

EPA/600/R-06/031
April 2006

Arsenic Removal from Drinking Water by Adsorptive Media
U.S. EPA Demonstration Project at Bow, NH
Six-Month Evaluation Report

by

Jeffrey L. Oxenham
Abraham S.C. Chen
Lili Wang

Battelle
Columbus, OH 43201-2693

Contract No. 68-C-00-185
Task Order No. 0019

for

Thomas J. Sorg
Task Order Manager

Water Supply and Water Resources Division
National Risk Management Research Laboratory
Cincinnati, Ohio 45268

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

DISCLAIMER

The work reported in this document is funded by the United States Environmental Protection Agency (EPA) under Task Order 0019 of Contract 68-C-00-185 to Battelle. It has been subjected to the Agency's peer and administrative reviews and has been approved for publication as an EPA document. Any opinions expressed in this paper are those of the author(s) and do not, necessarily, reflect the official positions and policies of the EPA. Any mention of products or trade names does not constitute recommendation for use by the EPA.

FOREWORD

The U.S. Environmental Protection Agency (EPA) 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 actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and groundwater; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

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

Sally Gutierrez, Director
National Risk Management Research Laboratory

ABSTRACT

This report documents the activities performed during and the results obtained from the first six months of the arsenic removal treatment technology demonstration project at the White Rock Water Company (WRWC) public water system, a small residential drinking water facility in Bow, NH. The objectives of the project are to evaluate the effectiveness of the ADI Group, Inc. (ADI) G2 media in removing arsenic to meet the new arsenic maximum contaminant level (MCL) of 10 µg/L, the reliability of the treatment system, the required system operation and maintenance (O&M) and operator's skills, and the capital and O&M costs of the technology. The project also characterizes the water in the distribution system and process residuals produced by the treatment system.

The arsenic adsorption system consisted of two vertical, 72-inch-diameter and 72-inch-sidewall-height stainless steel vessels configured in series. The adsorption vessels were originally designed to operate in parallel for the Holiday Acres Mobile Home Park in Allentown, NH with a flowrate of 70 gallons per minute (gpm) (35 gpm per vessel). Due to the switch to the site in Bow with a total flowrate of about 40 gpm, the flowrate was reduced by 43%; therefore, the system was reconfigured to operate in series. At 40 gpm, each vessel provided an empty bed contact time (EBCT) of 16 min (or 32 min total contact time) and a hydraulic loading rate of 1.4-gpm/ft². The 16-min EBCT was 60% longer than that normally recommended by the vendor and the 1.4-gpm/ft² hydraulic loading rate was about 50% lower than that normally applied to the G2 media.

The G2 media is a granular, calcined diatomite substrate coated with ferric hydroxide. Because of its inherently high pH values from the manufacturing process, the G2 media was conditioned on-site with sulfuric acid before the system was put into service. To increase the media adsorption capacity, the raw water was adjusted to a target value of 6.8, and later 6.4, using a 93% sulfuric acid solution. The treated water was adjusted for pH again to a target value of 7.5 using a 25% caustic solution before entering the distribution system. In-line pH probes were used to monitor the pH values of the feed water and treated water but the rates of acid and caustic addition were controlled via manual adjustments to the pump stroke length. The relative feed rates were then flow-paced with a water meter located on the discharge line following the treatment system.

The arsenic adsorption system became operational on October 13, 2004. Through April 24, 2005, the system operated for 1,741 hr, treating approximately 3,858,000 gal of water or 6,067 bed volumes (BVs). Total As concentrations in the raw water averaged 49.3 µg/L, present almost entirely as As(V). After the lead vessel, greater than 30 µg/L of total As was unexpectedly detected in samples collected just after startup on October 13 and about one week later on October 19, 2004. After about 380 BVs of throughput, total As concentrations decreased to 12.6 to 15.6 µg/L before beginning a steady increase to 26.3 µg/L at about 2,600 BVs by April 12, 2005. Total As concentrations after the lag vessel also were high during the first two weeks of system operation, with 16.7 to 21.8 µg/L of arsenic measured on October 13 and October 19, 2004, respectively. Afterwards, the concentrations dropped to 1.7 µg/L after about 2,500 BVs and then increased steadily to 5.8 µg/L after about 5,700 BVs by April 12, 2005. ADI attributed the elevated arsenic concentrations just after the system startup to the leaching of arsenic from the G2 media prepared with FeCl₃ containing arsenic and manganese as impurities. While this might explain the elevated arsenic levels observed in the treated water during the first two weeks of system operation, it does not explain why the arsenic concentrations remained high (i.e., 12.6 µg/L or greater) following the lead vessel throughout the first six months of operation.

Increases in both manganese and silica were observed in the treated water following the adsorption vessels, indicating leaching of these constituents from the media. After about 3,000 BVs, manganese concentrations decreased to levels similar to those in the raw water. The leaching of silica from both

vessels leveled off after about 2,000 BVs, but continued throughout the remainder of the study period with an increase in concentrations ranging from 1.6 to 6.2 mg/L.

The system was backwashed only twice during this period because of low pressure losses (i.e., 1-2 pounds per square inch [psi]) across the adsorption vessels. Analysis of the backwash water indicated that soluble As concentrations were either similar to or lower than the levels measured in the source water. Since finished water was used for backwash, some arsenic might have been desorbed from the media during backwashing. Future backwash samples will include collection and analysis of total suspended solids (TSS) and total As, Fe, and Mn.

Comparison of the distribution system sampling results before and after the installation of the ADI G2 media system showed a decrease in arsenic concentration (from 36.9 - 52.3 µg/L to 3.9 - 12.4 µg/L) at all three EPA Lead and Copper Rule (LCR) sampling locations. Manganese concentrations increased to as high as 16.0 µg/L in the distribution system during the first three months of system operation, apparently due to leaching of manganese from the G2 media, as mentioned above. Following a drop in pH of the treated water in December 2004, the lead concentration in the January 12, 2005 sample increased to 9.9 µg/L at one sampling location and copper levels increased across all three sampling locations, with the most noticeable increase exceeding the action level of 1.3 mg/L at one location. During the subsequent monthly sampling events, the pH values were better controlled; however, the lead and copper levels continued to be higher than those observed before the pH drop in January.

The most significant operational issue observed was related to the addition of acid and caustic necessary to maintain the desired pH ranges of the feed water to the treatment system and the finish water to the storage tank and distribution system. Confounding the proper addition of acid and caustic were continuing discrepancies observed in pH readings from the inline pH probes versus a WTW field meter used to measure pH at sampling locations across the treatment train. In fact, an inadvertent lowering of the caustic addition in late December resulted in the pH drop observed in the distribution system samples collected on January 12, 2005, and the corresponding increase in lead and copper levels in the distribution system as described above.

The capital investment cost of \$154,700 includes \$102,600 for equipment, \$12,500 for site engineering, and \$39,600 for installation. Using the system's actual capacity of 40 gpm (57,600 gal per day [gpd]), the capital cost was \$3,868/gpm (\$2.68/gpd) and equipment-only cost was \$2,565/gpm (\$1.78/gpd). These calculations did not include the cost of the building construction.

O&M costs included only incremental costs associated with the adsorption system, such as media replacement and disposal, chemical supply, electricity, and labor. Incremental costs for electricity were negligible. Although media replacement and disposal did not take place during the first six months of operation, the cost to change out the lead vessel was estimated to be \$9,396 based on information provided by the vendor and a local subcontractor. This cost was used to estimate the media replacement cost per 1,000 gal of water treated as a function of the projected media run length to the 10-µg/L arsenic breakthrough.

CONTENTS

DISCLAIMER	ii
FOREWORD	iii
ABSTRACT.....	iv
APPENDICES	vii
FIGURES.....	vii
TABLES	vii
ABBREVIATIONS AND ACRONYMS	viii
ACKNOWLEDGMENTS	x
1.0 INTRODUCTION	1
1.1 Background.....	1
1.2 Treatment Technologies for Arsenic Removal	1
1.3 Project Objectives	2
2.0 CONCLUSIONS.....	3
3.0 MATERIALS AND METHODS.....	5
3.1 General Project Approach.....	5
3.2 System O&M and Cost Data Collection	6
3.3 Sample Collection Procedures and Schedules	6
3.3.1 Source Water Sample Collection.	8
3.3.2 Treatment Plant Water Sample Collection.....	8
3.3.3 Backwash Water Sample Collection	8
3.3.4 Backwash Solid Sample Collection	8
3.3.5 Distribution System Water Sample Collection	8
3.4 Sampling Logistics.....	8
3.4.1 Preparation of Arsenic Speciation Kits	9
3.4.2 Preparation of Sampling Coolers	9
3.4.3 Sample Shipping and Handling.....	9
3.5 Analytical Procedures	9
4.0 RESULTS AND DISCUSSION	11
4.1 Facility Description.....	11
4.1.1 Source Water Quality.....	11
4.1.2 Pre-Demonstration Treated Water Quality.....	14
4.1.3 Distribution System.....	14
4.2 Treatment Process Description	14
4.3 System Installation.....	20
4.3.1 Permitting.....	20
4.3.2 Building Construction	20
4.3.3 Installation, Shakedown, and Startup	21
4.4 System Operation.....	21
4.4.1 Operational Parameters	21
4.4.2 Backwash	22
4.4.3 Residuals Management	22
4.4.4 System Operation Reliability and Simplicity	22
4.5 System Performance	24
4.5.1 Treatment Plant Sampling.....	24
4.5.2 Backwash Water Sampling	33

4.5.3	Distribution System Water Sampling.....	33
4.6	System Costs.....	34
4.6.1	Capital Costs	34
4.6.2	Operation and Maintenance Costs.....	36
5.0	REFERENCES	39

APPENDICES

APPENDIX A:	Operational Data.....	A-1
APPENDIX B:	Analytical Results.....	B-1

FIGURES

Figure 4-1.	Existing Underground Treatment and Control Structure	11
Figure 4-2.	Existing Storage Tanks in Underground Concrete Structure	12
Figure 4-3.	Existing Activated Alumina System in the Underground Treatment and Control Structure	12
Figure 4-4.	Schematic of G2 Media Adsorption System (Provided by ADI).....	16
Figure 4-5.	Process Flow Diagram and Sampling Locations.....	18
Figure 4-6.	ADI G2 Media Arsenic Adsorption System	19
Figure 4-7.	New Treatment Building Addition.....	20
Figure 4-8.	Concentration of Arsenic Species at the IN, AP, TA, and TB Sampling Locations	28
Figure 4-9.	Total Arsenic Breakthrough Curves.....	29
Figure 4-10.	Total Manganese Concentrations Over Time.....	30
Figure 4-12.	Silica Concentrations Over Time	32
Figure 4-13.	Media Replacement and O&M Costs	38

TABLES

Table 1-1.	Summary of Arsenic Removal Demonstration Technologies and Source Water Quality Parameters	2
Table 3-1.	Pre-Demonstration Study Activities and Completion Dates.....	5
Table 3-2.	Evaluation Objectives and Supporting Data Collection Activities	5
Table 3-3.	Sample Collection Schedule and Analyses	7
Table 4-1.	Raw and Treated Water Quality Data	13
Table 4-2.	Physical and Chemical Properties of G2 Media.....	15
Table 4-3.	Design Specifications of the G2 Media System.....	17
Table 4-4.	Summary of G2 Media Treatment System Operation.....	22
Table 4-5.	Summary of Arsenic, Iron, and Manganese Analytical Results.....	25
Table 4-6.	Summary of Water Quality Parameter Measurements.....	26
Table 4-7.	Calculation of Acid Consumption for pH Adjustment at the WRWC Site.....	32
Table 4-8.	Backwash Water Sampling Results	33
Table 4-9.	Distribution System Sampling Results.....	35
Table 4-10.	Capital Investment for the G2 Media Treatment System.....	36
Table 4-11.	O&M Costs for the G2 Media Treatment System.....	37

ABBREVIATIONS AND ACRONYMS

Δp	differential pressure
AA	activated alumina
AAL	American Analytical Laboratories
ADI	ADI Group, Inc.
Al	aluminum
AM	adsorptive media
As	arsenic
bgs	below ground surface
BV	bed volume(s)
C/F	coagulation/filtration
Ca	calcium
Cl ₂	chlorine
CRF	capital recovery factor
Cu	copper
DO	dissolved oxygen
EBCT	empty bed contact time
EPA	U.S. Environmental Protection Agency
F	fluoride
Fe	iron
gal	gallons
GFH	granular ferric hydroxide
GFO	granular ferric oxide
gpd	gallons per day
gpm	gallons per minute
HDPE	high-density polyethylene
HAMHP	Holiday Acres Mobile Home Park
hr	hours
ICP-MS	inductively coupled plasma-mass spectrometry
ID	identification
IX	ion exchange
LCR	(EPA) Lead and Copper Rule
MCL	maximum contaminant level
MDL	method detection limit
MDWCA	Mutual Domestic Water Consumers Association
Mg	magnesium
mg/L	milligrams per liter
µg/L	micrograms per liter
min	minutes

ABBREVIATIONS AND ACRONYMS (CONTINUED)

Mn	manganese
Mo	molybdenum
mV	millivolts
N/A	not applicable
Na	sodium
NA	not available
NaOCl	sodium hypochlorite
NHDES	New Hampshire Department of Environmental Services
NRMRL	National Risk Management Research Laboratory
NSF	NSF International
NTU	nephelometric turbidity unit
O&M	operation and maintenance
ORD	Office of Research and Development
ORP	oxidation-reduction potential
Pb	lead
psi	pounds per square inch
PO ₄	orthophosphate
PVC	polyvinyl chloride
QA	quality assurance
QA/QC	quality assurance/quality control
QAPP	Quality Assurance Project Plan
RPD	relative percent difference
Sb	antimony
SDWA	Safe Drinking Water Act
SiO ₂	silica
SM	system modification
SO ₄	sulfate
STMGID	South Truckee Meadows General Improvement District
STS	Severn Trent Services
TBD	to be determined
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
TOC	total organic carbon
TSS	total suspended solids
V	vanadium
VOC	volatile organic compound
WRWC	White Rock Water Company

ACKNOWLEDGMENTS

The authors wish to extend their sincere appreciation to the staff of C&C Water Services of Gilford and Bow in New Hampshire. The C&C Water Services staff monitored the treatment system daily, and collected samples from the treatment system and distribution system on a regular schedule throughout this reporting period. This performance evaluation would not have been possible without their efforts.

1.0 INTRODUCTION

1.1 Background

The Safe Drinking Water Act (SDWA) mandates that the U.S. Environmental Protection Agency (EPA) identify and regulate drinking water contaminants that may have adverse human health effects and that are known or anticipated to occur in public water supply systems. In 1975 under the SDWA, EPA established a maximum contaminant level (MCL) for arsenic at 0.05 mg/L. Amended in 1996, the SDWA required that EPA develop an arsenic research strategy and publish a proposal to revise the arsenic MCL by January 2000. On January 18, 2001, EPA finalized the arsenic MCL at 0.01 mg/L (EPA, 2001). In order to clarify the implementation of the original rule, EPA revised the rule text on March 25, 2003 to express the MCL as 0.010 mg/L (10 µg/L) (EPA, 2003). The final rule requires all community and non-transient, non-community water systems to comply with the new standard by January 23, 2006.

In October 2001, EPA announced an initiative for additional research and development of cost-effective technologies to help small community water systems (<10,000 customers) meet the new arsenic standard, and to provide technical assistance to operators of small systems in order to reduce compliance costs. As part of this Arsenic Rule Implementation Research Program, EPA's Office of Research and Development (ORD) proposed a project to conduct a series of full-scale, on-site demonstrations of arsenic removal technologies, process modifications, and engineering approaches applicable to small systems. Shortly thereafter, an announcement was published in the *Federal Register* requesting water utilities interested in participating in the first round of this EPA-sponsored demonstration program to provide information on their water systems. In June 2002, EPA selected 17 sites from a list of 115 sites to be the host sites for the demonstration studies. Holiday Acres Mobile Home Park (HAMHP) in Allenstown, NH, was originally selected as one of the 17 Round 1 host sites for the demonstration program.

In September 2002, EPA solicited proposals from engineering firms and vendors for cost-effective arsenic removal treatment technologies for the 17 host sites. EPA received 70 technical proposals for the 17 host sites, with each site receiving from one to six proposals. In April 2003, an independent technical panel reviewed the proposals and provided its recommendations to EPA on the technologies that it determined were acceptable for the demonstration at each site. Because of funding limitations and other technical reasons, only 12 of the 17 sites were selected for the demonstration project. Using the information provided by the review panel, EPA in cooperation with the host sites and the drinking water programs of the respective states selected one technical proposal for each site. The ADI G2 adsorptive media was selected for the Allenstown site. In January 2004, HAMHP decided to withdraw from the demonstration study due to the facility's decision to switch to an alternate public water supply source.

In March 2004, EPA decided to replace HAMHP with the White Rock Water Company (WRWC) public water system, operated by C&C Water Services, serving the community of Village Shore Estates at Bow, NH. Because the design flowrate for the WRWC system was about half of the flowrate at HAMHP, the ADI adsorption system was re-configured to operate in series, increasing the empty bed contact time (EBCT) from 18 to 32 min total (i.e., 16 min per vessel, two vessels in series).

1.2 Treatment Technologies for Arsenic Removal

The technologies selected for the 12 Round 1 EPA arsenic removal demonstration host sites include nine adsorptive media systems, one anion exchange system, one coagulation/filtration system, and one process modification with iron addition. Table 1-1 summarizes the locations, technologies, vendors, and key source water quality parameters (including arsenic, iron, and pH) of the 12 demonstration sites. The technology selection and system design for the 12 demonstration sites have been reported in an EPA report (Wang et al., 2004) posted on an EPA Web site (<http://www.epa.gov/ORD/NRMRL/arsenic/resource.htm>).

Table 1-1. Summary of Arsenic Removal Demonstration Technologies and Source Water Quality Parameters

Demonstration Site	Technology (Media)	Vendor	Design Flowrate (gpm)	Source Water Quality		
				As (µg/L)	Fe (µg/L)	pH
WRWC (Bow), NH	AM (G2)	ADI	70 ^(a)	39	<25	7.7
Rollinsford, NH	AM (E33)	AdEdge	100	36 ^(b)	46	8.2
Queen Anne's County, MD	AM (E33)	STS	300	19 ^(b)	270 ^(c)	7.3
Brown City, MI	AM (E33)	STS	640	14 ^(b)	127 ^(c)	7.3
Climax, MN	C/F	Kinetico	140	39 ^(b)	546 ^(c)	7.4
Lidgerwood, ND	SM	Kinetico	250	146 ^(b)	1,325 ^(c)	7.2
Desert Sands MDWCA, NM	AM (E33)	STS	320	23 ^(b)	39	7.7
Nambe Pueblo, NM	AM (E33)	AdEdge	145	33	<25	8.5
Rimrock, AZ	AM (E33)	AdEdge	90 ^(d)	50	170	7.2
Valley Vista, AZ	AM (AAFS50)	Kinetico	37	41	<25	7.8
Fruitland, ID	IX	Kinetico	250	44	<25	7.4
STMGID, NV	AM (GFH)	USFilter	350	39	<25	7.4

AM = adsorptive media process; C/F = coagulation/filtration process; IX = ion exchange process;

SM = system modification; MDWCA = Mutual Domestic Water Consumers Association

STMGID = South Truckee Meadows General Improvement District; WRWC = White Rock Water Company

(a) System reconfigured from parallel to series operation due to lower flowrate of 40 gpm at the WRWC site

(b) Arsenic exists mostly as As(III).

(c) Iron exists mostly as soluble Fe(II).

(d) Due to system reconfiguration from parallel to series operation, the design flowrate is reduced by 50%.

1.3 Project Objectives

The objective of the Round 1 arsenic demonstration program is to conduct 12 full-scale arsenic treatment technology demonstration studies on the removal of arsenic from drinking water supplies. The specific objectives are to:

- Evaluate the performance of the arsenic removal technologies for use on small systems.
- Determine the simplicity of required system operation and maintenance (O&M) and operator's skill levels.
- Determine the capital and O&M costs of the technologies.
- Characterize process residuals produced by the technologies.

This report summarizes the results gathered during the first six months of the ADI system operation from October 13, 2004 through April 24, 2005. The types of data collected include system operational data, water quality data (both across the treatment train and in the distribution system), residuals characterization data, and capital and preliminary O&M cost data.

2.0 CONCLUSIONS

Based on the information collected during the first six months of system operation, the following conclusions were made relating to the overall objectives of the treatment technology demonstration study.

Performance of the arsenic removal technology for use on small systems:

- Higher than 10 µg/L of arsenic breakthrough was observed after the lead vessel throughout this study period. The arsenic concentration increased to 26.3 µg/L after about 5,700 BVs of throughput. Elevated arsenic concentrations also were measured after the lag vessel immediately after the system startup. The concentration decreased to 1.7 µg/L and then increased to 5.8 µg/L at 5,700 BVs of throughput. Lowering the pH values to as low as 6.1 did not appear to improve the media performance.
- Increases in manganese and silica concentrations to as high as 35.8 µg/L and 61.8 mg/L, respectively, were observed in the treated water following the G2 media treatment, indicating leaching of these constituents from the media. According to the vendor, some arsenic and manganese existed as impurities in the FeCl₃ solution used to produce the G2 media; silica was the base substrate of the G2 media. The concentrations of both manganese and silica leveled off after 2,000 to 3,000 BVs of throughput.
- Other than a few exceptions, arsenic, iron, and manganese concentrations in the distribution system closely mirrored those measured after the treatment system. A loss of pH control resulted in lower than normal pH values in the distribution system, causing a significant increase in the lead and copper levels with the copper concentration at one location exceeding its action level of 1.3 mg/L.
- Total and free chlorine residuals measured before and after the adsorption vessels were similar, indicating little or no chlorine consumption by the G2 media.

Required system O&M and operator's skill levels:

- Generally, the operation of the treatment system did not require additional skills beyond those necessary to operate the original treatment equipment used at the site prior to the demonstration. The daily demand on the system operator was typically about 20 min to inspect the system and record operational parameters. Based on the size of the population served and the treatment technology, the State of New Hampshire requires Level 1A Certification for operation of the treatment system and is considering upgrading this requirement to Level 1 certification.
- A significant O&M issue for this system was the need for acid and caustic addition to maintain the desired pH ranges of the feed water to the treatment system and the finished water to the distribution system.

Process residuals produced by the technology:

- Residuals produced by the operation of the treatment system included backwash water and spent media. Because the media was not replaced during the first six months of system operation, the only residual produced was backwash water.

- Because the pressure drop across the vessels was low (i.e., 1-2 psi), the system was backwashed only twice during the first six months of operation. Each backwash event produced approximately 2,000 gal of wastewater per vessel. Soluble arsenic concentrations in the backwash water from the lead vessel ranged from 40.3 to 42.8 µg/L. Soluble arsenic concentrations in the backwash water from the lag vessel ranged from 11.4 to 26.1 µg/L.

Cost-effectiveness of the technology:

- Using the system's actual capacity of 40 gallons per minute (gpm) (57,600 gallons per day [gpd]), the capital cost was \$3,868/gpm (\$2.68/gpd) and equipment-only cost was \$2,565/gpm (\$1.78/gpd). These calculations did not include the cost of the building construction.
- Although media replacement and disposal did not take place during the first six months of operation, the cost to change out the lead vessel was estimated to be \$9,396 based on information provided by the vendor and a local subcontractor.

3.0 MATERIALS AND METHODS

3.1 General Project Approach

Following the pre-demonstration activities summarized in Table 3-1, the performance evaluation study of the ADI adsorption system began on October 13, 2004. Table 3-2 summarizes the types of data collected and/or considered as part of the technology evaluation process. The overall performance of the system was determined based on its ability to consistently remove arsenic to the target MCL of 10 µg/L; this was monitored through the collection of biweekly and monthly water samples across the treatment train. The reliability of the system was evaluated by tracking the unscheduled system downtime and frequency and extent of repair and replacement. The unscheduled downtime and repair information were recorded by the plant operator on a Repair and Maintenance Log Sheet.

Table 3-1. Pre-Demonstration Study Activities and Completion Dates

Activity	Date
Introductory Meeting Held	April 22, 2004
Revised Vendor Quotation Submitted to Battelle	May 10, 2004
Purchase Order Modification Completed	June 10, 2004
Engineering Package Submitted to NHDES	June 14, 2004
Steel Floor for Treatment System Installed	June 25, 2004
Adsorption Vessels Delivered to Site	June 28, 2004
Permit Issued by NHDES	August 23, 2004
Draft Study Plan Issued	September 2, 2004
System Installation Completed	September 13, 2004
Final Study Plan Issued	October 6, 2004
Media Conditioning and System Shakedown Completed	October 11, 2004
Performance Evaluation Begun	October 13, 2004

NHDES = New Hampshire Department of Environmental Services.

Table 3-2. Evaluation Objectives and Supporting Data Collection Activities

Evaluation Objectives	Data Collection
Performance	-Ability to consistently meet 10 µg/L of arsenic in effluent
Reliability	-Unscheduled downtime for system -Frequency and extent of repairs to include labor hours, problem description, description of materials, and cost of materials
Simplicity of Operation and Operator Skill	-Pre- and post-treatment requirements -Level of system automation for data collection and system operation -Staffing requirements including number of operators and labor hours -Task analysis of preventive maintenance to include labor hours per month and number and complexity of tasks -Chemical handling and inventory requirements -General knowledge needed of safety requirements and chemical processes
Cost-Effectiveness	-Capital costs including equipment, engineering, and installation -O&M costs including chemical and/or media usage, electricity, and labor
Residual Management	-Quantity of the residuals generated by the process -Characteristics of the aqueous and solid residuals

Simplicity of the system operation and the level of operator skill required were evaluated based on a combination of quantitative data and qualitative considerations, including any pre-treatment and/or post-treatment requirements, level of system automation, operator skill requirements, task analysis of the preventive maintenance activities, frequency of chemical and/or media handling and inventory requirements, and general knowledge needed for safety requirements and chemical processes. The staffing requirements on the system operation were recorded on an Operator Labor Hour Log Sheet.

The cost-effectiveness of the system is evaluated based on the cost per 1,000 gal (\$/1,000 gal) of water treated. This requires the tracking of capital costs such as equipment, engineering, and installation costs, as well as O&M costs for media replacement and disposal, chemical supply, electrical power use, and labor hours. The capital costs have been reported in an EPA report (Chen et al., 2004) posted on an EPA Web site (<http://www.epa.gov/ORD/NRMRL/arsenic/resource.htm>). Data on O&M costs were limited to chemicals, electricity, and labor hours because media replacement did not take place during the six months of operation.

The quantity of aqueous and solid residuals generated was estimated by tracking the amount of backwash water produced during each backwash cycle and the need to replace the media upon arsenic breakthrough. Backwash water was sampled and analyzed for chemical characteristics.

3.2 System O&M and Cost Data Collection

The plant operator performed daily, weekly, and monthly system O&M and data collection following the instructions provided by ADI and Battelle. On a daily basis, the plant operator recorded system operational data, such as pressure, flowrate, totalizer, and hour meter readings on a System Operation Log Sheet; checked the sodium hypochlorite, acid, and caustic drum levels; and conducted visual inspections to ensure normal system operations. In the event of problems, the plant operator would contact the Battelle Study Lead, who then would determine if ADI should be contacted for troubleshooting. The plant operator recorded all relevant information on the Repair and Maintenance Log Sheet. Once a week the plant operator measured water quality parameters, including temperature, pH, dissolved oxygen (DO)/oxidation-reduction potential (ORP), and residual chlorine, and recorded the data on a Weekly On-Site Water Quality Parameters Log Sheet.

Capital costs for the ADI system consisted of costs for equipment, site engineering, and system installation. The O&M costs consisted primarily of costs for the media replacement and spent media disposal, chemical and electricity consumption, and labor. Chemical usage, including sodium hypochlorite, acid, and caustic, and electricity consumption were tracked using the System Operation Log Sheet. Labor hours for various activities, such as the routine system O&M, system troubleshooting and repair, and demonstration-related work, were tracked using an Operator Labor Hour Log Sheet. The routine O&M included activities such as completing the daily field logs; replenishing the sodium hypochlorite, acid, and caustic solutions; ordering supplies; performing system inspections; and other items as recommended by the equipment vendor. The demonstration-related work included activities such as performing field measurements, collecting and shipping samples, and communicating with the Battelle Study Lead. The demonstration-related activities were recorded but not included in the cost analysis.

3.3 Sample Collection Procedures and Schedules

To evaluate the performance of the system, samples were collected from the source, treatment plant, distribution system, and adsorptive vessel backwash. Table 3-3 provides the sampling schedules and analytes measured during each sampling event. Specific sampling requirements for analytical methods, sample volumes, containers, preservation, and holding times are presented in Table 4-1 of the EPA-endorsed Quality Assurance Project Plan (QAPP) (Battelle, 2003).

Table 3-3. Sample Collection Schedule and Analyses

Sample Type	Sample Locations^(a)	No. of Samples	Frequency	Analytes	Date(s) Samples Collected
Source Water	Storage Tanks	1	Once during the initial site visit	As(total), particulate and soluble As, As(III), As(V), Fe (total and soluble), Mn (total and soluble), Al (total and soluble), Na, Ca, Mg, V, Mo, Sb, Cl, F, SO ₄ , SiO ₂ , PO ₄ , TOC, alkalinity, and pH.	04/22/04
Treatment Plant Water	After wells combined (IN), after chlorination and pH adjustment (AP) , after Vessel A (TA), and after Vessel B (TB)	4	Biweekly	On-site: pH, temperature, DO/ORP, Cl ₂ (free and total) (except IN location). Off-site: As (total), Fe (total), Mn (total), SiO ₂ , PO ₄ , turbidity, and alkalinity.	10/19/04, 10/26/04, 11/02/04, 11/16/04, 11/30/04, 01/04/05, 01/18/05, 02/15/05, 03/01/05, 03/15/05, 04/12/05
			Bimonthly	On-site: pH, temperature, DO/ORP, and Cl ₂ (free and total) (except IN location). Off-site: As(total), particulate and soluble As, As(III), As(V), Fe (total and soluble), Mn (total and soluble), Ca, Mg, F, NO ₃ , SO ₄ , SiO ₂ , PO ₄ , turbidity, and alkalinity.	10/13/04, 12/14/04, 02/01/05, 03/29/05
Distribution Water	Three residences previously used as LCR sampling locations	3	Monthly	pH, alkalinity, As, Fe, Mn, Pb, and Cu.	Baseline sampling ^(b) : 07/21/04, 08/05/04, 08/18/04, 09/08/04 Monthly sampling: 11/03/04, 12/08/04, 01/12/05, 02/09/05, 03/09/05, 04/20/05
Backwash Water	Sample ports on backwash discharge line from each vessel	2	During each backwash event	TDS, turbidity, pH, As (soluble), Fe (soluble), and Mn (soluble)	01/11/05 04/12/05
Residual Sludge	Backwash discharge area	2-3	TBD	TCLP Metals	TBD

(a) The abbreviation in each parenthesis corresponds to the sample location in Figure 4-5.

(b) Four baseline sampling events were performed before the system became operational.

TBD = to be determined.

3.3.1 Source Water Sample Collection. During the initial visit to the WRWC site, Battelle collected one set of source water samples for detailed water quality analyses. The source water also was speciated for particulate and soluble As, iron (Fe), manganese (Mn), aluminum (Al), and As(III) and As(V). The sample tap was flushed for several minutes before sampling; special care was taken to avoid agitation, which might cause unwanted oxidation. Arsenic speciation kits and containers for water quality samples were prepared as described in Section 3.4.

3.3.2 Treatment Plant Water Sample Collection. During the system performance evaluation study, water samples were collected across the treatment train by the plant operator. Samples were collected biweekly on an eight-week cycle. For the first three biweekly events, treatment plant samples were collected at four locations (i.e., after wells combined [IN], after chlorination and pH adjustment [AP], after Vessel A [TA], and after Vessel B [TB]), and analyzed for the analytes listed under the biweekly treatment plant analyte list (see Table 3-3). Bimonthly (once every eight weeks) treatment plant samples collected at the same four locations were speciated for arsenic and analyzed for the analytes listed in Table 3-3 under “bimonthly.” The sampling frequency was reduced from weekly as stated in the Study Plan to biweekly following the first month of system operations.

3.3.3 Backwash Water Sample Collection. Two backwash water samples were collected on January 11 and April 12, 2005 from the sample taps located at the backwash water effluent line from each vessel. Unfiltered samples were measured on site for pH using a field pH meter, and a 1-gallon sample was sent to American Analytical Laboratories (AAL) for total dissolved solids (TDS) and turbidity measurements. Filtered samples using 0.45- μ m filters were sent to Battelle’s inductively coupled plasma-mass spectrometry (ICP-MS) laboratory for soluble As, Fe, and Mn analyses. Arsenic speciation was not performed for the backwash water samples.

3.3.4 Backwash Solid Sample Collection. Backwash solid samples were not collected in the initial six months of this demonstration. Solid/sludge samples will be collected from the backwash discharge during the second half of the demonstration. The solid/sludge samples will be collected in glass jars and submitted to TCCI Laboratories for Toxicity Characteristic Leaching Procedure (TCLP) tests.

3.3.5 Distribution System Water Sample Collection. Samples were collected from the distribution system to determine the impact of the arsenic treatment system on the water chemistry in the distribution system, specifically arsenic, lead, and copper levels. During July through September 2004, prior to the startup of the treatment system, four baseline distribution system sampling events were conducted at three locations within the distribution system. Following the startup of the arsenic adsorption system, distribution system sampling continued on a monthly basis at the same three locations.

The three homes selected for the sampling had been included in the Lead and Copper Rule (LCR) sampling in the past. The samples were collected following an instruction sheet developed according to the *Lead and Copper Rule Reporting Guidance for Public Water Systems* (EPA, 2002). First-draw samples were collected from cold-water faucets that had not been used for at least six hours to ensure that stagnant water was sampled. The sampler recorded the date and time of last water use before sampling and the date and time of sample collection for calculation of the stagnation time. Analytes for the baseline samples coincided with the monthly distribution system water samples as described in Table 3-3. Arsenic speciation was not performed for the distribution water samples.

3.4 Sampling Logistics

All sampling logistics including arsenic speciation kits preparation, sample cooler preparation, and sample shipping and handling are discussed as follows:

3.4.1 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) (Edwards et al., 1998). Arsenic speciation kits were prepared in batches at Battelle laboratories according to the procedures detailed in Appendix A of the EPA-endorsed QAPP (Battelle, 2003).

3.4.2 Preparation of Sampling Coolers. All sample bottles were new and contained appropriate preservatives. Each sample bottle was taped with a pre-printed, colored-coded, and waterproof label. The sample label consisted of sample identification (ID), date and time of sample collection, sampler initials, location, sent to, analysis required, and preservative. The sample ID consisted of a two-letter code for a specific water facility, the sampling date, a two-letter code for a specific sampling location, and a one-letter code for the specific analysis to be performed. The sampling locations were color-coded for easy identification. For example, red, orange, yellow, and green were used to designate sampling locations for IN, AP, TA, and TB, respectively. Pre-labeled bottles were placed in one of the plastic bags (each corresponding to a specific sampling location) in a sample cooler. When arsenic speciation samples were to be collected, an appropriate number of arsenic speciation kits also were included in the cooler. When appropriate, the sample cooler also was packed with bottles for the three distribution system sampling locations and/or the two backwash sampling locations (one for each vessel).

In addition, a packet containing all sampling and shipping-related supplies, such as latex gloves, sampling instructions, chain-of-custody forms, prepaid Federal Express air bills, ice packs, and bubble wrap, also was placed in the cooler. Except for the operator's signature, the chain-of-custody forms and prepaid Federal Express air bills had already been completed with the required information. The sample coolers were shipped via Federal Express to the facility approximately one week prior to the scheduled sampling date.

3.4.3 Sample Shipping and Handling. After sample collection, samples for off-site analyses were packed carefully in the original coolers with wet ice and shipped to Battelle. Upon receipt, sample custodians verified that all samples indicated on the chain-of-custody forms were included and intact. Sample label identifications were checked against the chain-of-custody forms and the samples were logged into the laboratory sample receipt log. Discrepancies, if noted, were addressed by the field sample custodian, and the Battelle Study Lead was notified.

Samples for water quality analyses by Battelle's subcontract laboratories were packed in coolers at Battelle and picked up by a courier from either AAL (Columbus, OH) or TCCI Laboratories (New Lexington, OH). The samples for arsenic speciation analyses were stored at Battelle's ICP-MS Laboratory. The chain-of-custody forms remained with the samples from the time of preparation through analysis and final disposition. All samples were archived by the appropriate laboratories for the respective duration of the required hold time, and disposed of properly thereafter.

3.5 Analytical Procedures

The analytical procedures are described in detail in Section 4.0 of the EPA-endorsed QAPP (Battelle, 2003). Field measurements of pH, temperature, and DO/ORP were conducted by the plant operator using a WTW Multi 340i handheld meter, which was calibrated prior to use following the procedures provided in the user's manual. The plant operator collected a water sample in a 400-mL plastic beaker and placed the Multi 340i probe in the beaker until a stable, measured value was reached. The plant operator also performed free and total chlorine measurements using Hach chlorine test kits.

Laboratory quality assurance/quality control (QA/QC) of all methods followed the guidelines provided in the QAPP (Battelle, 2003). Data quality in terms of precision, accuracy, method detection limit (MDL), and completeness met the criteria established in the QAPP, i.e., relative percent difference (RPD) of 20%,

percent recovery of 80-120%, and completeness of 80%. The quality assurance (QA) data associated with each analyte will be presented and evaluated in a QA/QC Summary Report to be prepared under separate cover and to be shared with the other 11 demonstration sites included in the Round 1 arsenic study.

4.0 RESULTS AND DISCUSSION

4.1 Facility Description

The WRWC public water system is operated by C&C Water Services and supplies water to 96 homes in the community of Village Shore Estates at Bow, NH. The facility is located on a wooded lot at 6 Rocky Point Drive, Bow, NH. Figure 4-1 shows the small underground structure that housed the existing water system components prior to installation of the ADI adsorption system. The water source is groundwater from three on-site bedrock wells (Wells 1, 2, and 3). The total flowrate from the three wells is approximately 40 gpm at startup, based on the information provided by the plant operator. The well pumps are activated based on the water level in two 15,000-gallon storage tanks (Figure 4-2) housed in a separate underground structure located about 50 ft from the treatment and control structure. Prior to the beginning of the demonstration study, the system was estimated to run approximately 6 to 8 hr per day with an average daily use rate of 15,000 to 20,000 gpd. The existing treatment process included the addition of a dilute sodium hypochlorite solution for disinfection and a caustic solution to raise pH to make the treated water less corrosive in the distribution system. Approximately 10-15% of the total flow also was treated with a small activated alumina (AA) system, shown in Figure 4-3, which had been at the site for many years. The AA system was removed from the site prior to installation of the ADI adsorption system.



Figure 4-1. Existing Underground Treatment and Control Structure

4.1.1 Source Water Quality. Source water samples were collected on April 22, 2004, and subsequently analyzed for the analytes shown in Table 3-3. The results of the source water analyses, along with those provided by the facility to EPA for the demonstration site selection and those obtained from the New Hampshire Department of Environmental Services (NHDES) are presented in Table 4-1.



Figure 4-2. Existing Storage Tanks in Underground Concrete Structure



Figure 4-3. Existing Activated Alumina System in the Underground Treatment and Control Structure

Table 4-1. Raw and Treated Water Quality Data

Parameter	Units	U.S. EPA Raw Water Data ^(a)	Battelle Raw Water Data	NHDES Raw Water Data ^(b)	NHDES Treated Water Data ^(c)
<i>Sampling Date</i>		06/10/98	04/22/04	06/02	12/29/99- 04/26/04
pH	–	7.7	6.8	N/A	7.6-7.8
Total Alkalinity	mg/L	56.0	54.0	N/A	N/A
Hardness (as CaCO ₃)	mg/L	83.0	92.7	N/A	N/A
Turbidity	mg/L	0.4	N/A	N/A	N/A
Chloride	mg/L	N/A	41.0	N/A	34-35
Fluoride	mg/L	0.8	0.6	N/A	0.9-1.0
Sulfide	mg/L	N/A	N/A	N/A	N/A
Sulfate	mg/L	15.5	12.0	N/A	11-12
Nitrate-Nitrite	mg/L	0.3	N/A	N/A	N/A
Silica (as SiO ₂)	mg/L	N/A	19.7	N/A	N/A
Orthophosphate	mg/L	N/A	<0.10	0.019-0.076	N/A
TOC	mg/L	1.0	<0.7	<0.5	N/A
As(total)	µg/L	44.2	39.2	32-47	36.3-47
As (total soluble)	µg/L	44.9	44.1	N/A	N/A
As (particulate)	µg/L	N/A	<0.1	N/A	N/A
As(III)	µg/L	0.5	0.5	N/A	N/A
As(V)	µg/L	44.4	43.6	N/A	N/A
Total Fe	µg/L	60.0	<25	N/A	<50
Soluble Fe	µg/L	N/A	<25	N/A	N/A
Total Al	µg/L	<400	<10	N/A	N/A
Soluble Al	µg/L	N/A	<10	N/A	N/A
Total Mn	µg/L	25.0	2.1	N/A	<5
Soluble Mn	µg/L	N/A	1.5	N/A	N/A
Total V	µg/L	N/A	0.6	N/A	N/A
Soluble V	µg/L	N/A	0.6	N/A	N/A
Total Mo	µg/L	N/A	1.9	N/A	N/A
Soluble Mo	µg/L	N/A	3.0	N/A	N/A
Total Sb	µg/L	N/A	0.2	N/A	<3
Soluble Sb	µg/L	N/A	0.7	N/A	N/A
Total Na	mg/L	N/A	17.0	N/A	16.6-17.5
Total Ca	mg/L	24.7	28.3	18.2-39.7	N/A
Total Mg	mg/L	5.2	5.3	3.5-7.1	N/A

(a) Results of source water sample collected in 1998.

(b) Raw water samples from Wells 1, 2, and 3 separately.

(c) Treated water samples are blended water from Wells 1, 2, and 3.

N/A = not analyzed.

Total arsenic concentrations of the source water ranged from 32 to 47 µg/L. Based on the April 22, 2004 sampling results, the majority of arsenic present was in the As(V) form, with only a small amount (0.5 µg/L) present as As(III).

The pH values of the raw water ranged between 6.8 and 7.7, higher than the desired range of 6.0 to 7.0 indicated by ADI for using the G2 media.

The concentrations of iron (<25 to 60 µg/L) and other ions in the raw water were sufficiently low that pretreatment prior to the adsorption process was not required. The concentrations of orthophosphate and silica also were sufficiently low (i.e., <0.1 mg/L and 19.7 mg/L, respectively) and, therefore, were not expected to affect the As adsorption on the G2 media.

4.1.2 Pre-Demonstration Treated Water Quality. Table 4-1 presents historic data for several analytes from treated water samples collected in compliance with the state monitoring and reporting requirements. Because the treatment process prior to distribution included only chlorination and caustic addition, concentrations of analytes in the treated water were very similar to those of the raw water. Total arsenic concentrations in the treated water ranged from 36.3 to 47 µg/L. Iron and manganese concentrations were below the respective detection limits of 50 and 5 µg/L. The pH values of the treated water ranged from 7.6 to 7.8.

4.1.3 Distribution System. The distribution system serving the community of Village Shore Estates consists of a looped distribution line constructed primarily of polyvinyl chloride (PVC) pipe. The connections to the distribution system and piping within the residences themselves are primarily PVC and some copper pipe. It is believed that a few homes may have pipe with lead solder, and that no homes have lead pipe.

Compliance samples from the distribution system are collected monthly for bacterial analysis and yearly for volatile organic compounds (VOCs). Under the EPA LCR, samples are collected from customer taps at five residences every three years.

4.2 Treatment Process Description

The ADI adsorption system uses G2 media for arsenic removal. The media consists of a granular, calcined diatomite substrate coated with ferric hydroxide. Table 4-2 presents physical and chemical properties of the media. The G2 media has NSF International (NSF) Standard 61 listing for use in drinking water applications.

The ADI system is a fixed-bed downflow adsorption system. When the media reaches its capacity, the spent media may be removed and disposed of after being subjected to the EPA TCLP test. The media also can be regenerated using a 1% sodium hydroxide solution. However, due to the relatively small size of the treatment facility, spent media will be removed and disposed of to simplify system operations.

The adsorption system at the WRWC site consists of two vertical, 72-inch-diameter and 72-inch-sidewall-height cylindrical filter vessels, configured in series. The adsorption vessels were originally designed to operate in parallel for HAMHP with a flowrate of 70 gpm (35 gpm per vessel). Due to the switch to the site in Bow with a total flowrate of about 40 gpm, the flowrate was reduced by 43%; therefore, the system was reconfigured to operate in series. As such, each vessel would provide for an EBCT of 16 min, compared to the 18 min per vessel EBCT the system would have provided as originally designed for the HAMHP site. Note that both of these EBCTs are much longer than the 10-min EBCT normally recommended by the vendor. Additionally, the hydraulic loading rate of the system was increased slightly from 1.2 to 1.4 gpm/ft² with the switch from the HAMHP to the WRWC site. Both of these loading rates are significantly lower than the 2.5 to 3.0 gpm/ft² that would normally be applied to the G2 media. ADI recommended the use of 72-inch-diameter vessels with the intent of extending the media run length for the HAMHP site. Figure 4-4 is a process flow diagram of the adsorption system supplied by

Table 4-2. Physical and Chemical Properties of G2 Media

<i>Physical Properties</i>	
Parameter	Value
Matrix	Diatomite impregnated with ferric hydroxide
Physical Form	Dry granules
Color	Dark brown
Bulk Density (lb/ft ³)	47
Specific Gravity (dry)	0.75
Hardness (lb/in ²)	210
Effective Size (mm)	0.32
Uniformity Coefficient	1.8-2.0
Bulk Relative Density	1.073
Adsorption (%)	51.1
<i>Chemical Analysis</i>	
Constituents	Weight %
Fe	5 – 6
Na	9 – 10
Al	0.5
Diatomaceous Earth (a silica based material)	Balance
Trace Elements	< 0.1

Source: ADI

ADI. The design features of the treatment system are summarized in Table 4-3, and a flow diagram along with the sampling/analysis schedule are presented in Figure 4-5. Key process components include:

- **Intake.** Raw water was pumped from the three on-site bedrock wells (Wells 1, 2, and 3) and fed to the G2 media treatment system. The entry piping consisted of 2-inch PVC pipe from the three supply wells, which were combined into a single line located in the existing underground portion of the treatment building. The single line extended up through an opening in the floor of the treatment building and connected to the 3-inch entry point of the treatment system.
- **Prechlorination.** The existing sodium hypochlorite feed system was used to add chlorine ahead of the adsorption vessels to prevent biological growth in the vessels and maintain a target chlorine residual value of 0.5 mg/L in the distribution system for disinfection purposes. The chlorine addition system consisted of a LMI™ chlorine metering pump, a 50-gallon high-density polyethylene (HDPE) chemical feed tank, and polyethylene tubing to transfer the hypochlorite solution from the tank to the injection point. The sodium hypochlorite solution was injected directly into the raw water line after the wells were combined as described above. Operation of the chlorine feed system was tied to the well pumps so that the chlorine injected only when the wells were on. Chlorine consumption was measured using volumetric markings on the outside of the feed tank.

Figure 4-4. Schematic of G2 Media Adsorption System (Provided by ADI)

Table 4-3. Design Specifications of the G2 Media System

Parameter	Value	Remarks
Adsorption Vessels		
Vessel Size (inch)	72 D × 72 H	–
Cross-Sectional Area (ft ² /vessel)	28.3	–
Number of Vessels	2	–
Configuration	Series	–
Adsorptive Media		
Media Type	G2	–
Media Quantity (lbs)	8,000	4,000 lbs/vessel
Media Volume (ft ³)	170	36-inch bed depth or 85 ft ³ /vessel
Service		
System Flowrate (gpm)	40	System originally designed for 70 gpm at HAMHP in Allenstown, NH
Hydraulic Loading Rate (gpm/ft ²)	1.4	–
EBCT (min)/Vessel	16	Total EBCT for both vessels ~32 min
Estimated Working Capacity (BV)	10,300	Vendor-provided estimate based on As breakthrough at 10 µg/L in lead vessel with incoming arsenic concentration at 39 µg/L in source water
Throughput To Breakthrough (gal)	6,550,000	1 BV = 636 gal
Average Use Rate (gal/day)	15,000	Based on ~6 hr of daily operation at 40 gpm.
Estimated Media Life (months)	14	Estimated frequency of media change-out in lead vessel based on average throughput to system.
Pre-treatment	NaClO	Prechlorination
	H ₂ SO ₄	pH adjustment before adsorption
Post-treatment	NaOH	pH adjustment after adsorption
Backwash		
Backwash Frequency	As needed	–
Backwash Hydraulic Loading Rate (gpm/ft ²)	4	–
Backwash Flowrate (gpm)	115	–
Backwash Duration (min/vessel)	10-15	–
Wastewater Production (gal/vessel)	1,700	–

- pH Adjustment Prior to Adsorption.** The pH of the source water was adjusted using a 93% sulfuric acid from an average of 7.3 to a target value of 6.8 then 6.4 in order to increase the adsorption capacity of the media. The 93% sulfuric acid solution was delivered to the site in 15-gal containers (200 lb per container). The acid was metered directly from these containers to the injection point using a ProminentTM solenoid dosing pump. The acid was injected at a second injection point located on the raw water line (after the wells are combined) just downstream of the chlorine injection point described above. These injection points were installed about 3 ft apart and approximately 25 ft upstream of the adsorption system.

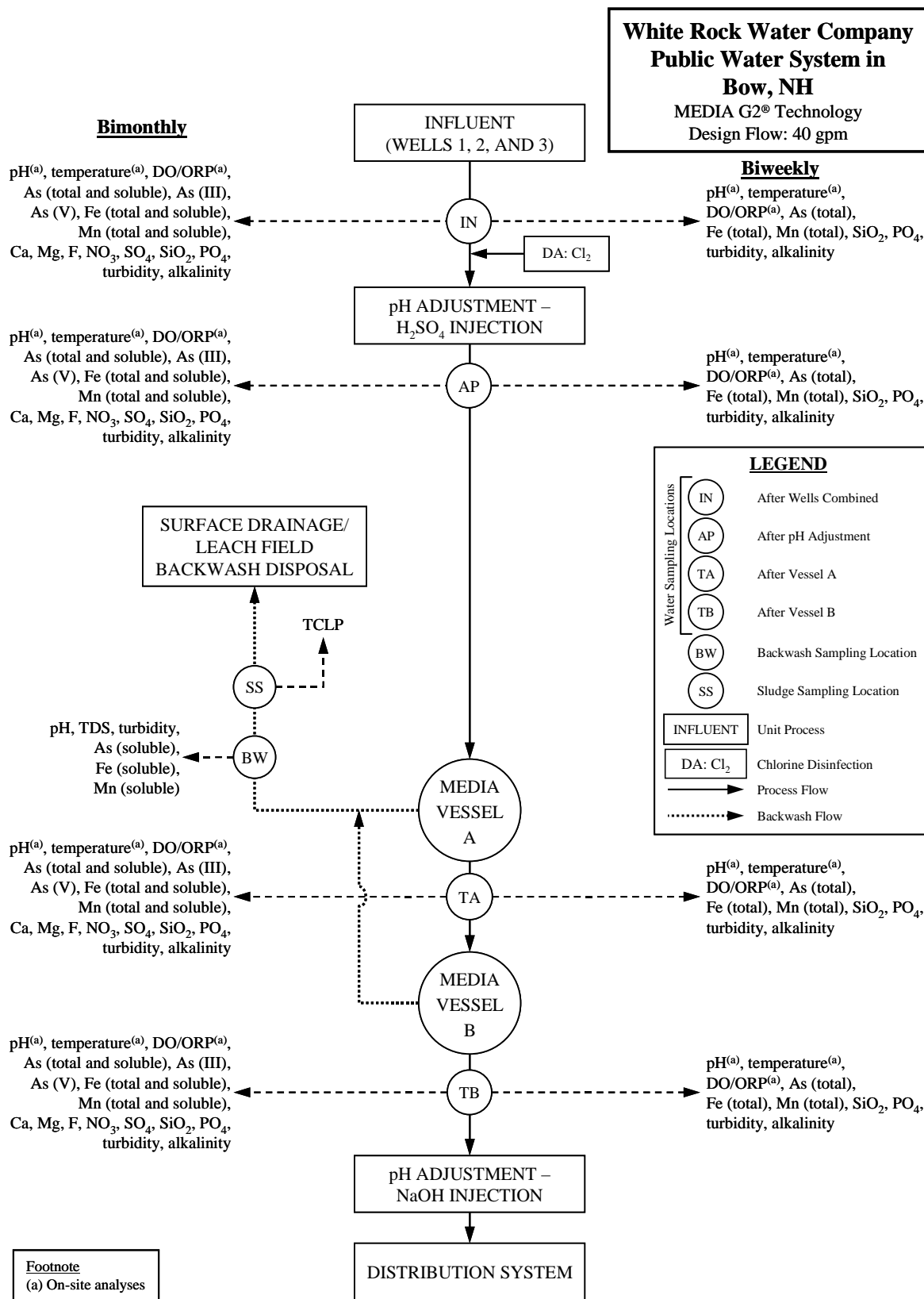


Figure 4-5. Process Flow Diagram and Sampling Locations

- Arsenic Adsorption.** The two 72-inch-diameter, 72-inch-sidewall-height vessels were constructed of 304 stainless steel and rated for 50 pounds per square inch (psi) working pressure. The system was delivered to the site with a pre-assembled pipe and valve manifold consisting of 3-inch schedule 80 PVC with flanged and solvent weld connections. The manifold was mounted directly on a uni-strut steel frame bolted directly to the front of the adsorption vessels as shown in Figure 4-6. Inlet and outlet pressure gauges, PVC manually-actuated butterfly valves, air release/vacuum valves, and sampling ports were installed as part of the pre-assembled unit. There were no automated controls included as part of the adsorption system; all valves were manually actuated. Initiation of system backwash or other operational adjustments required manual adjustment of valves. Two inline pH probes were installed in the piping manifold in order to measure the pH values of the water following the acid and caustic addition. Additionally, a pH chart recorder was installed for continuous logging of the inline probe readings. The addition of the acid and caustic was flow paced based on a 4-20 mA control signal from a flowmeter located on the treated water line downstream of the adsorption system. Each vessel contained about 85 ft³ of G2 media.
- pH Adjustment Prior to Storage and Distribution.** After passing through the adsorption vessels, the pH values of the treated water were adjusted using a 25% NaOH solution to raise the pH value from about 6.5 to a target value of 7.5 before going to the storage tanks and distribution system. The pH was increased to reduce the tendency for dissolution of metals, especially lead and copper, from distribution piping. The 25% NaOH solution was delivered to the site in 15-gal containers (160 lb per container). The caustic solution was metered directly from these containers to the injection point using a Prominent™ solenoid dosing pump. The injection point was located downstream of the adsorption system and before the treated water went out to the 15,000-gal storage tanks.



Figure 4-6. ADI G2 Media Arsenic Adsorption System

4.3 System Installation

The installation of the treatment system at the site was completed in September 2004; shakedown and startup activities continued into October 2004. The system installation and building construction activities were carried out by the plant operator, C&C Water Services, as a subcontractor to ADI.

4.3.1 Permitting. Engineering plans for the system permit application were prepared by Lewis Engineering, an ADI subcontractor located in Litchfield, NH. The plans included diagrams and specifications of the G2 media treatment system, as well as site drawings showing the proposed layout of the new treatment building. The plans were submitted to the NHDES (Water Supply Engineering Bureau) for review and approval on June 14, 2004. The NHDES issued a letter of approval on August 23, 2004. The state did not issue a separate permit for discharging the system backwash water at the time of start-up.

4.3.2 Building Construction. To house the G2 media treatment system, C&C Water Services constructed an aboveground addition to the existing underground pump house structure (Figure 4-1). Construction included placement of steel support beams on top of the existing concrete structure, and construction of a wood frame building on the steel supports. The new building is roughly the same size as the existing structure, approximately 20 ft by 22 ft. A photograph of the aboveground addition to the treatment building is shown in Figure 4-7. Building construction began on June 16, 2004 with placement of the steel support beams and continued through the end of August 2004, including placement and setting of the vessels, which were put into place before completing the walls and roof of the new treatment building.



Figure 4-7. New Treatment Building Addition

4.3.3 Installation, Shakedown, and Startup. The adsorption vessels arrived on site and were placed on the steel supports of the new treatment building on June 28, 2004. During shipment, some minor damage was made to welds on the bottom flanges of both vessels. The manufacturer arranged for repair of the welds by a local certified welding shop. C&C Water Services performed the system installation, including all plumbing, mechanical, and electrical work. Installation of system piping was completed on September 2, 2004.

The G2 media was loaded into the vessels on September 13, 2004. Prior to system startup, the media was first backwashed at 115 gpm for about 1 hr to remove media fines in the bed. The G2 media was then conditioned using a downflow acid rinse to neutralize the pH of the media from about 12 as a result of the manufacturing process. To minimize the amount of wastewater produced, conditioning was done by recirculating the rinse water through each vessel at a flowrate of 70 gpm using a 5-hp pump. Meanwhile, a chemical metering pump was used to add a 93% sulfuric acid solution at the inlet of each vessel. Each vessel was conditioned separately for two 8-hr days and the total acid consumption was about 3 gal per vessel (or 6 gal total). The volume of wastewater produced per vessel was equivalent to the volume of water required to fill one vessel and some additional piping (i.e., about 1,500 gal). The wastewater (about 3,000 gal per vessel over the two-day period) was discharged to a rip-rap lined surface drainage area near the treatment building at the end of each day. The pH of the wastewater as it was discharged ranged from about 10 on the first day to 7 on the second.

Because of some delay in receiving the required components for the recirculation pump, the media conditioning did not begin until September 28, 2004 and continued for about four days. The system was put into service and the performance evaluation study officially began on October 13, 2004. A Battelle staff member visited the site on this date to inspect the system, provide operator training for data and sample collection, and collect the first set of samples from the treatment system.

4.4 System Operation

4.4.1 Operational Parameters. The operational parameters of the system are tabulated and attached as Appendix A. Key parameters are summarized in Table 4-4. From October 13, 2004 through April 24, 2005, the treatment system operated for 1,741 hr based on the well pump hour meter readings collected daily at the well head. The operational time represented a utilization rate of approximately 38% over the 28-week period with the supply wells operating at an average of 9.3 hr per day. The total system throughput from October 13, 2004 through April 24, 2005 was approximately 3,858,000 gal based on the flow totalizer readings from the finished water magnetic meter. This corresponds to 6,067 bed volumes (BVs) of water processed through the system. The average flowrate through the system was 40.8 gallons per minute (gpm) with an average EBCT of 31.7 min total or approximately 16 min per vessel.

Pressure loss across the vessels averaged less than 1 psi across the lead vessel and less than 2 psi across the lag vessel for the first 28 weeks of operation. Because the pressure drop observed was low and did not change significantly during system operation, the system was backwashed only twice during this period.

During the first 28 weeks of operation, the system experienced some operational problems with the inline pH meters. In general, the inline probe located after the acid addition upstream of the adsorption vessels read approximately 0.4 pH units lower than the corresponding measurements using a WTW field pH probe. The inline probe located after the caustic addition following the adsorption vessels typically read about 1.3 pH units higher than the corresponding measurements using the same field pH probe. The field

Table 4-4. Summary of G2 Media Treatment System Operation

Total Operating Time (hr) - October 13, 2004 to April 24, 2005	1741
Average Daily Operating Time (hr/day)	9.3
Throughput (kgal)	3,858
Throughput (BV)	6,067
Average Flowrate (gpm)	40.8
Range of Flowrate (gpm)	10.6 – 49.0
Average EBCT (min) ^(a)	31.7
Range of EBCT (min) ^(a)	26 - 120
Average Differential Pressure Loss across Vessel A (psi)	0.8
Average Differential Pressure Loss across Vessel B (psi)	1.8

(a) Calculated based on 170 ft³ of media total (85 ft³ in each vessel; vessels in series).

pH readings after caustic addition were, in most cases, close to the pH readings of distribution water samples measured by AAL (6.4 to 7.8 with the field probe vs. 6.6 to 8.1 in the distribution samples), suggesting that the field pH probe was more accurate than the inline probes.

Although several attempts were made by the plant operator and ADI to correct the problems associated with the inline probes (including cleaning and calibrating the probes, consulting with the vendor and manufacturer, switching the “acid” inline probe [which seemed to read more accurately] with the “caustic” inline probe, and conducting an on-site service call by ADI to investigate and replace the “acid” inline probe with a new probe), correlation between the inline pH meters and the field meter continued to be poor throughout the first 28 weeks of operation.

4.4.2 Backwash. During the first six months of system operation, the system was backwashed twice, one time each on January 11, 2005 and April 12, 2005 after about three and six months of system operation, respectively. Backwash was performed manually using finished water from the storage tanks. During backwash, the system was taken off-line and treated water was drawn via a booster pump from the storage tanks at a flowrate of approximately 115 gpm (or about 4 gpm/ft²). The backwash lasted for 20 and 10 min per vessel during the first and second backwash events, respectively, producing approximately 2,200 and 1,200 gal of wastewater for each vessel.

4.4.3 Residuals Management. Residuals produced by the operation of the treatment system include spent media and backwash water. The media was not exhausted during the first six months of system operation; therefore, the only residual produced was backwash water. Backwash water is discharged to a rip-rap lined surface drainage and allowed to infiltrate into the ground.

4.4.4 System Operation Reliability and Simplicity. A significant O&M issue for this system was the need for acid and caustic addition to maintain the desired pH values of the feed water to the treatment system and the finished water to the distribution system. Confounding the proper dosing of acid and caustic were the continuing discrepancies observed in pH readings from the inline probes versus the field probe as discussed in Section 4.4.1. Further discussion on the impact of pH adjustment in the distribution system is included in Section 4.5.3. The system did not experience any unscheduled downtime during the first six months of operation.

Additional discussion regarding system operation and operator skill requirements are provided below in relation to pre- and post-treatment requirements, levels of system automation, operator skill requirements, preventive maintenance activities, and frequency of chemical/media handling and inventory requirements.

Pre- and Post-Treatment Requirements. Pre-treatment consisted of the addition of a 6% sodium hypochlorite solution for disinfection, which was already performed at the site prior to the installation of the arsenic treatment system, and a 93% sulfuric acid solution for lowering the water pH in order to maximize the arsenic removal capacity of the G2 media. Post-treatment included the addition of a 25% NaOH solution to raise the pH values back to approximately 7.5 to reduce corrosivity prior to entering the storage tanks and distribution system. The rate of chemical consumption is provided below under chemical handling and inventory requirements.

System Controls. The G2 media adsorption system was a passive system, requiring only the operation of the well pumps and chemical metering pumps for chlorination and acid and caustic addition. The adsorption system itself required no automated parts and all valves were manually activated. Power supply to the chemical metering pumps was tied into the supply well pumps so that when the supply wells were started, triggered by a level switch in the storage tanks, the chemical metering pumps also were energized to dispense chlorine, acid, and caustic at a pre-determined rate. The system had the capability to adjust the chemical feed rates based on the inline probe readings to maintain a specified pH value; however, this control setup was disabled during the first 6 months of the demonstration period. The acid and caustic feed rates were controlled by manually setting the pump stroke-length and automatically pacing the pump based on a 4-20 mA control signal provided by a BadgerTM magnetic flowmeter located on the treated water line. Additionally, a two-pen pH chart recorder was installed for continuous logging of the pH values after the acid and caustic addition. Although useful for tracking the operation of the system, the pH chart recorder proved somewhat problematic to operate as it was initially installed without the proper relays to allow it to communicate with the inline pH probes. As a result, the system operated for several weeks with the pH recorder giving erroneous readings. In early January 2005, the proper relays were installed and the chart recorder was adjusted so that the readings better reflected the inline probe readings. However, the inline probes continued to give erroneous readings as described in Section 4.4.1. Backwash cycles were initiated manually and required the operator to adjust system valves accordingly prior to initiating the system backwash.

Operator Skill Requirements. Generally, the operation of the treatment system did not require additional skills beyond those necessary to operate the original treatment equipment used at the site prior to the demonstration. The daily demand on the system operator was typically about 20 minutes to visually inspect the system and record operating parameters such as totalizer and hour meter readings, flowrates, and system pressure readings on the field log sheets. Based on the size of the population served and the treatment technology, the State of New Hampshire requires Level 1A Certification for operation of the treatment system and is considering upgrading this requirement to Level 1 certification.

In addition to the standard checks and data recording performed daily for the system, C&C water services personnel typically spent 3-4 hr per week troubleshooting various problems associated with the system, especially during the first few months of the system operation. Primarily this time was spent making adjustments to the acid and caustic addition. Because the system was not set to make these adjustments automatically, all adjustments were made by manually adjusting the stroke-length of the chemical metering pumps. Adding to the complexity of achieving the proper balance of acid and caustic addition was the disagreement in readings between the inline pH probes and the WTW field probe, as discussed in Section 4.4.1. In early December, acid addition was increased to further lower the pH of the feed water to attempt to increase arsenic removal by the G2 media. To counterbalance this increase in acid addition, intuitively, the caustic addition also would have to be increased. In fact, in late December, the caustic metering pump was inadvertently ramped down such that the pH values of water going to the storage

tanks were lower than what had been measured historically at the site. The drop in pH values was noticeable in the subsequent distribution system samples collected on January 12, 2005. Further discussion on the impact of this pH drop in the distribution system is included in Section 4.5.3.

Preventive Maintenance Activities. Regular maintenance activities required for the operation of the G2 media treatment system consisted primarily of daily visual inspection of the system to ensure that it appeared to be operating appropriately, maintaining chemical supply for feed chemicals, collecting routine water samples, cleaning and calibrating the inline pH probes, and system backwashing as necessary.

Chemical/Media Handling and Inventory Requirements. Chemicals required for system operation included a 6% sodium hypochlorite, a 93% sulfuric acid, and a 25% NaOH solution. Proper handling and storage of these chemicals were required, including secondary containment for the chemical storage area and proper safety equipment for plant operators, including eye wash station and use of personal protective equipment (gloves, chemical apron, and faceshield as required). During the first 28 weeks of system operation, approximately 1½ to two 15-gal containers (160 lb per container) of 25% NaOH and one 15-gal container (200 lb per container) of 93% sulfuric acid were consumed per month for pH control purposes. The average chemical consumption was 0.24 lb/1,000 gal of water treated for sulfuric acid and 0.45 lb/1,000 gal for NaOH.

Media change-out was not required during the first six months of operation; thus, no additional media handling was required after the initial installation.

4.5 System Performance

The system performance was evaluated based on analyses of samples collected from the raw and finished water from the treatment plant, backwash lines, and distribution system.

4.5.1 Treatment Plant Sampling. Water samples were collected at four locations through the treatment train: at the inlet (IN), after chlorination and pH adjustment (AP), at the effluent of Vessel A (TA), and at the effluent of Vessel B (TB). Field-speciated samples at each location were collected once every eight weeks throughout this reporting period. Table 4-5 summarizes the arsenic, iron, and manganese analytical results. Table 4-6 summarizes the results of other water quality parameters. Appendix B contains a complete set of analytical results through the first six months of system operation. The results of the water samples collected throughout the treatment plant are discussed below.

Arsenic. The key parameter for evaluating the effectiveness of the G2 media treatment system was the concentration of arsenic in the treated water. The treatment plant water was sampled on 15 occasions during the first six months of system operation, with field speciation performed on four of the 15 occasions. Samples were collected at all four sampling locations (IN, AP, TA, and TB) at each of the 15 sampling events.

Figure 4-8 contains four bar charts showing the concentrations of total As, particulate As, As(III), and As(V) at the IN, AP, TA, and TB locations for each of the four field speciation events. Total arsenic concentrations in raw water ranged from 38.0 to 91.3 µg/L and averaged 49.3 µg/L (Table 4-5). As(V) was the predominating species, ranging from 47.5 to 54.1 µg/L and averaging 50.9 µg/L. Only trace amounts of As(III) existed with concentrations averaging 0.6 µg/L. Particulate As also was low with concentrations typically less than 1 µg/L. During the system startup on October 13, 2004, an unusually high concentration of particulate As (i.e., greater than 40 µg/L, or almost 50% of total As) was measured. It was not clear why such a high particulate As concentration was detected during this sampling event.

Table 4-5. Summary of Arsenic, Iron, and Manganese Analytical Results

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
As (total)	IN	µg/L	17 ^(a)	38.0	91.3	49.3	11.7
	AP	µg/L	17 ^(a)	38.7	96.1	50.1	12.8
	TA	µg/L	17 ^(a)	12.6	37.5	— ^(b)	— ^(b)
	TB	µg/L	17 ^(a)	1.7	50.9	— ^(b)	— ^(b)
As (total soluble)	IN	µg/L	4	48.2	54.6	51.5	2.8
	AP	µg/L	4	49.7	55.7	53.0	2.6
	TA	µg/L	4	15.5	25.3	— ^(b)	— ^(b)
	TB	µg/L	4	3.6	14.3	— ^(b)	— ^(b)
As (particulate)	IN	µg/L	4	<0.1	40.8	10.4	20.3
	AP	µg/L	4	<0.1	43.8	11.1	21.8
	TA	µg/L	4	<0.1	12.2	— ^(b)	— ^(b)
	TB	µg/L	4	<0.1	47.2	— ^(b)	— ^(b)
As(III)	IN	µg/L	4	0.5	0.7	0.6	0.1
	AP	µg/L	4	0.5	0.6	0.6	0.1
	TA	µg/L	4	0.4	0.8	— ^(b)	— ^(b)
	TB	µg/L	4	0.4	1.1	— ^(b)	— ^(b)
As(V)	IN	µg/L	4	47.5	54.1	50.9	2.9
	AP	µg/L	4	49.1	55.1	52.5	2.7
	TA	µg/L	4	14.8	24.5	— ^(b)	— ^(b)
	TB	µg/L	4	3.0	13.1	— ^(b)	— ^(b)
Total Fe	IN	µg/L	17 ^(a)	<25	22.1	13.1	2.3
	AP	µg/L	17 ^(a)	<25	60.0	15.3	11.5
	TA	µg/L	17 ^(a)	<25	<25	<25	0.0
	TB	µg/L	17 ^(a)	<25	39.0	14.1	6.4
Dissolved Fe	IN	µg/L	4	<25	<25	<25	0.0
	AP	µg/L	4	<25	<25	<25	0.0
	TA	µg/L	4	<25	<25	<25	0.0
	TB	µg/L	4	<25	<25	<25	0.0
Total Mn	IN	µg/L	17 ^(a)	0.12	2.0	0.9	0.6
	AP	µg/L	17 ^(a)	<0.1	7.2	1.4	1.7
	TA	µg/L	17 ^(a)	0.49	27.0	— ^(b)	— ^(b)
	TB	µg/L	17 ^(a)	<0.1	35.8	— ^(b)	— ^(b)
Dissolved Mn	IN	µg/L	4	0.44	1.2	0.6	0.4
	AP	µg/L	4	0.32	1.0	0.6	0.3
	TA	µg/L	4	1.15	9.0	— ^(b)	— ^(b)
	TB	µg/L	4	1.32	12.5	— ^(b)	— ^(b)

(a) Including two duplicate samples

(b) Average concentration and standard deviation not calculated. See Figures 4-9 and 4-10 for As and Mn breakthrough curves.

Note: One-half of the detection limit was used for samples with concentrations less than the detection limit for calculations. Duplicate samples were included in the calculations.

Table 4-6. Summary of Water Quality Parameter Measurements

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Alkalinity	IN	mg/L	15 ^{(a)(b)}	55	77	65.1	5.4
	AP	mg/L	17 ^(b)	28	61	— ^(c)	— ^(c)
	TA	mg/L	17 ^(b)	29	62	— ^(c)	— ^(c)
	TB	mg/L	17 ^(b)	28	68	— ^(c)	— ^(c)
Fluoride	IN	mg/L	4	0.7	1.1	0.91	0.16
	AP	mg/L	4	0.7	1.0	0.93	0.14
	TA	mg/L	4	0.7	1.1	0.87	0.17
	TB	mg/L	4	0.3	0.8	0.66	0.25
Sulfate	IN	mg/L	4	11	24	14.3	6.5
	AP	mg/L	4	26	51	— ^(c)	— ^(c)
	TA	mg/L	4	12	48	— ^(c)	— ^(c)
	TB	mg/L	4	9.6	48	— ^(c)	— ^(c)
Orthophosphate (as PO ₄)	IN	mg/L	17 ^(b)	<0.05	<0.06	0.03	0.00
	AP	mg/L	17 ^(b)	<0.05	<0.06	0.03	0.00
	TA	mg/L	17 ^(b)	<0.05	<0.06	0.03	0.00
	TB	mg/L	17 ^(b)	<0.05	<0.06	0.03	0.00
Silica	IN	mg/L	17 ^(b)	18.7	21.4	19.7	0.7
	AP	mg/L	17 ^(b)	18.5	21.4	19.8	0.7
	TA	mg/L	17 ^(b)	21.1	50.8	— ^(c)	— ^(c)
	TB	mg/L	17 ^(b)	23.5	61.8	— ^(c)	— ^(c)
Nitrate (as N)	IN	mg/L	4	0.2	1.0	0.41	0.40
	AP	mg/L	4	0.1	0.5	0.24	0.15
	TA	mg/L	4	0.2	1.3	0.48	0.55
	TB	mg/L	4	0.2	1.4	0.52	0.59
Turbidity	IN	NTU	17 ^(b)	<0.1	1.1	0.31	0.31
	AP	NTU	17 ^(b)	<0.1	0.5	0.18	0.16
	TA	NTU	17 ^(b)	<0.1	0.6	0.16	0.16
	TB	NTU	17 ^(b)	<0.1	0.5	0.20	0.16
pH	IN	S.U.	15	6.8	7.8	7.3	0.21
	AP	S.U.	15	6.1	7.8	— ^(c)	— ^(c)
	TA	S.U.	15	6.1	7.9	— ^(c)	— ^(c)
	TB	S.U.	15	6.1	8.0	— ^(c)	— ^(c)
Temperature	IN	°C	15	11.5	12.4	11.9	0.27
	AP	°C	15	11.5	12.7	11.9	0.35
	TA	°C	15	11.2	12.9	11.8	0.41
	TB	°C	15	11.2	13.0	11.7	0.47
Dissolved Oxygen	IN	mg/L	13	4.5	6.8	5.6	0.73
	AP	mg/L	13	2.9	5.6	4.2	0.65
	TA	mg/L	13	3.5	5.3	4.3	0.51
	TB	mg/L	13	3.5	5.4	4.4	0.47
ORP	IN	mV	14	195	498	233	77.1
	AP	mV	14	190	607	435	172.8
	TA	mV	14	183	610	471	172.7
	TB	mV	14	173	608	484	158.8

Table 4-6. Summary of Water Quality Parameter Measurements (Continued)

Parameter	Sampling Location	Units	Number of Samples	Minimum Concentration	Maximum Concentration	Average Concentration	Standard Deviation
Free Cl ₂	AP	mg/L	15	0.1	0.7	0.3	0.2
	TA	mg/L	15	0.1	0.5	0.2	0.1
	TB	mg/L	15	0.1	0.6	0.2	0.1
Total Cl ₂	AP	mg/L	15	0.1	0.5	0.3	0.1
	TA	mg/L	15	0.1	0.4	0.2	0.1
	TB	mg/L	15	0.1	0.5	0.2	0.1
Total Hardness (as CaCO ₃)	IN	mg/L	4	84.0	163.3	108.7	36.7
	AP	mg/L	4	81.5	128.5	100.5	20.0
	TA	mg/L	4	85.0	166.6	111.6	37.3
	TB	mg/L	4	86.8	101.8	94.2	7.1

(a) Two outlying alkalinity values, 254 mg/L (as CaCO₃) measured on November 16, 2004 and 120 mg/L (as CaCO₃) measured on March 1, 2005, were excluded from this summary table.

(b) Including two duplicate samples

(c) Average concentration and stand deviation not calculated. See Figures 4-11 and 4-12 for alkalinity, sulfate, pH, and silica measurements.

Note: One-half of the detection limit was used for samples with concentrations less than the detection limit for calculations. Duplicate samples were included in the calculations.

The arsenic concentrations measured during this six-month period were generally consistent with those in the raw water sample collected on April 22, 2004 (Table 4-1).

As expected, arsenic concentrations at the AP location were similar to those in the raw water. Because the majority of arsenic present in raw water was already in the As(V) oxidation state, chlorination had little or no effect on the concentration or oxidation state of arsenic entering the adsorption vessels. Similar to those at the IN location, total arsenic concentrations at the AP location ranged from 38.7 to 96.1 µg/L and averaged 50.1 µg/L.

Free and total chlorine levels were measured at the AP, TA, and TB locations. Free chlorine levels were measured at 0.1 to 0.7 mg/L at the AP location, with total chlorine levels ranging from 0.1 to 0.5 mg/L (Table 4-6). The residual chlorine levels measured after each vessel at the TA and TB locations were very similar to those measured at the AP location, indicating little or no chlorine consumption by the G2 media.

Total As concentrations after the lead (A) and lag (B) vessels are plotted against the BVs of water treated in Figure 4-9. The figure also shows the total As concentrations in the source water and after prechlorination and pH adjustment. After the lead vessel, greater than 30 µg/L of total As was unexpectedly detected in samples collected just after startup on October 13 and about one week later on October 19, 2004. After about 380 BVs of throughput, total As concentrations decreased to 12.6 to 15.6 µg/L before beginning a steady increase at about 2,600 BVs to 26.3 µg/L by April 12, 2005. Total As concentrations after the lag vessel also were high during the first two weeks of system operation, with 16.7 to 21.8 µg/L of arsenic measured on October 13 and October 19, 2004, respectively. Afterwards, the concentrations dropped to 1.7 µg/L after about 2,500 BVs and then increased steadily to 5.8 µg/L after about 5,700 BVs by April 12, 2005.

Total As concentration measured after the lag vessel (B) on December 14, 2004 was unusually high at 50.9 µg/L, of which 47.3 µg/L existed as particulate As (See Figure 4-8). It was not clear what caused the elevated particulate As concentration.

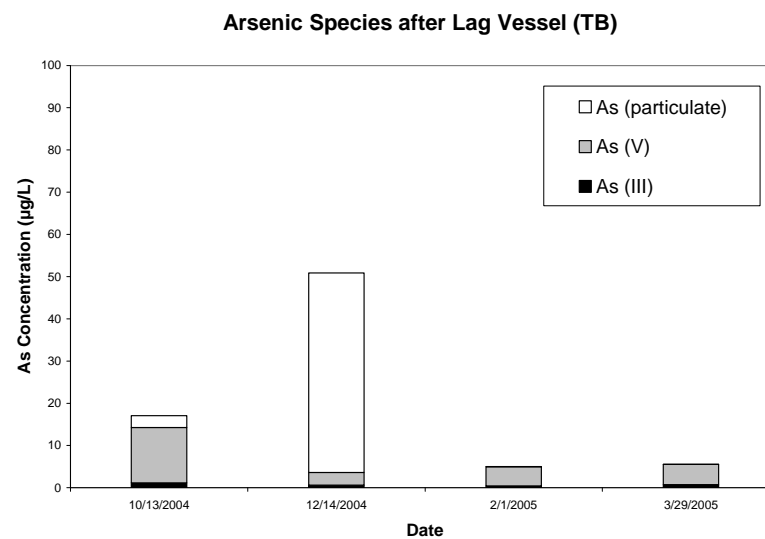
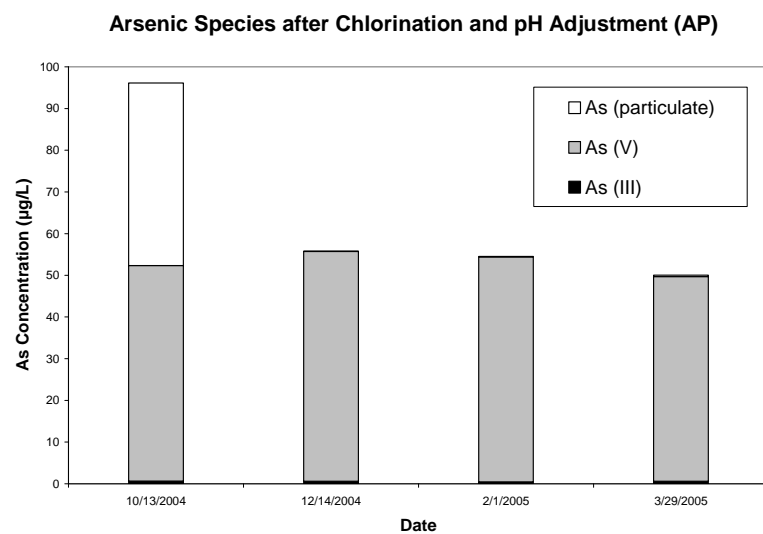
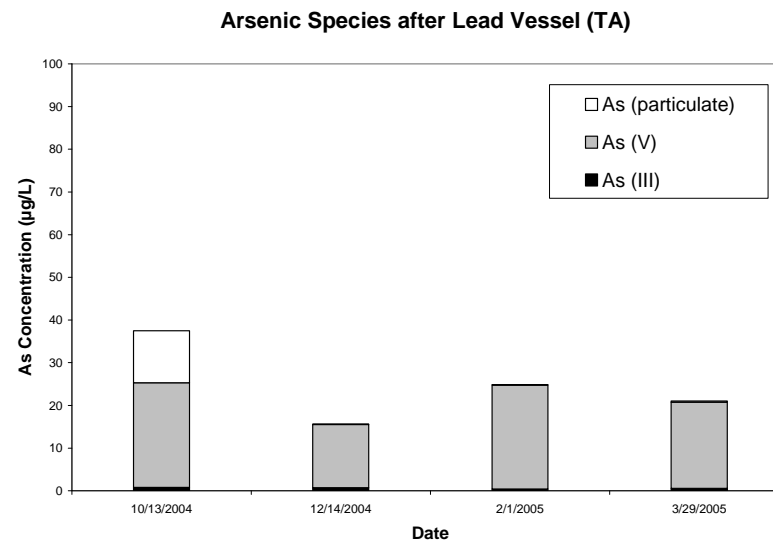
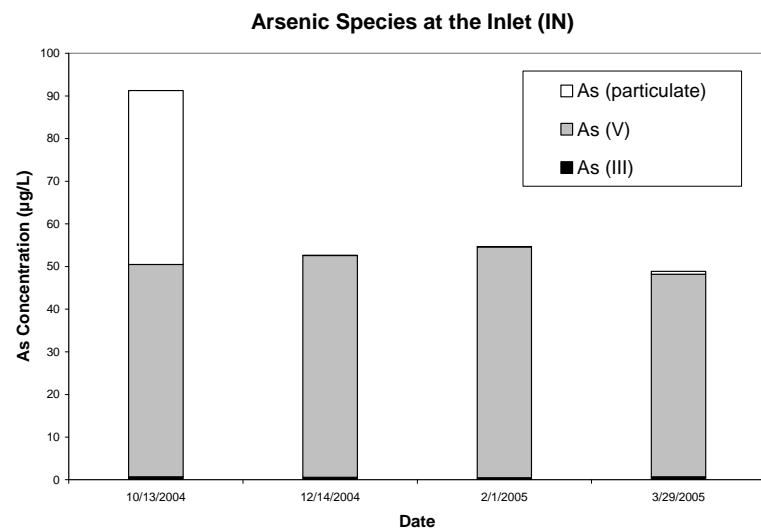


Figure 4-8. Concentration of Arsenic Species at the IN, AP, TA, and TB Sampling Locations

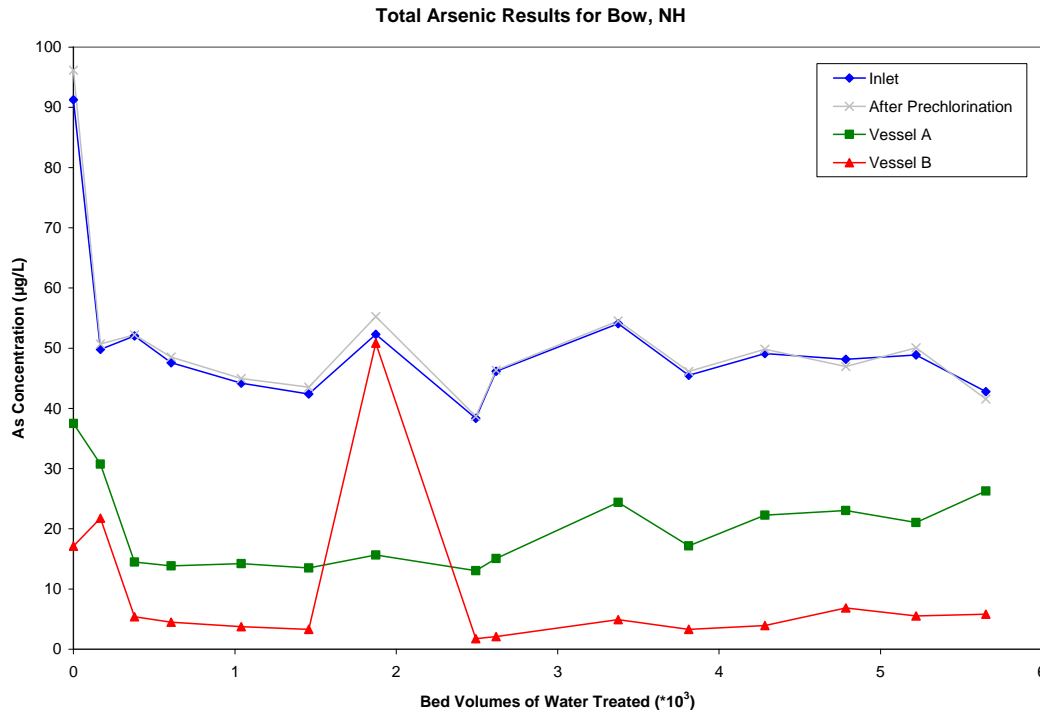


Figure 4-9. Total Arsenic Breakthrough Curves

ADI attributed the elevated arsenic concentrations just after system startup to the leaching of arsenic from the G2 media prepared with FeCl_3 containing arsenic and manganese as impurities. While this might explain the elevated arsenic levels observed in the treated water during the first two weeks of system operation, it did not explain why the arsenic concentrations remained high (i.e., 12.6 µg/L or greater) following the lead vessel throughout the first six months of system operation.

Iron. Iron concentrations in the source water were low. With the exception of only a few data points, the iron concentrations, both total and dissolved, were less than the detection limit of 25 µg/L at all sampling locations throughout the first 6 months of system operation (Table 4-5).

Manganese. Treatment plant water samples were analyzed for total Mn during all sampling events and for soluble Mn during speciation sampling events. Figure 4-10 shows the total manganese concentrations over time at each of the four sampling locations across the treatment train. Similar to iron, manganese concentrations in the raw water were low, ranging from 0.12 to 2.0 µg/L (Table 4-5). However, manganese concentrations in the treated water following the lead and lag vessels were significantly elevated to over 35 µg/L after the system start-up, apparently due to the leaching of manganese from the media. After about 3,000 BVs, manganese concentrations following the lead and lag vessels decreased to levels similar to those in the raw water.

Other Water Quality Parameters. The results of other water quality parameters are included in Appendix B and are summarized in Table 4-6. Figure 4-11 presents the results of pH, alkalinity, and sulfate measurements collected across the treatment train.

The first few samples taken during October 13 through November 2, 2004 showed somewhat erratic pH results across the treatment train, which were thought to have been caused, in part, by erroneous on-site

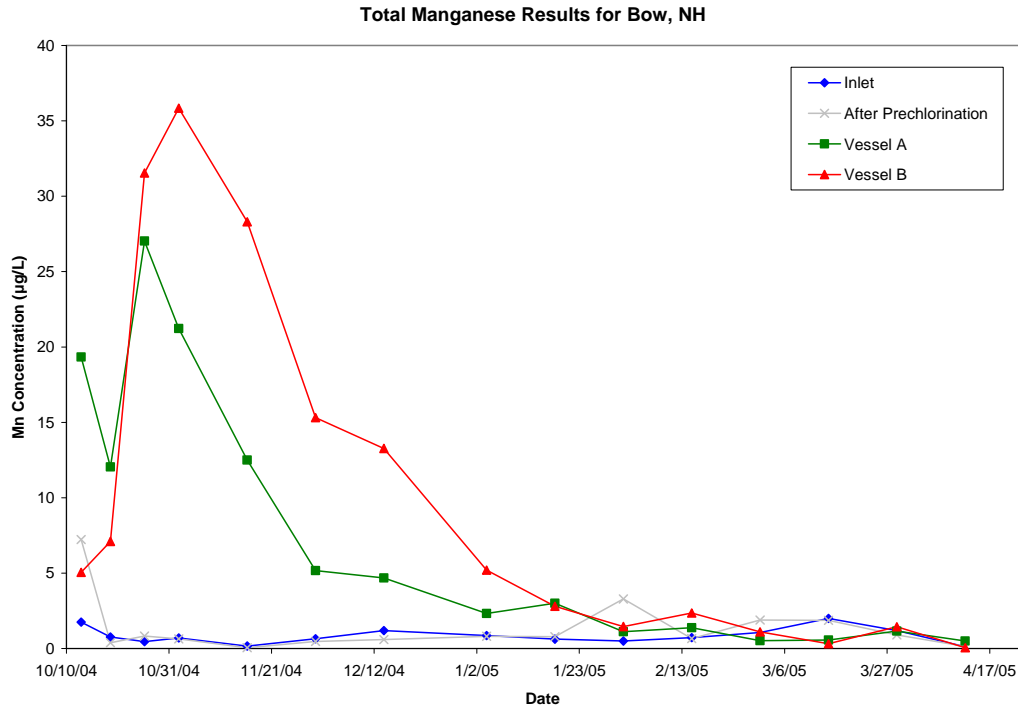


Figure 4-10. Total Manganese Concentrations Over Time

measurements using the WTW handheld meter. The plant operators were retrained for the use of the meter on November 9, 2004 and the results obtained since then appeared to follow a steadier trend.

The pH values of the source water typically ranged from 7.3 to 7.5. At the suggestion of ADI, the target pH value for the feed water was set at 6.8 at the system start up and then reduced to 6.4 by mid-November 2004. The target pH value for the treated water following caustic addition was set at 7.5. For the most part, the measured pH values after the acid addition and after Vessels A and B were very close to the target value of 6.8 and later 6.4. The measured pH values after the caustic addition, however, deviated by as much as 1.0 pH unit from the target value of 7.5. As described under *Operator Skill Requirements* in Section 4.4.4, the operator had some difficulties in adjusting the rate of caustic addition to account for the increased acid addition.

From early December 2004 through April 2005, the sulfuric acid consumed to lower the pH of the source water from 7.5 to 6.4 was 0.26 lb/1,000 gal of water treated (or 31 mg/L) based on the amount of acid used and the volume of water treated during this period. This consumption rate matched that of a theoretical calculation using the method described by Rubel (2003) as shown in Table 4-7.

Alkalinity readings of the source water ranged from 55 to 77 mg/L (as CaCO_3) and averaged 65.1 mg/L. After the acid addition, the decreases in alkalinity ranged from 24 to 38 mg/L (as CaCO_3) and averaged 31.8 mg/L (as CaCO_3). This amount matched the 30 mg/L (as CaCO_3) decrease as shown in Table 4-7.

Sulfate concentrations in the source water ranged from 11 to 24 mg/L and averaged 14.3 mg/L. Immediately after the system start up, sulfate concentrations were reduced to 12.0 and 9.6 mg/L following the lead and lag vessels, respectively, apparently being removed by the G2 media. Since the adjustment

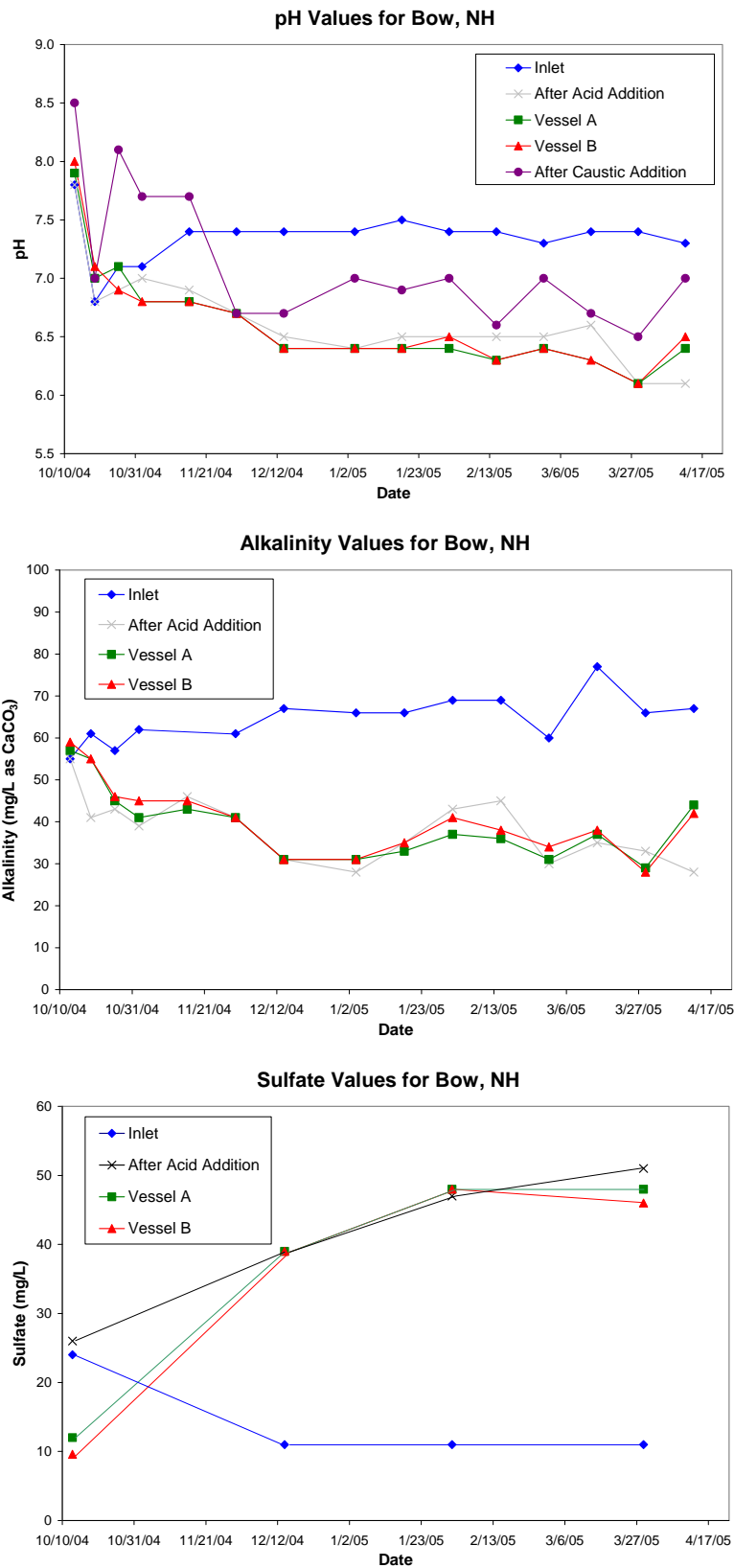


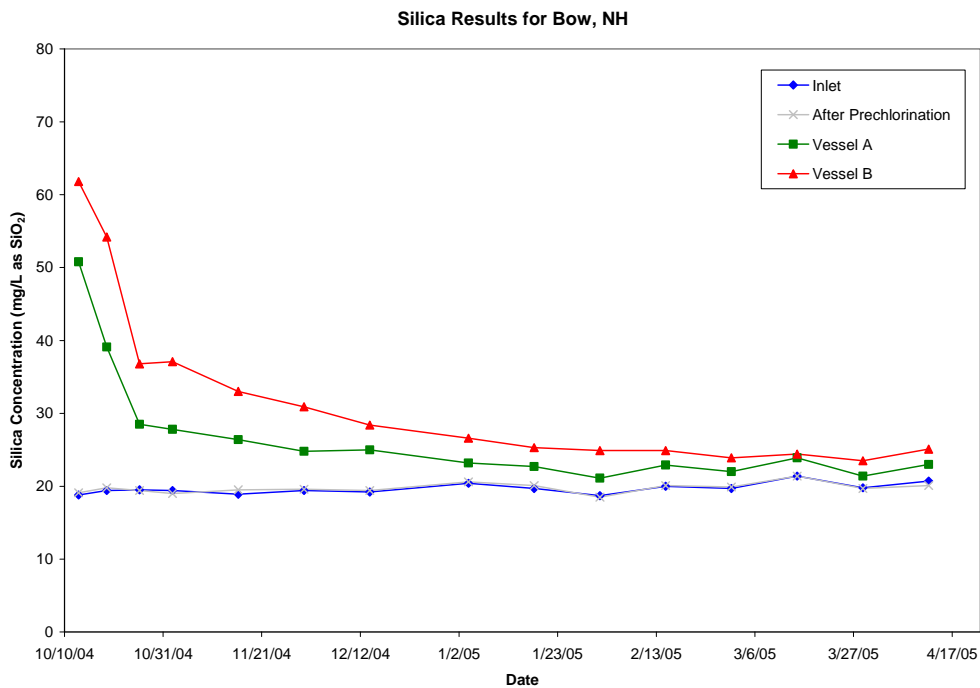
Figure 4-11. pH, Alkalinity, and Sulfate Values over Time

Table 4-7. Calculation of Acid Consumption for pH Adjustment at the WRWC Site

Parameter	Raw Water	After pH Adjustment
pH (S.U.)	7.5	6.4
Total Alkalinity (mg/L as CaCO ₃)	70	40
Free CO ₂ (mg/L)	4.2	31
Total Alkalinity Reduction (mg/L as CaCO ₃)	30	
Acid Required (meq/L)	0.6	
93% Sulfuric Acid Required (mg/L)	31	
93% Sulfuric Acid Required (lb/1,000 gal)	0.26	

of the source water pH to 6.4 in mid-December 2004, increases in sulfate concentration averaged 34 mg/L. This amount closely matched the 31 mg/L derived from the actual acid consumption and the theoretical calculation shown in Table 4-7.

Figure 4-12 shows the silica concentrations (as SiO₂) over time across the treatment train. Silica concentrations in the source water ranged from 18.7 to 21.4 mg/L, which were similar to those in samples collected at the AP location following chlorination and pH adjustment. Elevated silica concentrations as high as 61.8 mg/L were measured in the treated water following the lead and lag vessels. The increase in silica concentration was attributed to the G2 media which, as discussed in Section 4.2, is a silica based material. The leaching of silica from both vessels leveled off after about 2,000 BVs, but continued throughout the remainder of the study period with increase in concentrations ranging from 1.6 to 3.0 mg/L after the lead vessel and from 3.7 to 6.2 mg/L after the lag vessel.

**Figure 4-12. Silica Concentrations Over Time**

Total hardness results ranged from 81.5 to 166.6 mg/L as CaCO₃. Hardness, which was predominantly calcium hardness, was consistent across the treatment train and did not appear to be affected by any of the steps involved in the treatment process. Fluoride concentrations ranged from 0.3 to 1.1 mg/L. Orthophosphate was below the detection limit in all samples collected during this period. Nitrate (as N) ranged from 0.1 to 1.4 mg/L.

Free and total chlorine was measured at the AP, TA, and TB sampling locations. Typically, free chlorine levels were measured at 0.1 to 0.7 mg/L at the AP location, with total chlorine levels ranging from 0.1 to 0.5 mg/L. Residual chlorine levels measured at the TA and TB locations were similar to those measured at the AP location, indicating little or no chlorine consumption by the G2 media.

DO levels ranged from 2.9 to 6.8 mg/L across the treatment train and were consistent at each location. ORP readings at the IN location varied from 195 to 498 mV and averaged 233 mV. After chlorination, the ORP readings increased significantly, ranging from 173 to 610 mV and averaging 435, 471, and 484 mV, respectively, at the AP, TA, and TB locations.

4.5.2 Backwash Water Sampling. Backwash water was sampled on January 11 and April 12, 2005. Samples were collected from the sample port located in the backwash effluent discharge line from each vessel. Unfiltered samples were analyzed for pH, turbidity, and TDS. Filtered samples (using 0.45-µm disc filters) were analyzed for soluble As, Fe, and Mn. Soluble iron was below the detection limit in each of the samples collected; soluble manganese concentrations also were low, comparable to the levels observed in the raw water. Soluble As concentrations in the Vessel A backwash water were 40.3 to 42.8 µg/L, similar to the levels measured in the source water. Soluble As concentrations in the Vessel B backwash water were lower, ranging from 11.4 to 26.1 µg/L. Because finished water was used for backwash, these concentrations suggest that some arsenic might have been desorbed from the media during backwashing. The analytical results from the two backwash water sampling events are summarized in Table 4-8. Note that future backwash samples collected during the remainder of this demonstration study will include collection and analysis of total suspended solids (TSS) and total As, Fe, and Mn. These parameters were not included in the sampling performed during the first six months of system operation.

Table 4-8. Backwash Water Sampling Results

	Date	pH	Turbidity	TDS	Soluble As ^(a)	Soluble Fe ^(a)	Soluble Mn ^(a)
		S.U.	NTU	mg/L	µg/L	µg/L	µg/L
Vessel A	01/11/05	6.9	140	38.0	40.3	<25	0.8
	04/12/05	6.2	200	244	42.8	<25	2.0
Vessel B	01/11/05	6.7	390	72.0	11.4	<25	2.3
	04/12/05	6.6	120	240	26.1	<25	0.7

(a) Filtered (0.45 µm) samples.

4.5.3 Distribution System Water Sampling. Distribution system samples were collected to investigate if the water treated by the arsenic removal system would impact the lead and copper level and water chemistry in the distribution system. Prior to the installation and operation of the system, baseline distribution system water samples were collected at three homes on July 21, August 5, August 18, and September 8, 2004. Following the installation of the system, distribution system water sampling continued on a monthly basis at the same three locations. The samples were analyzed for pH, alkalinity,

arsenic, iron, manganese, lead, and copper. The results of the distribution system sampling are summarized in Table 4-9.

As expected, prior to the installation of the arsenic removal system, arsenic concentrations in the distribution system were similar to those measured in the raw water, ranging from 36.9 to 52.3 µg/L. After the treatment system was installed and put into service, arsenic concentrations in the distribution system decreased significantly and closely mirrored those measured after the treatment system at sampling location TB, ranging from 3.9 to 12.4 µg/L.

Iron concentrations were similar to those observed in the raw water, and were typically below the detection limit of 25 µg/L. The iron concentration in the sample collected on January 12, 2005 at the DS1 location was high; it was not clear why this concentration was significantly higher than the other relevant data points.

Manganese concentrations in the distribution system generally followed those measured after the lag vessel with the highest concentrations (i.e., 16.0 µg/L) observed soon after the system was installed. Sampling location DS2 did not show as significant an increase in the manganese levels. The manganese concentrations declined steadily to levels only slightly higher than those observed during the baseline sampling after about three months of system operation (or about 2,500 BVs).

The pH values measured during the baseline sampling ranged from 7.2 to 7.8. After the system was installed, the pH values ranged from 6.6 to 8.1. The pH values across all three locations were high during the sampling event on December 8, 2004. During the next sampling event on January 12, 2005, however, the pH values were significantly lower, ranging from 6.6 to 6.8. This swing in pH was likely caused by difficulties encountered with adjustments to the rate of caustic addition as described under *Operator Skill Requirements* in Section 4.4.4. The lower pH values appeared to have had a significant impact on the lead and copper levels in the distribution system. Prior to the January 2005 sampling event, the lead and copper levels measured at the three sampling locations ranged from 1.4 to 2.4 µg/L for lead and from 35.4 to 147.0 µg/L for copper, which were consistent with the baseline values of 0.8 to 4.6 µg/L for lead and 62.1 to 240.1 µg/L for copper. With the pH drop in January 2005, the lead concentration increased to 9.9 µg/L at the DS3 location; and copper levels increased across all three sampling locations, with the most noticeable increase exceeding the action level of 1.3 mg/L at the DS3 location. During the subsequent monthly sampling events, the pH values were better controlled; however, the lead and copper levels continued to be higher than those observed before the pH drop in January.

For the most part, alkalinity levels were consistent throughout the baseline sampling and five of the six monthly sampling events, ranging from 54 to 80 mg/L (as CaCO₃). In January 2005, alkalinity values were lower (i.e., 43 to 55 mg/L), consistent with the low pH values measured during this sampling event.

4.6 System Costs

The cost-effectiveness of the system is evaluated based on the dollar cost per 1,000 gal of water treated. This includes the tracking of capital costs such as equipment, engineering, and installation costs and O&M costs such as media replacement and disposal, chemical supply, electrical power use, and labor.

4.6.1 Capital Costs. The capital investment costs for equipment, site engineering, and installation were \$154,700 (see Table 4-10). The equipment costs were \$102,600 (or 66% of the total capital investment), which included \$76,100 for the adsorption system (vessels and piping), \$6,000 for the G2 media (i.e., \$35/ft³ or \$0.75/lb to fill two vessels), \$3,900 for the backwash booster pump, and vendor's labor and travel for the system shakedown and startup.

Table 4-9. Distribution System Sampling Results

No. of Sampling Events	Sampling Location	DS1								DS2								DS3							
	Sampling Date	Stagnation Time (hrs)	pH	Alkalinity	Total As	Total Fe	Total Mn	Total Pb	Total Cu	Stagnation Time (hrs)	pH	Alkalinity	Total As	Total Fe	Total Mn	Total Pb	Total Cu	Stagnation Time (hrs)	pH	Alkalinity	Total As	Total Fe	Total Mn	Total Pb	Total Cu
BL1	07/21/04	8.5	7.4	80	44.1	<25	1.1	2.5	93.7	7.8	7.4	68	41.1	<25	0.5	1.1	163.5	6.3	7.4	60	41.4	<25	0.4	2.0	149.8
BL2	08/05/04	7.5	7.2	68	52.3	<25	5.0	4.6	88.7	8.0	7.2	66	45.8	<25	0.6	2.7	240.1	7.0	7.3	60	48.2	<25	1.6	2.2	62.1
BL3	08/18/04	7.0	7.7	60	36.9	28	0.7	1.9	122.2	7.5	7.6	60	41.3	38	1.8	3.8	62.8	7.0	7.6	60	39.5	34	0.5	2.4	129.1
BL4	09/08/04	9.3	7.8	64	51.0	<25	0.9	0.8	92.7	7.8	7.8	64	49.1	<25	0.5	0.8	75.9	8.2	7.7	64	50.0	<25	0.6	1.0	128.7
1	11/03/04 ^(a)	8.8	7.5	62	11.2	<25	11.7	1.5	107.0	8.8	7.6	66	8.5	<25	3.0	0.8	94.9	8.3	7.8	62	9.3	<25	16.0	1.4	41.0
2	12/08/04	10.0	8.1	61	5.6	<25	7.5	0.9	35.4	7.8	8.1	61	12.4	<25	2.4	1.6	111.0	8.8	8.0	61	9.6	<25	4.0	2.4	147.0
3	01/12/05	9.0	6.8	44	3.9	174/ 257	7.7	3.1	375.0/ 464.0	7.7	6.8	55	5.7	<25	3.5	3.7	747.0/ 844.0	10.7	6.6	43	5.3	30	10.4	9.9	1,345/ 1,378
4	02/09/05	5.5	7.5	54	4.4	<25	2.6	5.9	379.0	7.8	7.4	61	4.8	28	2.7	1.9	731.0	8.3	7.2	64	5.1	<25	6.3	6.7	814.0
5	03/09/05	7.0	7.6	70	7.1	<25	2.1	1.6	56.0	7.7	7.4	57	5.3	<25	2.2	4.2	882.0	9.0	7.4	71	7.3	<25	2.1	5.0	461.0
6	04/20/05	7.4	7.3	72	7.7	<25	2.6	3.7	262.1	7.7	7.1	67	4.2	<25	2.4	3.6	739.1	8.3	7.1	64	9.9	26	3.0	5.0	429.8

BL = baseline sampling

DS = distribution sampling

(a) Sample at DS2 was taken on November 8, 2004

(/) indicates laboratory re-run data with original result/re-run result

Lead action level = 15 µg/L; copper action level = 1.3 mg/L

The unit for analytical parameters is µg/L, except for pH (standard unit) and alkalinity (mg/L as CaCO₃)

Table 4-10. Capital Investment for the G2 Media Treatment System

Description	Quantity	Cost	% of Capital Investment Cost
<i>Equipment Costs</i>			
Adsorption System	1 unit	\$76,100	–
G2 Media	170 ft ³	\$6,000	–
Backwash Booster Pump	1	\$3,900	–
Field Services (Vendor Labor and Travel)	–	\$16,600	–
Equipment Total	–	\$102,600	66%
<i>Engineering Costs</i>			
Vendor Labor	–	\$12,500	–
Engineering Total	–	\$12,500	8%
<i>Installation Costs</i>			
Subcontractor	–	\$32,500	–
Vendor Labor	–	\$3,550	–
Vendor Travel	–	\$3,550	–
Installation Total	–	\$39,600	26%
Total Capital Investment	–	\$154,700	100%

The engineering costs included the costs for the preparation of the system layout and footprint, design of the piping connections up to the distribution tie-in points, design of the electrical connections, and assembling and submission of the engineering plans for the permit application (Section 4.3.1). The engineering costs were \$12,500, which was 8% of the total capital investment.

The installation costs included the costs for the equipment and labor to unload and install the adsorption unit, perform the piping tie-ins and electrical work, and load and condition the media (Section 4.3.3). The installation was conducted by Lewis Engineering and C&C Water Services subcontracted to ADI. The installation costs were \$39,600, or 26% of the total capital investment.

C&C Water Services constructed an aboveground addition to the existing underground pump house structure to house the G2 media treatment system (Section 4.3.2). The cost of building the addition was approximately \$25,000, including placement of a steel support on top of the existing concrete structure and construction of a wooden frame building on this steel support.

The total capital cost of \$154,700 and equipment cost of \$102,600 were converted to a unit cost of \$0.28/1,000 gallon and \$0.19/1,000 gallon, respectively, using a capital recovery factor (CRF) of 0.06722 based on a 3% interest rate and a 20-year return period (Chen et al., 2004). These calculations assumed that the system operated 24 hr per day, 7 days per week at the original system design flowrate of 70 gpm. The system operated an average of 9.3 hr per day (see Table 4-4), producing 3,858,000 gal of water during the 6-month period, so the total unit cost and equipment-only unit cost were increased to \$1.32/1,000 gallons and \$0.83/1,000 gallons, respectively, at this reduced rate of usage. Using the system's actual capacity of 40 gpm (57,600 gpd), the capital cost was \$3,868/gpm (\$2.68/gpd) and equipment-only cost was \$2,565/gpm (\$1.78/gpd). These calculations did not include the cost of the building construction.

4.6.2 Operation and Maintenance Costs. O&M costs for the G2 media treatment system include only incremental costs associated with the adsorption system, such as media replacement and disposal, chemical supply, electricity, and labor. These costs are summarized in Table 4-11. Although media replacement and disposal did not take place during the first six months of operation, the cost to change out the lead vessel was estimated to be \$9,396 based on information provided by the vendor and a local

Table 4-11. O&M Costs for the G2 Media Treatment System

Cost Category	Value	Assumptions
Volume processed (kgal)	3,858	Through April 24, 2005
<i>Media Replacement and Disposal</i>		
Media cost (\$/ft ³)	40	Vendor quote
Total media volume (ft ³)	85	Both vessels
Media replacement cost (\$)	3,400	Vendor quote
Freight (\$)	580	-
Labor cost (\$)	4,226	Vendor quote
Waste Analysis, TCLP (\$)	300	-
Media disposal fee (\$)	890	Vendor quote
Subtotal	\$9,396	Vendor quote
Media replacement and disposal cost (\$/1,000 gal)	See Figure 4-13	Based upon media run length at 10-μg/L arsenic breakthrough
<i>Chemical Usage</i>		
Acid unit price (\$/lb)	0.40	200 lb container at \$80
Acid consumption rate (lb/1,000 gal)	0.24	925 lb used to treat 3,858 kgal
Acid cost (\$/1,000 gal)	0.10	-
Caustic unit price (\$/lb)	0.63	160 lb container at \$100
Caustic consumption rate (lb/1,000 gal)	0.45	1740 lb used to treat 3,858 kgal
Caustic cost (\$/1,000 gal)	0.28	-
Total chemical cost (\$/1,000 gal)	0.38	Cost for acid and caustic addition, no additional costs for chlorination
<i>Electricity</i>		
Electricity cost (\$/1,000 gal)	\$0.001	Electrical costs assumed negligible
<i>Labor</i>		
Average weekly labor (hrs)	2.33	20 min/day
Labor cost (\$/1,000 gal)	\$0.34	Labor rate = \$20/hr
Total O&M cost (\$/1,000 gal)	See Figure 4-13	Based upon media run length at 10-μg/L arsenic breakthrough

subcontractor. This cost was used to estimate the media replacement cost per 1,000 gal of water treated as a function of the projected media run length to the 10-μg/L arsenic breakthrough (Figure 4-13).

With a system that operates in series, the media in the lead vessel is ideally replaced when the arsenic concentration in the treated water following the lead vessel equals the incoming raw water concentration and before the arsenic concentration following the lag vessel reaches the 10-μg/L target value. Once the lead vessel is rebedded, the lead and lag vessels are switched, so that the lag vessel is placed in the lead position and the former lead vessel, now with new media, is placed in the lag position. This method maximizes the usage of the media so that the entire capacity for arsenic removal is exhausted before the media is replaced.

Chemical costs included sodium hypochlorite for chlorination and sulfuric acid and NaOH for pH adjustment. Sodium hypochlorite was in use prior to the installation of the G2 media treatment system for the purpose of maintaining chlorine residual in the distribution system. The treatment system did not

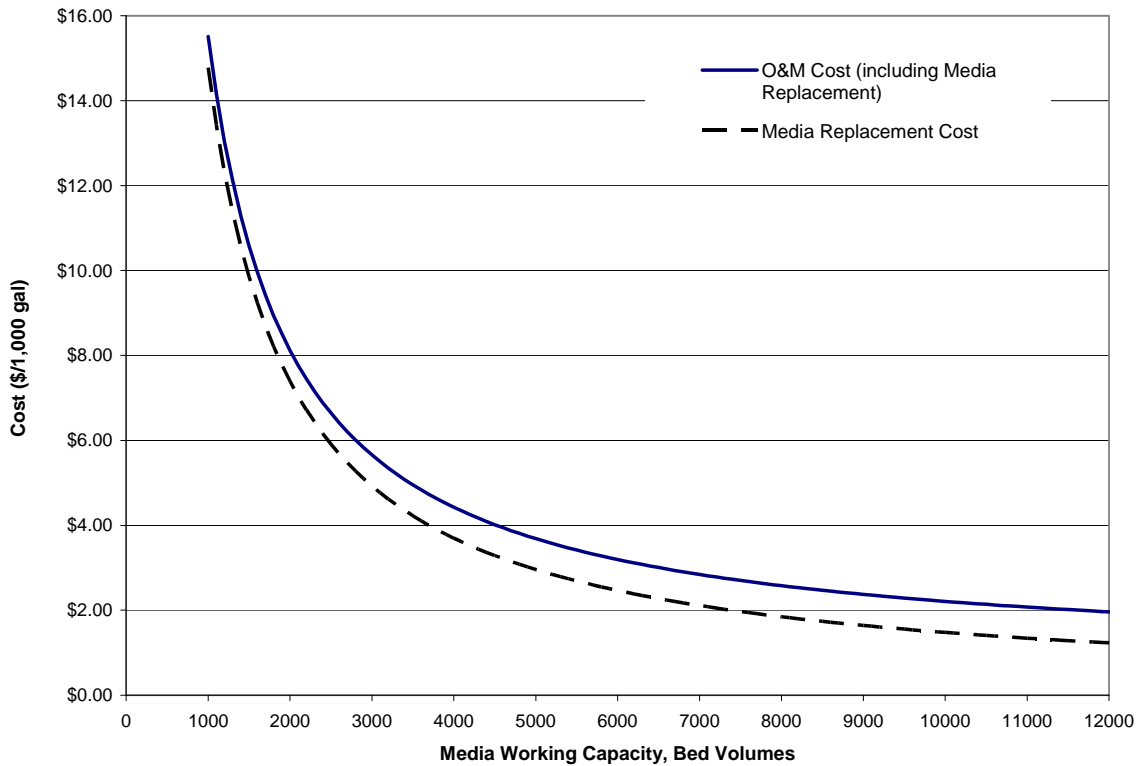


Figure 4-13. Media Replacement and O&M Costs

change the use rate of the sodium hypochlorite solution. Therefore, the chemical cost related to the use of sodium hypochlorite was unchanged. During the first six months of system operation, 5 containers (15-gal, 200 lb per container) of 93% sulfuric acid and 11 containers (15-gal, 160 lb per container) of 25% NaOH were consumed for pH adjustment. Based on the price per drum of approximately \$80 and \$100 for acid and caustic, respectively, the total chemical cost for this period was about \$1,500 or \$0.38/1,000 gallons.

The electrical usage rate for the pump station averaged 131 kWh per day during the six-month study period. Comparison of electrical bills prior to system installation and since startup indicated that the treatment system did not cause a noticeable increase in power consumption. Therefore, electrical costs associated with operation of the G2 media treatment system were negligible.

The routine, non-demonstration-related labor activities consumed about 20 minutes per day, as noted in Section 4.4.4. Therefore, the estimated labor cost is \$0.34/1,000 gal of water treated.

5.0 REFERENCES

- Battelle. 2003. *Revised Quality Assurance Project Plan for Evaluation of Arsenic Removal Technology*. Prepared under Contract No. 68-C-00-185, Task Order No. 0019, for U.S. EPA NRMRL. November 17.
- Battelle. 2004. *Final System Performance Evaluation Study Plan: U.S. EPA Demonstration of Arsenic Removal Technology at Bow, New Hampshire*. Prepared under Contract No. 68-C-00-185, Task Order No. 0019 for U.S. EPA NRMRL. October 6.
- Chen, A.S.C., L. Wang, J. Oxenham, and W. Condit. 2004. *Capital Costs of Arsenic Removal Technologies: U.S. EPA Arsenic Removal Technology Demonstration Program Round 1*. EPA/600/R-04/201. U.S. EPA NRMRL, Cincinnati, OH.
- Edwards, M., S. Patel, L. McNeill, H. Chen, M. Frey, A.D. Eaton, R.C. Antweiler, and H.E. Taylor. 1998. "Considerations in As Analysis and Speciation." *J. AWWA* (March): 103-113.
- EPA, see U.S. Environmental Protection Agency.
- Rubel, Jr., F. 2003. *Design Manual: Removal of Arsenic from Drinking Water by Adsorptive Media*. EPA/600/R-03/019. U.S. EPA NRMRL, Cincinnati, OH.
- U.S. Environmental Protection Agency. 2003. Minor Clarification of the National Primary Drinking Water Regulation for Arsenic. *Federal Register*, 40 CFR Part 141. March 25.
- U.S. Environmental Protection Agency. 2002. *Lead and Copper Monitoring and Reporting Guidance for Public Water Systems*. Prepared by EPA's Office of Water. EPA/816/R-02/009. February.
- U.S. Environmental Protection Agency. 2001. National Primary Drinking Water Regulations: Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring. *Fed. Register.*, 66:14:6975. January 22.
- Wang, L., W. Condit, and A. Chen. 2004. *Technology Selection and System Design: U.S. EPA Arsenic Removal Technology Demonstration Program Round 1*. EPA/600/R-05/001. U.S. EPA NRMRL, Cincinnati, OH.

APPENDIX A

OPERATIONAL DATA

EPA Arsenic Demonstration at WRWC in Bow, NH – Summary of Daily System Operational Data (Page 1 of 5)

Week No.	Date	Avg Operation Hours hr	Cumulative Operation Hours hr	Outlet Magnetic Meter					Vessel A			Vessel B		
				Outlet Flowrate gpm	Outlet Totalizer gal	Daily Flow Totalizer gal	Cumulative Volume Treated gal	Cumulative Bed Volumes Treated	Inlet Pressure psi	Outlet Pressure psi	Δp psi	Inlet Pressure psi	Outlet Pressure psi	Δp psi
1	10/11/2004	NA	NA	NM	NM	NA	NA	NA	NM	NM	NA	NM	NM	NA
	10/12/2004	6.7	6.7	NM	NM	NA	NA	NA	0	3	NA	0	3	NA
	10/13/2004	NA	NA	36	537,160	NA	NA	NA	3	5	NA	2	5	NA
	10/14/2004	NA	NA	NM	NM	NA	NA	NA	NM	NM	NA	NM	NM	NA
	10/15/2004	NA	NA	NM	NM	NA	NA	NA	NM	NM	NA	NM	NM	NA
	10/16/2004	NA	NA	NM	NM	NA	NA	NA	NM	NM	NA	NM	NM	NA
	10/17/2004	NA	NA	NM	NM	NA	NA	NA	NM	NM	NA	NM	NM	NA
2	10/18/2004	NA	NA	NM	NM	NA	NA	NA	NM	NM	NA	NM	NM	NA
	10/19/2004	7.3	14.0	38.6	643,625	106,465	106,465	167	2.0	3.0	1.0	1.0	2.0	1.0
	10/20/2004	8.4	22.4	26.9	664,300	20,675	127,140	200	1.0	2.0	1.0	0.5	2.0	1.5
	10/21/2004	6.6	29.0	30.6	680,661	16,361	143,501	226	1.0	3.0	2.0	1.0	2.0	1.0
	10/22/2004	8.9	37.9	39.0	702,593	21,932	165,433	260	2.0	2.0	0.0	1.0	2.0	1.0
	10/23/2004	7.8	45.7	44.0	721,837	19,244	184,677	290	2.0	2.0	0.0	1.0	2.0	1.0
	10/24/2004	7.2	52.9	47.0	739,366	17,529	202,206	318	3.0	4.0	1.0	2.0	3.0	1.0
3	10/25/2004	8.8	61.7	48.0	760,847	21,481	223,687	352	2.0	3.0	1.0	2.0	3.0	1.0
	10/26/2004	6.8	68.5	38.0	777,478	16,631	240,318	378	2.0	3.0	1.0	1.0	2.0	1.0
	10/27/2004	8.4	76.9	45.0	797,624	20,146	260,464	410	2.0	4.0	2.0	2.0	3.0	1.0
	10/28/2004	7.5	84.4	46.0	816,002	18,378	278,842	439	2.0	4.0	2.0	2.0	3.0	1.0
	10/29/2004	7.6	92.0	48.0	834,796	18,794	297,636	468	2.0	3.0	1.0	2.0	3.0	1.0
	10/30/2004	9.6	101.6	49.0	858,346	23,550	321,186	505	2.0	3.0	1.0	1.0	2.0	1.0
	10/31/2004	9.7	111.3	44.0	880,781	22,435	343,621	540	2.0	3.0	1.0	1.0	2.0	1.0
4	11/1/2004	7.9	119.2	41.7	899,790	19,009	362,630	570	5.0	5.0	0.0	4.0	5.0	1.0
	11/2/2004	9.2	128.4	44.0	921,975	22,185	384,815	605	8.0	10.0	2.0	8.0	10.0	2.0
	11/3/2004	6.9	135.3	44.0	938,108	16,133	400,948	631	8.0	10.0	2.0	6.0	8.0	2.0
	11/4/2004	8.6	143.9	43.0	957,946	19,838	420,786	662	8.0	10.0	2.0	6.0	8.0	2.0
	11/5/2004	8.8	152.7	43.3	978,591	20,645	441,431	694	8.0	10.0	2.0	6.0	8.0	2.0
	11/6/2004	8.1	160.8	41.0	997,718	19,127	460,558	724	8.0	8.0	0.0	6.0	8.0	2.0
	11/7/2004	8.8	169.6	43.0	1,017,767	20,049	480,607	756	8.0	10.0	2.0	6.0	8.0	2.0
5	11/8/2004	9.2	178.8	45.0	1,038,441	20,674	501,281	788	10.0	10.0	0.0	8.0	10.0	2.0
	11/9/2004	7.7	186.5	42.0	1,056,213	17,772	519,053	816	10.0	11.0	1.0	8.0	10.0	2.0
	11/10/2004	7.2	193.7	43.0	1,073,299	17,086	536,139	843	10.0	10.0	0.0	9.0	10.0	1.0
	11/11/2004	7.7	201.4	45.0	1,091,607	18,308	554,447	872	10.0	10.0	0.0	8.0	10.0	2.0
	11/12/2004	9.8	211.2	36.0	1,114,759	23,152	577,599	908	6.0	8.0	2.0	4.0	8.0	4.0
	11/13/2004	7.7	218.9	42.0	1,132,453	17,694	595,293	936	8.0	10.0	2.0	8.0	10.0	2.0
	11/14/2004	8.3	227.2	41.0	1,151,444	18,991	614,284	966	8.0	9.0	1.0	5.0	8.0	3.0
6	11/15/2004	8.9	236.1	48.0	1,171,547	20,103	634,387	998	9.0	10.0	1.0	8.0	9.0	1.0
	11/16/2004	8.2	244.3	40.0	1,198,461	26,914	661,301	1040	12.0	12.0	0.0	11.0	12.0	1.0
	11/17/2004	7.9	252.2	42.0	1,208,577	10,116	671,417	1056	10.0	12.0	2.0	9.0	11.0	2.0
	11/18/2004	7.5	259.7	43.0	1,226,155	17,578	688,995	1084	12.0	12.0	0.0	11.0	12.0	1.0
	11/19/2004	8.6	268.3	41.0	1,246,352	20,197	709,192	1115	10.0	12.0	2.0	9.0	11.0	2.0
	11/20/2004	9.7	278.0	44.0	1,268,470	22,118	731,310	1150	10.0	11.0	1.0	8.0	10.0	2.0
	11/21/2004	8.4	286.4	40.0	1,286,856	18,386	749,696	1179	10.0	11.0	1.0	10.0	11.0	1.0

EPA Arsenic Demonstration at WRWC in Bow, NH – Summary of Daily System Operational Data (Page 2 of 5)

Week No.	Date	Avg Operation Hours hr	Cumulative Operation Hours hr	Outlet Magnetic Meter					Vessel A			Vessel B		
				Outlet Flowrate gpm	Outlet Totalizer gal	Daily Flow Totalizer gal	Cumulative Volume Treated gal	Cumulative Bed Volumes Treated	Inlet Pressure psi	Outlet Pressure psi	Δp psi	Inlet Pressure psi	Outlet Pressure psi	Δp psi
7	11/22/2004	8.6	295.0	39.3	1,306,700	19,844	769,540	1210	10.0	11.0	1.0	8.0	10.0	2.0
	11/23/2004	7.3	302.3	40.3	1,323,674	16,974	786,514	1237	10.0	11.0	1.0	9.0	11.0	2.0
	11/24/2004	9.7	312.0	43.3	1,345,911	22,237	808,751	1272	11.0	12.0	1.0	10.0	12.0	2.0
	11/25/2004	8.2	320.2	41.7	1,364,685	18,774	827,525	1302	11.0	12.0	1.0	9.0	11.0	2.0
	11/26/2004	8.8	329.0	41.3	1,384,761	20,076	847,601	1333	12.0	12.0	0.0	10.0	11.0	1.0
	11/27/2004	8.4	337.4	40.3	1,403,810	19,049	866,650	1363	10.0	11.0	1.0	10.0	11.0	1.0
8	11/28/2004	11.0	348.4	39.4	1,427,681	23,871	890,521	1401	10.0	11.0	1.0	9.0	10.0	1.0
	11/29/2004	7.6	356.0	40.1	1,444,834	17,153	907,674	1428	10.0	11.0	1.0	10.0	12.0	2.0
	11/30/2004	8.5	364.5	46.7	1,463,974	19,140	926,814	1458	12.0	13.0	1.0	10.0	12.0	2.0
	12/1/2004	7.1	371.6	41.5	1,480,492	16,518	943,332	1484	12.0	13.0	1.0	10.0	12.0	2.0
	12/2/2004	8.1	379.7	41.6	1,499,233	18,741	962,073	1513	12.0	13.0	1.0	10.0	12.0	2.0
	12/3/2004	9.1	388.8	38.2	1,520,747	21,514	983,587	1547	9.0	9.0	0.0	7.0	9.0	2.0
9	12/4/2004	7.4	396.2	41.5	1,537,957	17,210	1,000,797	1574	10.0	10.0	0.0	8.0	10.0	2.0
	12/5/2004	9.2	405.4	42.5	1,558,903	20,946	1,021,743	1607	9.0	9.0	0.0	7.0	8.0	1.0
	12/6/2004	7.3	412.7	42.3	1,575,151	16,248	1,037,991	1633	12.0	12.0	0.0	10.0	12.0	2.0
	12/7/2004	7.6	420.3	41.1	1,592,399	17,248	1,055,239	1660	12.0	12.0	0.0	9.0	12.0	3.0
	12/8/2004	7.7	428.0	43.8	1,610,551	18,152	1,073,391	1688	13.0	13.0	0.0	11.0	12.0	1.0
	12/9/2004	8.0	436.0	43.4	1,628,928	18,377	1,091,768	1717	13.0	13.0	0.0	11.0	12.0	1.0
10	12/10/2004	8.2	444.2	43.7	1,648,334	19,406	1,111,174	1748	11.0	12.0	1.0	9.0	11.0	2.0
	12/11/2004	8.4	452.6	42.6	1,667,441	19,107	1,130,281	1778	12.0	12.0	0.0	13.0	12.0	1.0
	12/12/2004	10.2	462.8	36.8	1,690,927	23,486	1,153,767	1815	9.0	9.0	0.0	7.0	9.0	2.0
	12/13/2004	7.2	470.0	42.9	1,706,789	15,862	1,169,629	1840	13.0	12.0	1.0	12.0	12.0	0.0
	12/14/2004	9.4	479.4	45.5	1,728,436	21,647	1,191,276	1874	10.0	10.0	0.0	7.0	9.0	2.0
	12/15/2004	6.5	485.9	41.7	1,744,098	15,662	1,206,938	1898	9.0	9.0	0.0	7.0	8.0	1.0
11	12/16/2004	7.0	492.9	43.4	1,760,533	16,435	1,223,373	1924	10.0	10.0	0.0	7.0	9.0	2.0
	12/17/2004	9.2	502.1	41.6	1,782,219	21,686	1,245,059	1958	8.0	8.0	0.0	6.0	7.0	1.0
	12/18/2004	8.1	510.2	41.3	1,800,894	18,675	1,263,734	1988	9.0	8.0	1.0	6.0	7.0	1.0
	12/19/2004	9.4	519.6	38.0	1,822,426	21,532	1,285,266	2021	7.0	7.0	0.0	5.0	7.0	2.0
	12/20/2004	9.1	528.7	41.6	1,842,688	20,262	1,305,528	2053	7.0	8.0	1.0	6.0	7.0	1.0
	12/21/2004	7.2	535.9	42.3	1,854,450	11,762	1,317,290	2072	10.0	10.0	0.0	7.0	9.0	2.0
12	12/22/2004	8.7	544.6	41.4	1,878,671	24,221	1,341,511	2110	10.0	10.0	0.0	7.0	9.0	2.0
	12/23/2004	NA	NA	NM	NM	NA	NA	NA	NM	NM	NA	NM	NM	NA
	12/24/2004	20.8	565.4	41.8	1,924,958	NA	NA	NA	10.0	10.0	0.0	7.0	9.0	2.0
	12/25/2004	9.9	575.3	38.7	1,946,344	21,386	1,362,897	2144	10.0	9.0	1.0	7.0	9.0	2.0
	12/26/2004	10.6	585.9	40.6	1,969,074	22,730	1,385,627	2179	10.0	9.0	1.0	7.0	8.0	1.0
	12/27/2004	9.7	595.6	42.1	1,988,059	18,985	1,404,612	2209	9.0	9.0	0.0	7.0	8.0	1.0
12	12/28/2004	8.8	604.4	39.5	2,008,591	20,532	1,425,144	2241	9.0	9.0	0.0	7.0	8.0	1.0
	12/29/2004	9.8	614.2	40.8	2,030,335	21,744	1,446,888	2276	8.0	7.0	1.0	6.0	8.0	2.0
	12/30/2004	10.1	624.3	36.5	2,052,360	22,025	1,468,913	2310	7.0	7.0	0.0	5.0	7.0	2.0
	12/31/2004	11.7	636.0	35.4	2,077,382	25,022	1,493,935	2350	7.0	7.0	0.0	5.0	6.0	1.0
	1/1/2005	7.4	643.4	38.5	2,093,961	16,579	1,510,514	2376	9.0	9.0	0.0	7.0	8.0	1.0
	1/2/2005	23.5	666.9	31.5	2,134,111	40,150	1,550,664	2439	6.0	4.0	2.0	3.0	6.0	3.0

EPA Arsenic Demonstration at WRWC in Bow, NH – Summary of Daily System Operational Data (Page 3 of 5)

Week No.	Date	Avg Operation Hours hr	Cumulative Operation Hours hr	Outlet Magnetic Meter					Vessel A			Vessel B		
				Outlet Flowrate	Outlet Totalizer	Daily Flow Totalizer	Cumulative Volume Treated	Cumulative Bed Volumes Treated	Inlet Pressure	Outlet Pressure	Δp	Inlet Pressure	Outlet Pressure	Δp
				gpm	gal	gal	gal		psi	psi	psi	psi	psi	psi
13	1/3/2005	7.3	674.2	40.3	2,149,653	15,542	1,566,206	2463	10.0	10.0	0.0	7.0	9.0	2.0
	1/4/2005	8.5	682.7	41.6	2,168,274	18,621	1,584,827	2493	11.0	10.0	1.0	8.0	10.0	2.0
	1/5/2005	8.1	690.8	43.0	2,186,659	18,385	1,603,212	2522	11.0	11.0	0.0	8.0	10.0	2.0
	1/6/2005	10.5	701.3	38.2	2,210,604	23,945	1,627,157	2559	7.0	7.0	0.0	5.0	7.0	2.0
	1/7/2005	8.9	710.2	40.6	2,229,746	19,142	1,646,299	2589	9.0	8.0	1.0	7.0	9.0	2.0
	1/8/2005	8.5	718.7	40.1	2,248,542	18,796	1,665,095	2619	10.0	10.0	0.0	7.0	9.0	2.0
	1/9/2005	9.6	728.3	44.3	2,269,572	21,030	1,686,125	2652	10.0	10.0	0.0	7.0	9.0	2.0
14	1/10/2005	9.5	737.8	40.3	2,290,483	20,911	1,707,036	2685	9.0	8.0	1.0	7.0	8.0	1.0
	1/11/2005	12.4	750.2	31.5	2,317,137	26,654	1,733,690	2727	7.0	8.0	1.0	6.0	8.0	2.0
	1/12/2005	6.6	756.8	43.2	2,331,891	14,754	1,748,444	2750	15.0	15.0	0.0	13.0	15.0	2.0
	1/13/2005	9.4	766.2	40.3	2,352,893	21,002	1,769,446	2783	12.0	13.0	1.0	11.0	13.0	2.0
	1/14/2005	7.8	774.0	40.7	2,369,333	16,440	1,785,886	2809	15.0	15.0	0.0	13.0	15.0	2.0
	1/15/2005	9.8	783.8	40.0	2,391,115	21,782	1,807,668	2843	14.0	15.0	1.0	12.0	14.0	2.0
	1/16/2005	10.3	794.1	40.8	2,413,979	22,864	1,830,532	2879	12.0	13.0	1.0	11.0	13.0	2.0
15	1/17/2005	9.5	803.6	39.9	2,434,854	20,875	1,851,407	2912	11.0	13.0	2.0	10.0	12.0	2.0
	1/18/2005	8.5	812.1	43.7	2,452,751	17,897	1,869,304	2940	15.0	16.0	1.0	13.0	11.0	2.0
	1/19/2005	7.9	820.0	41.5	2,470,822	18,071	1,887,375	2969	14.0	15.0	1.0	12.0	15.0	3.0
	1/20/2005	8.6	828.6	40.3	2,490,330	19,508	1,906,883	2999	14.0	15.0	1.0	12.0	15.0	3.0
	1/21/2005	9.1	837.7	41.1	2,510,687	20,357	1,927,240	3031	12.0	13.0	1.0	10.0	13.0	3.0
	1/22/2005	9.4	847.1	40.4	2,531,399	20,712	1,947,952	3064	12.0	13.0	1.0	10.0	13.0	3.0
	1/23/2005	9.6	856.7	42.7	2,552,097	20,698	1,968,650	3096	13.0	13.0	0.0	11.0	14.0	3.0
16	1/24/2005	9.1	865.8	41.3	2,571,909	19,812	1,988,462	3127	14.0	15.0	1.0	12.0	15.0	3.0
	1/25/2005	8.1	873.9	40.1	2,590,546	18,637	2,007,099	3157	15.0	16.0	1.0	14.0	16.0	2.0
	1/26/2005	8.0	881.9	42.2	2,608,795	18,249	2,025,348	3186	15.0	16.0	1.0	14.0	16.0	2.0
	1/27/2005	8.4	890.3	44.3	2,627,629	18,834	2,044,182	3215	16.0	16.0	0.0	14.0	16.0	2.0
	1/28/2005	10.1	900.4	38.2	2,650,511	22,882	2,067,064	3251	11.0	12.0	1.0	9.0	12.0	3.0
	1/29/2005	8.0	908.4	37.0	2,668,851	18,340	2,085,404	3280	11.0	12.0	1.0	10.0	12.0	2.0
	1/30/2005	12.3	920.7	34.0	2,695,129	26,278	2,111,682	3321	8.0	8.0	0.0	6.0	9.0	3.0
17	1/31/2005	8.0	928.7	39.6	2,711,222	16,093	2,127,775	3347	16.0	16.0	0.0	14.0	16.0	2.0
	2/1/2005	7.9	936.6	42.4	2,729,013	17,791	2,145,566	3375	15.0	16.0	1.0	14.0	15.0	1.0
	2/2/2005	8.3	944.9	37.3	2,747,686	18,673	2,164,239	3404	16.0	16.0	0.0	14.0	16.0	2.0
	2/3/2005	8.3	953.2	45.9	2,766,522	18,836	2,183,075	3434	16.0	16.0	0.0	14.0	15.0	1.0
	2/4/2005	8.7	961.9	39.5	2,786,021	19,499	2,202,574	3464	16.0	16.0	0.0	14.0	15.0	1.0
	2/5/2005	9.8	971.7	45.7	2,807,547	21,526	2,224,100	3498	15.0	15.0	0.0	13.0	14.0	1.0
	2/6/2005	11.3	983.0	36.8	2,831,725	24,178	2,248,278	3536	10.0	10.0	0.0	8.0	9.0	1.0
18	2/7/2005	7.5	990.5	40.7	2,848,555	16,830	2,265,108	3563	16.0	16.0	0.0	14.0	15.0	1.0
	2/8/2005	7.9	998.4	41.1	2,866,591	18,036	2,283,144	3591	16.0	16.0	0.0	14.0	15.0	1.0
	2/9/2005	8.4	1006.8	47.2	2,885,410	18,819	2,301,963	3621	16.0	16.0	0.0	14.0	15.0	1.0
	2/10/2005	9.1	1015.9	43.1	2,906,231	20,821	2,322,784	3653	13.0	13.0	0.0	10.0	11.0	1.0
	2/11/2005	8.9	1024.8	39.7	2,925,923	19,692	2,342,476	3684	13.0	13.0	0.0	11.0	12.0	1.0
	2/12/2005	9.9	1034.7	33.6	2,948,119	22,196	2,364,672	3719	11.0	12.0	1.0	9.0	11.0	2.0
	2/13/2005	10.0	1044.7	38.8	2,969,745	21,626	2,386,298	3753	13.0	13.0	0.0	11.0	13.0	2.0

EPA Arsenic Demonstration at WRWC in Bow, NH – Summary of Daily System Operational Data (Page 4 of 5)

Week No.	Date	Avg Operation Hours hr	Cumulative Operation Hours hr	Outlet Magnetic Meter					Vessel A			Vessel B		
				Outlet Flowrate	Outlet Totalizer	Daily Flow Totalizer	Cumulative Volume Treated	Cumulative Bed Volumes Treated	Inlet Pressure	Outlet Pressure	Δp	Inlet Pressure	Outlet Pressure	Δp
				gpm	gal	gal	gal		psi	psi	psi	psi	psi	psi
19	2/14/2005	8.9	1053.6	39.9	2,989,704	19,959	2,406,257	3785	13.0	13.0	0.0	10.0	12.0	2.0
	2/15/2005	7.8	1061.4	40.1	3,007,034	17,330	2,423,587	3812	10.0	9.0	1.0	7.0	8.0	1.0
	2/16/2005	8.4	1069.8	40.3	3,026,039	19,005	2,442,592	3842	10.0	9.0	1.0	7.0	7.0	0.0
	2/17/2005	8.5	1078.3	41.0	3,045,281	19,242	2,461,834	3872	10.0	9.0	1.0	7.0	8.0	1.0
	2/18/2005	9.1	1087.4	41.2	3,066,022	20,741	2,482,575	3905	9.0	8.0	1.0	6.0	7.0	1.0
	2/19/2005	11.0	1098.4	36.0	3,090,622	24,600	2,507,175	3943	7.0	7.0	0.0	4.0	6.0	2.0
20	2/20/2005	11.0	1109.4	38.9	3,114,486	23,864	2,531,039	3981	7.0	7.0	0.0	4.0	6.0	2.0
	2/21/2005	8.6	1118.0	44.0	3,133,287	18,801	2,549,840	4010	9.0	8.0	1.0	7.0	8.0	1.0
	2/22/2005	9.1	1127.1	39.9	3,153,152	19,865	2,569,705	4042	20.0	21.0	1.0	17.0	20.0	3.0
	2/23/2005	10.4	1137.5	39.3	3,175,292	22,140	2,591,845	4077	19.0	19.0	0.0	16.0	18.0	2.0
	2/24/2005	9.6	1147.1	42.1	3,195,313	20,021	2,611,866	4108	19.0	19.0	0.0	17.0	19.0	2.0
	2/25/2005	10.5	1157.6	41.2	3,217,543	22,230	2,634,096	4143	21.0	22.0	1.0	19.0	21.0	2.0
21	2/26/2005	12.5	1170.1	42.2	3,243,080	25,537	2,659,633	4183	17.0	18.0	1.0	15.0	17.0	2.0
	2/27/2005	11.4	1181.5	38.0	3,266,391	23,311	2,682,944	4220	17.0	17.0	0.0	15.0	17.0	2.0
	2/28/2005	9.1	1190.6	42.9	3,285,641	19,250	2,702,194	4250	20.0	20.0	0.0	17.0	19.0	2.0
	3/1/2005	10.0	1200.6	38.0	3,307,138	21,497	2,723,691	4284	16.0	16.0	0.0	14.0	16.0	2.0
	3/2/2005	10.4	1211.0	36.4	3,329,356	22,218	2,745,909	4319	16.0	16.0	0.0	14.0	16.0	2.0
	3/3/2005	8.0	1219.0	41.3	3,346,888	17,532	2,763,441	4346	20.0	20.0	0.0	17.0	19.0	2.0
22	3/4/2005	11.5	1230.5	35.5	3,371,421	24,533	2,787,974	4385	15.0	15.0	0.0	12.0	14.0	2.0
	3/5/2005	11.0	1241.5	39.4	3,394,246	22,825	2,810,799	4421	17.0	18.0	1.0	15.0	17.0	2.0
	3/6/2005	13.2	1254.7	35.6	3,420,533	26,287	2,837,086	4462	15.0	16.0	1.0	13.0	15.0	2.0
	3/7/2005	10.6	1265.3	40.3	3,441,728	21,195	2,858,281	4496	19.0	19.0	0.0	17.0	18.0	1.0
	3/8/2005	13.2	1278.5	37.8	3,467,373	25,645	2,883,926	4536	17.0	18.0	1.0	15.0	18.0	3.0
	3/9/2005	14.1	1292.6	39.3	3,494,579	27,206	2,911,132	4579	17.0	18.0	1.0	15.0	17.0	2.0
23	3/10/2005	14.1	1306.7	37.2	3,521,436	26,857	2,937,989	4621	25.0	25.0	0.0	23.0	25.0	2.0
	3/11/2005	14.3	1321.0	38.4	3,548,297	26,861	2,964,850	4663	22.0	23.0	1.0	19.0	22.0	3.0
	3/12/2005	11.0	1332.0	38.7	3,568,879	20,582	2,985,432	4696	27.0	28.0	1.0	25.0	27.0	2.0
	3/13/2005	11.0	1343.0	42.6	3,590,313	21,434	3,006,866	4729	27.0	28.0	1.0	25.0	27.0	2.0
	3/14/2005	8.2	1351.2	36.4	3,606,707	16,394	3,023,260	4755	NA	27.0	NA	27.0	28.0	1.0
	3/15/2005	9.1	1360.3	44.3	3,625,853	19,146	3,042,406	4785	20.0	21.0	1.0	16.0	20.0	4.0
24	3/16/2005	8.1	1368.4	43.0	3,643,284	17,431	3,059,837	4813	22.0	22.0	0.0	19.0	21.0	2.0
	3/17/2005	8.4	1376.8	42.6	3,661,488	18,204	3,078,041	4841	22.0	23.0	1.0	19.0	21.0	2.0
	3/18/2005	8.7	1385.5	41.7	3,680,954	19,466	3,097,507	4872	17.0	17.0	0.0	15.0	16.0	1.0
	3/19/2005	9.2	1394.7	40.3	3,700,919	19,965	3,117,472	4903	15.0	16.0	1.0	13.0	15.0	2.0
	3/20/2005	10.7	1405.4	42.3	3,723,897	22,978	3,140,450	4939	12.0	13.0	1.0	10.0	12.0	2.0
	3/21/2005	8.0	1413.4	44.5	3,740,922	17,025	3,157,475	4966	21.0	22.0	1.0	18.0	20.0	2.0
24	3/22/2005	8.0	1421.4	47.7	3,758,479	17,557	3,175,032	4994	22.0	27.0	5.0	19.0	21.0	2.0
	3/23/2005	9.8	1431.2	43.6	3,780,333	21,854	3,196,886	5028	15.0	15.0	0.0	12.0	14.0	2.0
	3/24/2005	7.1	1438.3	42.5	3,796,412	16,079	3,212,965	5053	16.0	16.0	0.0	13.0	15.0	2.0
	3/25/2005	9.5	1447.8	36.7	3,817,763	21,351	3,234,316	5087	13.0	13.0	0.0	10.0	12.0	2.0
	3/26/2005	9.8	1457.6	42.9	3,838,499	20,736	3,255,052	5120	15.0	15.0	0.0	12.0	14.0	2.0
	3/27/2005	13.2	1470.8	35.7	3,866,379	27,880	3,282,932	5163	10.0	9.0	1.0	7.0	9.0	2.0

EPA Arsenic Demonstration at WRWC in Bow, NH – Summary of Daily System Operational Data (Page 5 of 5)

Week No.	Date	Avg Operation Hours hr	Cumulative Operation Hours hr	Outlet Magnetic Meter					Vessel A			Vessel B		
				Outlet Flowrate gpm	Outlet Totalizer gal	Daily Flow Totalizer gal	Cumulative Volume Treated gal	Cumulative Bed Volumes Treated	Inlet Pressure psi	Outlet Pressure psi	Δp psi	Inlet Pressure psi	Outlet Pressure psi	Δp psi
25	3/28/2005	8.2	1479.0	37.8	3,883,085	16,706	3,299,638	5190	15.0	16.0	1.0	13.0	15.0	2.0
	3/29/2005	8.5	1487.5	39.1	3,902,013	18,928	3,318,566	5220	14.0	14.0	0.0	12.0	13.0	1.0
	3/30/2005	9.6	1497.1	41.6	3,922,384	20,371	3,338,937	5252	16.0	16.0	0.0	13.0	15.0	2.0
	3/31/2005	8.9	1506.0	39.9	3,941,732	19,348	3,358,285	5282	16.0	16.0	0.0	13.0	15.0	2.0
	4/1/2005	8.5	1514.5	40.7	3,960,622	18,890	3,377,175	5312	16.0	16.0	0.0	14.0	15.0	1.0
	4/2/2005	9.8	1524.3	42.3	3,982,195	21,573	3,398,748	5346	15.0	15.0	0.0	13.0	14.0	1.0
26	4/3/2005	9.8	1534.1	43.9	4,003,448	21,253	3,420,001	5379	14.0	13.0	1.0	12.0	14.0	2.0
	4/4/2005	8.7	1542.8	40.6	4,022,552	19,104	3,439,105	5409	14.0	13.0	1.0	12.0	13.0	1.0
	4/5/2005	7.7	1550.5	42.5	4,038,787	16,235	3,455,340	5435	16.0	10.0	6.0	13.0	16.0	3.0
	4/6/2005	8.0	1558.5	44.4	4,056,802	18,015	3,473,355	5463	16.0	10.0	6.0	13.0	15.0	2.0
	4/7/2005	7.8	1566.3	38.7	4,074,577	17,775	3,491,130	5491	11.0	11.0	0.0	13.0	15.0	2.0
	4/8/2005	8.5	1574.8	39.6	4,093,908	19,331	3,510,461	5521	14.0	10.0	4.0	12.0	12.0	0.0
27	4/9/2005	9.1	1583.9	42.5	4,113,962	20,054	3,530,515	5553	16.0	10.0	6.0	13.0	15.0	2.0
	4/10/2005	10.2	1594.1	42.5	4,135,968	22,006	3,552,521	5587	15.0	10.0	5.0	12.0	14.0	2.0
	4/11/2005	9.2	1603.3	44.6	4,155,862	19,894	3,572,415	5619	16.0	10.0	6.0	13.0	15.0	2.0
	4/12/2005	10.2	1613.5	42.4	4,178,409	22,547	3,594,962	5654	15.0	15.0	0.0	12.0	14.0	2.0
	4/13/2005	7.5	1621.0	47.3	4,195,027	16,618	3,611,580	5680	16.0	16.0	0.0	14.0	15.0	1.0
	4/14/2005	8.8	1629.8	41.4	4,214,799	19,772	3,631,352	5711	15.0	14.0	1.0	12.0	13.0	1.0
28	4/15/2005	9.4	1639.2	10.6	4,235,652	20,853	3,652,205	5744	13.0	13.0	0.0	10.0	12.0	2.0
	4/16/2005	10.6	1649.8	39.3	4,258,123	22,471	3,674,676	5780	13.0	13.0	0.0	10.0	12.0	2.0
	4/17/2005	10.8	1660.6	45.4	4,280,778	22,655	3,697,331	5815	14.0	13.0	1.0	11.0	13.0	2.0
	4/18/2005	9.6	1670.2	44.7	4,300,836	20,058	3,717,389	5847	15.0	15.0	0.0	13.0	14.0	1.0
	4/19/2005	10.0	1680.2	40.9	4,321,862	21,026	3,738,415	5880	16.0	15.0	1.0	13.0	15.0	2.0
	4/20/2005	10.2	1690.4	41.9	4,343,599	21,737	3,760,152	5914	15.0	15.0	0.0	13.0	15.0	2.0
28	4/21/2005	9.0	1699.4	44.6	4,363,147	19,548	3,779,700	5945	16.0	15.0	1.0	13.0	15.0	2.0
	4/22/2005	24.7	1724.1	27.4	4,405,545	42,398	3,822,098	6011	8.0	7.0	1.0	4.0	7.0	3.0
	4/23/2005	7.8	1731.9	44.1	4,422,047	16,502	3,838,600	6037	13.0	13.0	0.0	11.0	13.0	2.0
	4/24/2005	9.0	1740.9	41.5	4,440,999	18,952	3,857,552	6067	14.0	13.0	1.0	12.0	13.0	1.0

NM = Not Measured

NA = Not Available

APPENDIX B
ANALYTICAL RESULTS

Analytical Results

Sampling Date		10/13/04 ^{(c)(d)}				10/19/04				10/26/04				11/02/04			
Sampling Location Parameter Unit		IN	AP	TA	TB	IN	AP	TA	TB	IN	AP	TA	TB	IN	AP	TA	TB
Bed Volume	10 ³	–	–	0		–	–	0.2		–	–	0.4		–	–	0.6	
Alkalinity	mg/L ^(a)	55	55	57	59	61	41	55	55	57	43	45	46	62	39	41	45
Fluoride	mg/L	0.7	0.7	1.1	0.8	–	–	–	–	–	–	–	–	–	–	–	–
NO ₃ -N	mg/L	1.0	0.5	1.3	1.4	–	–	–	–	–	–	–	–	–	–	–	–
Orthophosphate	mg/L ^(b)	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
Silica (as SiO ₂)	mg/L	18.8	19.1	50.8	61.8	19.4	19.8	39.1	54.2	19.5	19.4	28.5	36.8	19.4	19.0	27.8	37.1
Sulfate	mg/L	24.0	26.0	12.0	9.6	–	–	–	–	–	–	–	–	–	–	–	–
Turbidity	NTU	0.7	0.1	0.2	0.2	0.7	0.5	0.4	0.5	0.4	0.2	<0.1	<0.1	0.3	0.5	0.2	0.3
pH	S.U.	7.8	7.8	7.9	8.0	6.8	6.8	7.0	7.1	7.1	6.9	7.1	6.9	7.1	7.0	6.8	6.8
Temperature	°C	12.3	12.7	12.9	13.0	11.7	11.7	11.7	11.8	12.1	11.9	11.8	11.7	11.8	11.9	11.8	11.7
DO	mg/L	5.5	2.9	4.1	4.0	5.8	3.6	3.8	4.3	5.5	3.9	3.6	4.5	6.5	4.6	4.2	4.7
ORP	mV	198	190	183	173	234	233	227	231	NA ^(e)	NA ^(e)	NA ^(e)	NA ^(e)	215	228	224	217
Free Chlorine	mg/L	–	0.2	0.1	0.1	–	0.7	0.3	0.6	–	0.1	0.2	0.1	–	0.2	0.1	0.1
Total Chlorine	mg/L	–	0.1	0.1	0.1	–	0.4	0.3	0.5	–	0.1	0.2	0.1	–	0.1	0.1	0.1
Total Hardness	mg/L ^(a)	163.3	128.4	166.6	86.8	–	–	–	–	–	–	–	–	–	–	–	–
Ca Hardness	mg/L ^(a)	125.5	99.1	122.2	41.4	–	–	–	–	–	–	–	–	–	–	–	–
Mg Hardness	mg/L ^(a)	37.8	29.3	44.4	45.4	–	–	–	–	–	–	–	–	–	–	–	–
As (total)	µg/L	91.3/ 89.5	96.1/ 90.2	37.5/ 34.4	17.1/ 16.7	49.8	50.7	30.7	21.8	52.0	52.2	14.5	5.4	47.6	48.5	13.8	4.5
As (total soluble)	µg/L	50.5/ 46.9	52.3/ 47.8	25.3/ 23.3	14.3/ 14.6	–	–	–	–	–	–	–	–	–	–	–	–
As (particulate)	µg/L	40.8/ 42.6	43.8/ 42.4	12.2/ 11.1	2.8/ 2.1	–	–	–	–	–	–	–	–	–	–	–	–
As (III)	µg/L	0.7	0.6	0.8	1.1	–	–	–	–	–	–	–	–	–	–	–	–
As (V)	µg/L	49.8/ 46.2	51.7/ 47.2	24.5/ 22.5	13.2/ 13.5	–	–	–	–	–	–	–	–	–	–	–	–
Total Fe	µg/L	<25/ <25	60/ 56	<25	39/ 38	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25
Dissolved Fe	µg/L	<25	<25	<25	<25	–	–	–	–	–	–	–	–	–	–	–	–
Total Mn	µg/L	1.8/ 1.2	7.2/ 4.6	19.3/ 19.1	5.1/ 6.0	0.8	0.4	12.0	7.1	0.5	0.8	27.0	31.5	0.7	0.6	21.2	35.8
Dissolved Mn	µg/L	0.4/ 0.6	0.3/ 0.5	9.0/ 10.4	4.1/ 4.9	–	–	–	–	–	–	–	–	–	–	–	–

(a) as CaCO₃. (b) as PO₄. (c) (f) indicates re-run data with original result/re-run result. (d) System start-up on October 13, 2004. H₂SO₄ acid addition not yet operational. (e) ORP probe not working properly. IN = inlet; AP = after pH adjustment and after pre-chlorination; TA = after Vessel A; TB = after Vessel B; TT = after vessels combined. NA = data not available.

Analytical Results

Sampling Date		11/16/04 ^(c)				11/30/04				12/14/04 ^(d)				01/04/05 ^(e)			
Sampling Location Parameter Unit		IN	AP	TA	TB	IN	AP	TA	TB	IN	AP	TA	TB	IN	AP	TA	TB
Bed Volume	10 ³	–		1.0		–	–	1.5		–	–	1.9		–	–	2.5	
Alkalinity	mg/L ^(a)	254	46	43	45	61	41	41	41	67	31	31	31	66 65	28 29	31 31	31 31
Fluoride	mg/L	–	–	–	–	–	–	–	–	1.1	1.0	0.8	0.7	–	–	–	–
NO ₃ -N	mg/L	–	–	–	–	–	–	–	–	0.2	0.1	0.2	0.2	–	–	–	–
Orthophosphate	mg/L ^(b)	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06 <0.06	<0.06 <0.06	<0.06 <0.06	<0.06 <0.06
Silica (as SiO ₂)	mg/L	18.9	19.5	26.4	33.0	19.4	19.6	24.8	30.9	19.2	19.4	25.0	28.4	20.4 20.0	20.6 19.9	23.2 22.9	26.6 26.2
Sulfate	mg/L	–	–	–	–	–	–	–	–	11.0/ 11.1	39.0/ 46.7	39.0/ 45.7	39.0/ 46.6	–	–	–	–
Turbidity	NTU	0.3	0.4	0.3	0.3	1.1	0.3	0.1	0.4	0.5	0.2	0.3	0.4	0.3 0.2	0.1 0.2	0.2 0.6	0.2 0.4
pH	S.U.	7.4	6.9	6.8	6.8	7.4	6.7	6.7	6.7	7.4	6.5	6.4	6.4	7.4	6.4	6.4	6.4
Temperature	°C	11.9	11.8	11.7	11.5	11.8	11.9	11.7	11.5	11.5	11.6	11.5	11.5	11.8	11.8	11.9	12.1
DO	mg/L	5.7	4.4	4.5	4.4	4.7	4.7	4.7	4.7	5.6	4.6	4.4	4.5	6.8	4.7	4.5	4.7
ORP	mV	218	219	221	222	208	524	542	450	211	548	554	553	498	484	553	558
Free Chlorine	mg/L	–	0.1	0.1	0.1	–	0.2	0.1	0.1	–	0.2	0.1	0.1	–	0.2	0.2	0.1
Total Chlorine	mg/L	–	0.1	0.1	0.1	–	0.2	0.2	0.1	–	0.2	0.1	0.1	–	0.2	0.2	0.1
Total Hardness	mg/L ^(a)	–	–	–	–	–	–	–	–	92.1	98.7	93.5	101.8	–	–	–	–
Ca Hardness	mg/L ^(a)	–	–	–	–	–	–	–	–	72.3	77.5	72.6	79.2	–	–	–	–
Mg Hardness	mg/L ^(a)	–	–	–	–	–	–	–	–	19.8	21.2	20.9	22.6	–	–	–	–
As (total)	µg/L	44.2	44.9	14.2	3.8	42.4	43.5	13.5	3.3	52.3	55.2	15.6	50.9/ 50.8	38.4 38.0	38.7 38.9	13.0 12.6	1.7 1.7
As (total soluble)	µg/L	–	–	–	–	–	–	–	–	52.6	55.7	15.5	3.6	–	–	–	–
As (particulate)	µg/L	–	–	–	–	–	–	–	–	<0.1	<0.1	0.1	47.3	–	–	–	–
As (III)	µg/L	–	–	–	–	–	–	–	–	0.6	0.6	0.7	0.6	–	–	–	–
As (V)	µg/L	–	–	–	–	–	–	–	–	52.0	55.1	14.8	3.0	–	–	–	–
Total Fe	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25/ <25	<25 <25	<25 <25	<25 <25	<25 <25
Dissolved Fe	µg/L	–	–	–	–	–	–	–	–	<25	<25	<25	<25	–	–	–	–
Total Mn	µg/L	0.2	<0.1	12.5	28.3	0.7	0.5	5.2	15.3	1.2	0.6	5.0	13.3/ 12.8	0.9 0.8	0.8 0.8	2.3 2.4	5.2 5.3
Dissolved Mn	µg/L	–	–	–	–	–	–	–	–	0.4	0.4	4.8	12.5	–	–	–	–

(a) as CaCO₃. (b) as PO₄. (c) Began bi-weekly sampling instead of weekly sampling. (d) (/) indicates re-run data with original result/re-rerun result. (e) Duplicate sampling performed.
 IN = inlet; AP = after pH adjustment and after pre-chlorination; TA = after Vessel A; TB = after Vessel B; TT = after vessels combined, NA = data not available.

Analytical Results

Sampling Date		01/18/05				02/01/05				02/15/05				03/01/05			
Sampling Location Parameter Unit		IN	AP	TA	TB	IN	AP	TA	TB	IN	AP	TA	TB	IN	AP	TA	TB
Bed Volume	10 ³	–	–	2.6		–	–	3.4		–	–	3.8		–	–	4.3	
Alkalinity	mg/L ^(a)	66	35	33	35	69	43	37	41	69	45	36	38	120	61	62	68
Fluoride	mg/L	–	–	–	–	0.9	1.0	0.7	0.3	–	–	–	–	–	–	–	–
NO ₃ -N	mg/L	–	–	–	–	0.22	0.19	0.23	0.24	–	–	–	–	–	–	–	–
Orthophosphate	mg/L ^(b)	0.3	0.2	<0.05	<0.05	0.1	0.06	<0.05	<0.05	<0.05	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Silica (as SiO ₂)	mg/L	19.7	20.1	22.7	25.3	18.7	18.5	21.1	24.9	20.0	20.1	22.9	24.9	19.7	19.9	22.0	23.9
Sulfate	mg/L	–	–	–	–	11.0	47.0	48.0	48.0	–	–	–	–	–	–	–	–
Turbidity	NTU	0.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
pH	S.U.	7.5	6.5	6.4	6.4	7.4	6.5	6.4	6.5	7.4	6.5	6.3	6.3	7.3	6.5	6.4	6.4
Temperature	°C	12.4	12.6	12.3	12.3	11.5	11.6	11.4	11.2	11.5	11.5	11.5	11.2	11.9	12.0	11.8	11.5
DO	mg/L	6.0	4.5	4.0	3.9	6.6	5.6	5.3	5.4	NA ^(c)	NA ^(c)	NA ^(c)	NA ^(c)	5.1	3.9	3.9	3.9
ORP	mV	238	207	548	584	211	587	591	586	212	580	594	595	195	607	610	608
Free Chlorine	mg/L	–	0.3	0.2	0.2	–	0.2	0.2	0.2	–	0.3	0.3	0.2	–	0.5	0.5	0.4
Total Chlorine	mg/L	–	0.3	0.3	0.2	–	0.2	0.2	0.2	–	0.3	0.2	0.2	–	0.5	0.4	0.5
Total Hardness	mg/L ^(a)	–	–	–	–	84.0	81.5	85.0	89.6	–	–	–	–	–	–	–	–
Ca Hardness	mg/L ^(a)	–	–	–	–	65.9	64.0	66.6	70.0	–	–	–	–	–	–	–	–
Mg Hardness	mg/L ^(a)	–	–	–	–	18.1	17.5	18.4	19.6	–	–	–	–	–	–	–	–
As (total)	µg/L	46.1	46.3	15.1	2.1	54.1	54.5	24.4	5.0	45.5	46.1	17.2	3.3	49.1	49.8	22.3	3.9
As (total soluble)	µg/L	–	–	–	–	54.6	54.4	24.8	5.0	–	–	–	–	–	–	–	–
As (particulate)	µg/L	–	–	–	–	<0.1	0.1	<0.1	<0.1	–	–	–	–	–	–	–	–
As (III)	µg/L	–	–	–	–	0.5	0.5	0.4	0.4	–	–	–	–	–	–	–	–
As (V)	µg/L	–	–	–	–	54.1	53.9	24.4	4.6	–	–	–	–	–	–	–	–
Total Fe	µg/L	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25
Dissolved Fe	µg/L	–	–	–	–	<25	<25	<25	<25	–	–	–	–	–	–	–	–
Total Mn	µg/L	0.6	0.8	3.0	2.8	0.5	3.3	1.1	1.5	0.7	0.7	1.4	2.4	1.1	1.9	0.5	1.1
Dissolved Mn	µg/L	–	–	–	–	0.5	0.5	1.2	1.3	–	–	–	–	–	–	–	–

(a) as CaCO₃. (b) as PO₄. (c) DO probe not working properly.

IN = inlet; AP = after pH adjustment and after pre-chlorination; TA = after Vessel A; TB = after Vessel B; TT = after vessels combined; NA = data not available.

Analytical Results

Sampling Date		03/15/05				03/29/05 ^(d)				04/12/05			
Sampling Location Parameter Unit		IN	AP	TA	TB	IN	AP	TA	TB	IN	AP	TA	TB
Bed Volume	10 ³	–	–	4.8		–	–	5.2		–	–	5.7	
Alkalinity	mg/L ^(a)	77 69	35 39	37 37	38 37	66	33	29	28	67	28	44	42
Fluoride	mg/L	–	–	–	–	0.9	1.0	0.9	0.8	–	–	–	–
NO ₃ -N	mg/L	–	–	–	–	0.2	0.2	0.2	0.3	–	–	–	–
Orthophosphate	mg/L ^(b)	<0.05 <0.05	<0.05 <0.05	<0.05 <0.05	<0.05 <0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Silica (as SiO ₂)	mg/L	21.4 20.3	21.4 20.8	23.9 22.7	24.4 24.3	19.8	19.7	21.4	23.5	20.7	20.1	23.0	25.1
Sulfate	mg/L	–	–	–	–	11.0	51.0	48.0	46.0	–	–	–	–
Turbidity	NTU	<0.1 <0.1	<0.1 <0.1	<0.1 <0.1	<0.1 <0.1	<0.1	<0.1	<0.1	0.3	<0.1	0.1	<0.1	<0.1
pH	S.U.	7.4	6.6	6.3	6.3	7.4	6.1	6.1	6.1	7.3	6.1	6.4	6.5
Temperature	°C	11.9	11.9	11.7	11.6	11.7	11.5	11.4	11.4	11.7	11.6	11.7	11.5
DO	mg/L	NA ^(c)	NA ^(c)	NA ^(c)	NA ^(c)	5.3	4.3	4.7	4.4	4.8	3.9	4.8	4.6
ORP	mV	213	608	606	608	212	577	590	594	192	560	577	578
Free Chlorine	mg/L	–	0.5	0.3	0.4	–	0.4	0.4	0.3	–	0.4	0.3	0.4
Total Chlorine	mg/L	–	0.5	0.4	0.4	–	0.4	0.3	0.3	–	0.3	0.4	0.3
Total Hardness	mg/L ^(a)	–	–	–	–	95.4	93.4	101.4	98.5	–	–	–	–
Ca Hardness	mg/L ^(a)	–	–	–	–	75.8	72.7	77.2	75.7	–	–	–	–
Mg Hardness	mg/L ^(a)	–	–	–	–	19.6	20.7	24.2	22.8	–	–	–	–
As (total)	µg/L	48.1 47.8	46.9 47.0	23.0 23.1	6.9 6.8	48.9	50.0	21.0	5.5	42.8	41.5	26.3	5.8
As (total soluble)	µg/L	–	–	–	–	48.2	49.7	20.8	5.5	–	–	–	–
As (particulate)	µg/L	–	–	–	–	0.7	0.3	0.2	<0.1	–	–	–	–
As (III)	µg/L	–	–	–	–	0.7	0.6	0.6	0.7	–	–	–	–
As (V)	µg/L	–	–	–	–	47.5	49.1	20.2	4.8	–	–	–	–
Total Fe	µg/L	<25 <25	<25 <25	<25 <25	<25 <25	<25	<25	<25	<25	<25	<25	<25	<25
Dissolved Fe	µg/L	–	–	–	–	<25	<25	<25	<25	–	–	–	–
Total Mn	µg/L	2.0 1.9	1.9 1.8	0.6 0.5	0.3 0.3	1.2	0.9	1.2	1.5	0.1	0.1	0.5	<0.1
Dissolved Mn	µg/L	–	–	–	–	1.2	1.0	1.4	1.4	–	–	–	–

(a) as CaCO₃. (b) as PO₄. (c) DO probe not working properly. (d) On-site water quality parameters measured on March 28, 2005.

IN = inlet; AP = after pH adjustment and after pre-chlorination; TA = after Vessel A; TB = after Vessel B; TT = after vessels combined; NA = data not available.