21.6	17.5	2.3
	After filtration	µg/L	12	2.9	17.6	9.0	4.1
	After softening	µg/L	12	1.2	5.0	2.5	1.4

(a) Inlet turbidity concentrations may be elevated due to oxidation of iron occurring after sample collection and prior to laboratory analysis.

The total arsenic concentrations in the supernatant discharge ranged from 9.4 µg/L to 167.0 µg/L, with an average of 72.4 µg/L. Approximately 40% of the total arsenic concentration was soluble and 60% was particulate. As expected, the average iron concentration in the supernatant water was relatively high at 5,780 µg/L. Practically all of the iron is in the oxidized form. The particulate arsenic is most likely sorbed to unsettled iron solids.

4.2.4.4 Sludge

Sludge is generated from cleaning sedimentation basins and from backwashing the greensand filters and zeolite resin softeners. The sedimentation basins are cleaned out once per year, and the wastewater and sludge are sent directly to the sanitary sewer. A water backwash is performed on the greensand filters every 24 hours and an air backwash is performed every 72 hours. Regeneration of the zeolite softeners occurs after every 275,000 gallons processed, and involves using a 27% solution of NaCl. The regeneration takes about 1 hour to complete, and consists of a 12-minute backwash, a 20-minute brine rinse, and slow/fast rinse cycle.

The backwash water and regenerant waste are sent to an outdoor settling pond. Historically, the retention pond

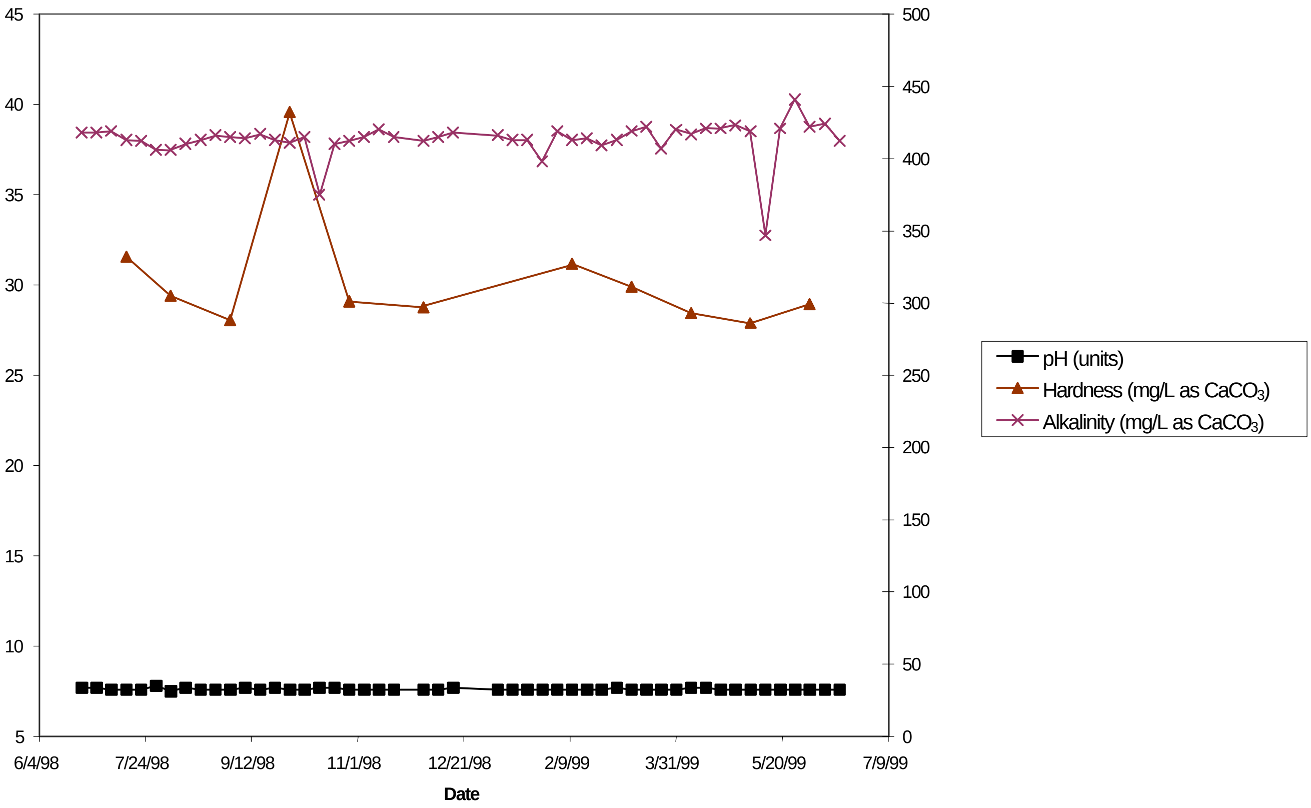


Figure 4-5. Inlet pH, Hardness, and Alkalinity Analytical Results at Plant A

was drained and the sludge removed once per year. Sludge then was transferred to the municipal wastewater treatment plant and placed on the wastewater plant drying beds. After drying, the sludge would be placed on local farm fields.

During the long-term evaluation phase of this project, sludge samples were collected from three locations within the sludge settling pond at Plant A. These sludge samples were analyzed for pH, percent moisture, total arsenic, total aluminum, total manganese, and total iron. Also, a TCLP test was performed on each sample to determine the quantities of leachable arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. Total arsenic concentrations ranged from 255 mg/kg to 392 mg/kg, and total iron ranged from 78,600 mg/kg to 93,000 mg/kg. Arsenic was detected at less than 0.05 mg/L in the TCLP extraction procedure. Also, concentrations were below the more stringent regulatory levels in California for total arsenic. Table 4-7 presents the results of sludge analysis at each of the three sampling locations.

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

Parameter	Units	Number of Sample Events	Minimum	Maximum	Average	Stardard Deviation
As (total)	µg/L	8	9.4	167.0	72.4	59.4
As (soluble)	µg/L	8	3.3	138.0	28.7	46.3
As (particulate)	µg/L	8	5.2	111.5	43.6	34.9
pH	–	8	4.6	7.9	7.2	1.1
Total Al	µg/L	8	<11	20.0	12.2	5.0
Total Fe	µg/L	8	1,048	14,470	5,780	4,527
Total Mn	µg/L	8	101.5	1746	974	666
Dissolved Al	µg/L	8	<11	<11	<11	NA
Dissolved Fe	µg/L	8	<30	92.0	<30	27.1
Dissolved Mn	µg/L	8	16.5	1020	186.3	342

Table 4-7. Analytical Results of Sludge Sampling at Plant A (November 18, 1998)

Parameter	Unit	*D.L.	Location 1	Location 2	Location 3
As-TCLP	mg/L	0.05	<0.05	<0.05	<0.05
Ba-TCLP	mg/L	1.0	19.4	18.2	5.1
Cd-TCLP	mg/L	0.020	<0.020	<0.020	<0.020
Cr-TCLP	mg/L	0.030	<0.030	0.040	<0.030
Pb-TCLP	mg/L	0.20	<0.20	<0.20	<0.20
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	<0.02	<0.02	<0.02
Percent moisture	%	0.1	40.5	46.9	46.1
TCLP extraction	–		complete	complete	complete
pH	–		7.6	7.6	7.5
Total As	mg/kg, dry		255[(a)]	392	372
Total Al	mg/kg, dry		7,300	5,000	4,580
Total Fe	mg/kg, dry		78,600[(a)]	89,070	93,000
Total Mn	mg/kg, dry		NA	1,490	1,950

* Detection limit

(a) Re-analyzed by Wilson Environmental Laboratories.

4.3 Plant B

Source water sampling at Plant B was performed in February 1998. Preliminary sampling consisted of weekly water sampling for a four-week period in May 1998. Long-term sampling was initiated in June 1998 and continued through December 1998. Arsenic speciation sampling was conducted every fourth week. The third phase of this study also included collection and analysis of recycle supernatant during two sampling events in November 1998 and January 1999. No sludge samples were collected at Plant B.

4.3.1 Plant B Description

Plant B began operation in the spring of 1993 and provides a portion of the treated water for approximately 6,000 residents and up to 20,000 tourists. The plant utilizes an iron removal process for water treatment and can process 1.4 mgd. The plant typically operates from June through November. Figure 4-6 is a schematic diagram of the treatment process at Plant A.

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

- **Intake.** The plant intake consists of water from a mining tunnel and recycle supernatant from backwashing activities.
- **Chlorination.** Approximately 3 mg/L (37-40 lb/day) of chlorine is added for iron and manganese oxidation.
- **Reaction Vessels.** There are two reaction vessels in series and sulfur dioxide (3-4 lb/day) is added after the first reaction vessel based on manufacturers recommendation to reduce polysulfide in the filter media. These reaction vessels are designed to handle 4,000 gallons per minute (gpm).
- **Filtration Vessel.** The filtration vessel contains five layers of filtering media, including anthracite coal. The filtering rate is 10 gpm/ft^2, and the vessel is backwashed every 8 hours or at 10 pounds per square inch (psi) pressure differential.
- **Blending.** Treated water is blended with nontreated water from another mining tunnel and one spring in the finished water wet well. No post-treatment chlorination is performed because the residual chlorine is 1 to 2 mg/L.
- **Backwash.** Backwash water is sent to a concrete vat where the solids are settled out and the supernatant water is recycled after about 90 minutes of settling. This water is sent back to the intake where it is blended with the raw water from the mining tunnel. The solids settle to the bottom of the concrete vat and are then sent to a sludge holding tank. This sludge is processed through a filter press and then sent to a municipal landfill.

4.3.2 Initial Source Water Sampling

Source water at Plant B comes from surface water runoff transported via a mining tunnel. Following treatment, this source water is blended with several other sources, including another mining tunnel, one spring, and three deep wells. These other sources do not require treatment. The blended water is chlorinated and distributed. Based on discussions with plant personnel, the water treated at Plant B has a turbidity of approximately 4-14 NTU and is supplied at a flowrate of approximately 7.5 cubic feet per second (cfs). Historically, arsenic concentrations in the source water have ranged from 40 to 80 µg/L.

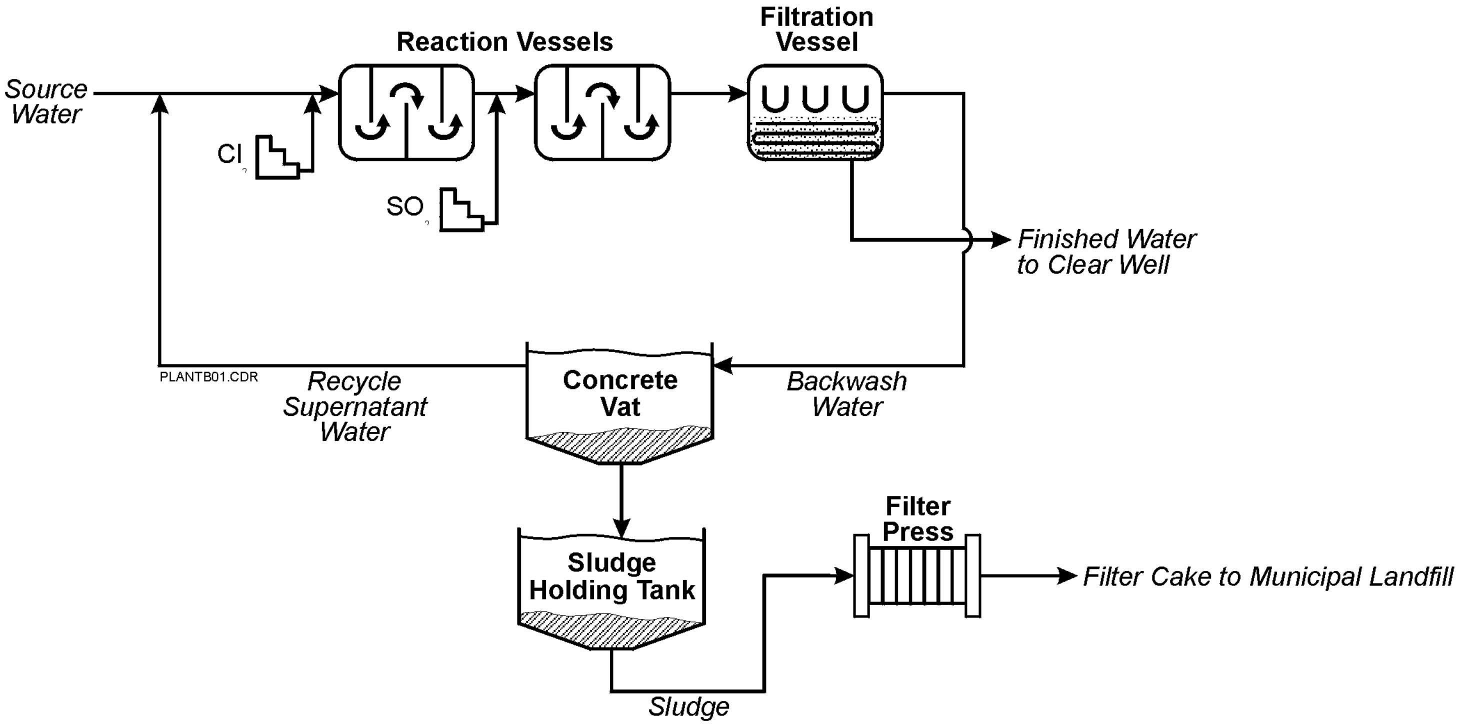

Reaction Vessels
Filtration Vessel
Source Water
Cl2
SO2
Finished Water to Clear Well
PLANTB01.CDR
Recycle Supernatant Water
Concrete Vat
Backwash Water
Filter Press
Sludge Holding Tank
Filter Cake to Municipal Landfill
Sludge

Figure 4-6. Schematic Diagram, Plant B

An initial site visit to Plant B was conducted on February 4, 1998, and source water samples were collected at that time. During this sampling event, samples were collected and analyzed for arsenic (total, particulate, soluble, As[III], and As[V]) and other water quality parameters that may affect arsenic removal. Table 4-8 presents the analytical results from the source water sampling. The total arsenic concentrations in the source water averaged 48.6 µg/L. Particulate arsenic averaged at 35.7 µg/L and the soluble arsenic was mostly As(V), measured at 10.8 µg/L. The average As(III) concentration measured during the initial source water sampling event was 2.1 µg/L. Also, the inlet iron concentration averaged 890 µg/L, the aluminum concentration was less than the detection limit, and the average manganese concentration was 50 µg/L.

Alkalinity concentrations averaged 135 mg/L (as $CaCO_3$) and total hardness concentrations averaged 522.5 mg/L. Therefore, the source water was considered very hard. Turbidity averaged 4.0 NTU and the sulfate concentration averaged 420 mg/L. The pH averaged 7.7, which is in the range where no effect on arsenic removal efficiency using iron hydroxide precipitation has been observed in previous studies (Sorg and Logsdon, 1978; Sorg, 1993; Hering et al., 1996).

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: the inlet to the plant (IN), before the filtration process (PF), and after the filtration process (AF). Sample taps were used to collect samples at each location. The IN samples were collected at the influent of the system after the source water was combined with the recycle supernatant from the concrete vat. The PF samples were collected after addition of chlorine and processing of water through the two reaction vessels. AF samples were collected immediately following filtration and represent finished water. Figure 4-7 is a process flow diagram for Plant B that shows sampling locations used during the preliminary and long-term sampling, as well as the analyses performed on samples collected from each location.

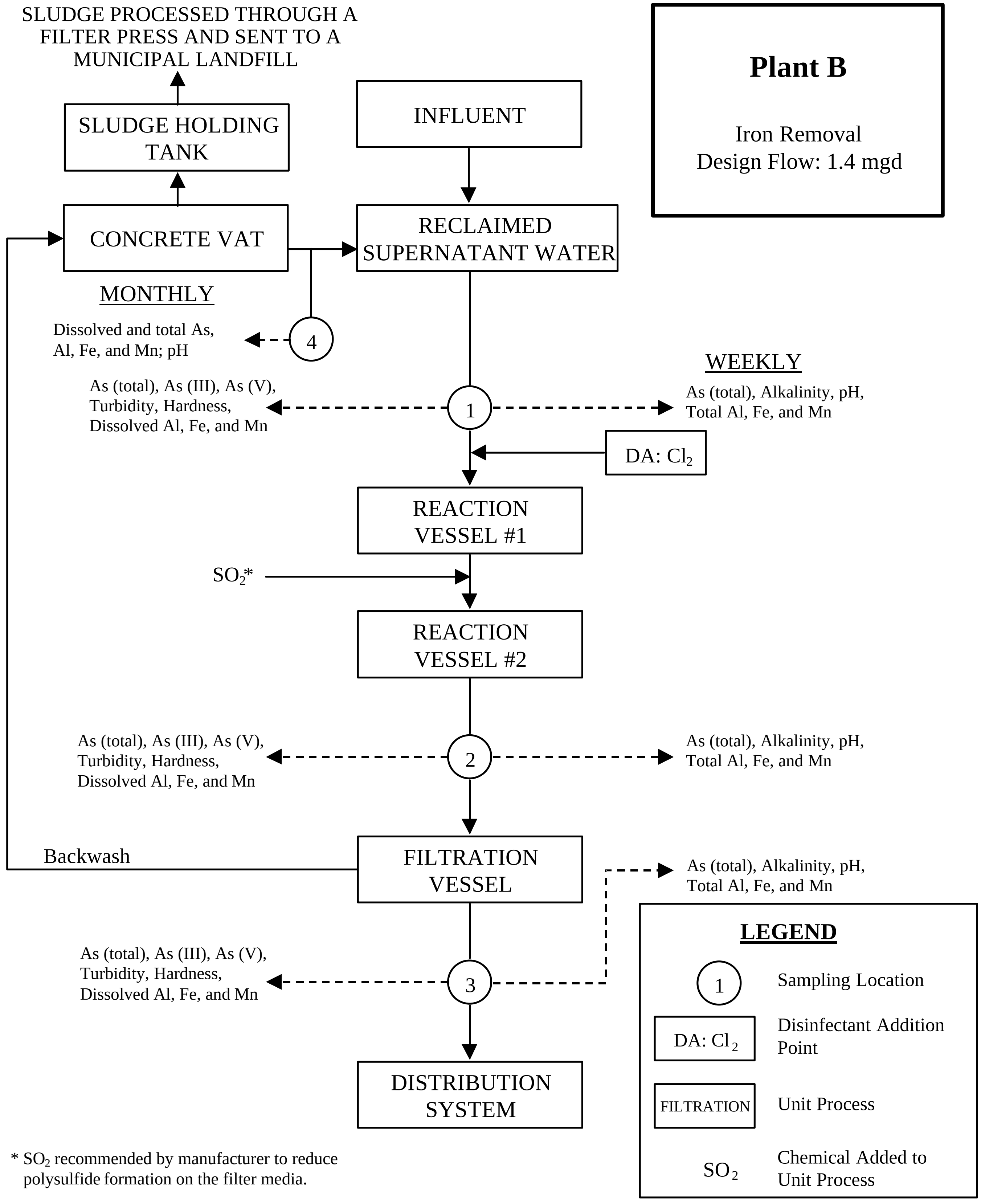
Alkalinity, pH, total iron, total manganese, and total arsenic analysis were performed on all water samples collected at Plant B. Turbidity and hardness analysis and arsenic speciation sampling were conducted at each sampling location once during the preliminary study. Arsenic form (soluble and particulate) and species (arsenate and arsenite) were determined as part of the arsenic speciation. Table 4-9 presents the results of the four-week preliminary sampling period.

Results from the preliminary sampling events indicated that inlet total arsenic concentrations ranged from 34.1 to 45.7 µg/L. The total arsenic in the source water was primarily particulate and the soluble fraction of the total arsenic was primarily As(V). The As(III) concentrations measured during the preliminary sampling period was relatively low, averaging only 2.6 µg/L. As expected, the species of arsenic did not vary significantly during the treatment process. The average total arsenic removed was approximately 64% during preliminary sampling, leaving an average of 15.0 µg/L of total arsenic in the finished water. Arsenic speciation sampling during the first week of the sampling period indicated that soluble arsenic was not removed and that only the arsenic entering the treatment plant as particulate was removed. Because

Table 4-8. Source Water Analytical Results at Plant B (February 4, 1998)

Parameter	Unit	Primary Sample	Duplicate Sample	Average Concentration
Alkalinity	mg/L[(a)]	134	136	135
Sulfate	mg/L	420	420	420
Turbidity	NTU	4	4.1	4.0
pH	–	7.7	7.7	7.7
Hardness	mg/L[(a)]	537	508	522
Ca Hardness	mg/L[(a)]	402	370	386
Mg Hardness	mg/L[(a)]	135	138	136
Total Al	µg/L	<400	<400	<400
Total Fe	µg/L	910	870	890
Total Mn	µg/L	60	40	50
NO_3–NO_2 (N)	mg/L[(b)]	0.11	0.11	0.11
TOC	mg/L	1	1	1
As (total)	µg/L	49.7	47.6	48.6
As (total soluble)	µg/L	13.0	12.8	12.9
As (particulate)	µg/L	36.7	34.8	35.7
As (III)	µg/L	2.0	2.3	2.1
As (V)	µg/L	11.0	10.5	10.8

(a) As $CaCO_3$.
(b) Combined NO_3–N and NO_2–N.


SLUDGE PROCESSED THROUGH A FILTER PRESS AND SENT TO A MUNICIPAL LANDFILL
SLUDGE HOLDING TANK
INFLUENT
Plant B
Iron Removal
Design Flow: 1.4 mgd
CONCRETE VAT
RECLAIMED SUPERNATANT WATER
MONTHLY
Dissolved and total As, Al, Fe, and Mn; pH
4
WEEKLY
As (total), As (III), As (V), Turbidity, Hardness, Dissolved Al, Fe, and Mn
1
As (total), Alkalinity, pH, Total Al, Fe, and Mn
DA: Cl_2
REACTION VESSEL #1
SO_2*
REACTION VESSEL #2
As (total), As (III), As (V), Turbidity, Hardness, Dissolved Al, Fe, and Mn
2
As (total), Alkalinity, pH, Total Al, Fe, and Mn
Backwash
FILTRATION VESSEL
As (total), Alkalinity, pH, Total Al, Fe, and Mn
As (total), As (III), As (V), Turbidity, Hardness, Dissolved Al, Fe, and Mn
3
DISTRIBUTION SYSTEM
LEGEND
1
Sampling Location
DA: Cl_2
Disinfectant Addition Point
FILTRATION
Unit Process
SO_2
Chemical Added to Unit Process

* SO_2 recommended by manufacturer to reduce polysulfide formation on the filter media.

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

Table 4-9. Analytical Results from Preliminary Sampling at Plant B (May 7 through May 28, 1998)

Sampling Date		5/7/98[a]			5/14/98			5/21/98			5/28/98		
Sampling Location Parameter	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L[b]	149 146	142 142	143 142	144	141	144	156	147	148	151	147	144
Turbidity	NTU	3.6 3.4	3.6 3.4	<0.1 <0.1									
pH	–	7.9 7.9	7.6 7.6	7.7 7.7	8.1	7.9	7.8	7.9	7.7	7.7	8.0	7.8	7.8
Hardness	mg/L[b]	431 530	469 486	498 456									
Ca Hardness	mg/L[b]	290 392	332 350	360 317									
Mg Hardness	mg/L[b]	141 138	137 136	138 139									
Total Fe	µg/L	520 560	550 620	50 <30	690	870	80	840	780	70	1,230	1,300	110
Total Mn	µg/L	40 40	50 50	<20 <20	60	50	<20	70	40	<20	50	40	<20
As (total)	µg/L	28.9 39.4	34.5 38.4	13.9 13.7	45.5	48.9	13.6	41.2	41.4	15.2	45.7	50.9	17.5
As (total soluble)	µg/L	14.8 15.1	14.5 14.1	14.9 14.6									
As (particulate)	µg/L	14.1 24.3	20.0 24.3	<0.1 <0.1									
As (III)	µg/L	1.2 4.0	2.8 2.7	2.3 2.6									
As (V)	µg/L	13.6 11.1	11.7 11.4	12.6 12.0									

(a) Duplicate samples were taken on 5/7/98.

(b) As $CaCO_3$.

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

of this, the simplified sorption model proposed by McNeill and Edwards (1997) does not apply to the arsenic removal results at this plant.

Other water quality parameters also were analyzed to support understanding of mechanisms of arsenic removal. Similar to Plant A, alkalinity concentrations and pH decreased slightly between the IN and PF sampling locations, due to the stoichiometry of iron oxidation in which hydrogen ions are produced and alkalinity is destroyed (Benefield and Morgan, 1990). As would be expected, alkalinity and pH remained constant between the PF and AF sampling locations. Source water turbidity concentrations averaged 3.5 NTU, which was consistent with plant data and data obtained during the initial source water sampling. Unlike Plant A, increased turbidity due to oxidation of iron after sample collection and prior to analysis was not an issue at Plant B because the iron entered the facility in oxidized form. Plant B effectively removed turbidity with finished water concentrations averaging <0.1 NTU. Also, as observed during the source water sampling event, the source water is very hard. No removal of hardness by the treatment process was observed during the preliminary sampling.

Total manganese concentrations were relatively low, averaging 55 µg/L in the source water, 45 µg/L prior to filtration, and <20 after filtration. Total iron concentrations averaged 825 µg/L in the source water, 884 µg/L prior to filtration, and 75 µg/L after filtration. The inlet iron concentrations were consistent with those observed during the initial source water sampling event. It appeared that arsenic removal was primarily achieved through filtration of iron particles to which arsenic was sorbed prior to treatment at Plant B.

Only minor changes were made to the approach for the long-term evaluation as a result of the preliminary sampling effort. As with Plant A, sampling locations and primary analytes remained unchanged, except for the addition of aluminum. Iron and manganese analysis were 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 determined dissolved aluminum, iron, and manganese concentrations.

4.3.4 Long-Term Sampling

Long-term sampling and analysis consisted of 26 weeks of water sampling at the three locations used during the preliminary sampling phase. All weekly samples were analyzed for total arsenic, alkalinity, pH, total aluminum, total iron, and total manganese. Turbidity, hardness, dissolved aluminum, dissolved iron, and dissolved manganese analysis, as well as arsenic speciation sampling were conducted at each sampling location a total of seven times during the long-term sampling phase. Arsenic speciation sampling included the determination of soluble arsenic, particulate arsenic, As(V), and As(III) concentrations. Recycle supernatant discharge analysis was performed twice during this phase. Sludge samples were not collected at Plant B during this study; however, results from sludge sampling conducted in 1994 are discussed in Subsection 4.3.4.4. The following subsections summarize the arsenic, water quality parameter, and residual analytical results.

4.3.4.1 Arsenic

Table 4-10 provides a summary of the arsenic analytical results collected at the three sampling locations at Plant B. Total arsenic concentrations at the inlet location ranged from 33.3 to 97.9 µg/L, with an average concentration of 48.5 µg/L. Total arsenic concentrations at the prefiltration location ranged from 6.7 to 81.1 µg/L

Table 4-10. Summary of Arsenic Analytical Results at Plant B (June 11, 1998–December 8, 1998)

Parameter	Sample Location	Units	Number of Samples	Minimum	Maximum	Average	Standard Deviation
As (total)	Inlet	µg/L	26	33.3	97.9	48.5	16.3
	Prefiltration	µg/L	26	6.7	81.1	41.8	16.6
	After filtration	µg/L	26	5.3	19.7	11.9	3.3
As (total soluble)	Inlet	µg/L	7	4.9	15.7	11.9	3.7
	Prefiltration	µg/L	7	0.8	14.4	10.8	4.7
	After filtration	µg/L	7	5.3	20.1	11.4	4.4
As (particulate)	Inlet	µg/L	7	20.9	70.0	38.9	18.3
	Prefiltration	µg/L	7	17.9	65.8	40.1	18.0
	After filtration	µg/L	7	<0.1	3.1	1.3	1.4
As (III)	Inlet	µg/L	7	0.1	2.2	1.4	0.82
	Prefiltration	µg/L	7	0.2	0.8	0.5	0.21
	After filtration	µg/L	7	0.1	0.8	0.3	0.28
As (V)	Inlet	µg/L	7	3.1	15.0	10.5	3.9
	Prefiltration	µg/L	7	0.4	14.0	10.2	4.7
	After filtration	µg/L	7	5.1	19.8	11.1	4.4

with an average of 41.8 µg/L. Therefore, very little arsenic was removed prior to filtration. Samples collected at the AF location contained total arsenic concentrations ranging from 5.3 to 19.7 µg/L, with an average of 11.9 µg/L. The average removal efficiency of total arsenic (comparing raw water to finished water concentrations) was 74%. Figure 4-8 is a graph showing the arsenic concentrations recorded at each sampling location throughout the study.

Particulate arsenic concentrations averaged 38.9 µg/L at the inlet, 40.1 µg/L prior to filtration, and 1.3 µg/L after filtration. These results indicate that very little adsorption and coprecipitation of soluble arsenic occurs during the treatment process. Instead, the arsenic most likely is attached to the oxidized iron particles prior to entering the facility.

This observation is supported by the As(III) and As(V) analytical results. As(III) and As(V) make up the soluble fraction of the total arsenic concentration. As(III) concentrations in the source water ranged from 0.1 to 2.2 µg/L, with an average of 1.4 µg/L. Some of the As(III) was converted to As(V) during chlorination, resulting in average As(III) concentrations at the prefiltration and after-filtration sampling locations of 0.5 µg/L and 0.3 µg/L, respectively. As(V) concentrations averaged 10.5 µg/L at the inlet, 10.2 µg/L prior to filtration, and 11.1 µg/L in the finished water. It is interesting that very little soluble arsenic was removed at Plant B. This observation is most likely a result of the lack of reduced iron in the source water. Approximately 90% of the iron entering the facility is in the oxidized form, to which arsenic has already sorbed. Figure 4-9 provides charts showing the fractions of the total arsenic concentration made up by particulate arsenic and soluble arsenic [As(III) and As(V)].

The Plant B water treatment system only removed arsenic that entered the facility in particulate form. This arsenic was most likely already sorbed to the oxidized iron entering the facility. Also, with an average finished water total arsenic concentration of 11.9 µg/L, Plant B was not able to consistently remove arsenic from source water to low levels. However, arsenic removal would most likely be enhanced if a coagulant such as ferric chloride was included in the treatment process.

4.3.4.2 Other Water Quality Parameters

Table 4-11 summarizes the analytical results for several water quality parameters obtained during long-term sampling. Similar to that observed during the preliminary study, alkalinity concentrations were relatively constant throughout long-term sampling as well as throughout the

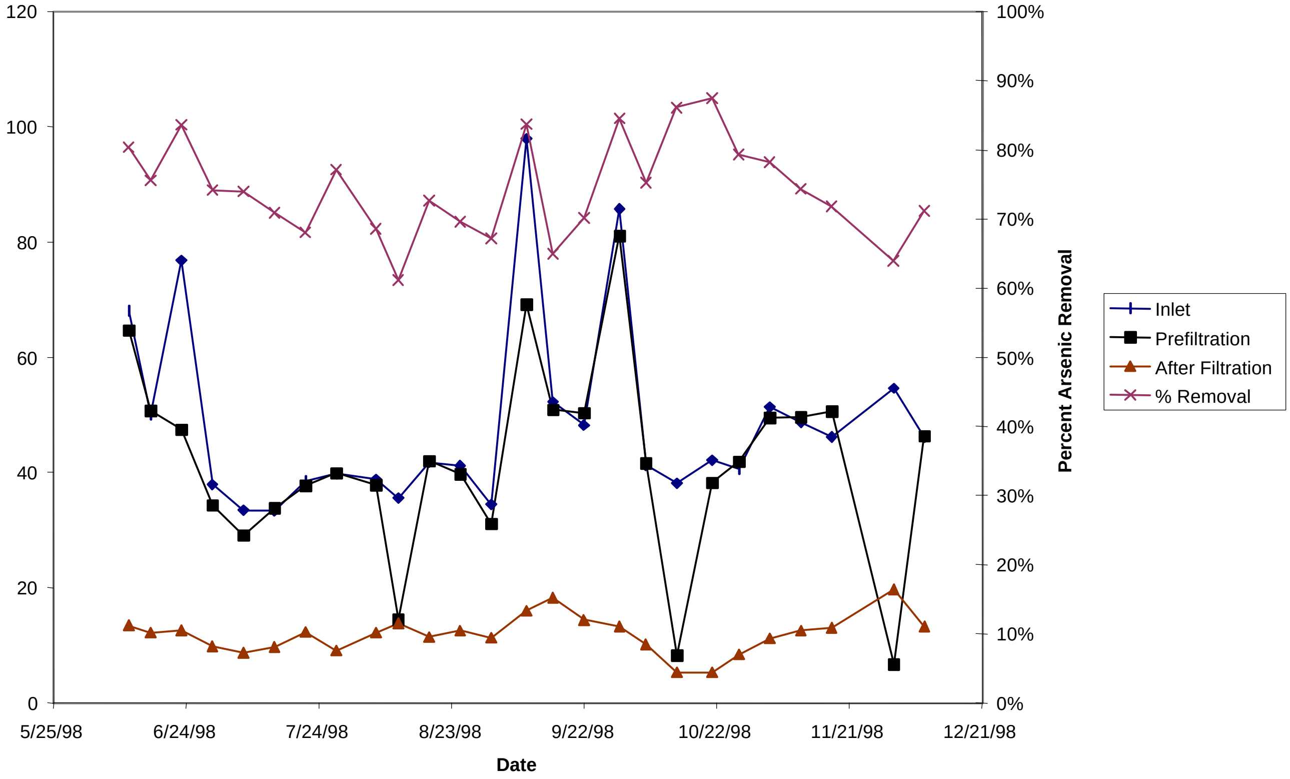
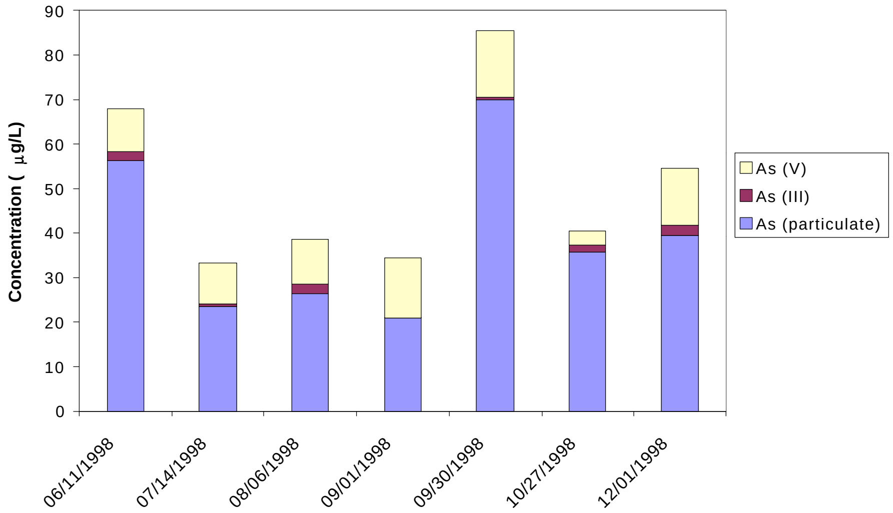
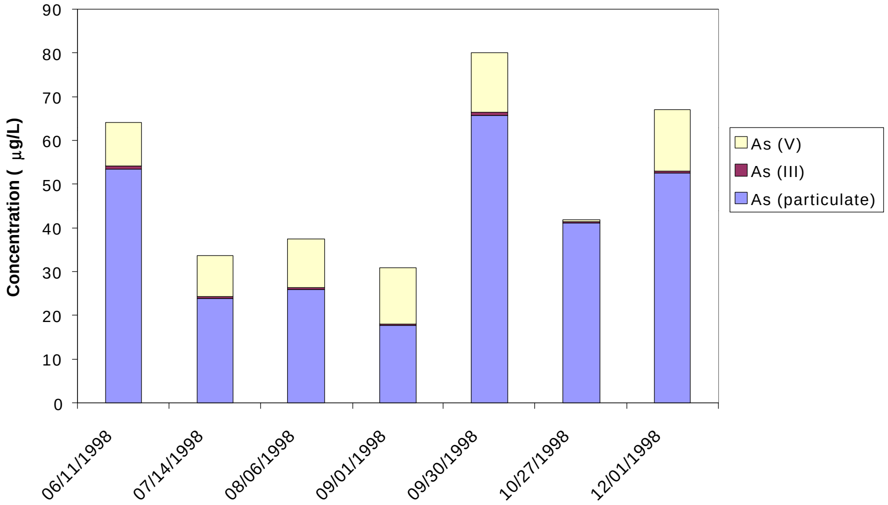


Figure 4-8. Total Arsenic Analytical Results During Long-Term Sampling at Plant B

Inlet



Prefiltration



After Filtration

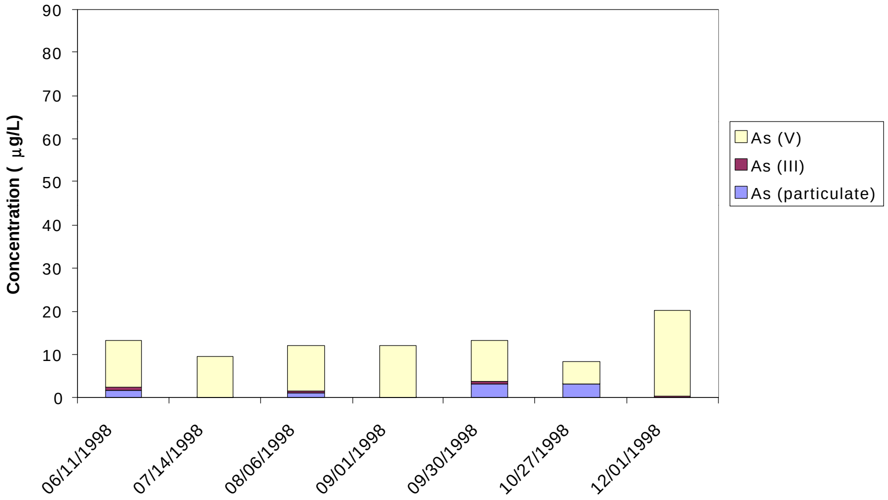


Figure 4-9. Arsenic Form and Species Analytical Results During Long-Term Sampling at Plant B

Table 4-11. Summary of Water Quality Parameter Analytical Results at Plant B (June 11, 1998–December 8, 1998)

Parameter	Sample Location	Units	Number of Samples	Minimum	Maximum	Average	Standard Deviation
Alkalinity	Inlet	mg/L	26	137	145	140	2.2
	Prefiltration	mg/L	26	133	143	137	2.6
	After filtration	mg/L	26	132	142	137	2.6
Turbidity	Inlet	NTU	7	4.6	13.3	8.8	3.5
	Prefiltration	NTU	7	4.0	13.1	8.0	3.6
	After filtration	NTU	7	0.2	0.8	0.4	0.22
pH	Inlet	–	26	7.5	8.6	7.9	0.20
	Prefiltration	–	26	7.2	7.9	7.7	0.14
	After filtration	–	26	7.5	7.8	7.7	0.08
Total Hardness	Inlet	mg/L	7	377	494	443	42.9
	Prefiltration	mg/L	7	329	473	421	52.4
	After filtration	mg/L	7	359	482	420	46.6
Total Al	Inlet	µg/L	26	<11	46.9	22.0	10.7
	Prefiltration	µg/L	26	<11	47.8	22.1	11.1
	After filtration	µg/L	26	<11	36.8	13.9	8.0
Total Fe	Inlet	µg/L	26	599	2,753	1,137	598
	Prefiltration	µg/L	26	116	2,167	1,001	509
	After filtration	µg/L	26	<30	306	66.7	60.8
Total Mn	Inlet	µg/L	26	29.9	135	61.6	27.0
	Prefiltration	µg/L	26	13.8	151	50.3	27.3
	After filtration	µg/L	26	<0.5	9.1	1.9	2.1
Dissolved Al	Inlet	µg/L	7	<11	<11	<11	NA
	Prefiltration	µg/L	7	<11	<11	<11	NA
	After filtration	µg/L	7	<11	<11	<11	NA
Dissolved Fe	Inlet	µg/L	7	<30	655	107	242
	Prefiltration	µg/L	7	<30	44.4	<30	11.1
	After filtration	µg/L	7	<30	31.5	<30	6.2
Dissolved Mn	Inlet	µg/L	7	25	41.1	31.9	4.9
	Prefiltration	µg/L	7	9.4	30.2	25.1	7.1
	After filtration	µg/L	7	<0.5	0.9	<0.5	0.30

treatment process, with only a slight decrease in concentration between samples collected at the inlet and prefiltration sampling locations. Figure 4-10 shows source water alkalinity, turbidity, pH, and hardness concentrations throughout the long-term sampling phase. Average alkalinity concentrations at the inlet, prefiltration, and after-filtration sampling locations were 140 mg/L, 137 mg/L, and 137 mg/L (as CaCO3), respectively. Because the iron entered the facility already oxidized, there was very little alkalinity reduction following chlorination.

During the long-term sampling, turbidity concentrations averaged 8.8 NTU at the inlet, 8.0 NTU at the PF location, and 0.4 NTU in the finished water, which are consistent with plant data. As shown in Figure 4-10, source water turbidity concentrations fluctuated significantly. These fluctuations would be expected for a surface water source and are probably a result of precipitation events and/or snowmelt. The plant was effective at removing turbidity. Hardness was not significantly removed by the treatment process. Average hardness concentrations in samples collected at the plant inlet, before filtration, and after filtration were measured at 443 mg/L, 421 mg/L, and 420 mg/L, respectively. As shown in Figure 4-10, source water hardness appears to increase throughout the study, although the reason for this is not clear. Values for pH were relatively constant throughout the duration of the study and throughout the treatment process. Average pH was 7.9 in the source water, 7.7 prior to filtration, and 7.7 after filtration.

Total aluminum concentrations at the IN and PF sampling locations averaged approximately 22.0 µg/L and decreased in the AF samples to 13.9 µg/L. The majority of the aluminum detected in water samples from the inlet sampling location was particulate form. The dissolved aluminum concentration was <11 µg/L throughout the study at each sampling location. Due to the relatively low total aluminum concentrations, aluminum is not believed to have a significant effect on arsenic removal.

Total manganese concentrations averaged 61.6 µg/L, 50.3 µg/L, and 1.9 µg/L in samples collected at the inlet, prefiltration, and after-filtration sampling locations, respectively. Average dissolved manganese concentrations were 31.9 µg/L in the source water, 25.1 µg/L before filtration, and <0.5 µg/L after filtration. Previous studies have not correlated manganese removal to arsenic removal; therefore, manganese is not believed to have a significant impact on arsenic removal efficiency.

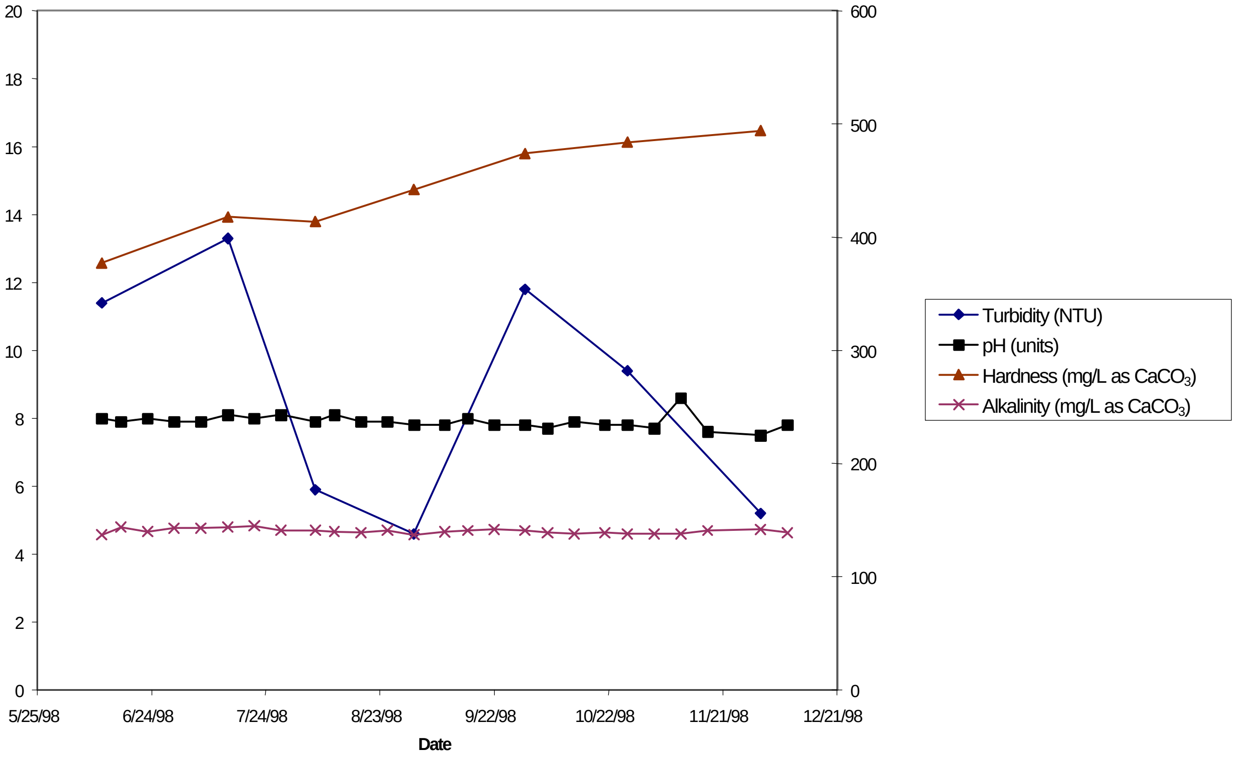


Figure 4-10. Inlet Turbidity, pH, Hardness, and Alkalinity Analytical Results at Plant B

Total iron concentrations in samples collected at the IN sampling location ranged from 599 to 2,753 µg/L, with an average of 1,137 µg/L. At the PF sampling location, total iron concentrations ranged from 116 to 2,167 µg/L, with an average of 1,001 µg/L. The average iron concentration in samples collected after filtration was 66.7 µg/L. Also, dissolved iron concentrations were relatively low in the source water, averaging 107 µg/L. All dissolved iron was oxidized during chlorination prior to filtration, resulting in average dissolved iron concentrations of <30 µg/L in samples collected at the prefiltration and after-filtration sampling locations. As stated previously, it is believed that arsenic removal at Plant B is achieved primarily through filtration of arsenic sorbed to iron particles formed prior to entering the facility.

4.3.4.3 Recycle Supernatant

The filtered backwash water is sent to a concrete vat, where it is given time to settle. The supernatant water then is recycled to the inlet of the plant and mixed with the source water from the mining tunnel. On November 10, 1998 and January 15, 1999, supernatant samples were collected to determine the concentrations of arsenic, aluminum, iron, and manganese recycled to the system. The November 10 test results show that essentially all of the arsenic (142 µg/L average) in the recycle supernatant water was in particulate form. In contrast, the arsenic results from January 15, 1999 were significantly lower (7.8 µg/L). This lower level most likely is because the plant did not operate in January 1999, thereby giving the backwash water in the concrete vat more time to settle. During typical operations, as observed in November 1998, the supernatant from the concrete vat is recycled every 90 minutes. The results for aluminum, iron, and manganese were significantly less on January 15, 1999 than on November 10, 1998, which is consistent with the results observed for arsenic. The recycled backwash water sample analytical results are shown in Table 4-12.

4.3.4.4 Sludge

Sludge is generated at Plant B from filter backwashing. Sludge that settles in the concrete vat is transferred to a sludge holding tank. Approximately once a year, sludge is removed from the sludge holding tank, processed through a filter press, and sent to a municipal landfill. Based on discussions with plant personnel, approximately 2 to 3 yd^3 of dewatered sludge is sent to a nonhazardous landfill every year. Sludge samples were not collected at Plant B as part of this study; however, the plant provided results from a sludge sampling event conducted in January 1994. A primary compound detected in the sludge was Fe_2O_3, which comprised 30.4% by weight. Arsenic was detected at 6,700 mg/kg in the sludge sample.

Table 4-12. Summary of Analytical Results from Recycle Supernatant Samples at Plant B

Parameter	Unit	11/10/98	01/15/99
pH	–	7.8 7.8	8.1 8.1
As (total)	µg/L	146 138	7.8 7.8
As (total soluble)	µg/L	5.3 4.8	7.7 7.8
As (particulate)	µg/L	141 133	<0.1 <0.1
Total Al	µg/L	58.2 51.5	<11 <11
Total Fe	µg/L	3,850 3,710	75.2 67.4
Total Mn	µg/L	326 267	1.6 1.7
Dissolved Al	µg/L	30.4 31.1	<11 <11
Dissolved Fe	µg/L	<30 <30	<30 <30
Dissolved Mn	µg/L	1.0 1.0	<0.5 <0.5

5.0 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 *Quality Assurance/ Quality Control (QA/QC) Summary Report* (Battelle, 2000), which was 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 in the *QA/QC Summary Report*. 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 in the *QA/QC Summary Report*. Other water quality parameters including alkalinity, pH, turbidity, hardness, nitrate-nitrite, sulfate, fluoride, total dissolved solids (TDS), and TSS were analyzed by Wilson Environmental Laboratories and their QA data are summarized in the *QA/QC Summary Report*. QA data for TOC analysis performed by CT&E Environmental Laboratory are presented in the *QA/QC Summary Report*. 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 Al, Fe, and Mn 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 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 ±25% (with only two Fe outliers: 27% on August 8, 1998 and 74% on December 22, 1998; three As outliers: 27% on August 18, 1998, 182% on October 1, 1998, and 27% on July 30, 1999; and four Al 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 matrix spike (MS) analysis on August 31, 1998 exceeded the QA limits of 75 to 125%. It is suspected that matrix spike analyses were not performed correctly on that day. After this problem had been identified, Battelle's Work Assignment Leader, laboratory QA officer, and Battelle's task leaders met to discuss the cause of the deviation. Corrective actions were taken including re-analyzing samples and adjusting the amount of spike added to samples (i.e., the Fe spike was increased from 50 to 100, 200, 225, or even as high as 2,000 µg/L because most of samples contain much more than 50 µg/L of Fe). As indicated in the *QA/QC Summary Report* (Battelle, 2000), the matrix spike 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 ±25% except for two Mn analyses 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 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 until October 15, 1998 at 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 limits 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 ±25%. The accuracy of matrix spikes 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).

6.0 References

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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 Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L[(a)]	418	389	388	392	418	399	394	394	419	403	396	391	413	399	386	390
Turbidity	NTU													26.0	4.9	0.8	<0.1
pH		7.7	7.7	7.6	7.7	7.7	7.7	7.7	7.7	7.6	7.7	7.6	7.6	7.6	7.8	7.7	7.7
Total Hardness	mg/L[(a)]													332	301	298	3.0
Ca Hardness	mg/L[(a)]													180	152	155	2.0
Mg Hardness	mg/L[(a)]													152	149	143	2.0
As (total)	µg/L	21.0	23.3	2.7	3.4	18.8	18.8	5.6	2.5	18.1	19.3	2.3	1.9	20.6 20.9	20.6 19.6	4.8 4.8	2.7 2.6
As (total soluble)	µg/L													25.6 25.1	5.3 5.3	2.9 3.1	3.3 3.1
As (particulate)	µg/L													<0.1 <0.1	15.3 14.3	2.0 1.8	<0.1 <0.1
As (III)	µg/L													18.1 20.7	0.3 0.3	0.2 0.2	0.3 0.3
As (V)	µg/L													7.5 4.4	5.1 5.0	2.7 2.9	3.0 2.9
Total Al	µg/L	14.9	<11	<11	11.9	<11	<11	<11	11.6	14.3	<11	<11	16.9	17.0 18.2	12.0 <11	19.4 15.5	<11 11.8
Total Fe	µg/L	2,015	2,178	<30	<30	1,958	2,005	440	<30	1,789	1,889	<30	128	1,918 1,939	1,897 1,824	309 300	<30 <30
Total Mn	µg/L	19.7	17.2	21.4	2.7	19.1	17.5	47.1	2.0	18.8	19.4	31.7	2.8	19.4 19.4	19.0 18.2	48.6 44.4	2.7 2.7
Dissolved Al	µg/L													<11 <11	<11 <11	<11 <11	<11 <11
Dissolved Fe	µg/L													1,901 1,612	<30 <30	<30 <30	<30 <30
Dissolved Mn	µg/L													18.4 18.7	15.4 14.9	13.4 13.8	1.9 2.0

(a) As $CaCO_3$.

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

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 Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L(a)	410 415	390 394	397 392	394 392	406	395	383	391	406	380	387	388	410 411	393 392	388 389	386 387
Turbidity	NTU									21	5.3	0.2	<0.1				
pH		7.6 7.6	7.6 7.6	7.6 7.6	7.6 7.6	7.8	7.7	7.7	7.7	7.5	7.8	7.6	7.6	7.7 7.7	7.7 7.7	7.7 7.7	7.6 7.6
Total Hardness	mg/L(a)									305	282	279	4.9				
Ca Hardness	mg/L(a)									147	127	127	2.9				
Mg Hardness	mg/L(a)									158	155	151	1.9				
As (total)	µg/L	19.6	20.5	3.0	2.8	20.5	18.7	3.1	2.0	19.0 12.3	20.3 18.6	2.9 2.9	2.0 2.1	19.5	15.6	3.0	0.8
As (total soluble)	µg/L									24.7 23.6	4.6 4.3	2.8 2.7	3.1 3.3				
As (particulate)	µg/L									<0.1 <0.1	15.7 14.3	0.1 0.2	<0.1 <0.1				
As (III)	µg/L									21.8 20.9	0.7 0.6	0.7 0.7	0.5 0.6				
As (V)	µg/L									2.9 2.7	3.9 3.7	2.0 2.0	1.5 1.5				
Total Al	µg/L	11.5	19.0	17.8	<11	12.6	<11	14.8	11.7	13.2 52.5	22.0 21.8	12.2 15.9	16.2 16.1	29.6	17.7	22.8	24.0
Total Fe	µg/L	1,419	1,778	<30	<30	2,070	1,927	56.4	<30	2,394 1,798	2,572 2,200	37.1 34.8	<30 <30	2,392	3,026	191	<30
Total Mn	µg/L	17.5	15.8	13.8	1.9	17.5	18.2	12.8	1.4	19.1 17.9	19.1 17.9	21.1 19.4	2.9 2.9	20.1	280(b)	36.0	2.2
Dissolved Al	µg/L									<11 <11	<11 <11	<11 <11	<11 <11				
Dissolved Fe	µg/L									2,052 1,835	<30 <30	<30 <30	<30 <30				
Dissolved Mn	µg/L									18.2 17.6	14.9 15.2	17.2 18.1	1.8 1.7				

(a) As $CaCO_3$.
(b) Confirmed by sample re-analysis.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.

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 Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L[a]	413	393	390	384	416	394	383	392	415	395	386	395	414 414	400 401	396 397	393 393
Turbidity	NTU									19.7	5.3	0.2	0.2				
pH		7.6	7.6	7.6	7.5	7.6	7.6	7.6	7.7	7.6	7.7	7.6	7.9	7.7 7.7	7.8 7.8	7.8 7.8	7.9 7.9
Total Hardness	mg/L[a]									288	270	274	4.0				
Ca Hardness	mg/L[a]									137	125	125	2.9				
Mg Hardness	mg/L[a]									150	145	149	1.5				
As (total)	µg/L	20.3	20.1	1.9	0.9	18.2	15.6	2.3	1.7	18.9 18.3	19.5 18.4	2.3 2.0	1.5 1.5	21.1	20.0	3.1	1.9
As (total soluble)	µg/L									23.0 22.2	4.4 4.5	2.3 2.4	1.8 1.7				
As (particulate)	µg/L									<0.1 <0.1	15.1 13.9	<0.1 <0.1	<0.1 <0.1				
As (III)	µg/L									7.5 16.1	0.1 <0.1	0.1 0.1	0.1 <0.1				
As (V)	µg/L									15.5 6.1	4.3 4.5	2.2 2.4	1.7 1.7				
Total Al	µg/L	25.9	18.0	17.5	23.7	40.2	35.9	17.8	34.4	<11 32.6	<11 11.3	11.0 11.5	<11 <11	<11	16.0	14.3	13.7
Total Fe	µg/L	2,343	2,499	<30	<30	3,289	2,972	<30	<30	1,983 1,936	2,000 1,943	31.1 <30	<30 <30	2,076	1,893	77.1	30.0
Total Mn	µg/L	19.7	18.3	19.0	1.8	25.6	24.6	16.0	2.8	15.8 15.2	15.2 14.7	9.4 8.8	1.3 1.3	17.4	16.8	12.0	3.3
Dissolved Al	µg/L									64.9 <11	<11 <11	<11 <11	<11 <11				
Dissolved Fe	µg/L									2,150 1,635	<30 <30	<30 <30	<30 <30				
Dissolved Mn	µg/L									21.3 19.6	15.5 15.9	9.4 9.7	1.7 1.3				

(a) As $CaCO_3$.

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

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	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L(a)	417	402	398	397	413	403	401	400	411	404	395	401	415	395	391	398
Turbidity	NTU									17.2	4.6	0.2	<0.1				
pH		7.6	7.6	7.7	7.8	7.7	7.8	7.8	8.0	7.6	7.8	7.7	7.8	7.6	7.8	7.7	7.9
Total Hardness	mg/L(a)									432	295	303	6.5				
Ca Hardness	mg/L(a)									295	145	150	3.9				
Mg Hardness	mg/L(a)									138	150	153	2.6				
As (total)	µg/L	22.0	22.0	3.0	2.0	23.4	22.6	3.5	6.9	25.5 24.1	13.4(b) 22.7	3.9 3.3	5.9 6.0	20.3	19.5	2.9	3.0
As (total soluble)	µg/L									25.4 25.4	6.0 6.0	3.5 3.5	6.7 6.7				
As (particulate)	µg/L									0.1 <0.1	7.4 12.7	0.4 <0.1	<0.1 <0.1				
As (III)	µg/L									20.1 20.5	0.6 0.6	0.6 0.6	0.8 0.7				
As (V)	µg/L									5.3 4.9	5.4 5.4	2.9 2.9	5.9 6.0				
Total Al	µg/L	11.6	17.6	16.0	15.5	21.8	12.9	16.6	25.4	18.3 12.2	20.5 20.1	15.5 19.2	13.1 15.4	<11	<11	14.1	<11
Total Fe	µg/L	2,325	2,287	<30	<30	2,387	2,175	45.0	57.5	2,176 2,227	2,040 2,165	31.3 38.9	<30 <30	2,185	2,028	<30	<30
Total Mn	µg/L	17.5	16.3	10.9	1.5	20.0	19.5	29.7	15.8	19.1 19.2	15.9 16.5	10.3 10.4	1.9 2.2	18.3	17.9	13.6	1.7
Dissolved Al	µg/L									<11 <11	<11 <11	<11 <11	<11 <11				
Dissolved Fe	µg/L									1,544 1,300	<30 <30	<30 <30	<30 <30				
Dissolved Mn	µg/L									17.3 17.6	13.8 14.0	8.4 8.3	1.7 1.6				

(a) As $CaCO_3$.
(b) Confirmed by sample re-analysis.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.

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	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L(a)	375	408	403	402	410	411	408	405	412	413	401	414	415 415	416 415	409 409	411 411
Turbidity	NTU									16.4	7.2	0.1	0.3				
pH		7.7	7.9	7.8	8.1	7.7	8.0	7.8	8.0	7.6	7.9	7.8	8.1	7.6 7.6	7.9 7.9	8.0 8.0	7.8 8.0
Total Hardness	mg/L(a)									301	301	294	11.4				
Ca Hardness	mg/L(a)									152	152	147	6.0				
Mg Hardness	mg/L(a)									149	149	147	5.4				
As (total)	µg/L	21.3	18.4	3.8	3.1	20.5	20.3	4.0	6.0	20.8 21.2	21.1 21.4	4.1 3.9	10.1 10.1	22.5	20.7	4.6	3.9
As (total soluble)	µg/L									19.2 18.6	9.7 10.1	4.1 4.1	10.2 10.3				
As (particulate)	µg/L									1.6 2.6	11.4 11.3	<0.1 <0.1	<0.1 <0.1				
As (III)	µg/L									17.1 16.5	5.1 4.6	0.7 0.3	<0.1 <0.1				
As (V)	µg/L									2.1 2.1	4.6 5.5	3.4 3.8	10.2 10.3				
Total Al	µg/L	<11	12.5	<11	21.4	13.0	11.8	<11	<11	<11 <11	<11 <11	<11 <11	<11 <11	<11	11.8	<11	11.8
Total Fe	µg/L	2,800	2,495	<30	<30	2,826	2,715	43.1	<30	2,312 2,406	2,252 2,325	<30 <30	41.2 49.0	2,388	2,233	<30	<30
Total Mn	µg/L	19.9	18.1	12.7	2.0	22.5	22.5	11.9	2.5	21.6 22.3	20.2 20.5	6.7 6.3	7.6 7.8	24.0	24.9	18.4	13.9
Dissolved Al	µg/L									<11 <11	<11 <11	<11 <11	<11 <11				
Dissolved Fe	µg/L									930 650	<30 <30	<30 <30	<30 <30				
Dissolved Mn	µg/L									21.6 21.9	18.6 18.6	5.1 5.2	4.2 4.1				

(a) As CaCO$_3$.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.

Table A-6. Analytical Results from Long Term Sampling, Plant A (November 11 to December 2, 1998)

Sampling Date		11/11/98				11/18/98				11/25/98[b]				12/02/98			
Sampling Location Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L[a]	420	396	392	388	415	401	386	377					412	397	391	393
Turbidity	NTU													15.8	4.8	0.3	0.1
pH		7.6	7.6	7.5	7.6	7.6	7.6	7.5	7.6					7.6	7.7	7.6	7.7
Total Hardness	mg/L[a]													297	298	165	3.0
Ca Hardness	mg/L[a]													152	150	150	1.5
Mg Hardness	mg/L[a]													145	148	15	1.4
As (total)	µg/L	23.0	23.8	2.6	2.1	20.0	6.5	2.3	1.9					19.9 20.3	17.1 19.1	3.3 3.3	2.0 1.9
As (total soluble)	µg/L													15.6 15.9	3.4 3.6	2.5 2.6	2.5 2.5
As (particulate)	µg/L													4.3 4.4	13.7 15.5	0.8 0.7	<0.1 <0.1
As (III)	µg/L													10.6 11.1	0.3 0.3	0.3 0.3	0.2 0.2
As (V)	µg/L													5.0 4.8	3.1 3.3	2.2 2.3	2.3 2.3
Total Al	µg/L	17.0	<11	<11	14.6	<11	12.4	17.6	12.8					13.4 11.2	15.3 15.3	16.9 <11	13.1 13.6
Total Fe	µg/L	2,642	2,573	<30	<30	2,322	401	<30	<30					2,383 2,302	2,337 2,331	144 142	<30 <30
Total Mn	µg/L	22.9	22.2	10.8	1.8	35.4	694	11.5	1.4					23.4 22.8	21.9 21.7	10.8 10.3	1.2 1.1
Dissolved Al	µg/L													11.3 31.8	12.1 31.0	<11 <11	<11 <11
Dissolved Fe	µg/L													31.1 39.1	<30 <30	<30 <30	<30 <30
Dissolved Mn	µg/L													25.0 23.3	18.6 18.2	6.3 6.3	1.2 1.3

(a) As $CaCO_3$.
(b) No sampling due to Thanksgiving holiday.
(c) Confirmed by sample re-analysis.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.

Table A-7. Analytical Results from Long Term Sampling, Plant A (December 16 to 30, 1998)

Sampling Date		12/09/98				12/16/98				12/23/98[b]				12/30/98[b]			
Sampling Location Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L[a]	416 415	393 394	388 387	385 386	418	396	392	394								
Turbidity	NTU																
pH		7.6 7.6	7.7 7.7	7.6 7.7	7.7 7.7	7.7	7.7	7.7	7.7								
Total Hardness	mg/L[a]																
Ca Hardness	mg/L[a]																
Mg Hardness	mg/L[a]																
As (total)	µg/L	24.4	22.5	2.7	1.8	20.8	18.9	2.9	2.7								
As (total soluble)	µg/L																
As (particulate)	µg/L																
As (III)	µg/L																
As (V)	µg/L																
Total Al	µg/L	12.6	<11	<11	<11	<11	<11	16.6	<11								
Total Fe	µg/L	2,441	2,475	<30	<30	2365	2588	98.1	65.2								
Total Mn	µg/L	21.7	21.3	11.0	2.1	25.4	26.1	12.2	1.4								
Dissolved Al	µg/L																
Dissolved Fe	µg/L																
Dissolved Mn	µg/L																

(a) As $CaCO_3$.
(b) No sampling due to Christmas holiday.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.

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 Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L(a)	416	401	394	395	413	396	397	396	413 414	393 394	396 395	391 390	398	398	378	388
Turbidity	NTU					13.8	3.0	0.1	<0.1								
pH		7.6	7.7	7.6	7.6	7.6	7.7	7.7	7.9	7.6 7.6	7.7 7.7	7.6 7.6	7.6 7.7	7.6	7.7	7.6	7.6
Total Hardness	mg/L(a)						281	281	8.0								
Ca Hardness	mg/L(a)						145	147	3.6								
Mg Hardness	mg/L(a)						136	134	4.0								
As (total)	µg/L	19.4	20.6	2.4	2.1	20.7 19.3	20.9 21.2	2.9 3.0	1.6 1.7	20.1	22.5	2.5	1.6	18.9	6.0	1.0	1.0
As (total soluble)	µg/L					15.4 14.8	3.2 3.0	3.3 3.4	2.2 2.2								
As (particulate)	µg/L					5.3 4.5	17.7 18.2	<0.1 <0.1	<0.1 <0.1								
As (III)	µg/L					11.3 12.1	0.4 0.4	0.2 0.2	0.6 0.6								
As (V)	µg/L					4.1 2.7	2.8 2.6	3.1 3.2	1.6 1.6								
Total Al	µg/L	<11	<11	16.6	<11	<11 <11	<11 <11	<11 <11	<11 <11	11.1	<11	<11	<11	<11	<11	<11	<11
Total Fe	µg/L	2,365	2,588	98.1	65.2	2,205 2,029	2,283 2,394	<30 <30	<30 116	2,245	2,506	41.7	<30	1,124	369	<30	9.1
Total Mn	µg/L	25.5	26.1	12.2	1.4	19.0 14.5	18.5 19.0	4.6 5.0	1.6 2.2	14.5	15.3	6.1	2.0	16.4	121	<30	9.3
Dissolved Al	µg/L					122 121	29.7 18.5	17.9 20.9	67.5 69.7								
Dissolved Fe	µg/L					<30 <30	<30 <30	<30 <30	<30 <30								
Dissolved Mn	µg/L					20.4 20.2	18.0 16.9	7.7 5.6	1.9 1.4								

(a) As $CaCO_3$.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.

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

Sampling Date		02/03/99				02/10/99				02/17/99				02/24/99			
Sampling Location Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L$^{(a)}$	419	398	391	391	413	394	389	395	414 415	391 390	393 394	390 391	409	391	387	389
Turbidity	NTU					17.7	4.8	0.6	<0.1								
pH		7.6	7.7	7.7	7.7	7.6	7.7	7.6	7.6	7.6 7.6	7.6 7.6	7.6 7.6	7.6 7.6	7.6	7.6	7.6	7.6
Total Hardness	mg/L$^{(a)}$					327	308	317	5.0								
Ca Hardness	mg/L$^{(a)}$					177	160	167	3.0								
Mg Hardness	mg/L$^{(a)}$					150	148	150	1.9								
As (total)	µg/L	19.5	21.0	3.3	2.7	19.7 20.0	20.7 19.9	3.6 3.8	2.2 2.2	18.7	21.0	4.2	2.9	12.5	3.8	2.3	3.1
As (total soluble)	µg/L					16.2 15.8	3.2 3.4	3.1 3.2	3.0 3.2								
As (particulate)	µg/L					3.5 4.2	17.5 16.5	0.5 0.6	<0.1 <0.1								
As (III)	µg/L					11.6 11.8	0.3 0.3	0.4 0.4	0.6 0.6								
As (V)	µg/L					4.6 4.0	2.9 3.1	2.7 2.8	2.4 2.6								
Total Al	µg/L	<11	<11	<11	<11	<11 <11	<11 <11	<11 <11	<11 <11	<11	<11	<11	<11	14.4	<11	13.3	<11
Total Fe	µg/L	2,295	2,318	177	<30	2,249 2,301	2,430 2,341	211 212	<30 <30	2,485	2,637	260	35.1	762	267	36.4	37.5
Total Mn	µg/L	19.6	19.3	24.3	24.3	21.8 22.3	25.3 24.6	39.6 38.4	1.4 1.5	20.6	19.0	19.0	2.1	22.8	16.5	18.8	2.2
Dissolved Al	µg/L					20.9 19.3	25.4 15.7	25.9 77.7	<11 <11								
Dissolved Fe	µg/L					<30 <30	<30 <30	<30 <30	<30 <30								
Dissolved Mn	µg/L					23.0 22.8	21.3 21.9	7.5 7.9	1.3 1.3								

(a) As $CaCO_3$.

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

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			
Sampling Location Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L(a)	413	396	393	391	419	392	392	391	424 422	391 393	389 388	389 389	407	393	388	393
Turbidity	NTU					22.0	5.1	2.3	0.1								
pH		7.7	7.7	7.7	7.7	7.6	7.7	7.6	7.7	7.6 7.6	7.7 7.7	7.6 7.6	7.6 7.6	7.6	7.7	7.6	7.7
Total Hardness	mg/L(a)					311	303	308	6.0								
Ca Hardness	mg/L(a)					160	155	157	3.0								
Mg Hardness	mg/L(a)					151	149	151	2.6								
As (total)	µg/L	20.3	23.2	5.1	3.6	21.1 22.6	19.0 18.8	8.1 7.9	3.4 3.4	22.1	20.7	2.3	2.7	21.5	20.0	2.3	3.3
As (total soluble)	µg/L					16.9 17.0	4.5 4.7	2.9 2.9	4.0 4.1								
As (particulate)	µg/L					4.2 5.6	14.5 14.1	5.2 5.0	<0.1 <0.1								
As (III)	µg/L					15.6 16.0	0.8 0.7	0.6 0.5	0.8 0.8								
As (V)	µg/L					1.3 1.0	3.7 4.0	2.3 2.4	3.2 3.3								
Total Al	µg/L	<11	<11	<11	12.9	<11 <11	<11 13.8	<11 <11	12.5 <11	12.9	13.5	<11	<11	14.7	<11	<11	<11
Total Fe	µg/L	2,543	2,778	370	<30	2,493 2,476	2,349 2,304	797 766	<30 <30	2,585	2,492	39.3	<30	2,115	2,266	<30	<30
Total Mn	µg/L	22.7	23.1	35.2	4.1	21.7 21.6	27.9 27.6	98.2 93.5	9.6 9.7	46.7	20.5	34.2	21.9	22.9	22.7	24.8	2.6
Dissolved Al	µg/L					<11 <11	<11 <11	<11 <11	<11 <11								
Dissolved Fe	µg/L					473 476	<30 <30	<30 <30	<30 <30								
Dissolved Mn	µg/L					22.7 22.8	19.0 20.0	3.0 2.9	5.1 5.0								

(a) As $CaCO_3$.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.

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

Sampling Date		03/31/99				04/07/99				04/14/99				04/21/99			
Sampling Location Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L$^{(a)}$	420	403	403	403	417	403	402	396	427 416	404 402	391 392	402 402	421	398	396	399
Turbidity	NTU					16.7	5.0	0.7	0.1								
pH		7.6	7.7	7.6	7.6	7.7	7.7	7.6	7.7	7.7 7.7	7.7 7.7	7.6 7.7	7.8 7.8	7.6	7.6	7.6	7.6
Total Hardness	mg/L$^{(a)}$					293	282	278	3.0								
Ca Hardness	mg/L$^{(a)}$					147	140	137	1.5								
Mg Hardness	mg/L$^{(a)}$					146	142	141	1.4								
As (total)	µg/L	20.6	20.1	2.3	1.6	21.9 21.7	19.8 19.6	2.4 2.5	2.1 2.2	19.6	19.9	2.4	4.9	21.5	20.9	3.0	2.1
As (total soluble)	µg/L					20.9 20.5	4.5 4.5	2.6 2.4	2.2 2.3								
As (particulate)	µg/L					1.0 1.2	15.3 15.1	<0.1 0.1	<0.1 <0.1								
As (III)	µg/L					18.3 16.0	0.5 0.3	0.4 0.4	0.7 0.6								
As (V)	µg/L					2.6 4.5	4.0 4.2	2.2 2.0	1.5 1.7								
Total Al	µg/L	<11	<11	<11	<11	<11 <11	<11 <11	<11 17.8	<11 <11	<11	<11	<11	<11	<11	<11	<11	<11
Total Fe	µg/L	2,310	2,337	39.3	59.3	2,329 2,335	2,357 2,359	<30 <30	<30 <30	2,644	2,689	<30	<30	2,436	2,422	58.7	<30
Total Mn	µg/L	21.0	20.2	43.3	2.9	20.8 21.0	22.3 22.5	64.8 66.5	3.6 3.6	22.6	22.7	24.7	9.6	22.6	22.9	15.5	2.4
Dissolved Al	µg/L					<11 <11	<11 <11	<11 <11	<11 <11								
Dissolved Fe	µg/L					1,000 1,000	<30 <30	<30 <30	<30 <30								
Dissolved Mn	µg/L					23.6 23.1	18.8 18.7	6.8 6.7	2.5 2.8								

(a) As $CaCO_3$.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.

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

Sampling Date		04/28/99				05/05/99				05/12/99				05/19/99			
Sampling Location Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L(a)	423	397	395	401	419	398	396	396	349 347	396 394	363 393	396 395	421	400	397	397
Turbidity	NTU					17.6	5.3	0.2	<0.1								
pH		7.6	7.6	7.6	7.7	7.6	7.7	7.6	7.7	7.6 7.6	7.7 7.7	7.6 7.6	7.7 7.7	7.6	7.6	7.6	7.6
Total Hardness	mg/L(a)					286	279	275	3.0								
Ca Hardness	mg/L(a)					142	137	135	1.2								
Mg Hardness	mg/L(a)					144	141	140	1.6								
As (total)	µg/L	20.1	21.4	2.9	4.9	21.0 22.9	21.4 20.7	3.2 3.1	2.0 2.0	20.0	21.0	2.6	1.8	19.5	19.6	2.6	1.0
As (total soluble)	µg/L					21.0 21.8	15.0 5.1	2.9 3.1	2.0 2.0								
As (particulate)	µg/L					<0.1 1.1	6.4 15.6	0.3 <0.1	<0.1 <0.1								
As (III)	µg/L					18.2 17.2	1.4 0.8	0.8 *	0.8 0.8								
As (V)	µg/L					3.5 4.6	3.6 4.3	2.1 *	1.2 1.3								
Total Al	µg/L	11.7	<11	<11	11.1 <11	<11 -	<11 25.9	<11 <11	15.2 <11	324	<11	<11	<11	18.7	<11	<11	<11
Total Fe	µg/L	2,647	2,711	<30	<30	2,463 2,437	2,449 2,487	<30 <30	<30 <30	2,986	2,687	58.3	44.8	2,166	2,141	<30	<30
Total Mn	µg/L	23.5	20.8	24.7	9.8	23.4 22.8	20.7 21.8	20.6 20.4	2.3 2.4	57.3	22.7	25.7	5.3	22.9	21.2	20.4	17.4
Dissolved Al	µg/L					<11 <11	<11 <11	<11 <11	<11 <11								
Dissolved Fe	µg/L					827 825	<30 <30	<30 <30	<30 <30								
Dissolved Mn	µg/L					21.1 21.3	20.1 19.9	10.6 10.5	2.1 2.1								

(a) As $CaCO_3$.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.
*Sample not received from field.

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

Sampling Date		05/26/99				06/02/99				06/09/99				06/16/99			
Sampling Location Parameter	Unit	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS	IN	PF	AF	AS
Alkalinity	mg/L$^{(a)}$	441	400	395	396	422	399	391	399	425 424	400 403	397 399	398 394	412	394	389	383
Turbidity	NTU					22	5.8	0.3	0.1								
pH		7.6	7.7	7.6	7.6	7.6	7.7	7.6	7.7	7.6 7.6	7.6 7.5	7.6 7.6	7.6 7.6	7.6	7.7	7.6	7.6
Total Hardness	mg/L$^{(a)}$					299	295	292	5.1								
Ca Hardness	mg/L$^{(a)}$					152	155	152	2.8								
Mg Hardness	mg/L$^{(a)}$					147	140	139	2.3								
As (total)	µg/L	42.5	21.7	2.8	1.3	21.6 20.9	20.4 20.3	2.5 2.4	3.0 2.8	16.7	20.8	2.3	2.2	19.8	19.8	2.5	2.6
As (total soluble)	µg/L					21.5 21.7	4.4 4.9	2.5 2.5	3.4 3.4								
As (particulate)	µg/L					0.1 <0.1	16.0 15.4	<0.1 <0.1	<0.1 <0.1								
As (III)	µg/L					17.7 18.5	0.7 0.6	0.4 0.4	0.5 0.4								
As (V)	µg/L					3.8 3.2	3.7 4.3	2.1 2.0	2.9 2.9								
Total Al	µg/L	<11	18.6	<11	<11	<11 <11	<11 <11	<11 <11	<11 <11	<11	<11	<11	<11	11.5	13.3	12.4	<11
Total Fe	µg/L	2,863	2,719	51.1	<30	1,953 1,858	2,073 2,073	56.9 56.8	30.3 <30	2,435	2,379	30.4	49.9	2,418	2,464	82.1	19.1
Total Mn	µg/L	17.7	62.7	25.7	15.6	21.3 20.3	19.3 20.3	22.4 21.9	8.3 7.2	21.4	21.7	19.9	4.5	21.2	22.7	20.8	5.6
Dissolved Al	µg/L					<11 <11	<11 <11	<11 <11	<11 <11								
Dissolved Fe	µg/L					1,237 1,291	<30 <30	<30 <30	<30 <30								
Dissolved Mn	µg/L					21.6 22.5	16.3 15.9	12.5 13.5	4.9 5.0								

(a) As $CaCO_3$.
IN = inlet; PF = prefiltration; AF = after filtration; AS = after softening.
*Sample not received from field.

APPENDIX B

Complete Analytical Results from Long-Term Sampling at Plant B

Table B-1. Analytical Results from Long Term Sampling, Plant B (June 11 to July 30, 1998)

Sampling Date		6/11/98			6/16/98			6/23/98			6/30/98		
Sampling Location Parameter	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L[(a)]	137	137	135	144 145	142 140	140 141	140	140	141	143	142	140
Turbidity	NTU	11.4	11.1	0.8									
pH		8.0	7.8	7.7	7.9 7.9	7.7 7.7	7.7 7.7	8.0	7.8	7.8	7.9	7.7	7.7
Total Hardness	mg/L[(a)]	377	386	392									
Ca Hardness	mg/L[(a)]	262	267	277									
Mg Hardness	mg/L[(a)]	115	119	115									
As (total)	µg/L	63.8 72.4	63.7 65.7	13.4 13.4	50.2 49.9	46.4 55.1	12.2 12.3	76.8	47.4	12.6	37.9	34.3	9.8
As (total soluble)	µg/L	11.9 11.4	11.1 11.5	11.8 11.6									
As (particulate)	µg/L	51.9 61.0	52.6 54.2	1.6 1.8									
As (III)	µg/L	1.9 1.8	0.6 2.0	0.7 0.6									
As (V)	µg/L	10.0 9.6	10.5 9.5	11.1 11.0									
Total Al	µg/L	36.1 53.6	40.8 50.1	11.2 <11	26.9 35.4	30.2 29.1	<11 <11	46.9	28.5	<11	34.9	28.6	16.8
Total Fe	µg/L	1,625 1,937	1,639 1,720	137 140	1,672 1,698	1,616 1,858	57.7 87.5	2,753	1,514	83.4	1,410	1,140	57.3
Total Mn	µg/L	54.9 66.4	42.9 47.3	1.2 1.2	71.7 72.4	62.2 72.0	0.8 2.7	101	81.0	0.8	81.7	51.6	0.6
Dissolved Al	µg/L	1.3 2.8	1.9 1.1	0.6 0.6									
Dissolved Fe	µg/L	<30 <30	<30 <30	<30 33.1									
Dissolved Mn	µg/L	32.0 32.2	30.3 30.1	<0.5 0.7									

(a) As $CaCO_3$.
IN = inlet; PF = prefiltration; AF = after filtration; ND = not detected.

Table B-2. Analytical Results from Long Term Sampling, Plant B (July 7 to July 28, 1998)

Sampling Date		7/7/98			7/14/98			7/21/98			7/28/98		
Sampling Location Parameter	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L(a)	143	143	140	144	139	136	146 144	142 139	142 141	141	137	135
Turbidity	NTU				13.3	13.1	0.3						
pH		7.9	7.2	7.7	8.1	7.9	7.8	8.0 8.0	7.8 7.7	7.7 7.7	8.1	7.8	7.8
Total Hardness	mg/L(a)				418	329	359						
Ca Hardness	mg/L(a)				304	232	260						
Mg Hardness	mg/L(a)				114	96.8	99.7						
As (total)	µg/L	33.4	29.1	8.7	32.9 33.7	34.3 33.3	9.7 9.7	38.5	37.7	12.3	39.8	39.9	9.1
As (total soluble)	µg/L				10.2 9.8	9.6 9.9	9.7 9.7						
As (particulate)	µg/L				22.7 23.9	24.7 23.4	<0.1 <0.1						
As (III)	µg/L				0.9 0.8	0.3 0.3	0.1 0.2						
As (V)	µg/L				9.3 9.0	9.3 9.6	9.6 9.4						
Total Al	µg/L	23.1	34.6	12.3	23.6 27.4	29.5 22.9	19.5 15.9	37.5	20.2	12.7	20.1	29.4	11.8
Total Fe	µg/L	832	752	30.5	820 796	801 747	<30 32.0	761	705	32.2	779	775	110
Total Mn	µg/L	55.4	40.3	<0.5	39.3 38.2	36.4 35.6	<0.5 0.5	43.8	37.4	0.8	42.5	35.3	2.0
Dissolved Al	µg/L				1.3 1.4	1.1 1.4	0.9 0.9						
Dissolved Fe	µg/L				<30 <30	<30 <30	<30 <30						
Dissolved Mn	µg/L				32.6 32.3	27.1 27.1	<0.5 <0.5						

(a) As $CaCO_3$.
IN = inlet; PF = prefiltration; AF = after filtration; ND = not detected.

Table B-3. Analytical Results from Long Term Sampling, Plant B (August 6 to August 25, 1998)

Sampling Date		8/6/98			8/11/98			8/18/98			8/25/98		
Sampling Location Parameter	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L(a)	141	138	137	140 140	137 137	137 137	139	135	136	141	138	137
Turbidity	NTU	5.9	4.7	0.2									
pH		7.9	7.7	7.7	8.1 8.1	7.8 7.7	7.7 7.7	7.9	7.8	7.8	7.9	7.8	7.7
Total Hardness	mg/L(a)	414	405	397									
Ca Hardness	mg/L(a)	285	277	272									
Mg Hardness	mg/L(a)	129	128	125									
As (total)	µg/L	40.1 37.6	36.5 39.1	12.2 12.2	35.5	14.5	13.8	41.7	42.0	11.4	41.1	39.7	12.5
As (total soluble)	µg/L	12.2 12.6	11.8 11.9	10.9 11.2									
As (particulate)	µg/L	27.9 25.0	24.7 27.2	1.3 1.0									
As (III)	µg/L	2.2 2.3	0.5 0.5	0.4 0.4									
As (V)	µg/L	10.0 10.3	11.3 11.4	10. 5 10.8									
Total Al	µg/L	17.1 13.6	12.3 14.6	<11 <11	<11	<11	<11	24.9	23.2	12.8	17.8	47.8	30.8
Total Fe	µg/L	845 769	730 738	53.2 76.9	722	302	53.9	833	848	37.2	843	823	31.0
Total Mn	µg/L	41.5 38.2	31.0 31.3	0.5 0.7	32.8	13.8	1.4	44.1	40.1	0.9	43.0	34.4	0.8
Dissolved Al	µg/L	1.6 2.1	1.4 7.5	1.3 1.7									
Dissolved Fe	µg/L	10.8 <30	<30 <30	<30 <30									
Dissolved Mn	µg/L	32.3 32.2	28.9 29.0	0.1 0.1									

(a) As $CaCO_3$.

IN = inlet; PF = prefiltration; AF = after filtration; ND = not detected.

Table B-4. Analytical Results from Long Term Sampling, Plant B (September 1 to September 22, 1998)

Sampling Date		9/1/98			9/9/98			9/15/98			9/22/98		
Sampling Location Parameter	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L[(a)]	137	135	137	140 140	137 137	137 137	141	137	139	142	136	136
Turbidity	NTU	4.6	4.0	0.2									
pH		7.8	7.7	7.6	7.8 7.8	7.7 7.7	7.7 7.7	8.0	7.7	7.8	7.8	7.7	7.7
Total Hardness	mg/L[(a)]	442	428	429									
Ca Hardness	mg/L[(a)]	312	300	300									
Mg Hardness	mg/L[(a)]	130	129	129									
As (total)	µg/L	34.5 34.4	29.3 32.9	11.4 11.2	97.9	69.2	16.0	52.2	50.9	18.3	48.2	50.3	14.4
As (total soluble)	µg/L	13.4 13.6	13.2 13.1	12.3 11.9									
As (particulate)	µg/L	21.1 20.8	16.1 19.8	<0.1 <0.1									
As (III)	µg/L	0.1 0.1	0.2 0.2	0.1 0.1									
As (V)	µg/L	13.3 13.5	13.0 12.9	12.2 11.8									
Total Al	µg/L	13.8 16.6	11.9 15.7	<11 12.5	26.4	23.7	18.6	16.3	19.2	15.2	31.4	22.0	36.8
Total Fe	µg/L	614 644	593 650	35.5 35.0	2,004	1,345	94.0	1,009	989	74.9	2,152	2,167	306
Total Mn	µg/L	29.2 30.7	25.7 27.3	<0.5 0.6	67.3	33.2	0.6	99.0	39.1	9.1	51.3	54.8	7.0
Dissolved Al	µg/L	1.6 4.0	2.0 1.6	1.7 5.7									
Dissolved Fe	µg/L	ND ND	ND ND	ND ND									
Dissolved Mn	µg/L	28.4 28.2	27.0 26.5	0.1 0.2									

(a) As $CaCO_3$.
IN = inlet; PF = prefiltration; AF = after filtration; ND = not detected.

Table B-5. Analytical Results from Long Term Sampling, Plant B (September 30 to October 21, 1998)

Sampling Date		9/30/98			10/6/98			10/13/98			10/21/98		
Sampling Location Parameter	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L(a)	141	135	137	139 139	133 135	134 133	138	136	135	139	135	133
Turbidity	NTU	11.8	10.9	0.3									
pH		7.8	7.7	7.7	7.7 7.7	7.5 7.5	7.5 7.5	7.9	7.7	7.8	7.8	7.6	7.6
Total Hardness	mg/L(a)	474	468	398									
Ca Hardness	mg/L(a)	337	332	287									
Mg Hardness	mg/L(a)	137	136	111									
As (total)	µg/L	79.2 92.3	80.0 82.2	14.6 12.1	41.2	41.6	10.2	38.1	8.3	5.3	42.1	38.2	5.3
As (total soluble)	µg/L	15.8 15.7	14.3 14.3	10.3 10.2									
As (particulate)	µg/L	63.4 76.6	65.7 65.9	4.3 1.9									
As (III)	µg/L	0.7 0.7	0.8 0.7	0.8 0.8									
As (V)	µg/L	15.1 15.0	13.5 13.6	9.5 9.4									
Total Al	µg/L	23.4 21.5	25.6 32.9	19.6 14.4	17.1	11.0	15.9	11.5	2.9	<11	20.1	17.3	11.9
Total Fe	µg/L	1,689 1,666	1,763 1,768	40.5 43.2	599	591	<30	612	116	<30	726	925	98.5
Total Mn	µg/L	110 93.2	77.1 100	3.9 4.0	36.0	30.8	0.6	49.2	60.9	4.6	43.3	37.5	2.6
Dissolved Al	µg/L	<11 <11	<11 <11	<11 <11									
Dissolved Fe	µg/L	<30 <30	<30 <30	<30 <30									
Dissolved Mn	µg/L	25 25	25.8 25.6	0.2 0.2									

(a) As $CaCO_3$.
IN = inlet; PF = prefiltration; AF = after filtration; ND = not detected.

Table B-6. Analytical Results from Long Term Sampling, Plant B (October 27 TO November 17, 1998)

Sampling Date		10/27/98			11/03/98			11/10/98			11/17/98		
Sampling Location Parameter	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L$^{(a)}$	138	135	134	138 138	133 133	132 133	138	137	136	141	138	142
Turbidity	NTU	9.4	5.7	0.5									
pH		7.8	7.6	7.6	7.7 7.7	7.6 7.6	7.6 7.6	8.6	7.7	7.7	7.6	7.5	7.7
Total Hardness	mg/L$^{(a)}$	484	461	480									
Ca Hardness	mg/L$^{(a)}$	345	327	345									
Mg Hardness	mg/L$^{(a)}$	139	134	135									
As (total)	µg/L	40.8 40.5	42.2 41.7	8.6 8.3	51.3	49.5	11.2	48.7	49.6	12.5	46.1	50.6	13.0
As (total soluble)	µg/L	4.7 5.1	0.9 0.8	5.4 5.2									
As (particulate)	µg/L	36.1 35.4	41.3 40.9	3.2 3.1									
As (III)	µg/L	1.7 1.8	0.5 0.4	0.2 0.1									
As (V)	µg/L	3.0 3.3	0.4 0.4	5.2 5.1									
Total Al	µg/L	19.7 15.8	22.3 15.2	15.5 <11	12.5	<11	12.9	14.2	31.2	16.8	12.5	13.6	<11
Total Fe	µg/L	2,185 1,945	1,858 1,851	140 131	685	670	<30	686	679	<30	1,021	1,130	61.4
Total Mn	µg/L	52.0 55.6	43.1 42.5	3.4 3.2	64.0	51.2	1.4	55.9	56.0	0.8	107	83.2	1.3
Dissolved Al	µg/L	<11 <11	<11 <11	<11 <11									
Dissolved Fe	µg/L	633 678	<30 58.9	<30 <30									
Dissolved Mn	µg/L	40.8 41.4	9.3 9.6	0.4 1.4									

(a) As $CaCO_3$.

IN = inlet; PF = prefiltration; AF = after filtration; ND = not detected.

Table B-7. Analytical Results from Long Term Sampling, Plant B (November 24, to December 8, 1998)

Sampling Date		11/24/98(b)			12/01/98			12/08/98			12/15/98		
Sampling Location Parameter	Unit	IN	PF	AF	IN	PF	AF	IN	PF	AF	IN	PF	AF
Alkalinity	mg/L(a)				142	135	139	140 139	134 136	138 136	139	137	139
Turbidity	NTU				5.2	6.7	0.2						
pH					7.5	7.5	7.8	7.8 7.8	7.7 7.7	7.8 7.8	7.6	7.4	7.6
Total Hardness	mg/L(a)				494	473	482						
Ca Hardness	mg/L(a)				352	337	340						
Mg Hardness	mg/L(a)				142	136	143						
As (total)	µg/L				55.2 54.1	67.7 66.4	19.9 19.5	46.1	46.3	13.3			
As (total soluble)	µg/L				15.5 14.8	14.6 14.3	20.2 20.1						
As (particulate)	µg/L				39.7 39.3	53.1 52.1	<0.1 <0.1						
As (III)	µg/L				2.3 2.2	0.4 0.4	0.4 0.3						
As (V)	µg/L				13.2 12.6	14.2 13.9	19.8 19.8						
Total Al	µg/L				23.4 20.9	18.1 22.1	30.4 25.2	<11	13.3	<11			
Total Fe	µg/L				1,039 1,023	1,445 1,428	75.4 72.2	648	616	<30			
Total Mn	µg/L				138 133	153 149	1.6 1.6	52.9	39.2	0.5			
Dissolved Al	µg/L				<11 <11	<11 <11	<11 <11						
Dissolved Fe	µg/L				<30 <30	<30 <30	<30 <30						
Dissolved Mn	µg/L				32.9 32.0	28.4 27.1	0.5 0.6						

(a) As $CaCO_3$.
(b) No sampling due to Thanksgiving holiday.
IN = inlet; PF = prefiltration; AF = after filtration; ND = not detected.