

Specifically Designed Constructed Wetlands: A Novel Treatment Approach for Scrubber Wastewater

**Scientific Final Report
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Foreword

This scientific progress report is organized by the three research objectives or tasks:

Task 1:

To measure performance of a pilot-scale constructed wetland treatment system in terms of decreases in targeted constituents (Hg, Se and As) in FGD wastewater.

Task 2:

To determine how the observed performance is achieved (both reactions and rates) through sequential extractions of these elements from sediments.

Task 3:

To measure performance in terms of decreased bioavailability of these elements (i.e. toxicity of sediments in constructed wetlands and toxicity of outflow waters from the treatment system).

Within the report, each section is divided and classified as TASK 1, 2, and 3. Discussions and conclusions are included in each section, along with an overall conclusion from data collected during the full year of funding.

Abstract

A pilot-scale wetland treatment system was specifically designed and constructed at Clemson University to evaluate removal of mercury, selenium, and other constituents from flue gas desulfurization (FGD) wastewater. Specific objectives of this research were: (1) to measure performance of a pilot-scale constructed wetland treatment system in terms of decreases in targeted constituents (Hg, Se and As) in the FGD wastewater from inflow to outflow; (2) to determine how the observed performance is achieved (both reactions and rates); and (3) to measure performance in terms of decreased bioavailability of these elements (i.e. toxicity of sediments in constructed wetlands and toxicity of outflow waters from the treatment system).

Performance of the pilot-scale constructed wetland treatment systems was assessed using two criteria: anticipated NPDES permit levels and toxicity evaluations using two sentinel toxicity-testing organisms (*Ceriodaphnia dubia* and *Pimephales promelas*). These systems performed efficiently with varied inflow simulations of FGD wastewaters removing As, Hg, and Se concentrations below NPDES permit levels and reducing the toxicity of simulated FGD wastewater after treatment with the constructed wetland treatment systems. Sequential extraction procedures indicated that these elements (As, Hg, and Se) were bound to residual phases within sediments of these systems, which should limit their bioavailability to aquatic biota.

Sediments collected from constructed wetland treatment systems were tested to observe toxicity to *Hyalella azteca* or *Chironomus tentans*. Complete survival (100%) was observed for *H. azteca* in all cells of the constructed wetland treatment system and *C. tentans* had an average of 91% survival over the three treatment cells containing sediments. Survival and growth of *H. azteca* and *C. tentans* did not differ significantly between sediments from the constructed wetland treatment system and controls. Since the sediments of the constructed wetland treatment system are repositories for As, Hg, and Se and the bioavailability of these elements decreased after deposition, the pilot-scale constructed wetland treatment system contributed significantly to mitigation of risks to aquatic life from these elements.

Executive Summary

A pilot-scale wetland treatment system was specifically designed and constructed at Clemson University to evaluate removal of mercury, selenium, and other constituents from flue gas desulfurization (FGD) wastewater. Specific objectives of this research were: (1) to measure performance of the pilot-scale constructed wetland treatment system in terms of decreases in targeted constituents (Hg, Se and As) in the FGD wastewater; (2) to determine how the observed performance is achieved (both reactions and rates); and (3) to measure performance in terms of decreased bioavailability of these elements (i.e. toxicity of sediments in constructed wetlands and toxicity of outflow waters from the treatment system). This Scientific Final Progress Report provides a description of the configuration and current design characteristics of the pilot constructed wetland treatment system and performance results. Initial evaluations of performance contained in this progress report involved FGD wastewaters formulated based upon analyses of several actual FGD waters.

Performance of the pilot constructed wetland treatment systems at this final stage indicates that the system is decreasing aqueous concentrations of the targeted wastewater constituents (As, Hg, and Se) for the majority of the wastewaters. The removal rates of mercury were consistently greater than 90% for three of simulated FGD wastewaters tested and ranged from 64% to 97% for all FGD wastewaters except for the high ionic strength FGD wastewater (week 7), in which the concentration of mercury was already below the predicted NPDES permit level of 0.001 mg/L. Selenium removal rates were relatively stable throughout this study with a range of 84 to 90% removal by the pilot-scale constructed wetland treatment systems. Arsenic removal, however, varied throughout the study with higher removal rates occurring during the high ionic strength FGD wastewaters (~70%). Removal rates of arsenic in these simulated FGD wastewaters are of lesser importance than Hg or Se, since the actual FGD wastewaters that we have analyzed to date had lower concentrations of arsenic than the specified NPDES limits. Sequential extraction procedures were used to quantitatively measure the immobilization of these elements of concern in the sedimentary component of these systems. Data gathered by this procedure indicate that most of As, Hg, and Se is bound to residue phases within the sediment, and the dissolution or re-solubility of these elements is unlikely to occur under environmental conditions within this treatment system (not thermodynamically favored). In toxicity experiments, we observed a significant increase in survival, growth, and reproduction for organisms exposed to samples of the final outflow versus inflow simulated FGD wastewater. Chloride concentrations are an important factor in this treatment process and satisfactory chloride levels (~4000mg/L) were achieved in these experiments by dilution with moderately hard water.

Components of the system were manipulated to enhance removal of these targeted constituents and the contributions of these changes to transfers and transformations of As, Se, and Hg were assessed. Toxicity evaluations were conducted to relate these system component changes to bioavailability of these elements to the sentinel species used in NPDES toxicity tests. Bulk sediment toxicity was evaluated using both *H. azteca* and *C. tentans*. Since the sediments of the constructed wetland treatment system are repositories for As, Hg, and Se and the bioavailability of these elements decreased after deposition, the pilot-scale constructed wetland treatment system contributed significantly to mitigation of risks to aquatic life from these elements.

Table of Contents

ABSTRACT	3
EXECUTIVE SUMMARY	4
TASK ONE	9-48
INTRODUCTION	9
MATERIALS AND METHODS	10
System Configuration	10
Actual FGD Wastewater	11
Simulated FGD Wastewater	11
Analytical Methods	13
Evaluation of Wetland Plants.....	14
RESULTS	14
Primary Targeted Constituents	14
Other Constituents of Interest	17
DISCUSSION	46
CONCLUSIONS	47
REFERENCES	48
TASK TWO	49-55
INTRODUCTION	49
MATERIALS AND METHODS	48
Sequential Extraction Procedures.....	49
RESULTS	51
DISCUSSION	54
CONCLUSIONS	54
REFERENCES	55
TASK THREE	56-69
INTRODUCTION	56
MATERIALS AND METHODS	57
Toxicity Experiments.....	57
RESULTS	60
DISCUSSION	69
CONCLUSIONS	70
OVERALL CONCLUSIONS	71
REFERENCES	72

List of Tables

- Table 1. Acclimation FGD wastewater loaded into the pilot-scale constructed wetland treatment system (listed as weeks 1-4).
- Table 2. Classification and targeted concentrations of elements of interest in four simulated FGD wastewaters used throughout this phase one DOE study.
- Table 3. Targeted constituents and sources for simulated FGD wastewater.
- Table 4. Analytical methods for parameters monitored weekly from the FGD pilot constructed wetland systems.
- Table 5. Simulated FGD wastewater physical and chemical properties analyzed in a pilot constructed wetland system.
- Table 6. Monthly hydrosol oxidation-reduction (redox) potential in the FGD pilot-scale constructed wetland systems.
- Table 7. Summary of sequential extraction procedures for Hg (modified from Lechler *et al.* 1997).
- Table 8. Summary of sequential extraction method for Se (modified from Chao and Sanzalone 1989).
- Table 9. Summary of sequential extraction procedure for As (modified from Wenzel *et al.* 2001 and Schank 2003).
- Table 10. Summary of sediment characteristics.
- Table 11. Elements and form used for amendments of simulated FGD wastewater.
- Table 12. Analytical methods for parameters monitored for FGD wastewater.
- Table 13. Measurements of parameters from inflow to outflow of the constructed wetland treatment systems.
- Table 14. Sediment toxicity results in terms of survival and growth measurements of *Hyaella azteca* for wetland treatments and controls.
- Table 15. Sediment toxicity results in terms of survival and growth measurements of *Chironomus tentans* for wetland treatments and controls.

List of Figures

- Figure 1. Schematic of the pilot constructed wetland system for evaluating treatment of FGD wastewater.
- Figure 2. Pilot constructed wetland system at Clemson University for treating FGD wastewater.
- Figure 3. Total mercury in simulated FGD wastewater treated by a pilot constructed wetland system during the acclimation period (Weeks 1 to 4).
- Figure 4. Average total mercury in simulated FGD wastewater treated by a pilot constructed wetland system for the high ionic strength FGD wastewater (Weeks 9 and 10).
- Figure 5. Average total mercury in simulated FGD wastewater treated by a pilot constructed wetland system for the high-intermediate ionic strength FGD wastewater (Weeks 11 to 20).
- Figure 6. Total mercury in simulated FGD wastewater treated by a pilot constructed wetland system for the first week of low-intermediate ionic strength FGD wastewater (Week 23).

- Figure 7. Total mercury in simulated FGD wastewater treated by a pilot constructed wetland system for the second week of low-intermediate ionic strength FGD wastewater (Week 24).
- Figure 8. Total selenium in simulated FGD wastewater treated by a pilot constructed wetland system during the acclimation period (Weeks 1 to 4).
- Figure 9. Average total selenium in simulated FGD wastewater treated by a pilot constructed wetland system for the high ionic strength FGD wastewater (Weeks 9 and 10).
- Figure 10. Average total selenium in simulated FGD wastewater treated by a pilot constructed wetland system for the high-intermediate ionic strength FGD wastewater (Weeks 11 to 20).
- Figure 11. Total selenium in simulated FGD wastewater treated by a pilot constructed wetland system for the first week of low-intermediate ionic strength FGD wastewater (Week 23).
- Figure 12. Total selenium in simulated FGD wastewater treated by a pilot constructed wetland system for the second week of low-intermediate ionic strength FGD wastewater (Week 24).
- Figure 13. Average total arsenic in simulated FGD wastewater treated by a pilot constructed wetland system for the high ionic strength FGD wastewater (Weeks 9 and 10).
- Figure 14. Average total arsenic in simulated FGD wastewater treated by a pilot constructed wetland system for the high-intermediate ionic strength FGD wastewater (Weeks 11 to 20).
- Figure 15. Total arsenic in simulated FGD wastewater treated by a pilot constructed wetland system for the first week of low-intermediate ionic strength FGD wastewater (Week 23).
- Figure 16. Total arsenic in simulated FGD wastewater treated by a pilot constructed wetland system for the second week of low-intermediate ionic strength FGD wastewater (Week 24).
- Figure 17. Hydrosol oxidation-reduction (redox) potential for Train A of the FGD pilot-scale constructed wetland system.
- Figure 18. Hydrosol oxidation-reduction (redox) potential for Train B of the FGD pilot-scale constructed wetland system.
- Figure 19. Hydrosol oxidation-reduction (redox) potential for Train C of the FGD pilot-scale constructed wetland system.
- Figure 20. Sequential extraction of Hg (A), Se (B), and As (C) in sediment collected from the first, second, and fourth planted wetland cells.
- Figure 21. Response, in terms of survival, of *C. dubia* to the inflow and the outflow from the treatment system for Sample One simulated FGD wastewater (Trains A, B, and C combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested
- Figure 22. Response, in terms of survival, of *C. dubia* to the inflow and the outflow from the treatment system for Sample Two simulated FGD wastewater (Trains A, B, and C combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested.
- Figure 23. Response, in terms of survival, of *P. promelas* to the inflow and the outflow from the treatment system for Sample One simulated FGD wastewater (Trains A, B, and C

- combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested.
- Figure 24. Response, in terms of survival, of *P. promelas* to the inflow and the outflow from the treatment system for Sample Two simulated FGD wastewater (Trains A, B, and C combined).
- Figure 25. Response, in terms of reproduction, of *C. dubia* to the inflow and the outflow from the treatment system for Sample One simulated FGD wastewater (Trains A, B, and C combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested.
- Figure 26. Response, in terms of reproduction, of *C. dubia* to the inflow and the outflow from the treatment system for Sample Two simulated FGD wastewater (Trains A, B, and C combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested.
- Figure 27. Comparative responses, in terms of survival, of *C. dubia* and *P. promelas* to simulated FGD wastewater Sample One.
- Figure 28. Comparative responses, in terms of survival, of *C. dubia* and *P. promelas* to simulated FGD wastewater Sample Two. Concentrations of 0.39%, 0.78%, 1.56%, and 3.125% for *P. promelas* and 37.5%, 50%, 62.5%, and 75% for *C. dubia* were not tested.
- Figure 29. Comparative responses, in terms of survival, of *C. dubia* to simulated FGD wastewater Samples One and Two.
- Figure 30. Comparative responses, in terms of survival, of *P. promelas* to simulated FGD wastewater samples one and two. Concentrations of 0.39%, 0.78%, 1.56%, and 3.125% for Sample Two and 37.5%, 50%, 62.5%, and 75% for Sample One were not tested.

Scientific Final Report

TASK 1

Introduction

The purpose of this document is to report progress on this study conducted to evaluate the efficacy of specifically designed constructed wetland systems for treatment of flue gas desulfurization (FGD) wastewater, reactions and rates (for Hg, Se, and As), and toxicity of discharged wastewater from these systems. In order to efficiently implement FGD units at fossil-fueled power plants, an effective and reliable wastewater treatment system is needed. Large volumes of wastewater will be produced at each site from the FGD process, and that water must be treated to eliminate contaminants in order to achieve discharge limitations established under the Clean Water Act and National Pollution Discharge Elimination System (NPDES). The treatment system must be reliable and performance must be continuously achieved throughout all seasons of the year. Elements such as chloride, mercury, selenium, and arsenic are generally of concern in these wastewaters. Generic parameters such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD) may also be targeted constituents for treatment. The specific targeted constituents vary spatially throughout the U.S., therefore discharge limits of these constituents were chosen to encompass the majority of regulatory NPDES limits.

Specifically designed constructed wetland treatment systems have been used to treat each of these elements independently, and we have recent data indicating success based upon this concept or technology for actual FGD wastewater. Wetlands possess unique reactions not occurring in other aquatic or terrestrial systems. Constructed wetlands can be poised or buffered to ensure that desired reactions (transfers and transformations) affecting the targeted wastewater constituents proceed at predictable rates over long periods. In order to develop confidence in the ability of a constructed wetland treatment system to treat a specific FGD wastestream, a pilot study is needed. A pilot study will provide strong proof-of-concept data and convincing information to assist with regulatory permitting of the full-scale facility. Alternatives to treatment with a constructed wetland system are not attractive due to high capital costs and continuing high costs associated with operation and maintenance.

The goal of this project was to design constructed wetland treatment systems to effectively and consistently treat FGD wastewater in pilot-scale constructed wetland treatment systems. This report describes the progress of this pilot study by reporting the performance of each system and evaluates treatment effectiveness during all seasons. The pilot study involves a scaled model constructed wetland treatment system (i.e., wetland microcosms to decrease uncertainties and confirm design features for the proposed full-scale constructed wetland treatment systems). This report identifies the project objectives, outlines methods of analyses, and provides results for the pilot study.

Experimental Methods

Specific objectives of this pilot-scale research are:

1. Measure performance of a pilot-scale constructed wetland treatment system in terms of decreases in targeted constituents (Hg, Se and As) in the FGD wastewater.
2. Determine how the observed performance is achieved (both reactions and rates).

3. Measure performance in terms of decreased bioavailability of these elements (i.e. toxicity of sediments in constructed wetlands and toxicity of outflow waters from the treatment system).

Materials and Methods

System Configuration

The pilot constructed wetland treatment system (Fig. 1 and 2) was configured at Clemson University in Clemson, SC. The system consists of a 6,800-L upstream equalization basin followed by three parallel treatment trains. Each treatment train consists of four stages in series (from upstream to downstream), including two wetland cells planted with bulrush, a gravel manganese oxidation basin, and a final wetland cell planted with cattails. Each treatment stage was comprised of a 378-L Rubbermaid® utility tank. Overlying water depth and hydrosol depths were 30 cm each in the wetland cells. Total hydraulic retention time (HRT) was four days (24 hours per treatment stage). Wastewater was pumped to each treatment train from the equalization basin at a constant rate using FMI® (Fluid Metering, Inc.) piston pumps (one pump per treatment train). Flow through the treatment system trains was by gravity.

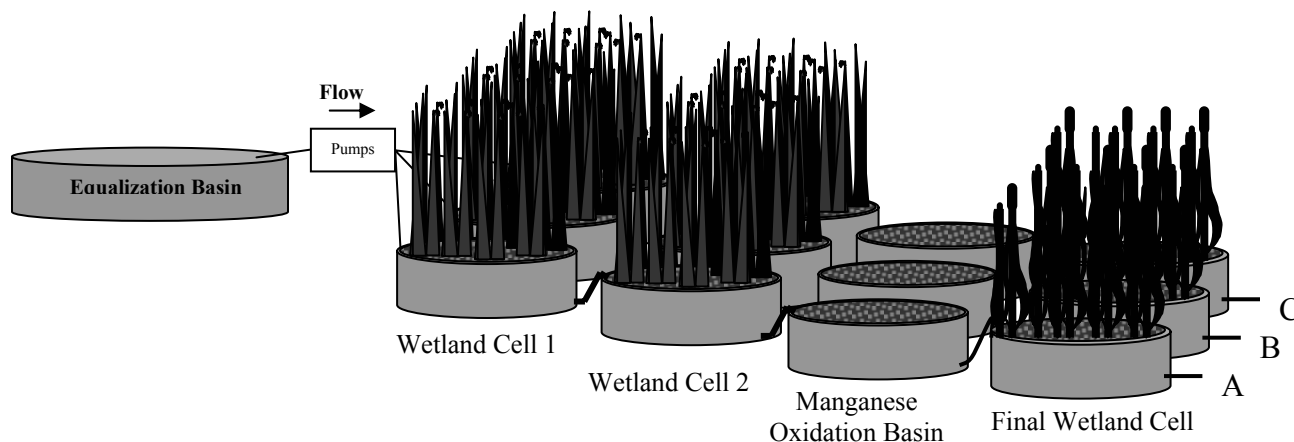


Figure 1. Schematic of the pilot constructed wetland system for evaluating treatment of FGD wastewater.



Figure 2. Pilot constructed wetland system at Clemson University for treating FGD wastewater.

Actual FGD Wastewater

Actual FGD wastewaters were analyzed for the major elemental constituents of concern (Hg, As, Se) using ICP-MS and for other water quality parameters such as Cl, SO_4^{2-} , COD, BOD, NPOC TSS, and TDS using *Standard Methods for the Examination of Water and Wastewater* (APHA 1998). Simulated FGD wastewater was synthesized based on results from these analyses.

Simulated FGD Wastewater

The chemical composition of FGD wastewater is site-specific and a treatment system must be robust to treat varying concentrations of toxic constituents. Therefore, four simulated FGD wastewaters were used, in order to understand the removal rates and extents of each independent wastewater resulting from treatment with specifically designed constructed wetlands. These wastewaters included acclimation, high, high-intermediate, low-intermediate, and low ionic strength simulated FGD wastewater (see Table 1 and 2).

Acclimation of the pilot constructed wetland system to mercury, selenium, arsenic, and chloride was accomplished (Table 1). Following the treatment acclimation period and finalization of a list of constituents targeted for removal, FGD wastewater was simulated and introduced to the pilot constructed wetland system. Several source materials were mixed with municipal water (5,000 L per week) in the upstream equalization basin to provide the targeted FGD wastewater constituents (Table 3).

Formulation of simulated FGD wastewater initially included CaCl_2 as a source for chloride, and nitric acid was added to neutralize pH. The final formulation differed from the initial formulation in that calcium and magnesium chloride salts were used as chloride sources. In subsequent formulations of simulated FGD wastewater fly ash was added and dibasic acid (DBA) replaced nitric acid. Formulations were consistent after that adjustment.

For the first phase of this project, sampling was conducted for elemental analysis (Hg, As, and Se) of inflow and outflow wastewater. After four weeks of loading, the pilot constructed wetland systems were sampled weekly for all water quality parameters listed in Table 3. Water samples were collected in 1000-mL Nalgene[®] containers from the equalization basin and outflow from each treatment stage. Outflow samples were collected on a time course commensurate with HRT (i.e., wetland cell 1 was sampled 24 h after sampling the equalization basin, wetland cell 2 was sampled 48 h after sampling the equalization basin, etc.). Aqueous samples of 10-ml were immediately preserved with concentrated trace metal grade nitric acid to pH < 2 for metals analysis, while the other 990-ml was retained for the remaining analyses and toxicity tests.

Table 1. Acclimation FGD wastewater loaded into the pilot-scale constructed wetland treatment system (listed as weeks 1-4).

Constituent	Week 1	Week 2	Week 3	Week 4
Mercury (Hg(NO ₃) ₂ ·H ₂ O)	0.027 mg/L	0.054 mg/L	0.070 mg/L	0.136 mg/L
Selenium (Na ₂ SeO ₄)	1.0 mg/L	2.0 mg/L	3.7 mg/L	7.5 mg/L
Chloride (CaCl ₂)	1,000 mg/L	2,000 mg/L	4,000 mg/L	6,000 mg/L

Table 2. Classification and targeted concentrations of elements of interest in four simulated FGD wastewaters used throughout this phase one DOE study.

FGD Wastewater Type	Treatment Period	Arsenic	Mercury	Selenium
High Ionic Strength	Weeks 5-10	0.300 mg/L	0.02 mg/L	8.00 mg/L
High-Intermediate Ionic Strength	Weeks 11-20	0.180 mg/L	0.002 mg/L	4.50 mg/L
Low-Intermediate Ionic Strength	Weeks 23-24	0.070 mg/L	0.160 mg/L	1.80 mg/L
Low Ionic Strength	Weeks 21-22	0.0025 mg/L	0.001 mg/L	0.060 mg/L

Table 3. Targeted constituents and sources for simulated FGD wastewater.

Constituent	Target Inflow Concentration	Source	Target Outflow Concentration ¹
Mercury (Hg)	0.02 mg/L	Hg(NO ₃) ₂ ·H ₂ O	0.001 mg/L
Selenium (Se)	7.4 mg/L	Na ₂ SeO ₄	0.4 mg/L
Arsenic (As)	0.28 mg/L	NaAsO ₂	0.15mg/L
Chloride (Cl)	4000 mg/L	CaCl ₂ MgCl ₂ ·6H ₂ O	
Sulfate (SO ₄ ⁻²)	3000 mg/L	CaSO ₄	
Boron (B)	20 mg/L	Na ₂ B ₄ O ₅ ·8H ₂ O	
Chemical Oxygen Demand	100 mg/L	Dibasic Acid (DBA)	
Total Suspended Solids	1000 mg/L	Fly ash	

¹ Target concentrations chosen from reviews of local NPDES permits.

Additional Analyses

Oxidation-reduction (redox) potential of wetland hydrosol was monitored monthly by placing platinum-tipped electrodes *in situ* and measuring the electrochemical potential with an Accumet[®] calomel reference electrode (Faulkner et al., 1989). Dissolved oxygen and pH of inflow and outflow wastewater were measured using YSI[®] and Orion[®] field instruments, respectively. Additional constituents and properties (Table 1) including alkalinity, hardness, conductivity, chloride and sulfate concentrations, chemical oxygen demand, biological oxygen demand, non-purgeable organic carbon, and total and suspended solids were determined according to *Standard Methods for the Examination of Water and Wastewater* (APHA 1998).

Table 4. Analytical methods for parameters monitored weekly from the FGD pilot constructed wetland system.

Parameter	Method	Method Detection Limit
Temperature	Direct Instrumentation: YSI Model 52	0.5°C
pH	Direct Instrumentation: Orion Model 420A	0.01
Conductivity	Direct Instrumentation: YSI 30	0.1 µS/cm
Alkalinity	Standard Methods: 2320 B	2 mg/L as CaCO ₃
Hardness	Standard Methods: 2340 C	2 mg/L as CaCO ₃
DO ¹	Direct Instrumentation: YSI Model 52	0.1 mg/L

COD ²	Closed reflux colorimetry (HACH - modified from Standard Methods: 5220D)	3 mg/L
NPOC ³	Shimadzu TOC-V CPH Total Organic Carbon Analyzer	4 µg/L
BOD ₅ ⁴	Standard Methods: 5210 B	0.1 mg/L
TSS ⁵	Standard Methods: 2540 D	0.1 mg/L
TDS ⁶	Standard Methods: 2540 C	0.1 mg/L
Selenium	Inductively Coupled Plasma (ICP): EPA 200.7	0.0022 mg/L
Mercury	Inductively Coupled Plasma (ICP): EPA 200.7	0.0001 mg/L
Chloride	HACH Colorimetric Method 8207	25 mg/L
Sulfate	Standard Methods: 4500 E	1 mg/L
Arsenic	ICP: EPA 200.7	0.0013 mg/L
Boron	ICP: EPA 200.7	0.0009 mg/L

¹ Dissolved Oxygen

² Chemical Oxygen Demand

³ Non-purgable Organic Carbon

⁴ Five-day Biological Oxygen Demand

⁵ Total Suspended Solids

⁶ Total Dissolved Solids

Evaluation of Wetland Plants

In response to observed stress of wetland vegetation due to chloride levels (target influent concentration 6,000 mg/L), the simulated FGD wastewater was decreased to a chloride concentration of 4,000 mg/L to ensure the health of aquatic vegetation.

Results

Primary Targeted Constituents

Mercury

High Ionic Strength FGD Wastewater

During the fifth week of treatment, the total mercury in the equalization basin was 0.0460 mg/L and by the final outflow, the total mercury had declined to 0.0003mg/L. The removal of total mercury by the pilot constructed wetland system was 98%, with a 91% removal by the outflow of the first wetland cell for this treatment. The following week (week 6), the system produced similar results, with removal of 64, 84, 94, and 93% at the outflows of the sequential treatment cells. At week 7, the total mercury measured in the equalization basin was 0.0019mg/L. There was no removal of mercury in the first two cells, however, 35% decrease in mercury content was observed in the manganese oxidation basin and 0.0007 mg/L at the final outflow, which achieved

a 61% removal. At week 8, total mercury decreased from 0.0154 mg/L (average inflow concentration) to 0.0012 mg/L (average final outflow). The next sampling event began in which total mercury decreased from 0.0080 mg/L (inflow average) to 0.0010 mg/L (outflow average) (Table 5). Performance between the three treatment trains was similar, with total mercury removal averaging 91% (Fig. 3).

High-Intermediate Ionic Strength FGD Wastewater

Dilution of the simulated FGD wastewater began with the high-intermediate ionic strength FGD wastewater (weeks 11 through 20) to achieve a chloride level (~4,000mg/L) compatible to the vegetation. Total mercury during this time decreased from an average (all treatment trains) of 0.0029 mg/L (± 0.0004) mg/L in the inflow to 0.0002 mg/L (± 0.00005) mg/L in the final outflow, or 94% removal (Fig. 5).

Low-Intermediate Ionic Strength FGD Wastewater

Analysis of mercury removal by the pilot constructed wetland systems for week 23 indicated an average influent mercury concentration of 0.1467 mg/L (± 0.0115) (Fig. 6). Final outflow concentrations at this sampling event for treatment trains A, B, and C were 0.0072 mg/L, 0.0010 mg/L, and 0.0069 mg/L, respectively, or an overall removal of 97%. The final week, week 24, influent mercury concentrations averaged 0.17 mg/L (± 0.0058), while final outflow concentrations for trains A, B, and C were 0.0069 mg/L, 0.0071 mg/L, and 0.0080 mg/L, respectively (96% removal) (Fig. 7).

Selenium

High Ionic Strength FGD Wastewater

Overall, performance of the pilot system treating undiluted simulated FGD wastewater (~6,000 mg/L chlorides) was approximately 85% removal of total selenium (Fig. 9). Total selenium concentrations in the equalization basin averaged 7.7 mg/L, and ranged from 7.1 to 8.5 mg/L for weeks 5 through 7 (Table 5). Selenium concentrations in the outflow of wetland cells 1 and 2, the manganese oxidation basins, and final wetland cells averaged 7.4 mg/L, 6.8 mg/L, 6.8 mg/L, and 6.0 mg/L, respectively (Fig 8). After week 7, wetland cell 2 from both Trains A and B were modified by addition of organic matter; train C remained the same as previous weeks. Total selenium was then analyzed in the equalization basin and the outflow from wetland cells 1 and 2 in each train. Total selenium decreased from 6.3 mg/L in the equalization basin to an average of 3.8 mg/L for the outflow of cell 1 and 1.3 mg/L for the outflow of cell 2 (Fig. 8) in Trains A and B. Total selenium in the final outflow was 0.78 mg/L and 0.88 mg/L from Trains A and B, respectively, compared to 2.10 mg/L from Train C (Table 5). Treatment trains improved during week 9 sampling and total selenium removal reached 87% compared to the previous 84%.

High-Intermediate Ionic Strength FGD Wastewater

Before beginning week 11, the simulated FGD wastewater was diluted with 40% municipal water reducing the chlorides to 4000 mg/L to allow for plant stability (health). Selenium removal averaged 87% between the A and B trains. The average outflow for 10 weeks (week 11 through

week 20) was 0.56mg/L. The average outflow selenium concentration for train A was 0.47 mg/L, approaching the target outflow concentration of 0.4 mg/L. Trains B and C have averaged 0.64 and 0.68 mg/L, respectively (Fig. 10).

Low-Intermediate Ionic Strength FGD Wastewater

Analysis of selenium removal by the pilot constructed wetland system beginning week 23 indicated an average influent selenium concentration of 1.87 mg/L (± 0.06) (Fig. 11). Final outflow concentrations for week 23 for treatment trains A, B, and C were 0.20 mg/L, 0.09 mg/L, and 0.28 mg/L, respectively, or an overall removal of 90% (Figure 11). For week 24 sampling, total selenium influent concentrations averaged 1.8 mg/L (no standard deviation). Outflow concentrations of selenium from the manganese oxidation basins (third treatment stage) reached the target level of 0.2 mg/L (Fig. 12). Final outflow selenium concentrations increased slightly in trains A, B, and C (concentrations: 0.47 mg/L, 0.70 mg/L, and 0.41 mg/L, respectively).

Arsenic

High Ionic Strength FGD Wastewater

Total arsenic concentrations in the equalization basin averaged 0.30mg/L, and ranged from 0.27 mg/L to 0.34 mg/L for weeks 5 through 7 (Table 5). Arsenic concentrations in the outflows of wetland cells 1 and 2, the manganese oxidation basin, and the final wetland cells averaged 0.6433 mg/L, 0.03588 mg/L, 0.0167 mg/L, and 0.0092 mg/L, respectively. Arsenic removal was not enhanced to a discernable degree following hydrosol amendments to Trains A and B. Total As in final outflow of week 8 was 0.0870mg/L and 0.0840 mg/L from Trains A and B, respectively, compared to 0.0700 mg/L from Trains C (no amendments made to hydrosol; Table 4). At the following sampling events, beginning week 10 performance of all treatment trains decreased, only removing 45% compared to 70%. Overall, performance of the pilot system treating undiluted simulated FGD wastewater was approximately 59% removal of As (week 8 to week 10; Figure 13). Average inflow As concentration for these two sampling events was 0.2983 mg/L compared to 0.1215 mg/L in the final outflow (Figure 13).

High-Intermediate Ionic Strength FGD Wastewater

After diluting the simulated FGD wastewater with 40% municipal water, As removal (average of treatment Trains A and B) was 49% (Figure 14). The average outflow As concentration from weeks 11 to week 20 for these trains was 0.0832 mg/L. The average outflow As concentration for Train A was 0.0616 mg/L, below the target outflow concentration of 0.15mg/L. Trains B and C averaged 0.0982 and 0.087 mg/L, respectively (Figure 14).

Low-Intermediate Ionic Strength FGD Wastewater

Analysis of arsenic removal by the pilot constructed wetland systems for week 23 indicated an average influent arsenic concentration of 0.075 mg/L (± 0.001) (Figure 15). Final outflow concentrations for week 23 sampling event for treatment trains A, B, and C were 0.043 mg/L, 0.012 mg/L, and 0.029 mg/L, respectively, or an overall removal of 62% (Figure 15). For week 24 sampling, total arsenic influent concentrations averaged 0.07 mg/L (± 0.003). Final outflow

arsenic concentrations increased in trains A, B, and C (concentrations: 0.18 mg/L, 0.23 mg/L, and 0.11 mg/L, respectively) and is possibly due to binding of arsenic onto particulates (total suspended solids) that is detected by total inorganic analysis.

Other Constituents of Interest

Simulated FGD wastewater physical and chemical characteristics are presented in Table 5. These parameters were analyzed at the following stages or locations in the pilot constructed wetland treatment system:

1. Equalization Basin
2. Outflow from the first wetland cell of each train (A-1, B-1, C-1)
3. Outflow from the second wetland cell of each train (A-2, B-2, C-2)
4. Outflow from the Manganese Oxidation Basin of each train (A-3, B-3, C-3)
5. Outflow from final wetland cell of each train (A-4, B-4, C-4)

pH, Alkalinity, and Hardness

In the equalization basin, pH, alkalinity, and hardness averaged 6.55 (n=2), 22 mg/L as CaCO₃ (n=2), and 4200 mg/L as CaCO₃ (n=2), respectively, for week 5 and week 6 of treatment. During the next three weeks of treatment (Weeks 7, 8, and 9) the pH, alkalinity, and hardness averaged 7.10 (n=3, sd=0.30), 106.67 mg/L as CaCO₃ (n=3, sd=21.39), and 9057 mg/L as CaCO₃ (n=3, sd=1006.54). For the following ten weeks of treatment (Weeks 11 through 20) during which the simulated FGD wastewater was diluted, pH averaged 7.00 (n=10, sd=0.26), alkalinity averaged 103.40 mg/L as CaCO₃ (n=10, sd=10.46), and hardness averaged 6540 mg/L as CaCO₃ (n=10, sd=2480.23). For the treatment of weeks 22 and 23, pH averaged 6.47, alkalinity averaged 115 mg/L as CaCO₃ and hardness averaged 7200 mg/L as CaCO₃. For the last two treatment weeks, weeks 23 and 24, FGD wastewater was had an average pH 6.72, average alkalinity of 63 mg/L as CaCO₃, and average hardness of 9800 mg/L as CaCO₃.

In the first cell of the treatment system, pH, alkalinity, and hardness averaged 6.44 (n=6, sd=0.33), 22.33 mg/L as CaCO₃ (n=6, sd=3.44), and 3850 mg/L as CaCO₃ (n=6, sd=467.97), respectively, for weeks 5 and 6. During the next three weeks of treatment (week 7 through week 9) the pH, alkalinity, and hardness averaged 7.32 (n=9, sd=0.17), 94 mg/L as CaCO₃ (n=9, sd=18.14), and 9022 mg/L as CaCO₃ (n=9, sd=603.69). For the following ten weeks of treatment (Weeks 11 through 20), during which the simulated FGD wastewater was diluted, pH averaged 7.07 (n=30, sd=0.23), alkalinity averaged 87.17 mg/L as CaCO₃ (n=30, sd=12.26), and hardness averaged 5373.33 mg/L as CaCO₃ (n=30, sd=1331.56). For the treatment of weeks 21 and 22, pH averaged 6.85 (n=6, sd=0.20), alkalinity averaged 112.33 mg/L as CaCO₃ (n=6, sd=1.97), and hardness averaged 6266.67 mg/L as CaCO₃ (n=6, sd=206.56). For the last two treatment weeks, week 23 and 24, the FGD wastewater had an average pH 6.79 (n=6, sd=0.06), average alkalinity of 69 mg/L as CaCO₃ (n=6, sd=5.48), and average hardness of 9800 mg/L as CaCO₃ (n=6, sd=912.14).

In the second cell of the treatment system, pH, alkalinity, and hardness averaged 5.94 (n=6, sd=0.37), 15.33 mg/L as CaCO₃ (n=6, sd=4.84), and 3833 mg/L as CaCO₃ (n=6, sd=422.69),

respectively, for weeks 5 and 6. During the next three weeks of treatment (Week 7 through 9) the pH, alkalinity, and hardness averaged 6.66 (n=9, sd=0.35), 98.22 mg/L as CaCO₃ (n=9, sd=33.11), and 8356 mg/L as CaCO₃ (n=9, sd=811.04). For the following ten weeks of treatment (week 11 through week 20), during which the simulated FGD wastewater was diluted, pH averaged 7.07 (n=30, sd=0.24), alkalinity averaged 88.93 mg/L as CaCO₃ (n=30, sd=17.39), and hardness averaged 5240 mg/L as CaCO₃ (n=30, sd=1580.39). For the treatment of week 21, pH averaged 7.34 (n=3, sd=0.20), alkalinity averaged 113.33 mg/L as CaCO₃ (n=3 sd=1.15), and hardness averaged 6000 mg/L as CaCO₃ (n=3, sd=400). For the last two treatment weeks, weeks 23 and 24, the FGD wastewater had an average pH 6.56 (n=6, sd=0.18), average alkalinity of 69.67 mg/L as CaCO₃ (n=6, sd=9.24), and average hardness of 10933.33 mg/L as CaCO₃ (n=6, sd=1377.92).

In the third cell of the treatment system, pH, alkalinity, and hardness averaged 7.21 (n=6, sd=0.19), 55 mg/L as CaCO₃ (n=6, sd=10.18), and 3783 mg/L as CaCO₃ (n=6, sd=495.65), respectively, for week 5 and week 6. During the next three weeks of treatment (week 7 through week 9) the pH, alkalinity, and hardness averaged 7.22 (n=9, sd=0.32), 101.33 mg/L as CaCO₃ (n=9, sd=24.82), and 7867 mg/L as CaCO₃ (n=9, sd=489.89). For the following ten weeks of treatment (week 11 through week 20), during which the simulated FGD wastewater was diluted, pH averaged 7.26 (n=30, sd=0.24), alkalinity averaged 90.67 mg/L as CaCO₃ (n=30, sd=15.04), and hardness averaged 5380 mg/L as CaCO₃ (n=30, sd=1238.85). For the treatment of weeks 21 and 22, FGD wastewaters had a pH averaged 7.03 (n=6, sd=0.28), alkalinity averaged 104.67 mg/L as CaCO₃ (n=6, sd=4.50), and hardness averaged 5933.33 mg/L as CaCO₃ (n=6, sd=733.94). For the last two treatment weeks, week 23 and 24, FGD wastewaters had an average pH 6.78 (n=6, sd=0.18), average alkalinity of 76.33 mg/L as CaCO₃ (n=6, sd=2.94), and average hardness of 11066.67 mg/L as CaCO₃ (n=6, sd=1671.73).

In the fourth cell of the treatment system, pH, alkalinity, and hardness averaged 6.77 (n=6, sd=0.09), 56.33 mg/L as CaCO₃ (n=6, sd=14.39), and 3616.67 mg/L as CaCO₃ (n=6, sd=604.70), respectively, for weeks 5 and 6. During the next three weeks of treatment (week 7 through week 9) the pH, alkalinity, and hardness averaged 7.27 (n=9, sd=0.26), 93.56 mg/L as CaCO₃ (n=9, sd=22.36), and 7244.44 mg/L as CaCO₃ (n=9, sd=904.31). For the following ten weeks of treatment (week 11 through week 20), during which the simulated FGD wastewater was diluted, pH averaged 7.24 (n=30, sd=0.27), alkalinity averaged 86.80 mg/L as CaCO₃ (n=30, sd=15.07), and hardness averaged 5846.67 mg/L as CaCO₃ (n=30, sd=1560.45). For the treatment weeks 21 and 22, FGD wastewaters had a pH averaged 7.06 (n=6, sd=0.26), alkalinity averaged 110.33 mg/L as CaCO₃ (n=6, sd=3.44), and hardness averaged 6000 mg/L as CaCO₃ (n=6, sd=252.98). For the last two treatment weeks, week 23 and week 24, FGD wastewaters had an average pH 6.82 (n=6, sd=0.11), average alkalinity of 77.67 mg/L as CaCO₃ (n=6, sd=5.28), and average hardness of 10600 mg/L as CaCO₃ (n=6, sd=1356.47).

Conductivity

Conductivity measurements were 14.98 mS (n=5, sd=0.79) for weeks 5 through 9 in the equalization basin. Outflow measurements for conductivity for this time period were 12.58 mS (n=15, sd=1.21). For the weeks in which the simulated FGD wastewater was diluted, week 11 through week 20, the equalization basin averaged 9.21 mS (n=10, sd=0.60) with the outflow averaging 9.27 mS (n=30, sd=1.25). For weeks 21 and 22, FGD wastewaters was diluted, with

resulting conductivity measurements of 11.06 mS (n=2) in the equalization basin and 10.89 mS (n=6, sd=0.58) in the outflow. In the last two weeks of treatment (week 23 and 24), conductivity measurements were 11.16 mS (n=2) in the equalization basin and 11.89 mS (n=6, sd=2.27) in the outflow.

NPOC (Non-Purgable Organic Carbon)

In the equalization basin, NPOC averaged 18.47 mg/L (n=2) for weeks 5 and 6. During the next three weeks of treatment (week 7 through week 10) NPOC averaged 99.72 (n=3, sd=43.22). For the following ten weeks of treatment (week 11 through week 20), during which the simulated FGD wastewaters was diluted, NPOC averaged 96.07 mg/L (n=10, sd=52.71). For the treatment of week 21 and week 22 NPOC averaged 106.97 mg/L (n=2). For the last two treatment weeks, week 23 and week 24, FGD wastewaters had an average NPOC of 161.25 mg/L (n=2).

In the first cell of the treatment system, NPOC averaged 11.60 mg/L (n=6, sd=1.80) for the first two weeks of treatment (week 5 and week 6). During the next three weeks of treatment (week 7 through week 10) the NPOC averaged 92.49 mg/L (n=9, sd=66.49). For the following ten weeks of treatment (week 11 through week 20), during which the simulated FGD wastewater was diluted, NPOC averaged 60.58 mg/L (n=30, sd=32.16). For the treatment of 21 and 22, NPOC averaged 97.95 mg/L (n=3, sd=34.89). For the last two treatment weeks, week 23 and 24, FGD wastewaters had an average NPOC of 61.76 mg/L (n=6, sd=41.25).

In the second cell of the treatment system, NPOC averaged 9.80 mg/L (n=6, sd=1.59) for the first two weeks of treatment (week 5 and week 6). During the next three weeks of treatment (week 7 through week 10) the NPOC averaged 75.62 mg/L (n=9, sd=46.59). For the following ten weeks of treatment (week 11 through week 20), during which the simulated FGD wastewater was diluted, NPOC averaged 53.07 mg/L (n=30, sd=26.68). For the treatment of week 21, NPOC averaged 44.28 mg/L (n=3, sd=26.02). For the last two treatment weeks, week 23 and 24, FGD wastewaters had an average NPOC of 47.96 mg/L (n=6, sd=7.74).

In the third cell of the treatment system, NPOC averaged 8.17 mg/L (n=6, sd=2.30) for the first two weeks of treatment (week 5 and week 6). During the next three weeks of treatment (week 7 through week 10) the NPOC averaged 61.21 mg/L (n=9, sd=33.83). For the following ten weeks of treatment (week 11 through week 20), during which the simulated FGD wastewater was diluted, NPOC averaged 47.42 mg/L (n=30, sd=21.91). For treatment of week 21, NPOC averaged 63.11 mg/L (n=3, sd=41.92). For the last two treatment weeks, week 23 and 24, FGD wastewaters had an average NPOC of 43.72 mg/L (n=6, sd=16.35).

In the fourth cell of the treatment system, NPOC averaged 11.52 mg/L (n=6, sd=6.84) for the first two weeks of treatment (week 5 and week 6). During the next three weeks of treatment (week 7 through week 10) the NPOC averaged 43.99 mg/L (n=9, sd=13.71). For the following ten weeks of treatment (week 11 through week 20), during which the simulated FGD wastewater was diluted, NPOC averaged 47.27 mg/L (n=30, sd=20.69). For the treatment of week 21, NPOC averaged 66.01 mg/L (n=3, sd=14.31). For the last two treatment weeks, week 23 and 24, FGD wastewaters had an average NPOC of 38.12 mg/L (n=6, sd=18.97).

Solids

Total suspended solids (TSS) was 7.40 mg/L for week 5 and 9.30 mg/L for week 6 in the equalization basin. For week 3 (week 7), TSS increased to 1,233 mg/L. Total dissolved solids (TDS) was 12,551 mg/L for week 5, 22,996 mg/L for week 6, and 22,080 mg/L for week 7 in the equalization basin. For weeks 9 and 10 (prior to diluting simulated FGD wastewater), TSS was 758 mg/L and 362 mg/L, respectively, and TDS averaged 23,332 mg/L (n=2). For the weeks 11 through 20, the simulated FGD wastewater was diluted. TSS in the equalization basin averaged 207 mg/L (n=10, sd=137) and TDS averaged 6,184 (n=10, sd=2967). For weeks 21 and 22, FGD wastewaters was diluted, resulting in an average TSS in the equalization basin of 55 mg/L (n=2) and an average TDS of 12,534 mg/L (n=2). For the last two weeks of treatment (week 23 and 24), FGD wastewaters had a TSS and TDS averaged 66.5 mg/L (n=2) and 12,267 mg/L (n=2).

In wetland cell 1, TSS averaged 2.2 mg/L (n=3, sd=0.7) and 12.3 mg/L (n=3, sd=3.7) for week 5 and week 6 TDS averaged 16,699 mg/L (n=3, sd=1,027) for week 5 and 27,909 mg/L (n=3, sd=5,424) for week 6. For week 7, TSS and TDS averaged 9.7 mg/L (n=3, sd=2.0) and 21,672 mg/L (n=3, sd=1,214), respectively. Prior to diluting simulated FGD wastewater during the weeks 9 and 10, TSS averaged 32.3 mg/L (n=6, sd=18.35) and TDS averaged 18,773 mg/L (n=6, sd=1315). For the following ten treatment weeks (week 11 through week 20), the simulated FGD wastewater was diluted. TSS averaged 68 mg/L (n=27, sd=64.6; for week 19, TSS averaged 5,408, n=3, sd=566) and TDS averaged 5,892 mg/L (n=30, sd=2,514). For weeks 21 and 22, TSS and TDS in wetland cell 1 averaged 55 mg/L (n=6, sd=2.6) and 12,769 mg/L (n=6, sd=439), respectively. For week 23 and 24, TSS averaged 83 mg/L (n=6, sd=42) and TDS averaged 13,069 mg/L (n=6, sd=5,354).

In wetland cell 2, TSS averaged 1.2 mg/L (n=3, sd=1.4) and 7.35 mg/L (n=3, sd=2.1) for week 5 and week 6). TDS averaged 14,023 mg/L (n=3, sd=336) for week 1 and 21,615 mg/L (n=3, sd=3,251) for week 2. For the week of 9-15-04, TSS and TDS averaged 11.55 mg/L (n=3, sd=2.5) and 19,362 mg/L (n=3, sd=1130), respectively. Prior to diluting simulated FGD wastewater during week 9 and week 10, TSS averaged 59 mg/L (n=6, sd=42) and TDS averaged 20,708 mg/L (n=6, sd=1,552). For the following ten treatment weeks (week 11 through week 20), the simulated FGD wastewater was diluted. TSS averaged 59 mg/L (n=30, sd=66) and TDS averaged 5,770 mg/L (n=30, sd=2,308). For week 21 and week 22, TSS and TDS in wetland cell 2 averaged 31 mg/L (n=6, sd=12.7) and 9,324 mg/L (n=6, sd=432), respectively. For week 23 and 24, TSS averaged 81 mg/L (n=6, sd=35) and TDS averaged 12,946 mg/L (n=6, sd=910).

In wetland cell 3, TSS averaged 2.42 mg/L (n=3, sd=1.0) and 5.93 mg/L (n=3, sd=2.2) for week 5 and 6. TDS averaged 17,765 mg/L (n=3, sd=1,447) for week 5 and 23,486 mg/L (n=3, sd=460) for week 6. For week 7, TSS and TDS averaged 6.45 mg/L (n=3, sd=1.86) and 18,677 mg/L (n=3, sd=269), respectively. Prior to diluting simulated FGD wastewater during week 9 and week 10, TSS averaged 34 mg/L (n=6, sd=27) and TDS averaged 19,345 mg/L (n=6, sd=779). For the following ten treatment weeks (week 11 through week 20), the simulated FGD wastewater was diluted. TSS averaged 59 mg/L (n=30, sd=56) and TDS averaged 5,736 mg/L (n=30, sd=3,854). For week 21 and week 22, TSS and TDS in wetland cell 3 averaged 51 mg/L (n=6, sd=20) and 12,851 mg/L (n=6, sd=748), respectively. For the weeks of week 23 and 24, TSS averaged 104 mg/L (n=6, sd=18) and TDS averaged 13,064 mg/L (n=6, sd=1,197).

In wetland cell 4, TSS averaged 0.65 mg/L (n=3, sd=0.71) and 12.22 mg/L (n=3, sd=12.29) for week 5 and week 6. TDS averaged 16,180 mg/L (n=3, sd=849) for week 5 and 17,687 mg/L (n=3, sd=6,679) for week 6. For week 7, TSS and TDS averaged 6.95 mg/L (n=3, sd=2.8) and 18,939 mg/L (n=3, sd=624), respectively. Prior to diluting simulated FGD wastewater during week 9 and 10, TSS averaged 32 mg/L (n=6, sd=22) and TDS averaged 16,734 mg/L (n=6, sd=2,522). For the following ten treatment weeks (week 11 through week 20), the simulated FGD wastewater was diluted. TSS averaged 60 mg/L (n=30, sd=71) and TDS averaged 6,061 mg/L (n=30, sd=2,802). For week 21 and week 22, TSS and TDS in wetland cell 4 averaged 46 mg/L (n=6, sd=15) and 12,949 mg/L (n=6, sd=893), respectively. For week 23 and 24, TSS averaged 103 mg/L (n=6, sd=46) and TDS averaged 12,289 mg/L (n=6, sd=603).

Chlorides

Chloride concentrations were 5,182 mg/L (n=5, sd=242) for week 5 through week 9 in the equalization basin. For weeks 10 through 14, the simulated FGD wastewater was diluted. Chlorides in the equalization basin averaged 3,463 mg/L (n=10, sd=464). For week 11 through week 20, FGD wastewaters had chloride concentration in the equalization basin of 4,113 mg/L (n=2). For the last two weeks of treatment (week 23 and 24), chloride concentration in the equalization basin for week 23 was 4,150 mg/L. In wetland cells 1, 2, 3, and 4, chloride concentrations were not significantly different from the equalization basin during all treatment weeks from week 5 through week 24.

Sulfate

Sulfate concentrations were 747 mg/L (n=5, sd=373) for the first five treatment weeks (week 5 through 9) in the equalization basin. For the week 10 through week 14, the simulated FGD wastewater was diluted. Sulfates in the equalization basin averaged 854 mg/L (n=10, sd=216). For week 11 through week 20, sulfate concentration in the equalization basin of 664 mg/L (n=2). For the last two weeks of treatment (week 23 and 24), the average sulfate concentration in the equalization basin the last two weeks was 432 mg/L (n=2). In wetland cells 1, 2, 3, and 4, sulfate concentrations were not significantly different from the equalization basin during all treatment week 5 through week 24.

Dissolved Oxygen, Biological Oxygen Demand, Chemical Oxygen Demand

In the equalization basin, dissolved oxygen (DO), biological oxygen demand (BOD), and chemical oxygen demand (COD) averaged 7.26 mg/L (n=5, sd=1.9), 10.30 mg/L (n=5, sd=4.3), and 373 mg/L (n=3, sd=43.4), respectively, for weeks five through week 9. For the following ten weeks of treatment (week 11 through week 20), during which the simulated FGD wastewater was diluted, DO averaged 7.75 mg/L (n=10, sd=1.56), BOD averaged 14.06 mg/L (n=10, sd=5.24), and COD averaged 227 mg/L (n=10, sd=45). For the treatment of week 21 and 22, DO averaged 7.95 mg/L and BOD averaged 9.63 mg/L. For the last two treatment weeks, week 23 and 24, FGD wastewaters had an average DO of 8.48 mg/L, average BOD of 10.48 mg/L, and average COD of 239 mg/L.

In the first wetland cell, DO averaged 8.19 mg/L (n=15, sd=0.95) for week 5 through week 9 prior to diluting the simulated FGD wastewater. For the treatment of week 5 and week 6, BOD

averaged 1.88 (n=6, sd=0.46). For the treatment weeks 7, 9 and 10, BOD averaged 8.41 mg/L (n=3, sd=0.11), 12.09 mg/L (n=3, sd=0.58), and 19.83 mg/L (n=3, sd=3.27), respectively. For the treatment weeks 7 through 10, COD averaged 329 mg/L (n=9, sd=44). For the treatment weeks 11 through 20, the simulated FGD wastewater was diluted, resulting in an average DO of 8.63 mg/L (n=30, sd=1.3) and average COD of 181 mg/L (n=30, sd=18). BOD averaged 12.65 mg/L (n=15, sd=5.7) for the weeks 11 through 15, and averaged 3.46 mg/L (n=15, sd=1.52) for the weeks 16 through 20. For treatment weeks 21 and 22, DO averaged 6.81 mg/L (n=6, sd=0.33) and BOD averaged 8.46 mg/L (n=6, sd=1.1). For the last two treatment weeks, (week 23 and 24). DO averaged 8.73 mg/L (n=6, sd=3.3), BOD averaged 2.92 mg/L (n=6, sd=1.8), and COD averaged 257 mg/L (n=6, sd=15).

In the second wetland cell, DO averaged 7.57 mg/L (n=15, sd=2.2) for weeks 5 through 9 prior to diluting the simulated FGD wastewater. For the treatment weeks of, BOD averaged 1.51 (n=6, sd=0.9). For the treatment weeks 7, 9 and 10, BOD averaged 8.44 mg/L (n=3, sd=0.06), 6.34 mg/L (n=3, sd=0.92), and 21.32 mg/L (n=3, sd=1.16), respectively. For the treatment weeks 7 through 10, COD averaged 278 mg/L (n=9, sd=36). For the treatment weeks 11 through 20, the simulated FGD wastewater was diluted, resulting in an average DO of 8.69 mg/L (n=30, sd=1.1) and average COD of 177 mg/L (n=30, sd=33). BOD averaged 10.49 mg/L (n=15, sd=2.9) for the weeks 11 through 15, and averaged 3.43 mg/L (n=15, sd=2.1) for the weeks 16 through 20. For the treatment weeks 21 and 22, DO averaged 6.19 mg/L (n=3, sd=0.07) and BOD averaged 6.55 mg/L (n=3, sd=0.34). For the last two treatment weeks (weeks 23 and 24), DO averaged 8.71 mg/L (n=6, sd=3.3), BOD averaged 4.78 mg/L (n=6, sd=1.7), and COD averaged 201 mg/L (n=6, sd=6.7).

In the third wetland cell, DO averaged 7.36 mg/L (n=15, sd=1.9) for weeks 5 through 9 prior to diluting the simulated FGD wastewater. For the treatment weeks 5 and 6, BOD averaged 1.17 (n=6, sd=0.16). For the treatment weeks 7, 9, and 10, BOD averaged 8.27 mg/L (n=3, sd=0.29), 7.44 mg/L (n=3, sd=0.5), and 15.46 mg/L (n=3, sd=0.56), respectively. For the treatment weeks of 7 through 10, COD averaged 253 mg/L (n=9, sd=29). For the treatment weeks of 11 through 20, the simulated FGD wastewater was diluted, resulting in an average DO of 8.84 mg/L (n=30, sd=1.4) and average COD of 163 mg/L (n=30, sd=30). BOD averaged 8.37 mg/L (n=15, sd=2.66) for the weeks 11 through 15, and averaged 2.25 mg/L (n=15, sd=1.57) for the weeks of 16 through 20. For the treatment weeks 21 and 22, DO averaged 6.72 mg/L (n=3, sd=0.25) and BOD averaged 3.45 mg/L (n=3, sd=1.96). For the last two treatment weeks (23 and 24), DO averaged 8.74 mg/L (n=6, sd=3.3), BOD averaged 1.94 mg/L (n=6, sd=0.74), and COD averaged 197 mg/L (n=6, sd=7).

In the fourth wetland cell, DO averaged 7.51 mg/L (n=15, sd=1.4) for weeks 5 through 9 prior to diluting the simulated FGD wastewater. For the treatment weeks 5 and 6, BOD averaged 0.96 (n=6, sd=0.26). For the treatment weeks of 7, 9, and 10 BOD averaged 6.30 mg/L (n=3, sd=1.27), 6.40 mg/L (n=3, sd=0.14), and 10.76 mg/L (n=3, sd=7.00), respectively. For the treatment weeks 7 through 10, COD averaged 202 mg/L (n=9, sd=48). For the treatment weeks 11 through 20, the simulated FGD wastewater was diluted, resulting in an average DO of 8.74 mg/L (n=30, sd=1.35) and average COD of 159 mg/L (n=30, sd=48). BOD averaged 4.71 mg/L (n=15, sd=2.9) for the weeks 11 through 15, and averaged 1.92 mg/L (n=15, sd=1.35) for the weeks 16 through 20. For the treatment weeks 21 and 22, DO averaged 6.73 mg/L (n=3,

sd=0.26) and BOD averaged 2.53 mg/L (n=3, sd=1.02). For the last two treatment weeks (week 23 and week 24) DO averaged 8.72 mg/L (n=6, sd=3.3), BOD averaged 3.18 mg/L (n=6, sd=0.95), and COD averaged 184 mg/L (n=6, sd=8.29).

Hydrosoil Oxidation-Reduction (Redox) Potential

Hydrosoil redox potential from the pilot constructed wetland system is presented in Fig. 13 and Table 5. Cells 1 and 2 were designed to be anaerobic, while cells 3 and 4 were designed to be essentially aerobic. Redox potential increased during winter months, but remained largely within the range of sulfate reduction (approximately -50 to -250 mV) in the anaerobic cells (as designed) (Fig. 13).

Table 5. Simulated FGD wastewater physical and chemical properties analyzed in a pilot constructed wetland system.

Week 5	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	14.18	7.48	6.21	18	4000	14.82	6.85	ND	7.40	12551	18.41	0.3400	19.4	8.50	0.04600	4880	455
A-1	17.56	6.55	6.09	20	3400	12.99	1.37	ND	1.45	17832	11.83	0.0150	14.4	6.50	0.00420	4490	708
B-1	17.54	6.95	6.20	18	3400	13.49	1.35	ND	2.30	16436	9.72	0.0150	15.5	6.60	0.00340	4500	631
C-1	17.08	7.56	6.15	20	3500	13.25	2.03	ND	2.85	15830	9.22	0.0170	15.8	6.90	0.00430	4010	667
A-2	17.51	7.78	5.51	8	3700	12.80	0.80	ND		13788	8.08	ND	11.9	5.50	0.00170	4200	559
B-2	16.45	4.67	5.57	12	3400	13.25	0.52	ND	0.90	13873	8.11	0.0059	13.5	6.30	0.00170	4370	557
C-2	16.92	7.16	5.81	18	3300	12.89	0.85	ND	2.70	14408	9.01	0.0076	13.1	6.00	0.00170	4170	697
A-3	14.12	10.53	7.57	60	3300	13.12	1.13	ND	2.05	16668	5.64	0.0190	12.4	5.80	0.00083	4310	576
B-3	12.83	7.44	7.11	68	3400	13.79	1.43	ND	3.60	19405	6.79	0.0052	14.4	6.20	0.00067	4570	527
C-3	13.19	8.02	7.26	64	3300	13.46	1.13	ND	1.60	17223	6.27	0.0096	13.4	6.00	0.00075	4330	607
A-4	13.35	7.77	6.70	60	3000	11.76	0.59	ND	1.45	15523	6.18	0.0081	10.5	4.10	0.00041	3750	524
B-4	12.78	7.40	6.65	74	3100	12.58	1.10	ND	0.40	17138	5.93	ND	12.7	5.50	0.00037	4260	516
C-4	12.26	8.38	6.84	72	3100	12.20	1.37	ND	0.10	15878	5.60	0.0051	11.9	4.50	0.00033	4010	500
Week 6	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	17.30	9.33	6.89	26	4400	14.46	8.83	ND	9.30	22996	18.52	0.2700	13.2	7.60	0.01300	5420	608
A-1	17.03	9.72	6.86	26	4400	14.93	2.15	ND	14.45	23736	13.70	0.1100	15.5	7.90	0.00530	5650	656
B-1	16.90	9.31	6.69	24	4100	14.82	1.82	ND	8.00	34040	13.18	0.0560	15.6	7.80	0.00440	5200	626
C-1	16.40	9.70	6.63	26	4300	14.83	2.55	ND	14.45	25952	11.96	0.0970	16.3	8.20	0.00420	5310	668
A-2	16.86	9.07	6.37	20	4200	14.85	2.72	ND	9.50	23698	11.52	0.0150	16.0	7.80	0.00260	5300.00	645.00
B-2	16.60	9.25	6.06	14	4200	14.80	2.24	ND	7.30	23278	11.36	0.0086	15.0	7.70	0.00190	5520.00	626.00
C-2	16.58	9.74	6.31	20	4200	14.96	1.91	ND	5.25	17868	10.71	0.0100	16.2	7.70	0.00170	5410.00	655.00

Table 4 (Continued).

A-3	17.28	9.01	7.22	46	4200	14.99	1.22	ND	7.75	23064	9.18	0.0120	16.1	7.70	0.00082	5390.00	632.00
B-3	17.54	7.75	7.01	46	4300	14.93	1.18	ND	3.50	23418	9.54	0.0052	16.7	8.00	0.00091	5490.00	642.00
C-3	18.00	7.57	7.08	46	4200	14.88	0.92	ND	6.55	23976	11.59	0.0072	15.4	7.70	0.00075	5510.00	625.00
A-4	18.90	7.31	6.77	44	4200	14.02	0.96	ND	7.35	23724	13.69	0.0085	15.3	7.10	0.00093	5270.00	590.00
B-4	18.85	7.47	6.79	42	4100	14.14	0.94	ND	26.20	18826	15.19	0.0050	15.7	7.40	0.00092	5210.00	527.00
C-4	19.11	7.69	6.89	46	4200	14.20	0.80	ND	3.10	10512	22.54	0.0100	16.0	7.50	0.00099	5380.00	650.00

Week 7	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	20.34	8.47	6.80	88	8000	14.96	7.79	384	1233.00	22080	63.42	0.3000	21.3	7.10	0.00190	5360	1180
A-1	20.11	8.64	7.51	90	8400	15.61	8.52	387	9.85	22226	40.19	0.0710	22.1	7.30	0.00130	5810	1120
B-1	20.49	8.54	7.06	56	9600	15.67	8.42	321	7.65	22510	24.96	0.0580	23.9	7.50	0.00270	6020	1090
C-1	20.21	8.41	7.04	82	9600	15.40	8.30	300	11.60	20280	47.92	0.1400	22.9	7.40	0.00190	5600	1210
A-2	20.30	8.50	6.75	64	8400	13.69	8.37	324	9.75	19903	40.71	0.0590	18.9	6.00	0.00160	4960	987
B-2	20.21	8.62	6.93	68	8400	13.93	8.50	321	14.45	20120	41.87	0.0610	20.9	6.90	0.00200	4860	945
C-2	20.43	8.59	7.00	74	8000	12.79	8.46	264	10.45	18063	47.65	0.1200	19.6	6.50	0.00230	4190	954
A-3	20.15	8.63	7.07	80	8400	13.01	7.94	249	4.35	18893	37.27	0.0280	19.5	6.30	0.00110	4580	888
B-3	20.48	8.60	6.94	80	8400	13.32	8.48	279	7.10	18376	39.22	0.0170	20.1	6.50	0.00120	4680	527
C-3	20.65	8.54	7.06	84	8000	12.80	8.39	288	7.90	18761	44.67	0.0470	20.0	6.50	0.00140	4700	905
A-4	19.88	8.69	7.26	84	8000	12.86	6.26	276	10.20	18285	35.84	0.0170	18.7	5.10	0.00064	4320	891
B-4	20.36	8.64	7.02	76	8400	13.33	7.58	237	4.95	19527	35.89	0.0110	19.3	6.10	0.00079	4980	954
C-4	20.42	8.60	7.10	82	8000	13.35	5.05	228	5.70	19005	35.40	0.0180	21.8	6.30	0.00077	4690	963

Week 8	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	Se mg/L
A-1 In	17.62	9.98	7.19	86	10400	15.09	8.04	310	5.80	22065	31.82	6.3000
B-1 In	17.02	8.85	7.13	90	9200	14.82	7.95	303	8.85	20218	32.74	6.3000
C-1 In	17.34	10.03	7.07	90	9200	15.14	8.83	-	6.65	20280	34.21	6.2000

A-1	17.63	10.12	7.17	92	10000	16.44	5.24	264	1.70	22369	24.43	4.4000
B-1	17.18	10.16	7.09	86	9600	16.33	4.99	250	9.65	22761	25.67	2.2000
C-1	17.42	10.05	7.15	90	9600	16.31	4.92	236	4.65	23086	30.54	4.9000
A-2	-	-	-	-	-	-	-	-	-	-	-	1.3000
B-2	18.21	8.98	6.98	84	9600	16.71	8.25	252	5.90	23717	26.09	0.9700
C-2	18.70	10.05	7.03	94	9600	16.75	2.94	235	2.30	23580	24.32	1.8000

Week 9	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	18.13	6.63	7.09	102	10000	16.32	10.44	326	758.30	22902	88.21	0.2700	23.7	8.00	0.01500	5280	899
A-1 In	17.62	8.01	7.30	104	9200	16.18	12.57	366	185.75	22814	86.07	0.3500	23.9	7.60	0.00710	5060	880
B-1 In	17.47	8.12	7.19	92	9200	16.11	12.84	340	71.40	22834	76.36	0.3100	24.4	8.00	0.02200	5320	882
C-1 In	17.73	8.37	7.28	90	9200	16.13	12.38	329	49.00	22752	75.99	0.2800	23.9	7.80	0.01700	5310	870
A-1	17.38	8.45	7.28	94	9200	16.38	11.44	300	31.20	23076	62.75	0.2300	24.4	7.30	0.00820	5310	910
B-1	17.25	7.86	7.33	98	9600	16.38	12.27	390	36.40	22322	54.64	0.2600	23.8	4.90	0.00600	5080	969
C-1	18.02	8.51	7.34	98	9600	16.38	12.57	383	46.95	23157	63.31	0.2600	24.2	7.50	0.01100	5320	904
A-2	18.22	3.87	6.98	118	9600	16.49	5.82	304	36.40	20800	63.63	0.2300	24.1	2.40	0.00330	5430	947
B-2	17.44	4.15	6.60	72	8400	16.46	7.40	299	48.65	21834	53.31	0.1600	24.0	2.70	0.00360	5300	921
C-2	18.44	4.03	6.96	94	9600	16.48	5.80	256	18.75	22759	50.57	0.1500	23.8	4.50	0.00340	5290	958
A-3	18.39	4.23	7.01	102	8000	14.18	7.95	242	81.90	19747	50.55	0.1700	21.0	1.40	0.00160	4530	852
B-3	18.06	4.35	7.02	94	7200	14.25	7.44	230	24.70	19828	46.50	0.1300	21.6	1.30	0.00150	4440	829
C-3	18.32	4.07	7.00	88	8400	13.51	6.94	201	47.70	18587	39.50	0.1300	19.7	3.60	0.00350	4340	744
A-4	18.85	4.99	7.12	82	5600	10.48	6.53	133	32.95	14123	37.41	0.0870	14.5	0.78	0.00096	3230	592
B-4	19.21	5.54	7.09	72	6800	10.70	6.43	153	25.05	14990	31.90	0.0840	15.4	0.88	0.00092	3150	588
C-4	19.65	4.50	7.04	78	6400	10.92	6.25	147	19.25	14279	34.12	0.0700	16.0	2.10	0.00170	3270	616

Week 10	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	21.57	4.39	7.40	130	9200	14.32	17.59	410	361.80	23763	147.53	0.3000	-	7.20	0.01600	4970	1340
A-1 In	21.20	6.31	7.12	86	8400	14.35	21.32	330	46.20	22093	245.18	0.3000	-	7.60	0.00830	4930	1370
B-1 In	22.00	6.40	7.14	84	8800	14.35	17.05	329	50.70	21.318	205.78	0.3000	-	7.80	0.00740	4960	1320
C-1 In	21.49	7.51	7.06	116	8000	12.60	20.55	313	24.30	19118	203.02	0.2500	-	6.30	0.00830	4310	1140
A-1	21.39	7.60	7.42	98	8400	13.37	22.89	282	11.50	20070	178.53	0.3000	-	2.80	0.00380	4650	1230
B-1	21.55	7.76	7.50	122	8400	14.12	20.21	309	49.00	22295	189.41	0.5500	-	2.00	0.00360	4900	1280
C-1	22.14	7.27	7.44	108	8400	13.34	16.38	293	18.80	20488	170.71	0.4700	-	1.90	0.00370	4590	1240
A-2	21.52	8.16	7.72	158	8000	13.48	20.38	234	139.30	20005	70.74	0.1100	-	1.40	0.00160	4730	1050
B-2	21.82	7.65	7.46	136	7200	13.62	20.96	270	53.70	21065	157.79	0.3300	-	1.60	0.00220	4650	1220
C-2	22.17	7.22	7.45	100	7600	13.06	22.62	227	55.70	18264	154.28	0.2800	-	1.30	0.00230	4530	1240
A-3	21.46	5.80	7.69	158	7600	13.09	14.82	285	15.30	19242	67.58	0.1400	-	1.30	0.00120	4550	1080
B-3	21.98	7.69	7.69	114	7600	13.10	15.67	235	27.50	20347	141.59	0.2300	-	1.20	0.00150	4550	1190
C-3	22.02	8.11	7.54	112	7200	12.59	15.88	269	7.80	18320	84.03	0.1500	-	0.98	0.00140	4320	1170
A-4	21.45	8.68	7.50	130	6800	12.49	3.65	215	33.90	18491	56.82	0.1700	-	0.97	0.00096	4820	1050
B-4	21.47	8.56	7.67	118	7600	13.17	17.64	234	72.50	19457	67.64	0.2300	-	0.96	0.00110	4650	1220
C-4	22.17	8.47	7.62	120	7600	12.45	11.00	197	6.70	19063	60.92	0.0880	-	0.86	0.00096	4240	1110
Week 11	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	19.33	8.63	7.40	122	10800	10.07	25.03	283	107.60	10745	91.72	0.1900	-	4.70	0.00210	3925	925
A-1 In	19.53	8.33	7.21	102	9200	9.94	25.12	235	18.40	10244	85.81	0.1800	-	4.50	0.00270	3825	1046
B-1 In	19.41	8.25	7.08	114	9200	10.13	24.97	265	20.10	10223	149.23	0.1700	-	4.20	0.00260	3825	1000
C-1 In	19.68	8.27	7.21	108	9600	10.00	25.08	304	41.20	10600	84.39	0.1800	-	4.50	0.00270	3825	1058

A-1	18.52	8.37	7.40	94	7600	9.47	20.43	171	ND	9798	65.69	0.2900	-	1.80	0.00240	3750	1100
B-1	18.29	8.92	7.19	106	5600	10.01	21.21	215	10.70	10481	59.27	0.3000	-	1.60	0.00230	3800	999
C-1	18.91	8.39	7.31	96	6800	10.33	22.76	231	7.50	10922	58.25	0.2200	-	2.30	0.00180	3650	935
A-2	18.31	9.09	7.54	140	7600	9.60	14.15	221	3.40	9592	42.83	0.0940	-	1.10	0.00086	3900	1016
B-2	17.83	8.90	7.42	82	6400	8.15	13.31	186	1.60	8056	36.20	0.1100	-	1.20	0.00110	3250	765
C-2	18.52	9.09	7.45	80	5600	8.09	10.96	169	4.10	8186	34.57	0.1500	-	1.10	0.00100	3025	731
A-3	18.55	9.01	7.45	142	7200	9.60	7.02	134	3.20	9784	37.38	0.1100	-	0.77	0.00035	3625	1002
B-3	17.71	9.23	7.55	100	6000	9.14	6.87	138	2.00	9412	34.71	0.1300	-	0.74	0.00038	3425	1007
C-3	18.27	9.18	7.13	88	6800	8.68	6.48	153	8.90	8814	33.51	0.1800	-	0.57	0.00046	3025	861
A-4	19.16	9.14	7.60	120	8800	10.31	2.83	117	1.60	10151	34.20	0.0550	-	0.52	<.0002	3625	1029
B-4	18.69	8.53	7.35	90	8000	9.29	1.45	220	0.10	9874	31.14	0.0760	-	0.55	<.0002	3325	903
C-4	18.90	8.94	7.43	66	8800	9.08	0.68	150	2.80	9135	31.12	0.1200	-	0.55	<.0002	3075	986

Week 12	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	22.73	7.51	7.41	96	10000	9.51	15.56	279	193.50	10599	177.73	0.1900	-	4.60	0.00310	3325	990
A-1 In	22.20	8.36	7.55	86	9200	9.38	10.67	222	24.20	9639	190.33	0.1800	-	4.50	0.00350	3625	1067
B-1 In	21.82	8.38	7.65	86	9200	9.46	13.24	192	24.20	10267	169.85	0.1800	-	4.50	0.00310	3175	1154
C-1 In	21.89	7.95	7.25	82	9200	9.46	14.84	212	17.90	10805	176.94	0.1600	-	4.30	0.00280	3300	1144
A-1	21.89	7.32	7.73	80	8400	8.58	15.40	177	13.50	9173	114.13	0.1700	-	1.10	0.00190	3000	1017
B-1	21.75	8.50	7.39	75	8800	9.27	11.29	193	3.90	9083	123.06	0.2000	-	1.90	0.00180	3125	1025
C-1	21.79	7.78	7.12	78	6400	8.24	14.49	161	4.10	9819	109.50	0.2100	-	1.30	0.00130	3175	1103
A-2	21.86	8.33	7.24	116	7600	8.92	14.31	221	54.00	10162	85.04	0.1200	-	0.66	0.00042	3350	850
B-2	22.25	7.56	7.01	112	8800	9.61	10.13	236	6.40	9347	109.21	0.1800	-	0.98	0.00086	3300	1079
C-2	21.63	8.36	6.78	76	7200	8.60	14.47	205	19.50	9615	94.34	0.2000	-	0.93	0.00081	3100	938
A-3	21.99	8.34	7.56	88	7600	7.69	13.82	221	20.30	8287	77.60	0.0680	-	0.50	0.00040	2850	812
B-3	21.81	8.44	7.30	76	6400	7.78	12.82	287	2.30	7803	71.76	0.1300	-	0.86	0.00071	2700	869
C-3	21.44	8.54	7.70	80	6000	7.80	9.10	161	3.60	9197	75.63	0.1300	-	0.64	0.00056	3200	891
A-4	21.46	8.58	7.75	100	7600	8.73	2.07	297	6.60	9169	55.72	0.0270	-	0.25	<.0002	3500	884

B-4	22.25	8.41	7.36	92	8400	9.33	4.37	224	50.80	10276	72.63	0.1600	-	0.51	0.00030	3350	956
C-4	21.36	8.47	7.32	72	7200	8.61	5.27	194	63.40	10132	69.18	0.1700	-	0.57	<.0002	3325	891

Week 13	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	21.17	7.91	7.06	104	9200	8.71	11.68	169	536.00	8894.5	165.64	0.1900	-	4.30	0.00410	4075	750
A-1 In	20.38	7.97	7.09	88	6400	8.65	14.30	210	25.70	8892.5	152.19	0.1600	-	4.10	0.00170	3250	703
B-1 In	21.04	7.87	7.10	98	6800	8.44	11.56	183	30.30	8827.5	143.99	0.1600	-	4.20	0.00190	3300	696
C-1 In	20.28	8.00	7.10	80	5600	8.62	12.01	192	21.10	8677	150.40	0.1600	-	4.00	0.00160	3375	822
A-1	20.51	8.01	7.37	62	5200	6.98	6.91	214	4.70	7206.5	97.98	0.1800	-	1.70	0.00090	3200	537
B-1	20.65	8.02	7.28	90	7200	9.04	13.51	174	9.10	8694.5	109.15	0.1900	-	2.10	0.00084	3275	841
C-1	20.26	8.01	7.33	60	4800	6.73	1.35	167	4.50	6696.5	51.58	0.1400	-	0.96	0.00091	2750	636
A-2	20.22	8.34	7.35	96	6400	7.94	11.56	234	8.30	8054.5	79.62	0.1400	-	0.83	0.00030	-	740
B-2	20.28	8.33	7.22	86	8400	8.15	10.89	141	8.60	8423.5	91.34	0.1800	-	1.20	0.00096	3350	719
C-2	20.18	8.11	7.14	64	6800	6.70	10.55	221	9.90	6923.5	63.19	0.1800	-	0.75	0.00088	3050	741
A-3	20.65	8.25	7.38	110	7600	8.53	8.28	173	5.50	8542.5	78.34	0.1000	-	0.29	<.0002	3225	801
B-3	20.83	6.80	7.30	116	8000	8.85	9.83	146	2.50	8690.5	80.93	0.1700	-	0.54	0.00026	3400	685
C-3	20.09	8.40	7.48	80	6000	6.56	3.88	148	3.20	6903.5	51.31	0.1800	-	0.48	0.00047	2900	863
A-4	21.63	7.92	7.48	114	8800	9.61	4.44	203	2.80	9296.5	63.61	0.0490	-	0.26	<.0002	3475	442
B-4	20.78	7.81	7.49	100	7600	9.24	3.05	100	1.40	9299.5	74.78	0.1300	-	0.51	<.0002	3600	782
C-4	21.14	7.51	7.24	86	4400	8.61	4.10	77	14.20	8115.5	59.34	0.0770	-	0.54	0.00026	3400	708

Week 14	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	14.04	11.16	6.99	118	5600	8.68	17.81	169	300.50	3782	142.29	0.1900	-	4.50	0.00210	3750	809
A-1 In	14.48	12.48	6.97	104	5200	8.61	16.88	210	168.40	4044	125.14	0.1800	-	4.70	0.00150	2825	931
B-1 In	13.48	12.29	6.92	102	5200	8.57	17.18	183	185.30	3680	135.74	0.1800	-	4.70	0.00150	2775	1020
C-1 In	13.98	11.94	6.95	108	5200	8.60	15.93	192	185.90	4070	126.79	0.1800	-	4.80	0.00130	2725	913

A-1	13.52	12.36	7.03	104	5200	9.13	10.38	214	225.90	4536	112.44	0.1700	-	3.70	0.00100	2975	872
B-1	12.96	12.30	7.03	106	4800	8.76	12.22	174	184.50	4087	102.06	0.2000	-	3.80	0.00062	2875	768
C-1	13.64	12.44	7.01	104	4400	8.12	7.87	167	214.80	4180	77.29	0.1200	-	2.30	0.00078	2750	742
A-2	13.60	11.67	7.13	112	5200	9.03	7.85	234	246.30	4352	86.92	0.0980	-	1.30	0.00051	3125	804
B-2	13.83	11.38	6.93	90	4400	7.86	10.93	141	237.50	4068	94.66	0.0830	-	0.88	0.00045	2825	789
C-2	13.55	12.02	7.13	112	4400	8.36	8.28	221	238.00	4947	81.65	0.1500	-	1.40	0.00048	2925	886
A-3	13.77	12.69	7.55	108	5200	9.52	8.93	173	256.80	4984	73.05	0.0880	-	0.64	0.00029	3250	799
B-3	13.34	12.47	7.57	104	5000	8.62	9.83	146	-	-	71.37	0.1700	-	1.10	0.00030	2950	765
C-3	12.66	12.62	7.08	82	4800	8.36	8.45	148	223.30	4621	72.17	0.0910	-	0.50	0.00028	3250	840
A-4	12.20	12.25	6.85	114	5200	9.77	12.19	203	281.10	4880	65.38	0.1200	-	0.62	0.00020	3300	763
B-4	12.53	12.69	7.26	96	5200	8.68	5.95	100	238.80	4446	71.11	0.1100	-	0.89	0.00023	3125	944
C-4	13.30	12.69	7.18	90	5200	8.79	5.59	77	231.20	4512	65.28	0.0660	-	0.47	0.00020	3000	760

Week 15	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	Bmg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	23.23	7.25	6.82	92	5200	9.84	15.05	213	148.40	3734.5	117.11	0.2000	-	4.70	0.00072	2525	1242
A-1 In	22.92	7.66	6.90	88	5200	9.48	14.37	180	-	3292.5	94.17	0.2000	-	4.70	0.00094	2975	1260
B-1 In	22.40	7.62	6.77	92	5200	9.69	13.74	180	55.50	2957.5	89.15	0.1900	-	4.50	0.00071	3235	1276
C-1 In	22.65	7.76	6.95	88	5200	9.78	15.38	189	43.70	3753.5	86.22	0.2000	-	4.90	0.00074	3240	1261
A-1	22.92	7.66	6.90	88	5200	9.48	14.37	180	-	3292.5	94.17	0.2000	-	4.70	0.00094	2975	1260
B-1	22.21	7.92	6.83	96	5600	9.98	11.53	165	31.90	3670.5	79.47	0.1900	-	2.50	0.00055	3175	1324
C-1	22.75	8.08	6.95	94	5600	10.04	11.93	188	38.90	3776.5	67.48	0.1900	-	2.40	0.00063	3360	1345
A-2	22.28	8.20	6.95	106	5600	10.30	8.01	173	32.00	4553.5	65.43	0.2400	-	1.10	0.00010	3450	1371
B-2	22.07	8.22	6.98	102	5600	10.17	8.00	185	58.20	4252.5	65.74	0.1700	-	1.40	0.00024	3450	1324
C-2	22.32	8.57	6.85	90	5600	10.40	3.93	179	35.20	3842.5	64.39	0.0880	-	0.73	0.00028	3485	1337
A-3	22.07	8.22	6.98	102	5600	10.17	8.00	185	58.20	4252.5	65.74	0.1700	-	1.40	0.00024	3450	1324
B-3	22.08	8.35	7.00	102	6000	10.41	8.17	191	57.20	3990.5	66.63	0.2400	-	0.65	0.00010	3465	1245
C-3	21.65	8.49	7.00	102	6000	10.21	7.67	180	38.30	3855.5	60.75	0.2100	-	0.69	0.00010	3450	1360
A-4	22.00	8.54	7.01	112	6200	11.02	3.64	183	47.20	4172.5	56.89	0.0780	-	0.43	0.00010	3585	1348
B-4	22.26	8.34	7.04	94	6200	10.80	7.91	165	22.00	4610.5	76.67	0.2300	-	0.88	0.00010	3635	1369

C-4	22.24	8.39	6.86	82	6200	10.75	7.16	195	30.20	4644.5	74.28	0.1000	-	0.51	0.00010	4390	1327
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Week 16	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	23.25	7.79	6.79	100	6000	9.94	15.82	184	72.20	5797.5	88.14	0.1600	-	3.90	0.00200	3725	1119
A-1 In	22.56	8.27	6.83	94	5200	9.97	10.47	179	84.10	5132.5	68.10	0.1600	-	4.20	0.00260	3815	1095
B-1 In	22.80	7.28	6.83	92	5200	9.97	6.91	174	110.50	4151.0	66.36	0.1500	-	4.00	0.00240	3250	1072
C-1 In	21.68	7.62	6.80	90	5200	10.02	5.98	179	96.20	5278.5	56.97	0.1600	-	4.00	0.00270	3650	1079
A-1	22.18	8.25	6.87	84	5200	10.32	2.65	174	69.20	6267.5	59.50	0.1700	-	2.80	0.00110	3850	1086
B-1	22.01	8.13	6.85	94	5600	10.28	4.01	165	161.60	5873.5	57.55	0.1800	-	2.70	0.00140	3425	1129
C-1	21.30	8.34	6.87	82	6400	12.25	2.88	183	69.50	6811.5	47.74	0.1100	-	1.20	0.00074	4825	1452
A-2	21.81	8.53	6.90	92	6000	10.75	2.10	165	73.30	6488.5	49.55	0.0690	-	0.90	0.00054	3625	1181
B-2	22.13	8.33	6.87	88	5600	10.48	1.87	165	62.80	6134.5	49.66	0.1300	-	1.80	0.00074	3500	1170
C-2	22.70	8.24	6.65	78	4800	11.17	1.16	156	77.00	6403.5	37.87	0.0330	-	0.21	0.00010	4425	1285
A-3	22.32	8.33	7.03	100	5600	11.07	1.32	165	53.00	5748.5	46.69	0.0500	-	0.36	0.00022	3750	1222
B-3	21.98	8.05	6.90	86	5600	10.45	6.92	165	58.70	5723.5	49.88	0.1000	-	0.51	0.00032	4100	1109
C-3	22.16	8.42	6.90	78	5600	10.58	4.00	152	70.90	6373.5	44.73	0.1400	-	0.38	0.00035	3750	1243
A-4	21.86	8.44	6.92	84	6400	11.74	0.57	170	98.70	6026.5	47.40	0.0280	-	0.37	0.00010	4375	1307
B-4	22.22	8.26	6.93	80	5200	11.01	3.72	164	44.60	6530.5	48.75	0.0540	-	0.46	0.00025	3625	1229
C-4	21.57	8.36	6.88	80	4800	11.77	2.72	194	86.50	6701.5	46.00	0.0410	-	0.43	0.00030	4375	1355

Week 17	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	21.24	6.65	7.19	96	4000	9.09	13.78	210	138.05	4965	48.47	0.1700	-	4.00	0.00094	3575	819
A-1 In	21.87	7.67	6.97	84	4400	9.12	7.23	176	112.35	5187	53.97	0.1600	-	4.20	0.00640	3500	609
B-1 In	22.14	6.87	6.95	78	4400	9.11	9.49	169	64.65	5074	56.94	0.1600	-	4.10	0.00490	3200	772
C-1 In	20.92	7.40	7.02	86	4800	9.11	6.08	173	84.15	5172	58.46	0.1500	-	4.00	0.00420	3575	764
A-1	21.40	8.34	6.90	76	3600	9.39	3.02	164	80.75	5077	37.85	0.1300	-	3.50	0.00170	3450	767
B-1	22.04	8.27	7.16	92	4800	9.35	2.32	163	77.85	5446	31.94	0.1600	-	3.20	0.00160	3250	793

C-1	21.02	8.35	7.02	88	4800	9.31	2.01	164	98.65	4915	36.09	0.1300	-	3.20	0.00160	3325	789
A-2	21.08	8.11	6.62	66	3600	7.11	5.83	162	53.95	4088	40.97	0.0700	-	1.20	0.00083	2825	658
B-2	22.06	7.78	6.81	76	3200	6.38	7.35	163	48.85	3840	44.62	0.1200	-	1.60	0.00085	2525	579
C-2	21.89	7.83	7.01	68	4000	6.10	7.22	164	56.25	3285	47.04	0.0970	-	1.30	0.00091	2525	842
A-3	22.28	8.26	7.38	76	4000	7.96	1.27	156	56.45	4309	27.89	0.0360	-	0.41	0.00010	2975	821
B-3	21.07	8.34	7.18	86	4000	8.78	1.99	160	79.85	4680	27.70	0.1300	-	0.49	0.00010	3225	767
C-3	22.03	8.24	7.17	74	4000	7.82	1.58	159	81.45	3946	29.10	0.1000	-	0.71	0.00037	2650	696
A-4	21.52	8.33	7.25	84	5200	9.36	1.24	165	81.75	4710	28.13	0.0220	-	0.34	0.00010	3300	895
B-4	22.65	8.14	7.37	80	4400	9.53	0.82	160	92.55	5113	26.66	0.0610	-	0.61	0.00010	3325	880
C-4	20.91	8.43	7.21	80	4800	9.55	0.53	150	45.55	5017	27.46	0.0490	-	0.56	0.00010	3350	924

Week 18	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	22.71	5.02	6.82	92	4400	9.18	7.42	256	240.90	5660	53.66	0.1200	-	3.80	0.00400	3500	655
A-1 In	23.08	5.80	7.21	82	4400	9.07	8.12	225	68.90	4624	48.91	0.1100	-	3.70	0.00300	3400	651
B-1 In	22.56	6.04	6.80	66	4000	9.02	9.95	236	63.20	4387	50.30	0.1000	-	3.70	0.00350	3450	678
C-1 In	23.03	6.52	6.90	70	4400	9.03	12.60	238	66.80	4370	45.44	0.1100	-	3.70	0.00240	3350	678
A-1	22.67	8.00	7.01	70	4000	9.07	4.55	187	62.90	4069	35.28	0.0920	-	3.60	0.00120	3575	648
B-1	22.83	8.10	7.13	74	4000	8.95	1.80	195	48.00	4776	31.36	0.0970	-	2.90	0.00110	3325	640
C-1	23.11	7.92	7.15	86	4400	9.15	5.42	201	52.80	5565	33.22	0.1000	-	3.40	0.00120	3625	711
A-2	22.25	8.28	6.99	70	3600	9.14	5.75	166	75.60	5426	30.66	0.0540	-	0.71	0.00040	3475	752
B-2	22.54	8.26	7.01	70	3600	9.17	1.96	176	55.70	5667	31.44	0.1000	-	1.70	0.00069	3725	720
C-2	23.15	8.24	6.95	72	4000	9.26	3.64	176	47.70	4221	28.80	0.1100	-	2.40	0.00083	3625	722
A-3	23.04	8.55	7.05	76	4000	9.15	2.31	165	45.80	5222	27.12	0.0190	-	0.27	0.00010	3575	709
B-3	23.61	8.51	6.92	78	4000	9.17	3.29	170	51.10	4575	27.53	0.0390	-	0.52	0.00025	3675	746
C-3	24.25	8.61	6.94	76	4000	9.15	3.08	175	153.00	4305	-	0.0940	-	1.50	0.00036	3425	905
A-4	23.14	8.21	6.90	70	4800	7.67	2.30	176	53.00	4214	-	0.0340	-	0.58	0.00010	3125	706
B-4	23.04	7.96	6.98	58	4400	7.07	4.76	172	40.30	4030	-	0.0760	-	0.71	0.00024	2850	604
C-4	22.69	8.25	6.96	60	4400	7.60	3.65	165	41.50	4346	-	0.0850	-	0.99	0.00027	3000	648

Week 19	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	22.01	7.30	6.83	104	5200	8.54	7.01	235	95.85	5670	34.83	0.1600	-	4.10	0.00360	3250	559
A-1 In	21.98	7.93	7.21	96	4800	8.60	5.70	193	108.65	5768	34.60	0.1600	-	4.10	0.00450	3225	523
B-1 In	22.17	7.54	7.43	90	5200	8.53	4.83	189	44.55	5728	44.84	0.1500	-	4.60	0.00510	3050	502
C-1 In	22.53	7.32	7.38	88	5200	8.88	5.98	190	-	5756	41.71	0.2100	-	4.50	0.00290	3225	793
A-1	21.64	8.25	7.05	80	4800	8.99	5.96	169	47.66	5029	31.48	0.1400	-	3.70	0.00180	3225	524
B-1	21.38	8.19	6.90	84	4800	8.93	5.62	173	38.45	6059	29.64	0.1500	-	3.50	0.00089	3075	590
C-1	22.36	8.02	6.72	80	5200	8.62	5.30	176	29.35	5137	27.05	0.1600	-	3.20	0.00150	3200	621
A-2	21.69	8.36	7.42	82	4000	8.66	2.75	156	39.55	5295	20.11	0.0260	-	0.37	0.00039	3050	560
B-2	21.65	8.11	6.90	84	3600	8.12	3.28	142	27.05	5406	20.89	0.0720	-	1.20	0.00082	3100	549
C-2	22.24	7.99	7.32	84	4000	8.71	2.37	150	32.25	5948	26.52	0.1200	-	2.20	0.00110	3100	584
A-3	22.52	7.84	7.63	90	4800	8.47	1.62	156	42.45	5598	19.75	0.0240	-	0.28	0.00010	3025	583
B-3	22.16	8.01	7.36	86	4400	8.66	1.03	150	32.75	5535	23.98	0.0530	-	0.43	0.00031	3200	545
C-3	22.12	7.96	7.54	80	5200	9.05	1.47	152	35.75	5400	22.82	0.0690	-	1.40	0.00045	3250	610
A-4	22.96	7.44	7.22	84	4800	9.32	1.02	150	36.25	5876	19.31	0.0120	-	0.26	0.00010	2975	602
B-4	22.50	7.65	7.05	80	4000	8.85	0.74	140	39.35	5817	20.57	0.0280	-	0.44	0.00010	3175	606
C-4	20.79	8.29	7.30	78	4800	9.30	0.61	125	51.65	6047	21.69	0.0520	-	1.30	0.00023	3400	600
Week 20	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	22.88	8.23	6.69	110	5000	8.50	11.47	276	237.40	1991	41.09	0.1700	-	4.10	0.00120	2975	670
A-1 In	21.94	8.35	6.71	104	5200	8.29	2.12	219	105.80	1930	28.70	0.1500	-	4.10	0.00310	3025	646
B-1 In	21.14	8.45	6.75	106	4800	8.30	2.54	199	81.00	1593	28.84	0.1700	-	4.40	0.00400	3000	607
C-1 In	20.78	8.60	6.80	104	4800	8.46	2.73	205	424.00	1785	29.80	0.1600	-	4.30	0.00270	2950	699
A-1	20.27	8.70	6.72	98	3600	8.62	2.35	176	61.00	1774	23.61	0.2600	-	2.90	0.00230	3025	738
B-1	19.82	8.81	6.92	98	4000	8.94	2.35	168	110.90	2039	20.93	0.0860	-	1.60	0.00055	3175	779
C-1	20.10	8.83	6.89	98	4000	8.63	1.70	166	22.40	2022	20.14	0.1500	-	2.40	0.00130	3200	623

A-2	20.55	8.75	7.06	94	4000	8.60	2.21	125	20.60	2395	25.15	0.0940	-	1.70	0.00080	3200	645
B-2	19.82	8.80	7.35	90	3600	8.73	1.74	138	17.60	2171	22.80	0.0970	-	1.90	0.00071	3100	664
C-2	19.95	8.85	7.08	90	4000	8.74	2.21	137	29.87	1837	20.80	0.2200	-	2.40	0.00090	3175	680
A-3	19.97	8.92	7.27	92	3600	8.56	1.50	129	20.20	1809	23.60	0.0430	-	0.47	0.00023	3175	702
B-3	19.70	8.85	7.24	90	4000	8.60	1.50	145	16.66	2049	24.35	0.1200	-	1.30	0.00056	3075	662
C-3	20.06	8.80	7.30	90	4400	8.68	0.91	142	16.80	2075	22.38	0.1800	-	1.00	0.00034	3125	678
A-4	20.47	8.72	7.70	86	4400	8.07	2.86	116	74.30	2026	20.25	0.1500	-	1.10	0.00010	2875	664
B-4	20.27	8.77	7.66	86	4800	7.48	1.76	110	13.30	1332	-	0.0870	-	0.83	0.00023	2925	550
C-4	20.26	8.79	7.60	86	4400	7.21	1.56	98	20.00	1333	21.39	0.1500	-	0.87	0.00010	2750	597
Week 21	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	24.43	7.58	6.56	120	7600	10.97	9.11	NA	51.05	12449	106.97	0.0025	-	0.06	0.00010	4100	673
A-1 In	23.51	6.46	6.76	122	7600	12.47	12.06	NA	57.15	14844	62.47	0.0051	-	0.07	0.00010	5125	773
B-1 In	23.34	6.34	6.79	120	7200	12.82	11.29	NA	60.25	14726	122.58	0.0025	-	0.09	0.00010	4850	818
C-1 In	23.29	6.49	6.77	122	7200	12.79	12.12	NA	55.95	15296	160.48	0.0025	-	0.13	0.00010	4850	816
A-1	23.46	7.53	7.04	116	6400	11.44	9.74	NA	53.25	14905	64.18	0.0200	-	0.12	0.00010	4325	713
B-1	23.25	7.55	7.05	112	6400	11.40	7.19	NA	54.55	15448	95.80	0.0220	-	0.09	0.00010	4400	746
C-1	23.52	7.95	7.00	112	6400	11.44	7.06	NA	56.55	14871	133.88	0.0120	-	0.11	0.00010	4425	711
A-2	23.66	8.18	7.16	114	5600	10.19	6.93	NA	45.65	8826	71.82	0.0180	-	0.11	0.00010	3925	560
B-2	24.13	8.30	7.30	112	6400	6.65	6.43	NA	24.35	9556	40.91	0.0150	-	0.08	0.00010	2725	462
C-2	24.11	8.29	7.56	114	6000	4.65	6.28	NA	22.95	9590	20.10	0.0410	-	0.64	0.00010	1875	427
A-3	25.55	7.53	7.20	108	6000	11.15	6.75	NA	88.85	11916	110.63	0.0083	-	0.08	0.00040	4225	741
B-3	24.86	7.75	7.22	108	6800	10.19	2.13	NA	39.45	13187	47.31	0.0370	-	0.12	0.00010	3900	867
C-3	24.95	7.58	7.40	110	6800	7.28	1.57	NA	32.35	13856	31.39	0.0690	-	0.32	0.00021	2750	620
A-4	24.97	7.61	7.19	112	6400	11.65	4.27	NA	70.25	12241	80.12	0.0640	-	0.14	0.00010	4425	903
B-4	24.89	7.73	7.31	114	5600	11.33	2.49	NA	46.05	12844	51.51	0.0120	-	0.13	0.00010	4200	1019
C-4	24.66	7.57	7.35	114	6000	10.44	2.59	NA	51.35	14123	66.39	0.0300	-	0.25	0.00010	3800	799

Week 22	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	22.65	8.31	6.37	110	6800	11.15	10.15	NA	58.80	12618	NA	0.0025	-	0.06	0.00010	4125	655
A-1 In	22.49	8.24	6.49	114	6400	13.43	13.56	NA	42.00	14923	NA	0.0025	-	0.07	0.00010	4825	921
B-1 In	22.10	8.35	6.48	112	6400	13.80	12.57	NA	35.60	14871	NA	0.0025	-	0.12	0.00010	5150	848
C-1 In	21.78	8.12	6.50	114	6000	13.05	13.12	NA	43.70	15534	NA	0.0025	-	0.08	0.00010	4250	865
A-1	21.08	8.07	6.60	112	6400	12.73	8.79	NA	51.90	14108	NA	0.0089	-	0.10	0.00010	4725	711
B-1	20.95	8.31	6.73	112	6000	11.70	8.91	NA	58.90	14987	NA	0.0170	-	0.13	0.00027	4375	837
C-1	20.86	8.23	6.68	110	6000	12.22	9.08	NA	53.20	15063	NA	0.0086	-	0.10	0.00010	4550	823
A-2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B-2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C-2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A-3	20.62	7.96	6.78	100	5600	9.01	4.37	NA	57.20	12019	NA	0.0270	-	0.14	0.00010	3500	596
B-3	21.06	8.04	6.79	102	5200	9.52	3.85	NA	49.00	12967	NA	0.0170	-	0.06	0.00010	3675	500
C-3	20.76	8.15	6.79	100	5200	8.76	2.01	NA	41.56	13158	NA	0.0450	-	0.14	0.00010	3400	548
A-4	20.74	8.12	6.85	106	6000	10.86	2.81	NA	49.20	11987	NA	0.0350	-	0.12	0.00010	3925	743
B-4	20.61	7.95	6.91	108	6400	10.06	1.49	NA	32.00	12548	NA	0.0120	-	0.06	0.00010	3875	628
C-4	21.81	8.16	6.72	108	6000	10.99	1.53	NA	29.30	13952	NA	0.1500	-	0.05	0.00035	3900	688
Week 23	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	19.93	8.59	6.88	58	12800	9.43	11.03	241	65.05	12536	228.52	0.0730	-	1.80	0.16000	4150	407
A-1 In	19.84	8.66	6.80	58	13000	9.31	2.46	256	82.80	13543	88.81	0.0740	-	1.80	0.13000	3975	406
B-1 In	-	-	6.79	60	11600	9.39	3.62	232	95.45	13977	57.54	0.0760	-	1.90	0.14000	4100	
C-1 In	19.55	8.58	6.85	58	10800	9.79	1.98	237	93.55	13358	22.34	0.0750	-	1.90	0.14000	4150	392
A-1	19.79	8.73	6.73	78	11600	9.32	2.58	269	75.95	13994	130.49	0.0500	-	1.50	0.04300	4175	440
B-1	19.51	8.72	6.82	72	10000	7.78	1.64	238	61.40	14631	81.86	0.0530	-	0.30	0.03600	3475	446

C-1	19.90	8.65	6.83	70	12800	9.62	5.63	255	66.30	14392	22.66	0.0600	-	1.70	0.04900	4350	454
A-2	20.64	8.53	6.55	64	11600	10.74	7.21	199	63.75	11495	37.24	0.1600	-	0.58	0.04300	3750	332
B-2	19.84	8.68	6.34	80	9600	9.57	3.87	206	82.80	13853	56.77	0.0580	-	0.20	0.02800	3525	445
C-2	20.21	8.65	6.33	54	8800	7.72	4.63	194	109.30	13796	55.65	0.0410	-	0.30	0.01100	2525	418
A-3	19.73	8.85	6.75	80	11600	11.31	2.04	205	123.60	12719	12.53	0.0560	-	0.14	0.01500	4100	488
B-3	19.45	8.95	6.54	80	8400	9.54	1.98	186	116.75	12161	54.67	0.0130	-	0.06	0.00640	3175	457
C-3	19.56	8.79	6.60	76	9600	10.13	2.39	193	108.10	13566	54.09	0.0850	-	0.25	0.01100	3800	420
A-4	19.56	8.80	6.83	76	10400	11.08	2.81	179	87.50	12646	ND	0.0430	-	0.20	0.00720	4150	449
B-4	20.14	8.66	6.72	74	8800	8.99	3.14	186	99.85	12554	42.03	0.0120	-	0.09	0.00100	3475	470
C-4	19.95	8.80	6.65	70	9200	9.67	3.36	181	64.25	13058	57.11	0.0290	-	0.28	0.00690	3775	516

Week 24	Temp C	DO mg/L	pH	Alk mg/L	Hard mg/L	Cond mS	BOD mg/L	COD mg/L	TSS mg/L	TDS mg/L	NPOC mg/L	As mg/L	B mg/L	Se mg/L	Hg mg/L	Chloride mg/L	SO4 mg/L
Equal. Basin	20.13	8.37	6.55	68	12400	12.88	9.92	236	67.75	11998	93.98	0.0710	-	1.80	0.16000	-	457
A-1 In	19.56	8.52	6.59	66	12400	13.14	0.84	233	80.35	12178	44.79	0.0690	-	1.80	0.16000	5175	458
B-1 In	20.25	8.57	6.68	64	12000	13.13	4.40	229	122.35	12770	62.81	0.0730	-	1.80	0.17000	5325	485
C-1 In	20.65	8.46	6.71	64	12400	13.06	2.44	245	136.65	11818	55.88	0.0680	-	1.80	0.17000	-	495
											2	0.0820	-	1.30	0.11000	5100	547
A-1	19.76	8.79	6.69	66	12000	12.34	3.24	275	65.75	8562	4.46						
B-1	19.56	8.85	6.79	68	11600	12.78	1.04	241	62.65	13396	41.72	0.0490	-	0.41	0.04100	5025	543
C-1	20.84	8.64	6.85	68	11600	13.38	11.12	264	168.85	13436	69.36	0.0640	-	1.60	0.05100	4950	553
A-2	19.37	8.80	6.73	74	12000	12.09	5.32	202	98.05	13182	44.74	0.0400	-	0.21	0.02000	4700	566
B-2	19.62	8.86	6.67	72	12000	12.46	2.04	210	61.65	13058	50.83	0.0570	-	0.34	0.03200	4725	598
C-2	19.18	8.76	6.72	74	11600	13.51	5.60	193	72.05	12298	42.52	0.0350	-	0.33	0.01900	5300	621
A-3	20.09	8.71	6.97	74	12400	12.87	0.48	199	88.85	13970	40.42	0.0270	-	0.10	0.00860	4975	531
B-3	19.63	8.45	6.88	74	12400	12.97	2.36	197	77.05	14588	54.68	0.0240	-	0.14	0.00960	5000	577
C-3	19.35	8.67	6.91	74	12000	13.84	2.40	204	111.45	11380	45.95	0.0170	-	0.21	0.01200	5250	595
A-4	19.44	8.72	6.89	82	11600	13.93	3.60	193	190.25	11374	43.38	0.1800	-	0.47	0.00690	5075	580
B-4	19.91	8.75	6.87	84	11600	13.67	4.52	193	105.15	11852	45.81	0.2300	-	0.70	0.00710	5650	647
C-4	19.72	8.61	6.94	80	12000	14.01	1.64	172	70.05	12252	38.82	0.1100	-	0.41	0.00800	5525	649

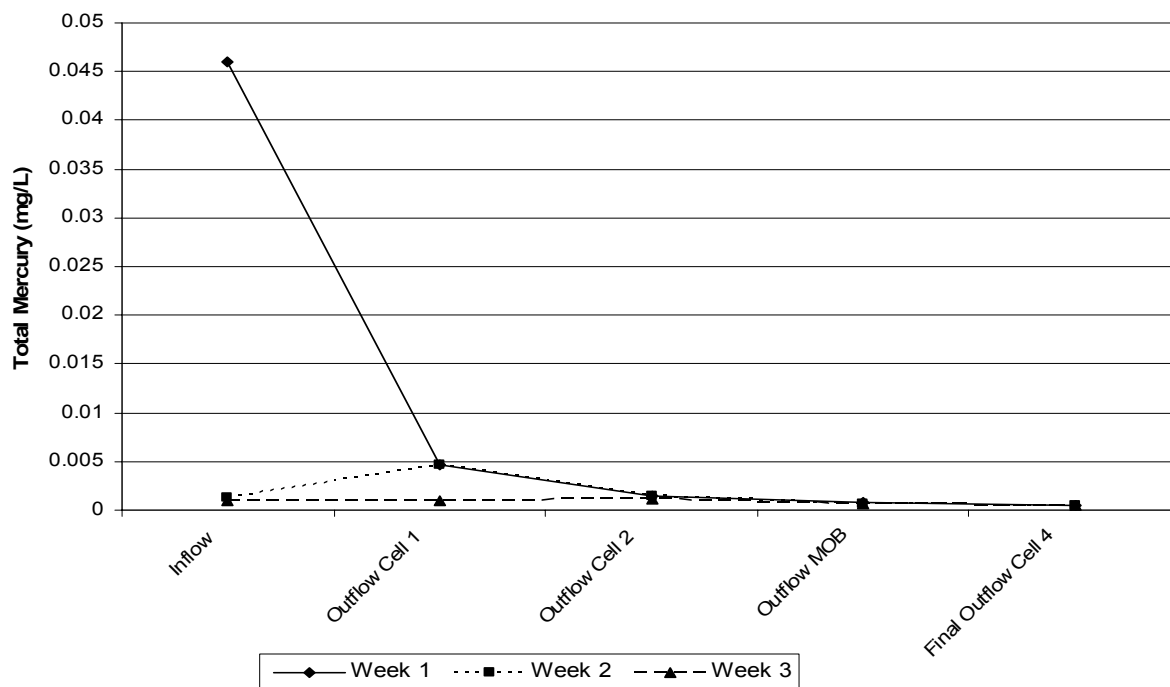


Figure 3. Total mercury in simulated FGD wastewater treated by a pilot constructed wetland system during the acclimation period (Weeks 1 to 4).

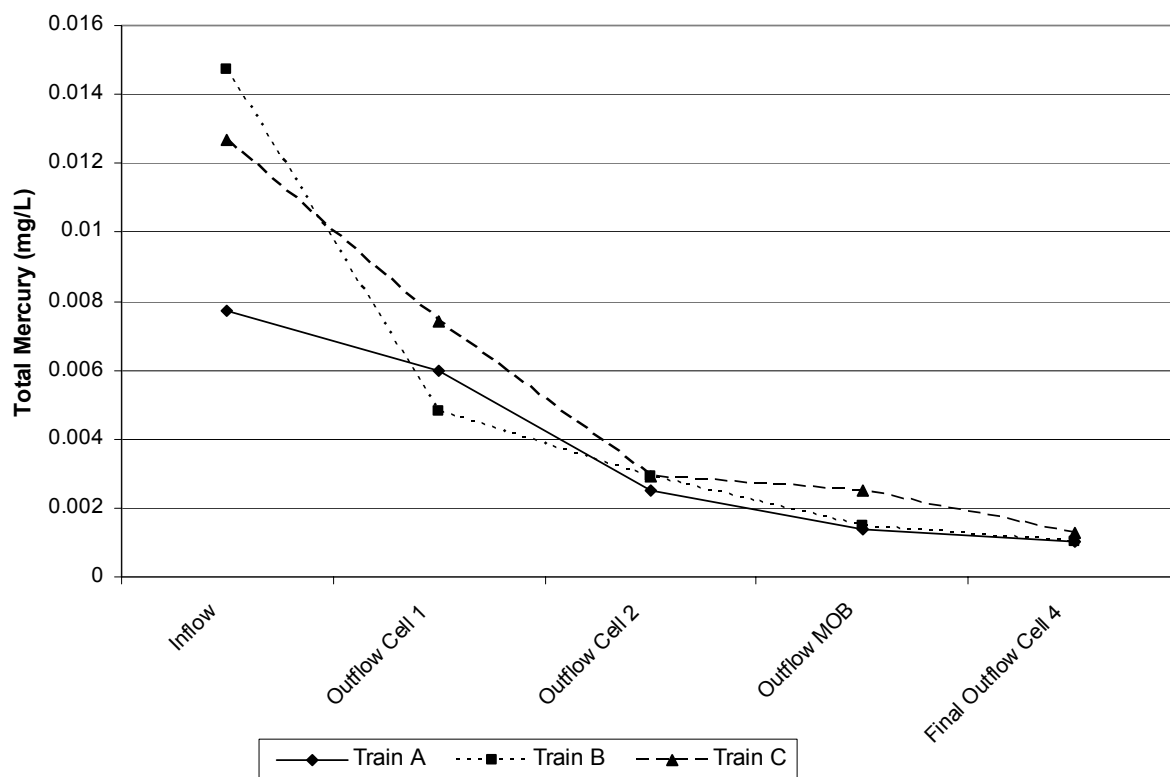


Figure 4. Average total mercury in simulated FGD wastewater treated by a pilot constructed wetland system for the high ionic strength FGD wastewater (Weeks 9 and 10).

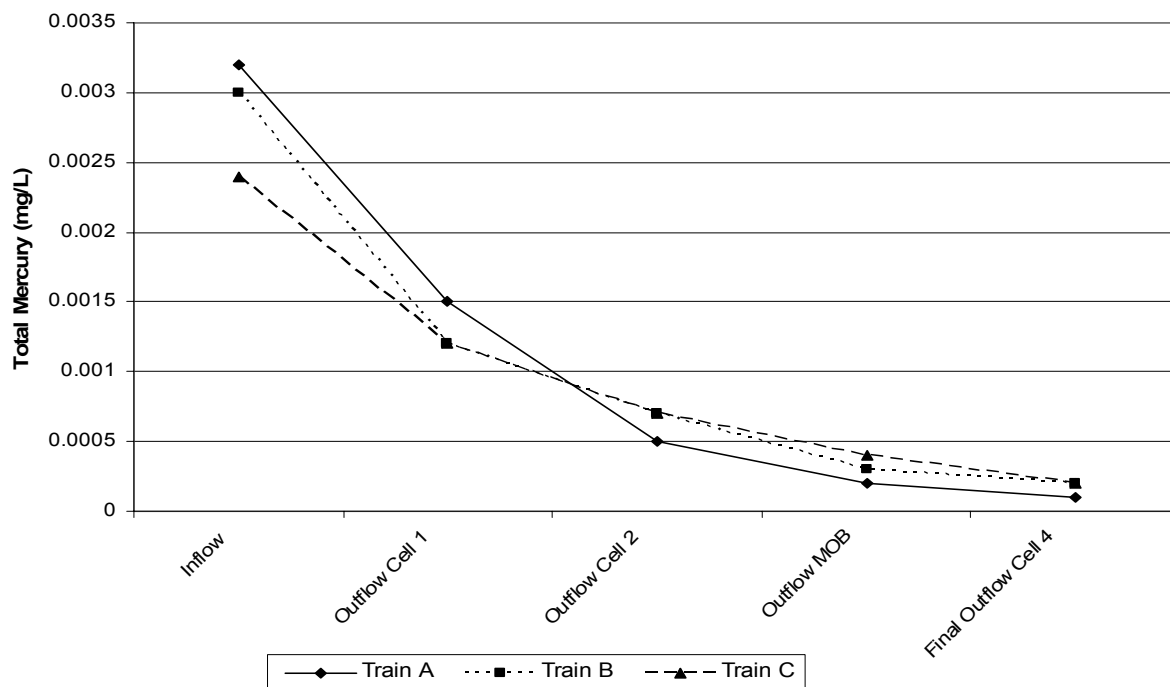


Figure 5. Average total mercury in simulated FGD wastewater treated by a pilot constructed wetland system for the high-intermediate ionic strength FGD wastewater (Weeks 11 to 20).

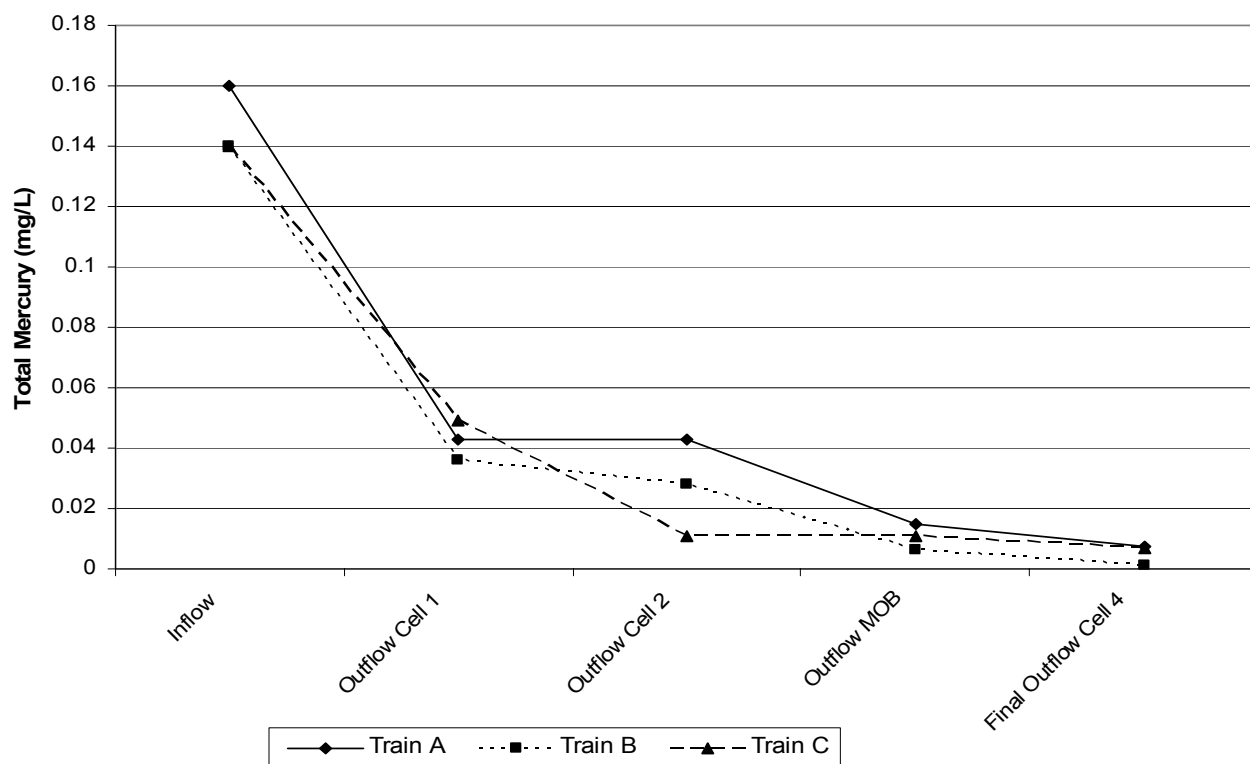


Figure 6. Total mercury in simulated FGD wastewater treated by a pilot constructed wetland system for the first week of low-intermediate ionic strength FGD wastewater (Week 23).

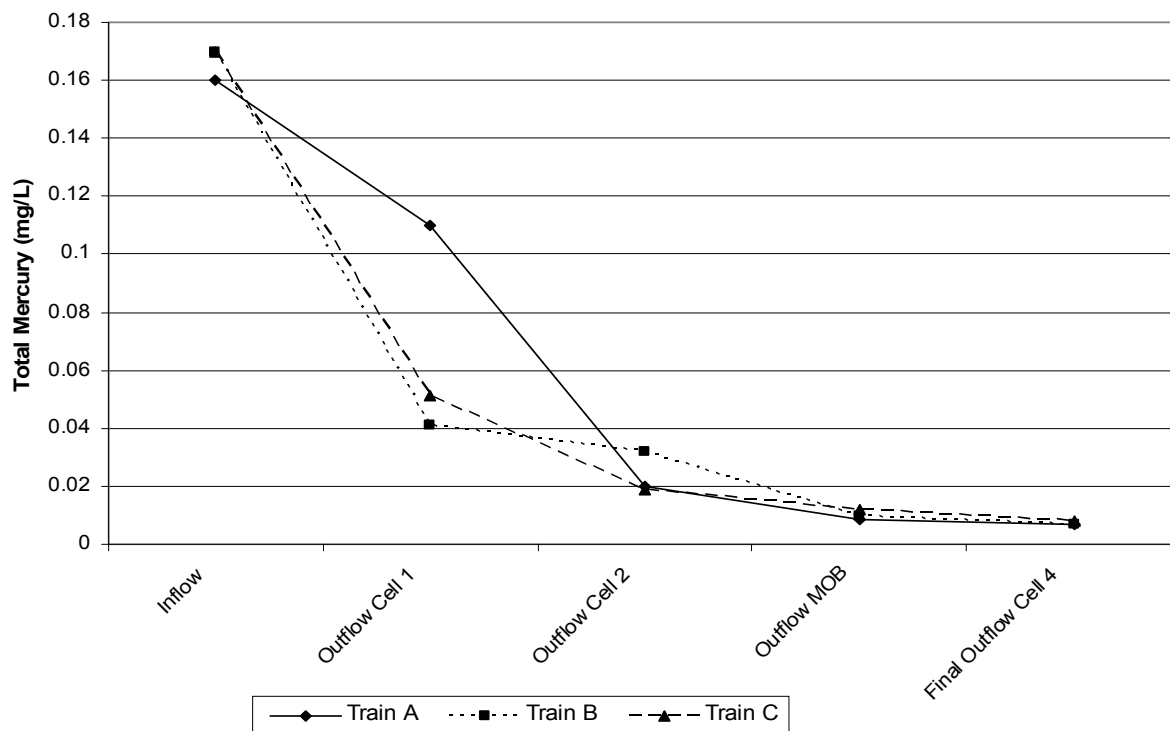


Figure 7. Total mercury in simulated FGD wastewater treated by a pilot constructed wetland system for the second week of low-intermediate ionic strength FGD wastewater (Week 24).

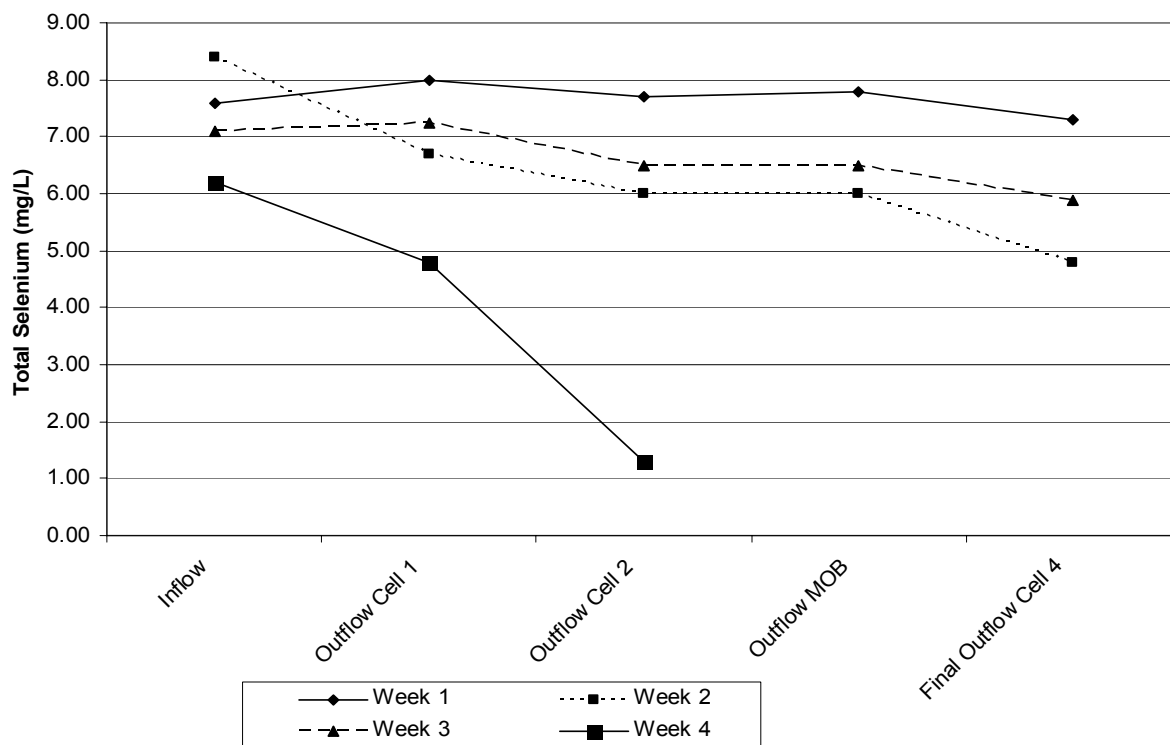


Figure 8. Total selenium in simulated FGD wastewater treated by a pilot constructed wetland system during the acclimation period (Weeks 1 to 4).

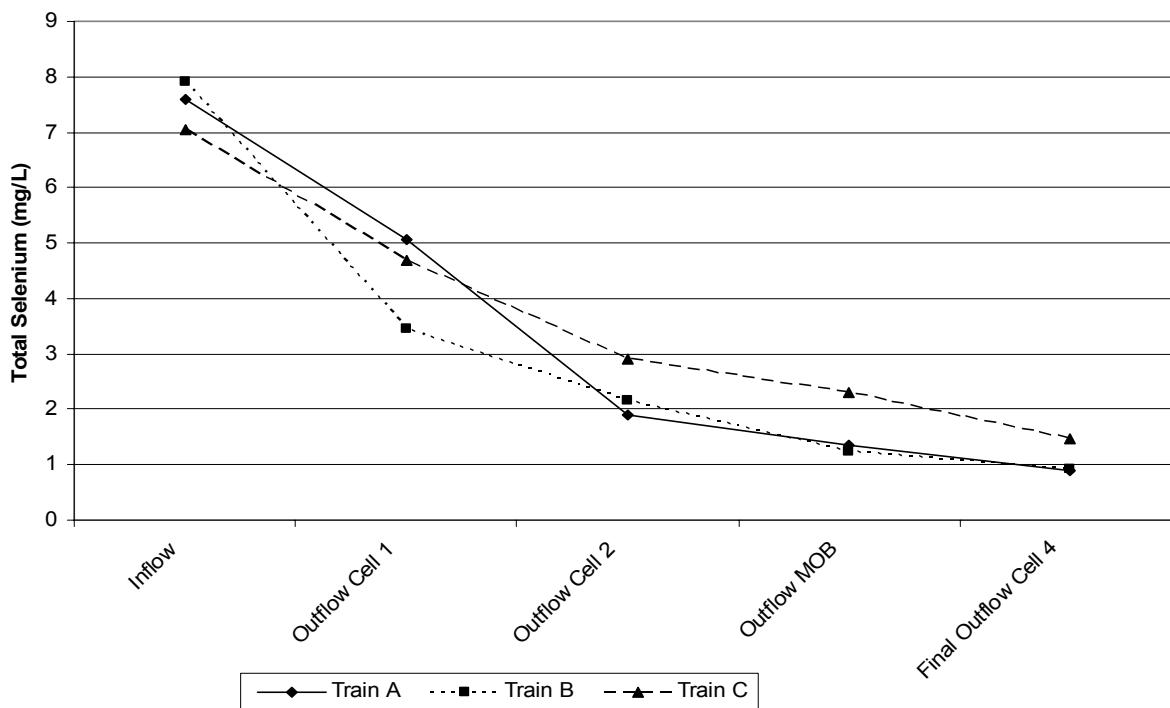


Figure 9. Average total selenium in simulated FGD wastewater treated by a pilot constructed wetland system for the high ionic strength FGD wastewater (Weeks 9 and 10).

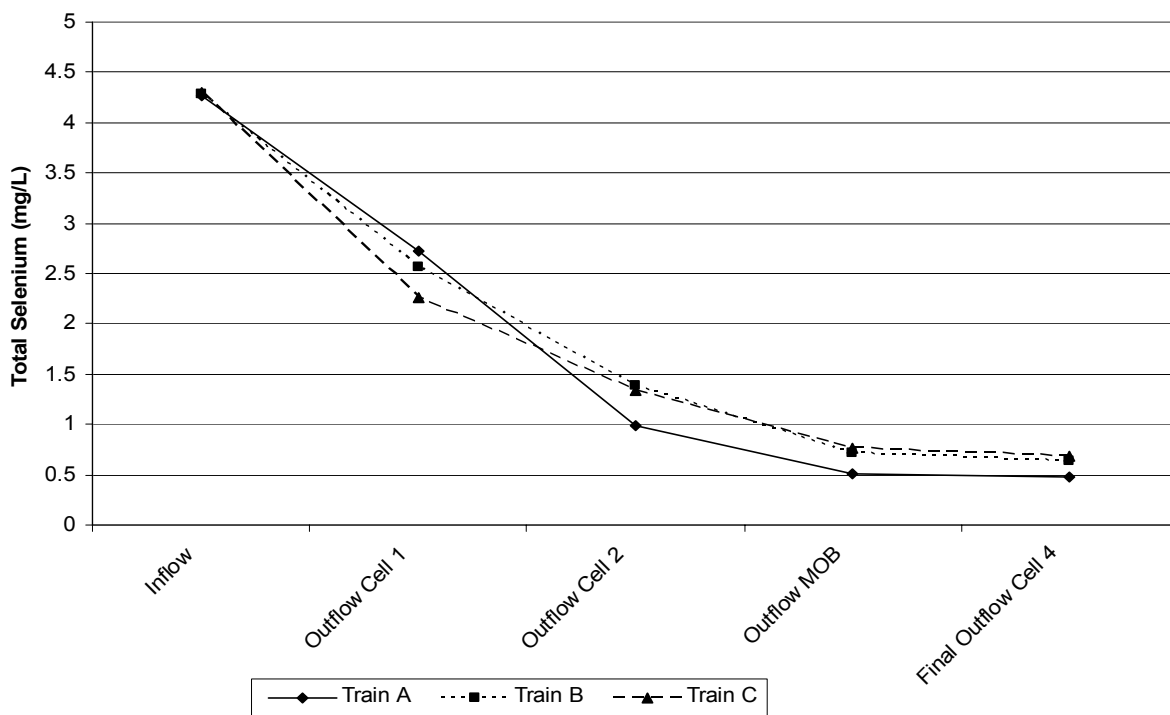


Figure 10. Average total selenium in simulated FGD wastewater treated by a pilot constructed wetland system for the high-intermediate ionic strength FGD wastewater (Weeks 11 to 20).

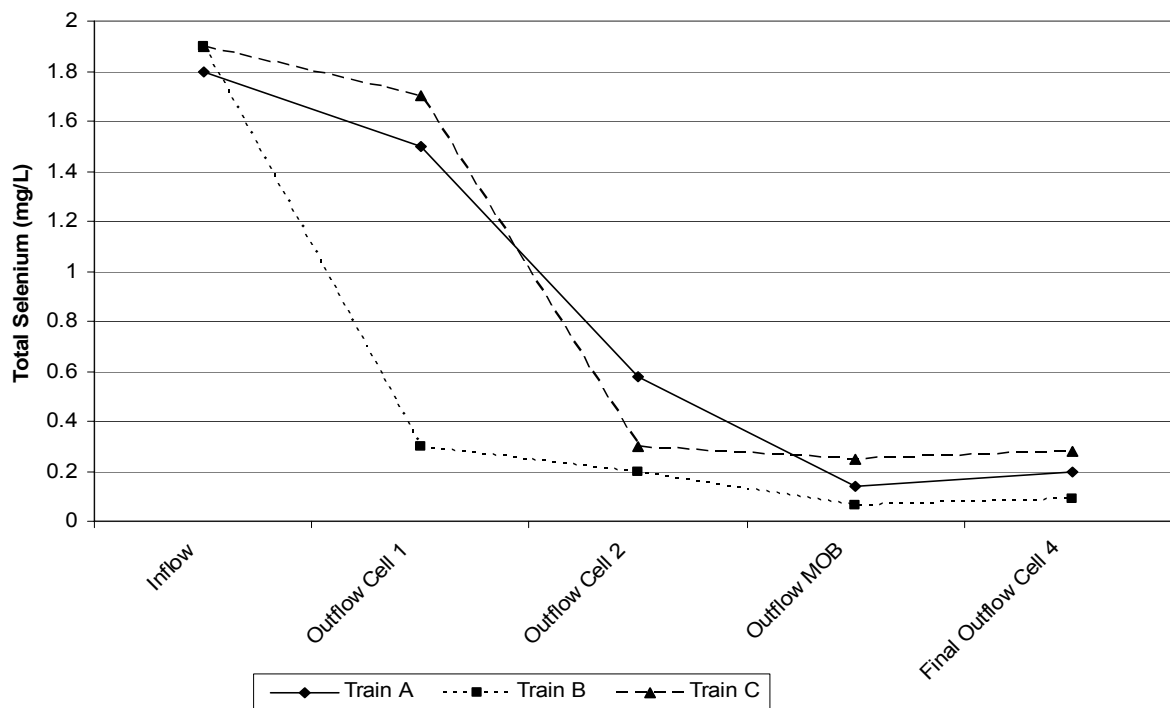


Figure 11. Total selenium in simulated FGD wastewater treated by a pilot constructed wetland system for the first week of low-intermediate ionic strength FGD wastewater (Week 23).

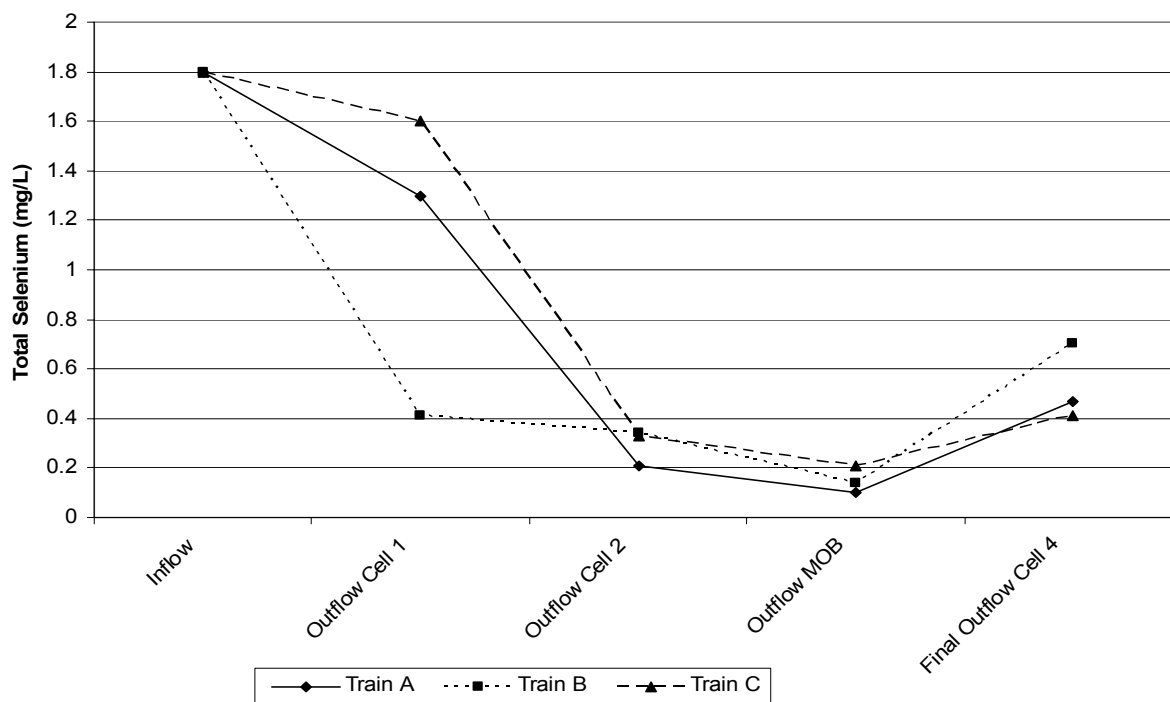


Figure 12. Total selenium in simulated FGD wastewater treated by a pilot constructed wetland system for the second week of low-intermediate ionic strength FGD wastewater (Week 24).

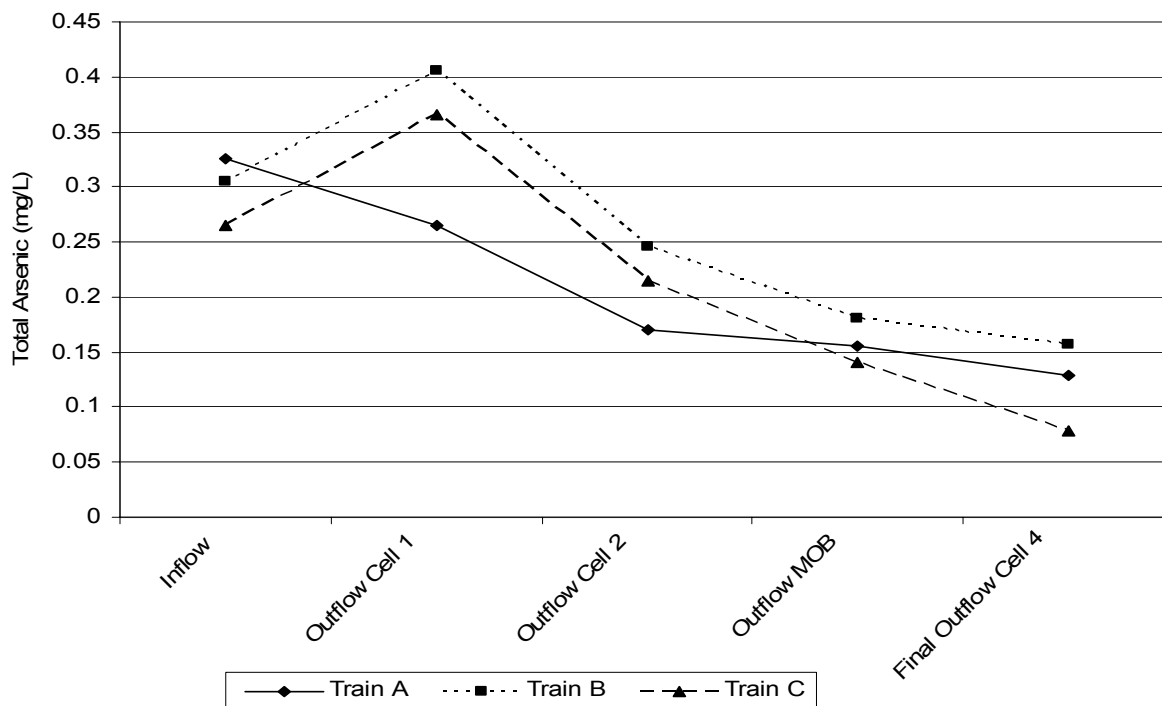


Figure 13. Average total arsenic in simulated FGD wastewater treated by a pilot constructed wetland system for the high ionic strength FGD wastewater (Weeks 9 and 10).

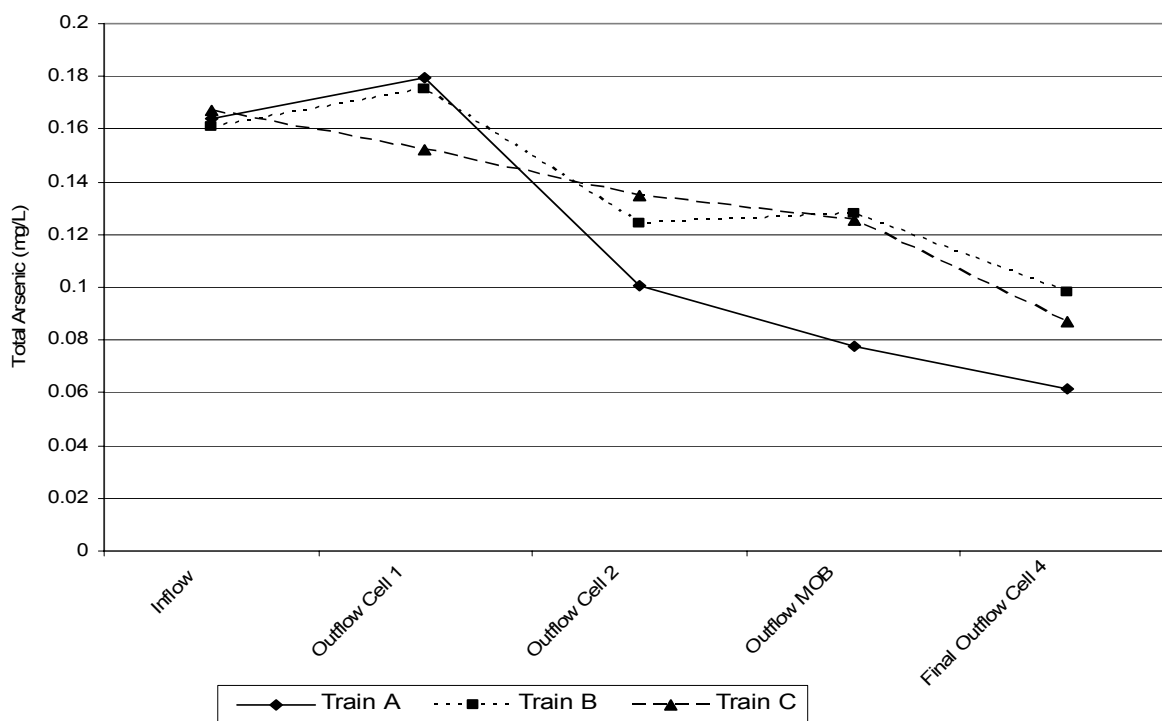


Figure 14. Average total arsenic in simulated FGD wastewater treated by a pilot constructed wetland system for the high-intermediate ionic strength FGD wastewater (Weeks 11 to 20).

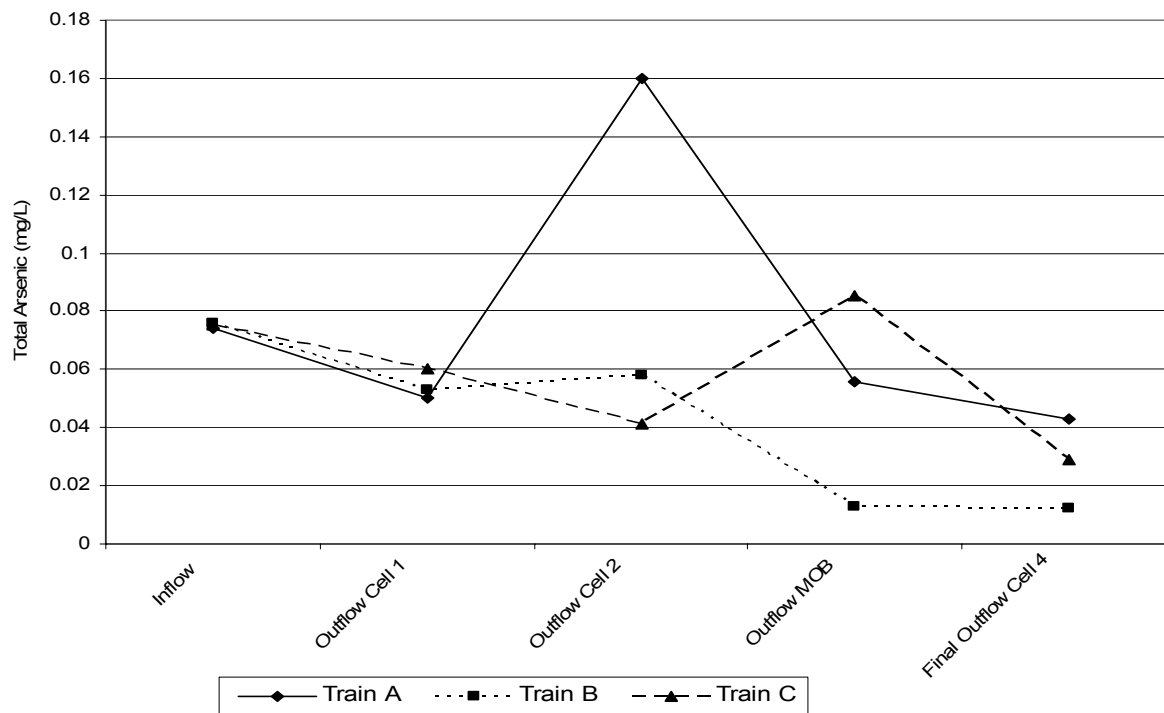


Figure 15. Total arsenic in simulated FGD wastewater treated by a pilot constructed wetland system for the first week of low-intermediate ionic strength FGD wastewater (Week 23).

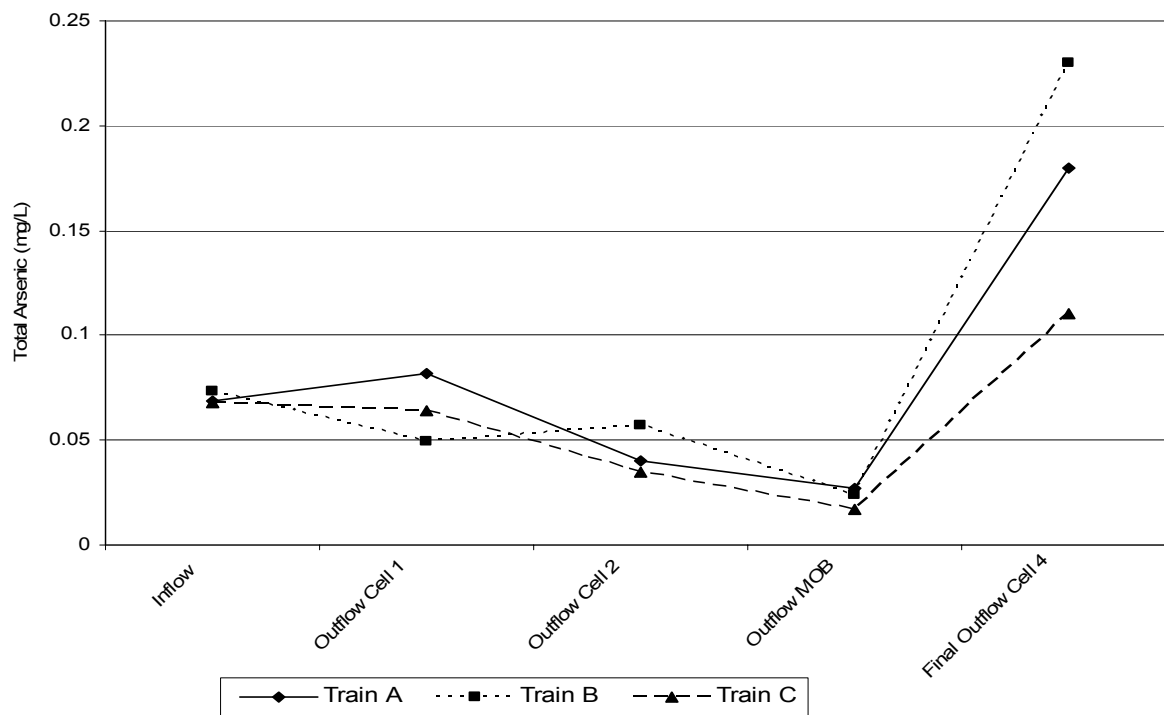


Figure 16. Total arsenic in simulated FGD wastewater treated by a pilot constructed wetland system for the second week of low-intermediate ionic strength FGD wastewater (Week 24).

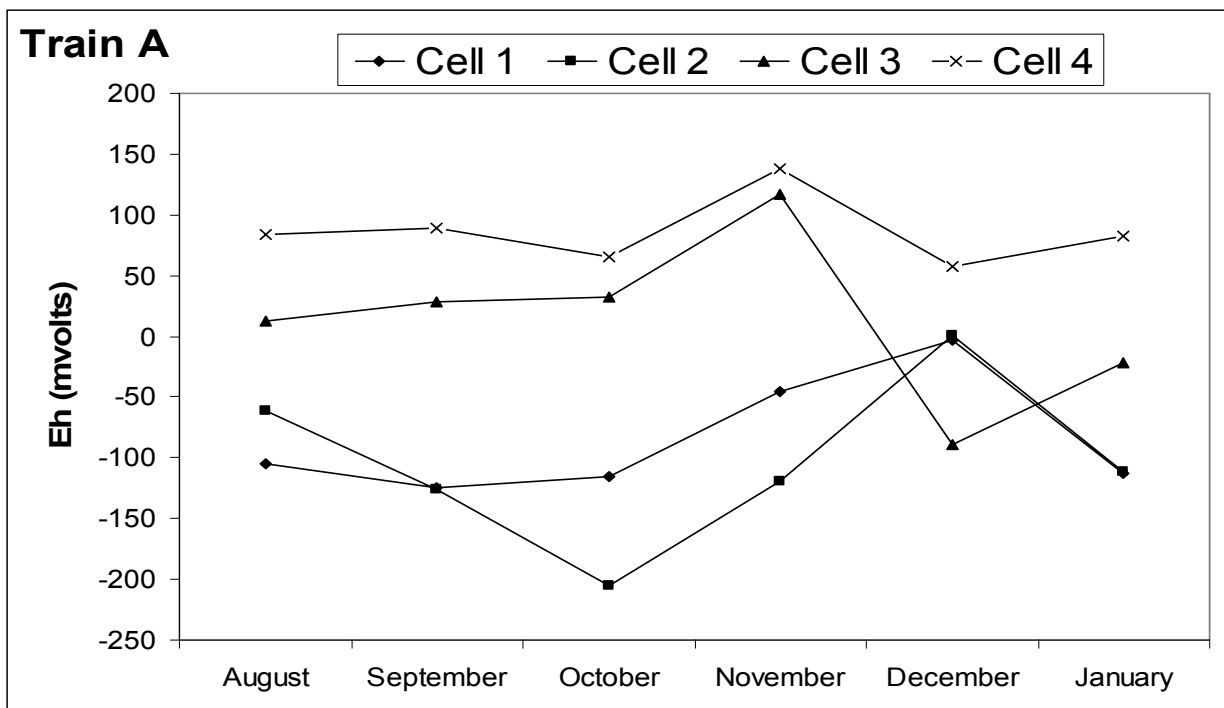


Figure 17. Hydrosol oxidation-reduction (redox) potential for Train A of the FGD pilot-scale constructed wetland system.

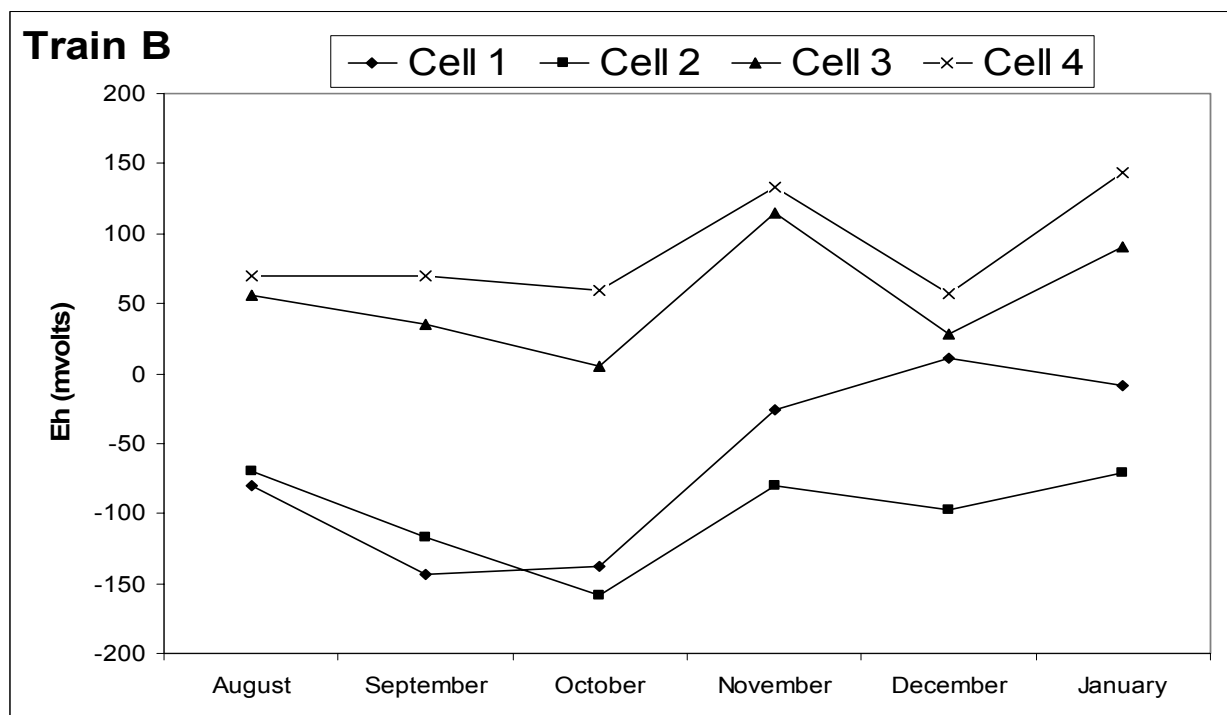


Figure 18. Hydrosol oxidation-reduction (redox) potential for Train B of the FGD pilot-scale constructed wetland system.

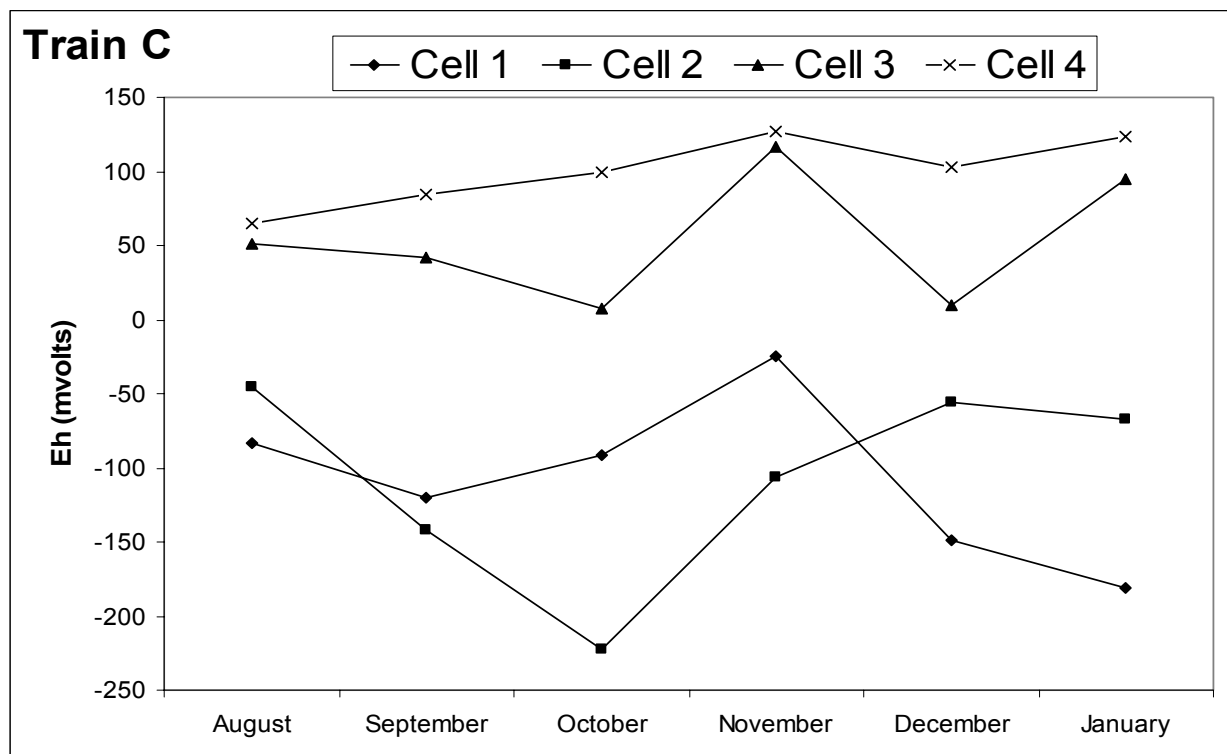


Figure 19. Hydrosol oxidation-reduction (redox) potential for Train C of the FGD pilot-scale constructed wetland system.

Table 6. Hydrosol oxidation-reduction (redox) potential in the FGD pilot constructed wetland system. Each redox value represents a mean of two measurements.

Treatment Week	Cell	Redox Potential (mV)			Treatment Week	Cell	Redox Potential (mV)		
		A Train	B Train	C Train			A Train	B Train	C Train
1 - 4	1	-105	-80	-83	14 - 17	1	-46	-26	-25
	2	-61	-70	-45		2	-120	-81	-107
	3	13	56	51		3	117	115	117
	4	84	70	65		4	138	134	127
5 - 9	1	-125	-144	-121	18 - 22	1	-3	11	-148
	2	-126	-117	-142		2	1	-98	-55
	3	28	35	43		3	-89	28	9
	4	89	70	85		4	58	57	102
10 - 13	1	-115	-138	-91	23 - 24	1	-113	-9	-182
	2	-205	-158	-222		2	-112	-71	-68
	3	32	5	7		3	-22	90	95
	4	66	59	100		4	83	144	124

Discussion

Wastewater constituents of primary concern in this study were mercury, arsenic, and selenium. These constituents and others were analyzed in the pilot constructed wetland treatment system for approximately six months using simulated FGD wastewater. During this time, the effects of manipulation and modifications of wetland hydrosol, hydroperiod, and vegetation were evaluated. These manipulations and various initial wastewater conditions have provided information for deriving removal rate coefficients necessary for determining adjustments to the system to achieve target outflow levels for these constituents.

The initial wetland cells in the series, planted with bulrush and amended with gypsum to provide sulfur ligands, effectively decreased the aqueous concentrations of mercury and arsenic dissolved in the simulated FGD wastewater. Hydrosol redox of wetland cells 1 and 2 (A, B, and C) and aqueous pH indicated that conditions were favorable for dissimilatory sulfate reduction, which provides reduced sulfide for precipitating available cationic metals such as mercury and arsenic (Brookins, 1988; Morse, 1995; Carbonell et al., 1999).

“Redox” is a term used to denote oxidation-reduction. In simple terms, oxidation is loss of electrons by a substance and reduction is the gain of electrons. Every oxidation is accompanied by a reduction, and vice versa. In wetland hydrosol, redox may be measured to indicate the propensity for certain reactions to occur in that sediment or hydrosol. Redox potential (Eh) is typically measured in hydrosols and sediments by using platinum electrodes and a portable voltmeter. Redox potential is a useful measure of sediment or hydrosol conditions. In a constructed wetland treatment system, multiple measurements of redox potential are required to achieve an accurate estimate for this parameter (bulk sediment redox potential) within each cell. From site to site within a wetland cell, redox potential can vary widely due to localized conditions (e.g. the presence of a root or root hair near an electrode). It is the general redox condition within the hydrosol of the wetland cell that is of interest in order to maintain predictable reactions and behaviors of targeted constituents in the hydrosol. Therefore, the range of redox potential measurements is an important functional control parameter for operating constructed wetlands treatment systems in a predictable manner. For oxidizing conditions, redox potentials greater than -50 mV are appropriate for the desired chemical reactions of this research (iron oxyhydroxide precipitates and decreases in COD and BOD). For mildly reducing conditions, redox potentials between -50 and -250 mV are the desirable redox ranges for elemental immobilization (sorption and precipitation) by reductive chemical pathways. Redox in constructed wetlands can be controlled by water depth and sediment amendments or composition (sediment oxygen demand).

Precipitated metal-sulfide minerals are highly insoluble in aqueous systems, which can significantly limit the availability of elements to aquatic and terrestrial biota, or in other terms, decreasing bioavailability of these elements (Morse, 1995). In anaerobic sediments and wetland hydrosols, mercury is strongly associated (i.e. bond or electrostatic attraction) by the following binding mechanisms: (1) sorption on hydrated ferric oxides, (2) surface sorption or ion exchange on mineral ion exchangers such as montmorillonite, and (3) sorption and/or chemical binding with organic material and sulfur-containing matter. Given an adequate source of sulfide, mercury will convert to a stable mercuric sulfide (HgS) with limited availability to aquatic plants and animals (Fagerstrom and Jernelov, 1972).

The preliminary design of the pilot constructed wetland system included several features for selenium removal from FGD wastewater. Not unlike other wastewater constituents, alterations in the form of selenium affect solubility and influence mobility, transport, and fate in wetland environments. At pH and redox conditions occurring in many aqueous and aerobic sedimentary environments, selenium exists as a soluble oxyanion. In strongly reduced environments, selenide ($\text{Se}^{(-II)}$), dominantly exists as H_2Se and as insoluble metal selenides (Masscheleyn and Patrick, 1993). With modifications to wetland cell 2 (addition of organic matter and zero-valent iron), enhancement of selenium removal was observed. Under reducing conditions in wetlands, elemental selenium and/or metal selenides and selenium-containing sulfur minerals govern selenium solubility. Reduction of $\text{Se}^{(VI)}$ to $\text{Se}^{(IV)}$ and $\text{Se}^{(IV)}$ to insoluble Se^0 or $\text{Se}^{(-II)}$ is expected to occur under the reduced hydrosol conditions formed by the addition of organic matter. The pilot constructed wetland system was designed to provide conditions under which insoluble selenium species (e.g., Se^0 or $\text{Se}^{(-II)}$) are likely to form (Masscheleyn et al., 1990; Masscheleyn and Patrick, 1993). In addition, zero-valent iron was added to wetland cell 2 and the final wetland cell (i.e. cell 4) to complex the residual selenium in the wastewater.

Chloride levels were not appreciably decreased by the pilot constructed wetland system. Chloride is not adsorbed by wetland hydrosol but is readily transported in aqueous phase through the system (Murray-Gulde and Rodgers, 2002). Chloride is taken up by the roots and moves upward to accumulate on shoots and leaves; however, these concentrations of chlorides within aquatic vegetation do not significantly affect the aqueous concentration as previously mentioned. Symptoms for chloride toxicity are leaf “burn” or a drying of leaf tissues. Some burn of the shoot and leaf tips was observed in the pilot constructed wetland system, indicating that salinity levels in the simulated FGD wastewater were approaching the salinity tolerance threshold for these plants. As a result, the simulated wastewater was diluted to 60% with municipal water. The wetland vegetation responded positively to the dilution.

Before the start of the low-intermediate ionic strength FGD wastewater (Week 23), further hydrosol modifications were made and HRT was increased to 30 hours per treatment stage (120 hours overall). Under these conditions, mercury removal was 96 to 97%, but only achieved the target outflow level of 0.001 mg/L in train B during week 23. Selenium removal achieved the target level of 0.2 mg/L during the treatment of the low-intermediate ionic strength FGD wastewater (weeks 23 and 24).

Conclusions

Evaluation of the pilot constructed wetland system clearly indicates that mercury, arsenic, and selenium concentrations in FGD wastewater are significantly decreased using this design. Target outflow concentrations of mercury and selenium are achievable, as indicated by favorable responses in treatment performance following adjustments to the pilot constructed wetland system.

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Scientific Final Report

TASK 2

Introduction

The second objective of this research was to determine how the observed performance of the pilot scale constructed wetland treatment system was achieved by investigating the reactions taking place in the sediments.

In a constructed wetland treatment system designed to treat constituents of flue gas desulfurization (FGD) wastewater, sediment becomes a sink for trace elements such as Hg, Se, and As. Determining total concentrations of these constituents in sediment cannot provide the required information about mobility, bioavailability, and the potential impact on the aquatic system (Michalke, 2003). The distribution of Hg, Se, and As in the constructed wetland treatment system depends on their speciation. Speciation defines a specific form of an element as to isotopic composition, electronic or oxidation state, or molecular structure (MITE, 2003). Speciation can greatly affect the fate and behavior of elements in this system, especially of those elements that exist in multiple oxidation states, such as Hg, Se, and As. These elements tend to form species differing from those of other metals.

Sequential extraction procedures have been widely used to provide critical information on the fate of trace elements in aquatic systems (Tessier *et al.*, 1979). These procedures extract trace elements from sediment with increasing reagent strengths to break down sediment matrices and release bound metals into soluble forms with the extractant (solvent) used in each step. While this process cannot be used to identify the actual form of a given metal in sediment, sequential extractions are useful in categorizing the metals into geochemical fractions (McLean and Bledsoe, 1992). Operationally-defined species characterization is the characterization of molecule groups (not single species) according to their similar behavior during an analytical procedure, such as extraction (Michalke, 2003).

Materials and Methods

Sequential extraction procedures have been developed for mercury (Lechler *et al.*, 1997; Wallschläger *et al.*, 1998; Bloom *et al.*, 2003; Beldowski and Pempkowiak, 2003), selenium (Chao and Sanzolone, 1989 and Wang and Chen, 2003), and arsenic (Miller *et al.*, 1986; Wenzel *et al.*, 2001; Schank, 2003; Bird *et al.*, 2003), utilizing common operationally-defined geochemical fractions to define the distribution of these metals in sediment. One fraction extracted is the water-soluble fraction, which contains species made up of free ions and ions complexed with soluble organic matter and other constituents. Element species in this fraction are the most mobile and potentially the most bioavailable species. Another is referred to as the exchangeable fraction, which corresponds to the form of elements that can be most readily released into the water column. This fraction includes elements that are weakly adsorbed to solid surfaces and elements that can be released by ion-exchange processes. Generally, elements in the

soluble and exchangeable fractions are considered readily and potentially bioavailable (Filgueiras *et al.*, 2002).

Two additional fractions extracted from sediment are the reducible and oxidizable fractions, both of which are relatively stable under normal wetland sediment conditions. The reducible fraction includes elements bound to Fe and Mn oxides, which are often found in large proportions in sediments. The reduction and dissolution of Fe(III) and Mn(IV) will release adsorbed trace elements. The oxidizable fraction includes element species that may be associated with various forms of organic matter through complexation. The degradation of organic matter, including detritus, under oxidized conditions can lead to the release of trace elements bound to this component. These two fractions are not considered very mobile or bioavailable (Filgueiras *et al.*, 2002).

The last fraction utilized in this research is the residual fraction, which includes species associated with the crystalline lattice structures of primary minerals and silicates. Species in this fraction can only be naturally mobilized as a result of weathering. In sequential extraction procedures, this fraction can be mobilized with a very strong acid, such as hydrofluoric acid (Filgueiras *et al.*, 2002).

By categorizing Hg, Se, and As into these geochemical fractions, hypotheses regarding reactions occurring in sediment in the constructed wetland treatment system can be tested. Furthermore, extractions of these element species are crucial for understanding metal biogeochemical behavior in constructed wetlands for FGD wastewater treatment.

Sequential extraction procedures (as outlined in Tables 7-9) were employed to operationally-define the species of Hg, Se, and As in the sediment. Concentrations of Hg, Se, and As in sediment fractions were measured according to the standard method EPA 200.8 (USEPA, 1994) using a Sciex Elan 9000 Inductively Coupled Plasma- Mass Spectrometer (ICP-MS) (Perkin-Elmer, Norwalk, CT). Sediment characteristics including pH, redox, cation exchange capacity (CEC), organic matter, solids, and particle size distribution were measured. Sediment pH, which is often one of the most important factors controlling speciation and equilibria for many contaminants, was measured using an YSI pH meter. Redox potential was measured using a digital millivolt meter and platinum-tipped electrodes prior to removing sediment samples from the wetland cell to avoid false measurements due to sediment disturbance. Particle size distribution analyses yielded three fraction sizes: sand, silt, and clay. The hydrometer method was used, as described by Gee and Gauder (1986). Percent solids of the sediment were measured according to Black (1986). The percent of organic matter in the sediment was measured using the lost-on-ignition method, as described by Nelson and Sommers (1996). Cation exchange capacity (CEC) of sediment is a measure of the reversibly bound cations in the sample. CEC was determined according to methods presented by Plumb (1981).

RESULTS

Table 7. Summary of sequential extraction procedures for Hg (modified from Lechler *et al.* 1997).

Fraction	Description	Extraction
1	Elemental	(Heating at 180°C)
2	Exchangeable	0.5 M MgCl ₂
3	Reducible	0.5 N HCl
4	Oxidizable	0.3 N NaOH / 4% CH ₃ COOH
5	Residual	(Subtraction from total Hg)

Table 8. Summary of sequential extraction method for Se (modified from Chao and Sanzalone 1989).

Fraction	Description	Extraction
1	Soluble; nonspecifically adsorbed	0.25 M KCl
2	Exchangeable; specifically adsorbed	0.1 M KH ₂ PO ₄
3	Reducible	4 M HCl
4	Oxidizable	KClO ₃ and HCl
5	Residual	HNO ₃

Table 9. Summary of sequential extraction procedure for As (modified from Wenzel *et al.* 2001 and Schank 2003).

Fraction	Description	Extractant
1	Soluble; nonspecifically sorbed	0.05 M (NH ₄) ₂ SO ₄
2	Exchangeable; specifically sorbed	0.05 M (NH ₄) ₂ H ₂ PO ₄
3	Reducible	0.2 M NH ₄ -oxalate buffer; pH 3.25
4	Oxidizable	0.2 M NH ₄ -oxalate buffer + 0.1 M ascorbic acid; pH 3.25
5	Residual	HNO ₃ /aqua regia

Sediment characteristics, including redox potential, pH, cation exchange capacity (CEC), percent organic matter (OM), percent solids, and particle size distribution, are listed in Table 9. The redox potentials of sediment in the first and second wetland cells were -410 mV and -337 mV, respectively. Sediment in the fourth wetland cell had a redox potential

of -26 mV. Measurements of sediment pH ranged from 6.63 to 6.80, and the cation exchange capacity of sediment ranged from 4.63 me 100g⁻¹ to 6.83 me 100g⁻¹. Percent organic matter and percent solids in all sediments ranged from 1.95% to 2.52%, and 74.67% to 79.14%, respectively. According to the particle size distribution of the sediments, a majority of the sediment was sand, with small fractions of clay and silt.

Results from the sequential extractions of Hg, Se, and As are summarized in Figure 20. The total sediment concentrations of Hg, as determined by the summation of individual fraction concentrations, were 0.0686 mg/kg, 0.0383 mg/kg, and 0.0282 mg/kg in the first, second, and fourth wetland cell, respectively. Mercury is primarily in its elemental fraction in the sediment. Unless the sediment is strongly oxidized, mercury in this fraction will remain immobile and will not be bioavailable to plants and organisms. Total sediment concentrations of Se were 9.353 mg/kg, 19.891 mg/kg, and 16.609 mg/kg in the first, second, and fourth wetland cell, respectively. Selenium is distributed amongst soluble, exchangeable, reducible, oxidizable, and residual fractions. Selenium is a required micronutrient; therefore, these results are not surprising. In a system containing large plant densities, selenium is likely to be readily available for plant uptake. Finally, total sediment concentrations of As were 25.87 mg/kg, 24.92 mg/kg, and 25.84 mg/kg in the first, second, and fourth wetland cell. For the most part, arsenic is not bioavailable to plants and organisms, as it resides primarily in the residual fraction.

Table 10. Summary of sediment characteristics.

Sediment	pH	Redox ^a	CEC ^b	% OM ^c	% Solids	Particle Size Distribution		
						% Sand	% Clay	% Silt
First wetland cell	6.74	-410	6.83	2.5%	79.1%	91.4%	5.5%	3.0%
Second wetland cell	6.63	-337	4.63	1.9%	78.8%	91.5%	5.5%	2.9%
Third wetland cell	6.80	-26	5.08	2.2%	74.6%	89.2%	5.6%	5.1%

^a Redox potential, measured in millivolts

^b Cation exchange capacity (me 100g⁻¹)

^c Organic matter

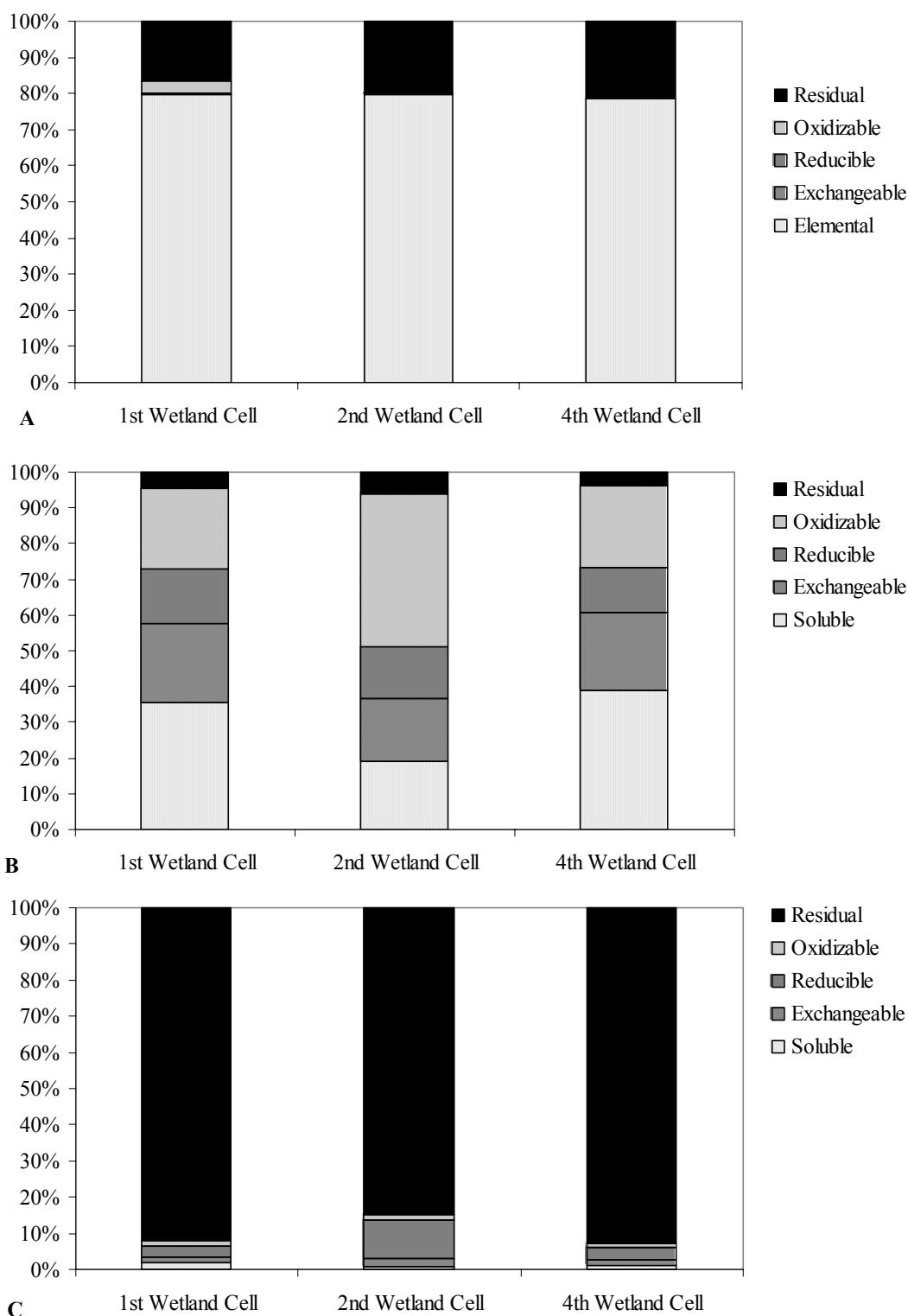


Figure 20. Sequential extraction of Hg (A), Se (B), and As (C) in sediment collected from the first, second, and fourth planted wetland cells.

Discussion and Conclusions

Sequential extraction procedures were used as a quantitative measure to evaluate the immobilization of these elements of concern in the sedimentary component of these systems. Data gathered by this procedure indicate that the majority of As, Hg, and Se are bound to residue phases within the sediment, meaning that the dissolution or re-solubility of these elements are unlikely to occur under natural environmental conditions set within this treatment system (not thermodynamically favored). Mercury was observed to exist in two main phases: the residual and elemental, both of which are highly insoluble in the aqueous media and relatively stable in terms of transfers and transformations to any other phase, except for further transfers into the residual phase. Most selenium existed in phases that should not contribute to bioavailability or toxicity, but this will be further confirmed with sediment toxicity experiments. Arsenic concentrations were highly correlated with the residual phase within these sediments and should not elicit toxicity effects due to its binding stability. Data collected from these experiments are utilized along with toxicity tests to confirm bioavailability parameters.

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Scientific Final Report

TASK 3

Introduction

For purposes of this research, simulated FGD wastewaters (based on projections from actual FGD wastewaters) were used as models for treatment of FGD wastewaters. These simulated FGD wastewaters were produced by amending municipal water with arsenic (As), mercury (Hg), selenium (Se), chloride (Cl⁻) and sulfate (SO₄²⁻) salts. Three elements (As, Hg, and Se) were identified as targeted constituents for this treatment process due to their relatively high concentrations in the actual FGD wastewaters, as well as background concentrations or pre-existing problems associated with these elements at most power company sites. For this research, simulated FGD wastewaters were treated using specially designed pilot-scale constructed wetland treatment systems. These systems consisted of a detention basin followed by three treatment trains with four wetland treatment cells in each train. Discharged wastewater (i.e. outflow wastewater) from the full-scale treatment system has to meet water quality criteria set forth under the Clean Water Act and the National Pollution Discharge Elimination System (NPDES). Along with aqueous concentration limits for selective elements, discharged wastewater must not elicit significant toxicity to testing organisms.

The first objective of this research was to measure changes in concentrations of targeted constituents in simulated FGD wastewater before and after treatment by a constructed wetland treatment system (untreated inflow versus final outflow of treated FGD wastewater). These measurements helped to characterize the potential chemical exposure that organisms may encounter if exposed to these wastewaters. Another objective of this research was to evaluate the toxicity of aqueous simulated FGD wastewater to *Ceriodaphnia dubia* Richard and *Pimephales promelas* Rafinesque before and after treatment by the pilot-scale constructed wetland treatment system. These two organisms are commonly used in the United States for testing waters and wastewaters (U.S. EPA, 1984). *C. dubia* is a sentinel invertebrate species widely used for toxicity testing in NPDES programs (Spehar and Fiandt, 1986, Mount *et al.*, 1997 Brix *et al.*, 2001). *P. promelas* is a freshwater minnow that is also widely distributed in North America and is found in lentic systems. Responses of *P. promelas* to exposures of metals and organics differ from those of *C. dubia*; therefore both test species were used in this research in order to better understand any toxicity of the simulated FGD wastewater (Spehar and Fiandt, 1986, USEPA, 1987, Mount *et al.*, 1997). Toxicity endpoints for *C. dubia* included mortality and reproduction and for *P. promelas* endpoints included mortality and growth.

An objective of this research also included toxicity assessment of the sediments within the pilot-scale constructed wetland treatment systems. Bulk sediment toxicity testing was conducted on previously exposed sediment (hydrosol) within the constructed wetland treatment systems for remediation of simulated FGD wastewaters (Task 1). Two commonly used sediment dwelling organisms (*Hyalella azteca* and *Chironomus tentans*) were used to measure responses of survival and growth after an exposure period of 10

days to the treatment hydrosol. To determine the toxicological significance of these results or responses, organisms exposed to sediments from the constructed wetland treatment system were compared to controls tested in reference sediment and moderate hardness water.

MATERIALS AND METHODS

Simulated FGD wastewaters used for this research were modeled after actual FGD wastewater projections. Arsenic and mercury were amended using a single reagent salt for each element. Selenium, however, was formulated using two reagent salts (sodium selenite and sodium selenate) to simulate the speciation of selenium found in actual FGD wastewater. All amendments and mixing of the simulated FGD wastewaters were conducted in the equalization basin of the system. The species of each element used in this research, and the source compound used for amendment of the simulated FGD wastewaters are listed in Table 11.

Sample Collection and Analysis

Water samples used for analysis (1000-ml) and toxicity testing (4-L) were collected in 1000-mL Nalgene® containers from the equalization basin and final outflow cell from the treatment system. Outflow samples were collected on a time course commensurate with hydraulic retention time (HRT). Of the 1000-mL water sample collected for analysis, a 10-mL aliquot was immediately preserved in the laboratory with concentrated trace metal grade nitric acid to pH < 2 for metals analysis, while the remaining volume was retained in order to complete the remaining analyses such as chemical oxygen demand (COD), pH, alkalinity, hardness, conductivity, and toxicity testing. Methods and detection limits for all analyses are listed in Table 12. In order to evaluate variance in concentrations of targeted constituents and its effect on toxicity in FGD wastewaters, two simulated FGD wastewaters were treated using the constructed wetland treatment system. These samples were collected during loading of the low-intermediate ionic strength FGD wastewater (treatment weeks 23 and 24), each with inflow (pre-treatment) and outflow (post-treatment). However, for clarity purposes throughout the remainder of this report, treatment Week 23 and 24 will be denoted as Sample One and Two.

Table 11. Elements and form used for amendments of simulated FGD wastewater.

Element	Form	Compound
Arsenic	As(+III) 100%	Sodium
		arsenite
Mercury	Hg(+II) 100%	Mercuric
		nitrate
Selenium	Se(+IV) 33.333%	Sodium selenite
	Se(+VI) 66.666%	Sodium selenate

Table 12. Analytical methods for parameters monitored for FGD wastewater.

Parameter	Method	Detection Limit
Temperature	Direct Instrumentation: YSI Model 52	0.5°C
pH	Direct Instrumentation: Orion Model 420A	0.01
Conductivity	Direct Instrumentation: YSI 30	0.1 µS/cm
Alkalinity	Standard Methods: 2320 B	2 mg/L as CaCO ₃
Hardness	Standard Methods: 2340 C	2 mg/L as CaCO ₃
DO ¹	Direct Instrumentation: YSI Model 52	0.1 mg/L
COD ²	Closed reflux colorimetry (HACH - modified from Standard Methods: 5220D)	3 mg/L
NPOC ³	Shimadzu TOC-V CPH Total Organic Carbon Analyzer	4 µg/L
BOD ₅ ⁴	Standard Methods: 5210 B	0.1 mg/L
TSS ⁵	Standard Methods: 2540 D	0.1 mg/L
TDS ⁶	Standard Methods: 2540 C	0.1 mg/L
Selenium	Inductively Coupled Plasma (ICP): EPA 200.7	0.0022 mg/L
Mercury	Mercury Analyzer: EPA 245.1	0.0001 mg/L
Chloride	HACH Colorimetric Method 8207	25 mg/L
Sulfate	Standard Methods: 4500 E	1 mg/L
Arsenic	ICP: EPA 200.7	0.0013 mg/L

¹ Dissolved Oxygen² Chemical Oxygen Demand³ Non-purgable Organic Carbon⁴ Five-day Biological Oxygen Demand⁵ Total Suspended Solids⁶ Total Dissolved Solids

Constructed Wetland Treatment System

Specially designed pilot-scale wetland treatment systems were constructed at Clemson University in Clemson, SC. The system consisted of a 6,800-L upstream equalization basin followed by three parallel treatment trains. The equalization basin was incorporated into this treatment process to simulate full-scale design parameters, such as settling of particulates and equilibration of elements within the bulk aqueous phase. Each treatment

train consisted of four stages in series (from upstream to downstream), including two wetland cells planted with *Schoenoplectus californicus* (C.A. Mey.) Palla (California bulrush), a gravel manganese oxidation basin, and a final wetland cell planted with *Typha angustifolia* Linneus (narrowleaf cattail). Each treatment cell consisted of a 378-L Rubbermaid® utility tank. Overlying water depth and hydrosol depths were 30 cm each in the wetland cells. Total hydraulic retention time (HRT) was four days (24 hours per treatment stage). Simulated FGD wastewater was mixed in the equalization basin and pumped to each treatment train at a constant flow rate (ml/min) using FMI® (Fluid Metering, Inc.) piston pumps (one pump per treatment train). Flow of FGD wastewater through the treatment system trains was surface flow propagated by gravity, and cells were connected by PVC piping.

Toxicity Experiments

Aqueous Toxicity

Treatment efficiency of simulated FGD wastewaters by pilot-scale constructed wetland treatment systems was assessed by measuring toxicity endpoints for *C. dubia* and *P. promelas*. Toxicity endpoints for *C. dubia* included mortality and reproduction, and for *P. promelas* endpoints was mortality. These two organisms are commonly used in the United States for testing of waters and wastewaters (Lewis *et al.*, 1994). *C. dubia* is a freshwater microcrustacean, widely distributed in temperate waters throughout North America. *P. promelas* is a freshwater minnow that is also widely distributed in North America and is found in lentic systems. For aqueous toxicity assessment, 7-d chronic toxicity experiments were conducted with both species using U.S. EPA methods (Lewis *et al.*, 1994). Test treatments included an untreated control, as well as inflow and final outflow dilutions of simulated FGD wastewater. Dilutions were made using moderate hardness laboratory water as defined by Lewis *et al.* (1994).

Bulk Sediment Toxicity

To further understand the chemical fate of As, Hg, and Se in constructed wetland treatment systems, evaluation of sediment toxicity was conducted with previously exposed hydrosol used in Task One of this report. Sediment dwelling organisms such as *Hyaella azteca* and *Chironomus tentans* can provide useful information on the bioavailability of toxic elements or molecules when exposed to non-contaminated or contaminated sediment. *H. azteca* and *C. tentans* have been used in many toxicity experiments due to their interaction with freshwater sediments and relative sensitivity to contaminants in the sediments (EPA 2000). These experiments along with studies of elemental binding strength (Task Two) can be used to further assess the risk posed by sediment used in treatment of simulated FGD wastewater with constructed wetland treatment systems. For sediment toxicity assessment, 10-d static toxicity experiments were conducted with *H. azteca* and *C. tentans* following U.S. EPA methods (EPA Test Methods 100.1 and 100.2). Test treatments included an untreated control and sediment samples from wetland cells 1, 2, and 4. Sediment toxicity experiments were not conducted with wetland cell 3, since sediment was not used in the construction of this cell (i.e. manganese-oxidation basin). Each experimental treatment included site-sediment

volumes of 40 ml and 160 ml of moderately hard water and three replicates. Controls were tested in a reference sediment and moderately hard water at the same ratios listed above. Survival and growth were measured at the conclusion of the test (10-d). Statistical differences were evaluated using chi-square analysis and analysis of variance (ANOVA) with least-squared differences (LSD) as the mean separator. *H. azteca* were supplied food in the form of three 7 mm maple leaf discs from initiation to conclusion of the experiments. *C. tentans* were feed 0.5 ml of ground tetramin daily.

RESULTS

Removal of Targeted Constituents for FGD Wastewater used in Toxicity Testing

In order to understand data from toxicity experiments and further characterize simulated FGD wastewaters, analyses of parameters such as COD, pH, alkalinity, hardness, conductivity, and solids were measured. These data for Sample One and Sample Two simulated FGD wastewaters are in Table 12. Results of the first objective, to measure the removal of the targeted constituents (As, Hg, Se) from the inflow to the outflow by the constructed wetland treatment system, are included in Table 13.

These data listed in Table 13 indicate that concentrations of arsenic, mercury, and selenium decreased from the inflow to final outflow of the treatment system, with the exception of arsenic in sample 2, in which the aqueous concentration increased from 0.071 mg/L to 0.16 mg/L. In this situation, it is assumed that possible particulate contamination occurred in the metal analysis aliquot. Another constituent of concern and potential source of toxicity, in the simulated FGD wastewater is chlorides. The concentration of chlorides decreased from inflow to outflow of treatment system for Sample One simulated FGD wastewater. However, in Sample Two simulated FGD wastewater, the concentration of chlorides increased from 5250 mg/L to 5416 mg/L.

Table 13. Water quality parameters of simulated FGD wastewater from inflow to final outflow of the pilot-scale constructed wetland treatment systems.

Parameter	Sample 1 Inflow	Sample 1 Outflow	Sample 2 Inflow	Sample 2 Outflow
Temp °C	19.93	19.88	20.13	19.69
DO mg/L	8.59	8.75	8.37	8.69
pH	6.68	6.73	6.55	6.9
Alk mg/L	58	74	68	82
Hard mg/L	12800	9400	12400	11700
Cond mS	9.43	9.91	12.88	13.87
BOD mg/L	11.03	3.1	9.92	3.25
COD mg/L	241	182	236	186
TSS mg/L	65.05	83.87	67.75	121.8
TDS mg/L	12536	12753	11998	11826
NPOC mg/L	228.52	33.04	93.98	42.67
As mg/L	0.073	0.028	0.071	0.17
Se mg/L	1.8	0.19	1.8	0.52

Hg mg/L	0.16	0.005	0.16	0.00733
Cl ⁻ mg/L	4150	3800	5250	5416
SO ₄ mg/L	407	478	457	625

Aqueous Toxicity Experiments

Survival (Inflow to Final Outflow)

To compare differences in survival from the inflow to final outflow of the treatment system using *C. dubia* and *P. promelas*, two by two contingency tables (chi squared) comparing survival probabilities of inflow vs. outflow dilutions of the simulated FGD wastewater were used. Differences were evaluated using Fisher's exact test (two sided probability $p=0.05$).

Survival data for Sample One FGD wastewater (Figure 21) indicate that for *C. dubia* there was a significant decrease in toxicity from inflow to final outflow of the system for the dilutions of 3.125%, 6.25%, 12.5%, and 25% wastewater. Survival data for Sample Two (Figure 22) indicate that for *C. dubia* there was a significant decrease in toxicity from inflow to final outflow for the dilutions of 6.25%, 12.5%, and 25% wastewater. For *P. promelas* survival data for the Sample One FGD wastewater (Figure 23) indicate that none of the dilutions of wastewater were statistically different from inflow to final outflow. Survival data for Sample Two (Figure 24) show that for *P. promelas* there was a significant decrease in toxicity for the dilutions of 6.25% and 12.5% wastewater.

C. dubia reproductive data (treatments; i.e. dilutions) were evaluated in comparison to control organisms using a one-way analysis of variance test (ANOVA; $\alpha=0.05$) and mean separation using a least significant difference test (LSD). For Sample One FGD wastewater (Figure 25), there was a significant increase in reproduction from the inflow to the outflow of the treatment system for the dilutions of 0.78%, 1.56%, 3.125%, and 6.25% wastewater. For Sample 2 FGD wastewater (Fig 2.6) there was a significant increase in reproduction for the dilutions of 3.125%, 6.25%, and 12.5% wastewater.

An additional objective of these toxicity experiments was to compare and contrast differences in responses of *C. dubia* and *P. promelas* to simulated FGD wastewaters. To compare differences in survival of *C. dubia* and *P. promelas*, a two-by-two contingency table (chi-squared) was used to compare the survival probabilities of *C. dubia* vs. *P. promelas* exposed to varying dilutions of simulated FGD wastewaters. Differences were further evaluated using Fisher's exact test (two sided probability $p=0.05$). For Sample One simulated FGD wastewater (Figure 27), there was a significant difference between the responses, in terms of mortality, of *C. dubia* and *P. promelas* to wastewater dilutions of 3.125%, 6.25%, 12.5%, and 25%. The observed potency (response in organism mortality to a change in percentage dilution of wastewater) of Sample One for *C. dubia* was 21.32 and 1.2 for *P. promelas*. For Sample Two (Fig 28) the responses of *C. dubia* and *P. promelas* were significantly different only at a wastewater dilution of 6.25%. The observed potency of Sample Two for *C. dubia* was 4.11 and 7.2 for *P. promelas*.

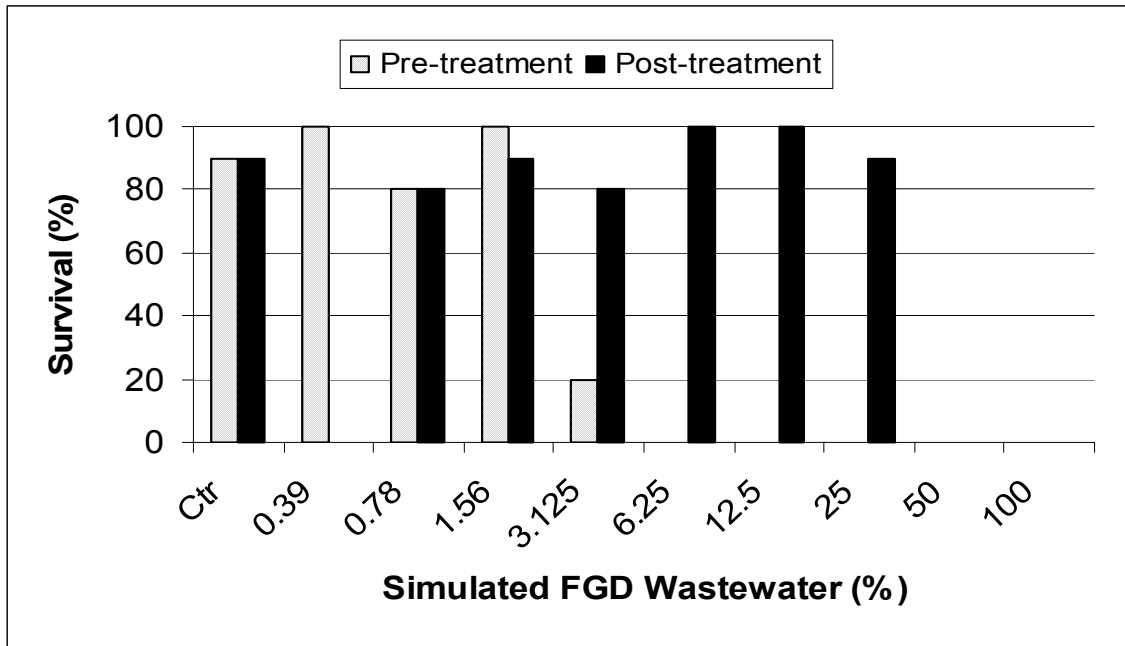


Figure 21. Response, in terms of survival, of *C. dubia* to the inflow and the outflow from the treatment system for Sample One simulated FGD wastewater (Trains A, B, and C combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested.

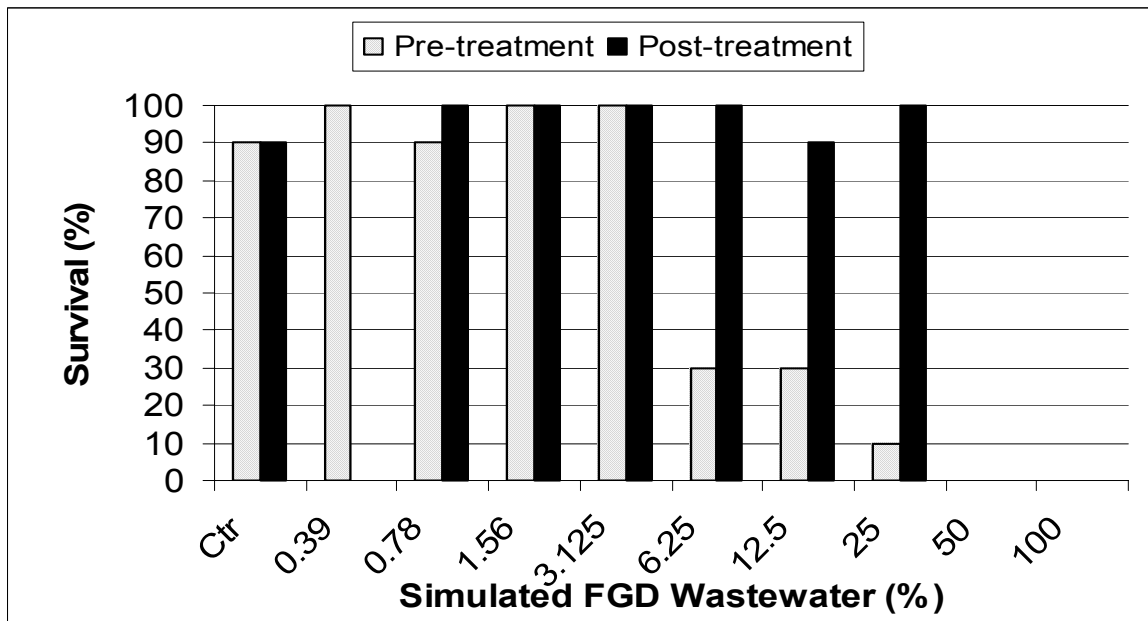


Figure 22. Response, in terms of survival, of *C. dubia* to the inflow and the outflow from the treatment system for Sample Two simulated FGD wastewater (Trains A, B, and C combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested.

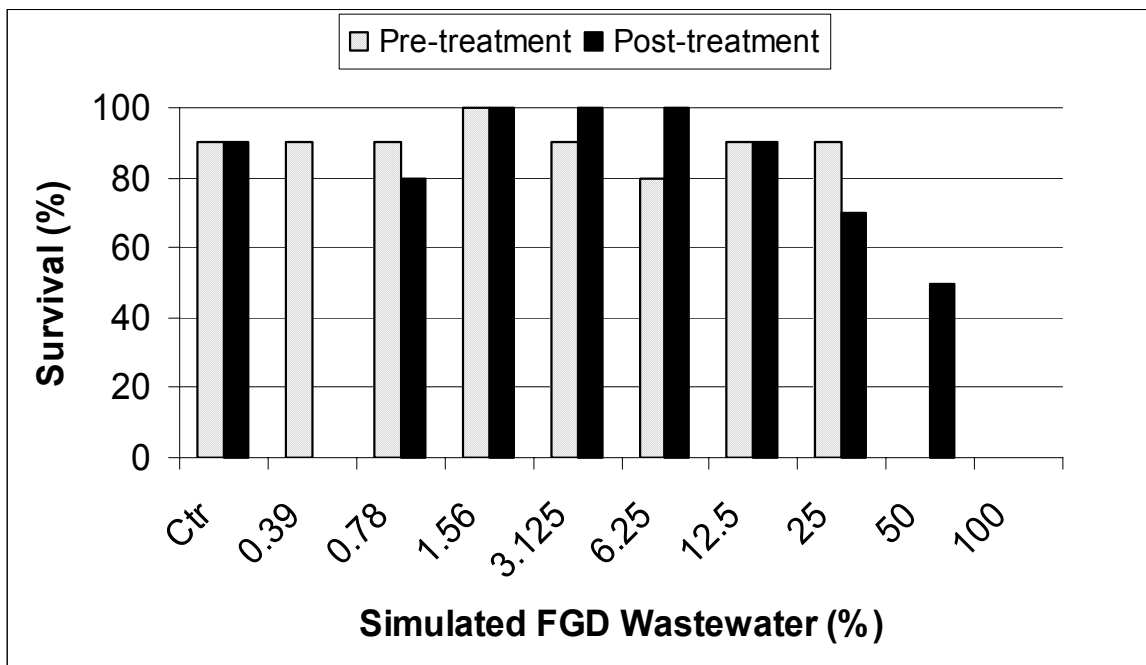


Figure 23. Response, in terms of survival, of *P. promelas* to the inflow and the outflow from the treatment system for Sample One simulated FGD wastewater (Trains A, B, and C combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested.

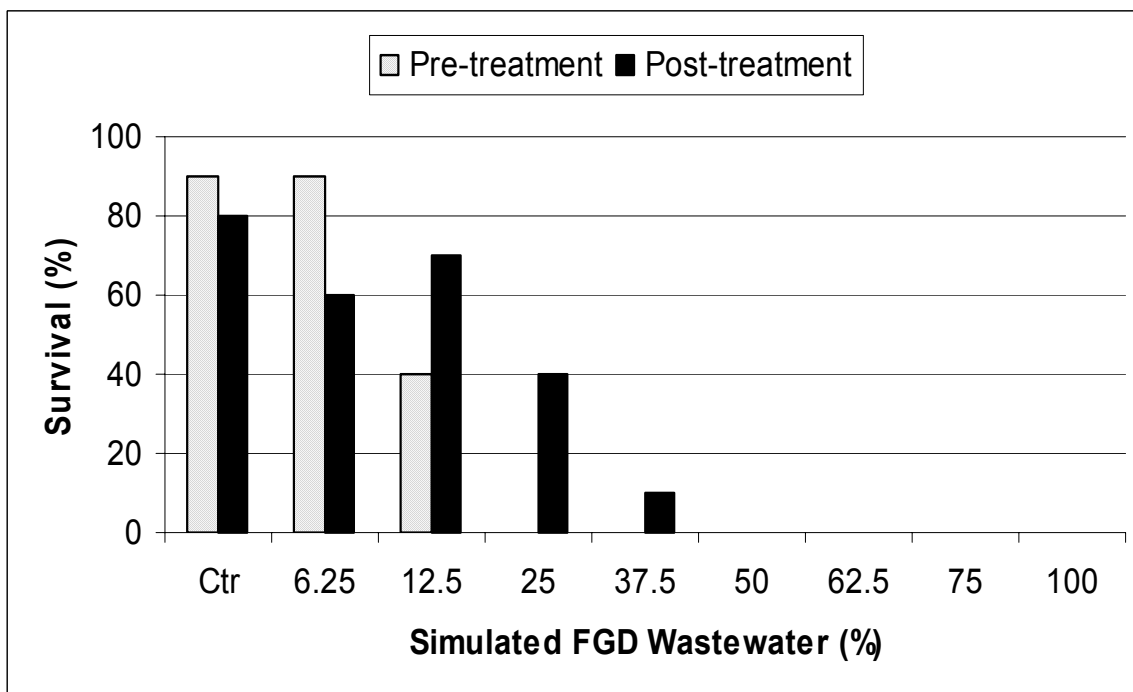


Figure 24. Response, in terms of survival, of *P. promelas* to the inflow and the outflow from the treatment system for Sample Two simulated FGD wastewater (Trains A, B, and C combined).

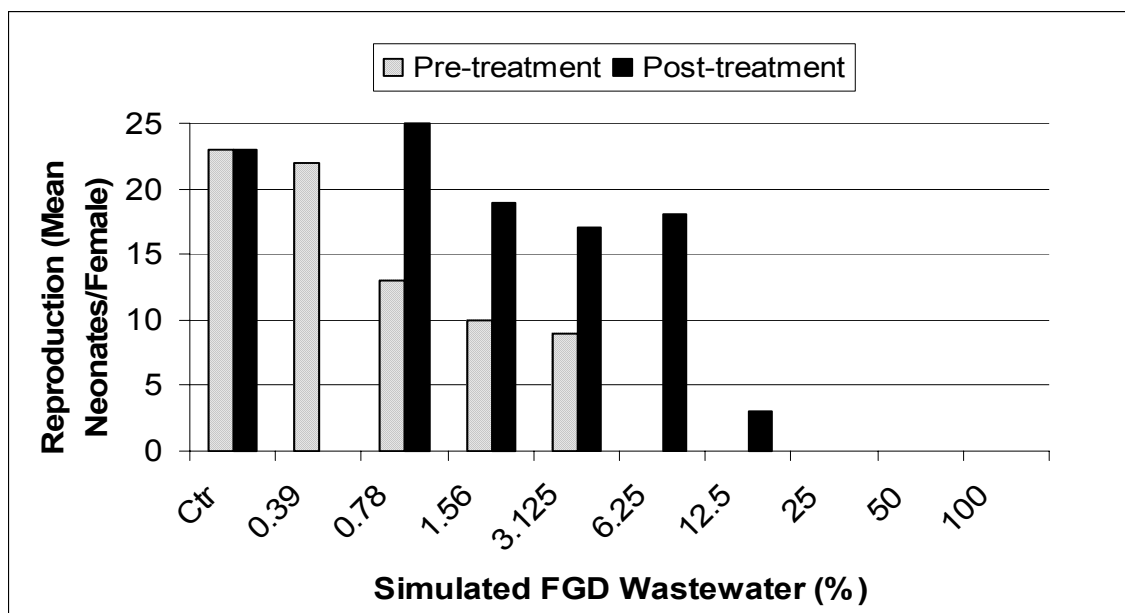


Figure 25. Response, in terms of reproduction, of *C. dubia* to the inflow and the outflow from the treatment system for Sample One simulated FGD wastewater (Trains A, B, and C combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested.

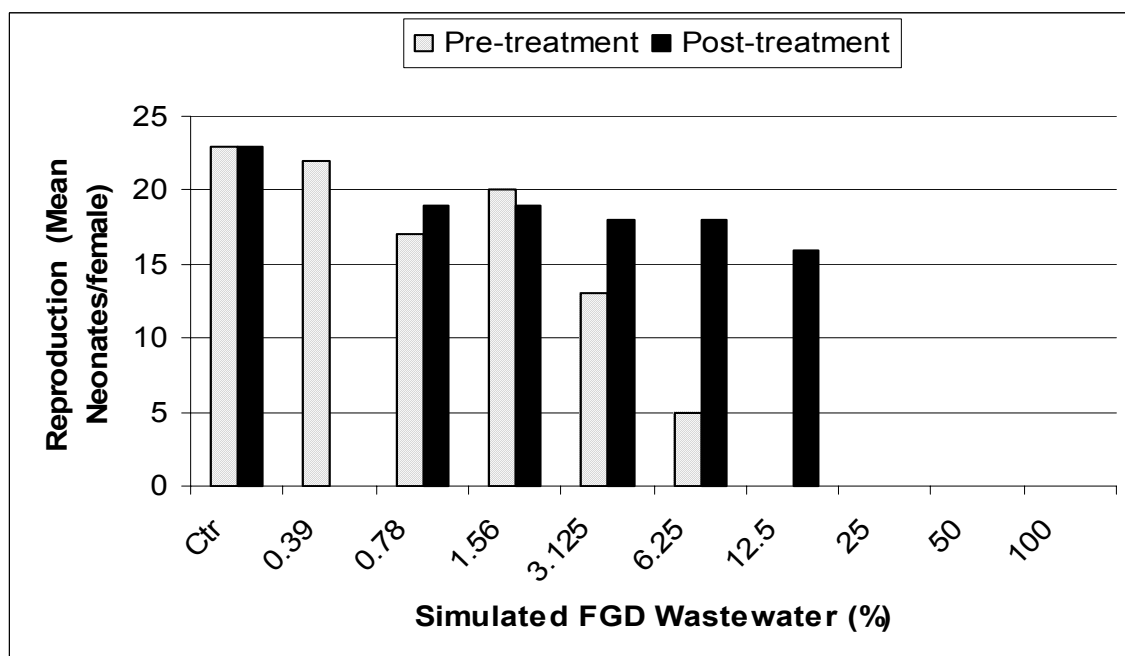


Figure 26. Response, in terms of reproduction, of *C. dubia* to the inflow and the outflow from the treatment system for Sample Two simulated FGD wastewater (Trains A, B, and C combined). Concentrations of 0.39% post-treatment and 50% pre-treatment were not tested.

Another component of this research was to measure changes in responses of *C. dubia* and *P. promelas* to two temporally separated samples of simulated FGD wastewater each possessing different concentrations of constituents. To compare differences in survival of *C. dubia* and *P. promelas*, a two by two contingency table (chi squared) was used to compare survival probabilities of Sample One vs. Sample Two simulated FGD wastewater dilutions. Differences were confirmed using Fisher's exact test (two sided probability $p = 0.05$) due to the sample sizes tested ($n < 10$).

When comparing *C. dubia* survival between Sample One and Two FGD wastewaters (Figure 29), only the dilutions of 3.125% were statistically different from each other. When comparing *P. promelas* survival between Sample One and Two FGD wastewaters (Figure 30), only the dilutions of 25% were statistically different, and the dilutions of 12.5% were close to being statistically different with a p value of 0.0573. Simulated FGD wastewaters used in this research were diluted as low as 0.39%, in order to find the no observable effect concentration (NOEC) defined in this research as the concentration at which reproduction and mortality were not affected (dilutions not statistically different in comparison to control organisms for the desired test parameter). Toxicity observed in the tested dilutions (both samples) was not solely due to the targeted constituents of concern (As, Hg, and Se), but primarily dependent on the chloride concentrations. This statement should be reconsidered when chloride concentrations are diluted and do not cause significant effects on mortality or reproduction. The NOEC for a chloride-only experiment was 640 mg/L as Cl^- (7-day static/renewal toxicity test). With these data, it is a fair assumption that toxicity observed at or below 640 mg/L of chlorides is due to multiple elements within the matrix tested. Therefore, the pilot-scale constructed wetland treatment systems can be classified as performing optimally when NPDES limits and toxicity tests are met, but only after dilutions or co-management other mixing waters, since chlorides are residual ions in solution that cannot be removed using this treatment system.

The constructed wetland treatment systems used in this research were not designed to remove chlorides from the wastewater; and nearly 100% of chlorides input into the system remain in solution after discharge from the final wetland cell (variation in concentrations occur, i.e. evaporation and precipitation of water). Concentrations of chlorides in the undiluted pre-treatment FGD wastewaters and the undiluted post-treatment samples exceeded the known 48-hr LC_{50} values reported in literature for *C. dubia* and *P. promelas* using MgCl_2 and CaCl_2 . Calcium chloride and magnesium chloride are the predominant chlorides found in the FGD wastewater. The 48-hr LC_{50} values of *C. dubia* for these two salts reported in literature are 0.88 and 1.83 g/L respectively, and 96-hr LC_{50} s were 2.12 and 4.63 g/L respectively for *P. promelas* (Mount *et al.*, 1997). Sample One simulated FGD wastewater had chloride concentrations in the pre-treatment and post-treatment that ranged from 3475 mg/L to 4150 mg/L. For Sample Two simulated FGD wastewater, chloride concentrations ranged from 5075 mg/L to 5650 mg/L throughout the test duration from inflow to final outflow.

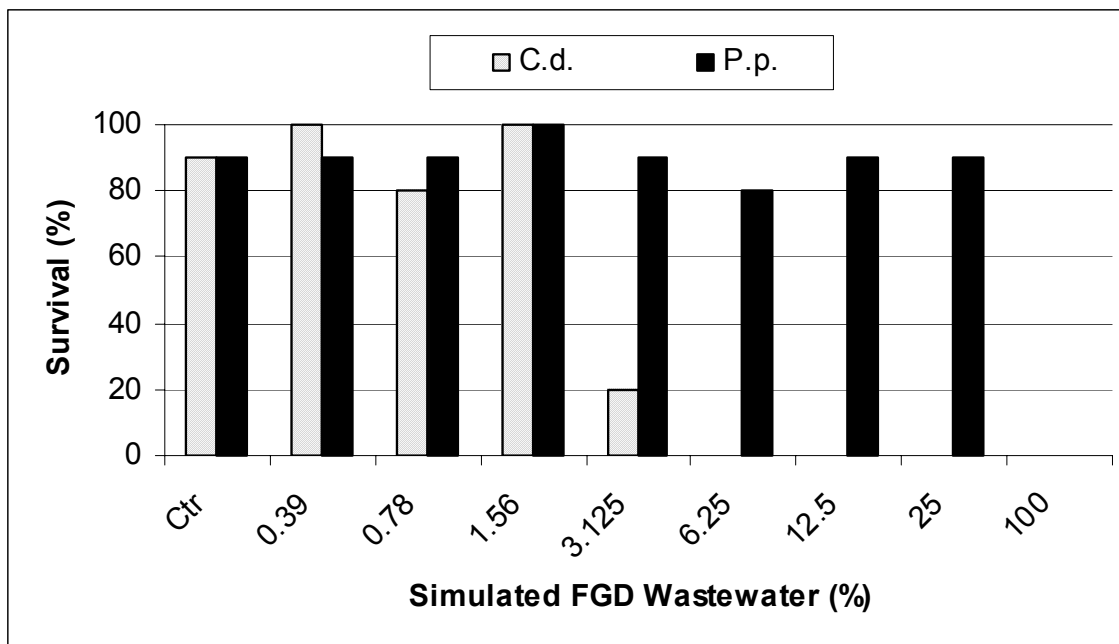


Figure 27. Comparative responses, in terms of survival, of *C. dubia* and *P. promelas* to simulated FGD wastewater Sample One.

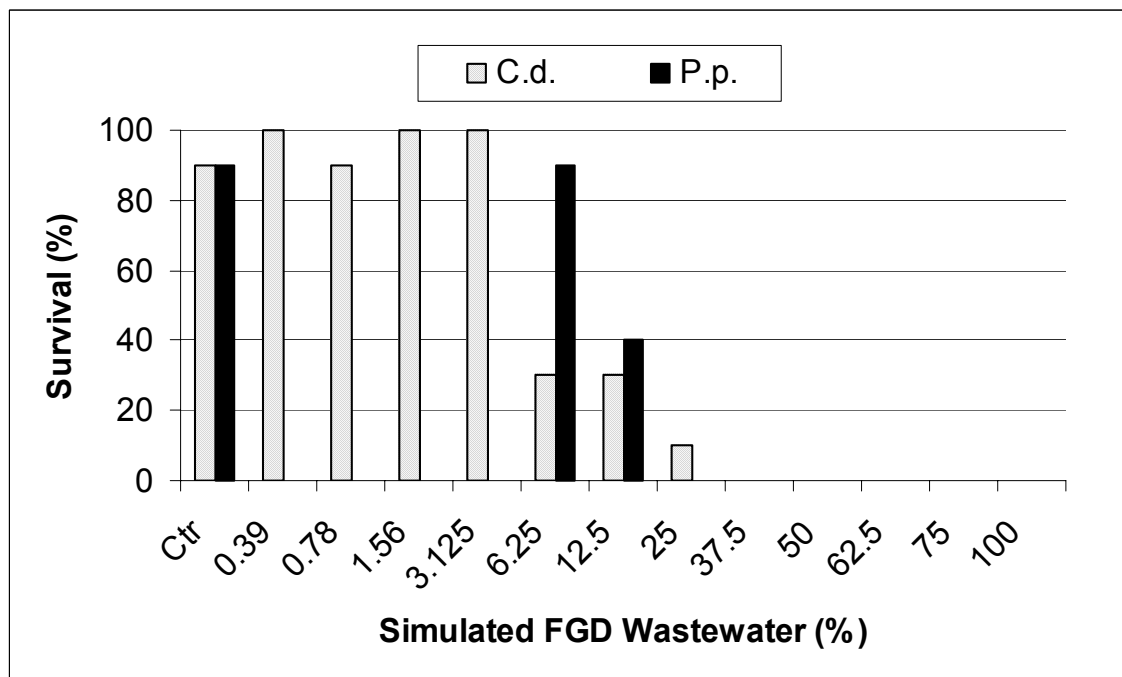


Figure 28. Comparative responses, in terms of survival, of *C. dubia* and *P. promelas* to simulated FGD wastewater Sample Two. Concentrations of 0.39%, 0.78%, 1.56%, and 3.125% for *P. promelas* and 37.5%, 50%, 62.5%, and 75% for *C. dubia* were not tested.

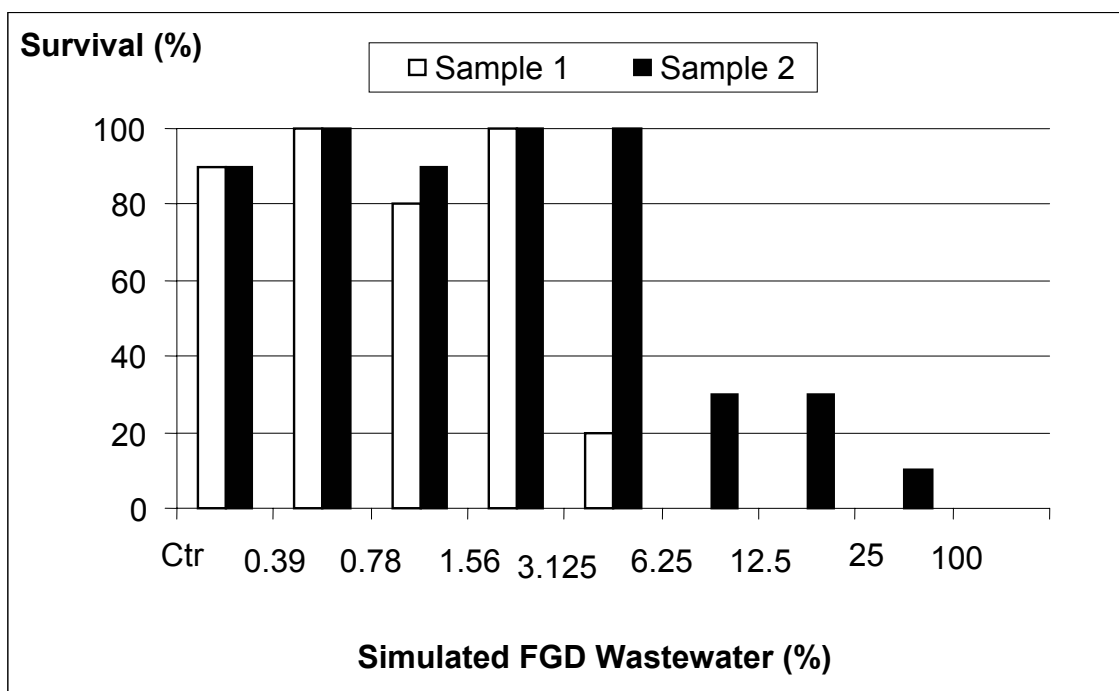


Figure 29. Comparative responses, in terms of survival, of *C. dubia* to simulated FGD wastewater Samples One and Two.

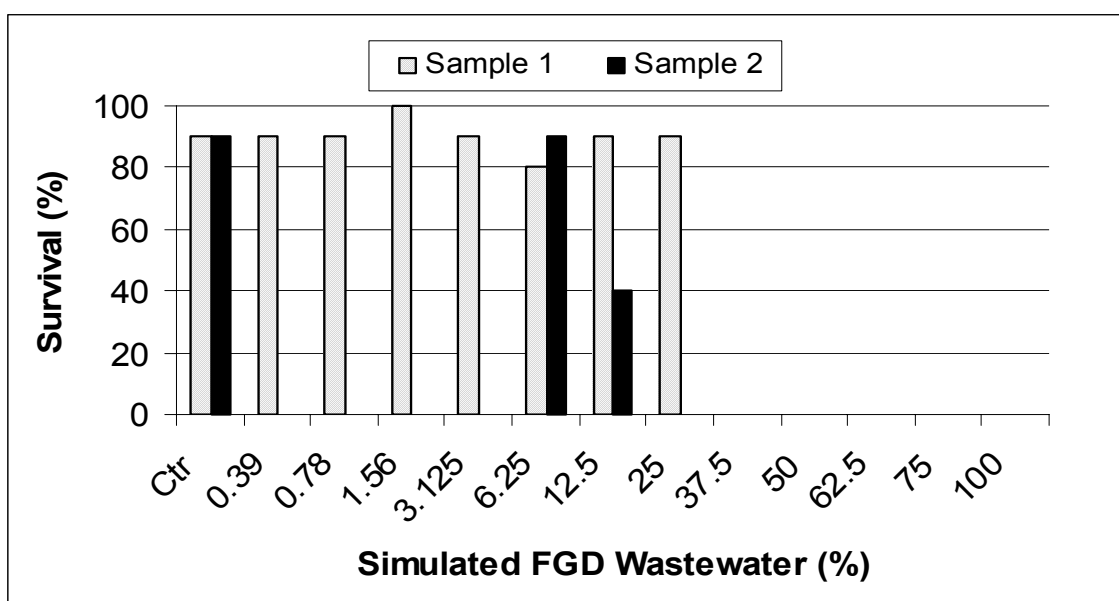


Figure 30. Comparative responses, in terms of survival, of *P. promelas* to simulated FGD wastewater Samples One and Two. Concentrations of 0.39%, 0.78%, 1.56%, and 3.125% for Sample Two (Sample One) and 37.5%, 50%, 62.5%, and 75% for Sample One (sample Two) were not tested.

Bulk Sediment Toxicity

To determine the bioavailability of inorganics (i.e. As, Hg, and Se) in the hydrosol of the constructed wetland treatment system, two sentinel toxicity testing organisms were exposed to sediment samples from each wetland cell. Testing organisms were chosen due to previous research on sediment toxicity characterization and appropriate EPA methods (Lewis et al. 1994; EPA Methods 100.1 and 100.2).

Hyaella azteca

In review of results, no observable toxicity effects (survival or growth) were measured for sediment samples collected from wetland cells 1, 2, and 4. Complete survival (100%) was observed in all treatment and control replicates. Average weight per organism was 0.00023 g for controls, 0.0006 g for wetland cell 1, 0.0093 g for wetland cell 2, and 0.00062 g for wetland cell 4. Final weights per organism were greater for treatments in comparison to control (Table 13). From these results, there is statistical evidence to conclude that survival and growth of *H. azteca* are impaired by exposure to sediments/hydrosol from constructed wetland treatment systems used in the remediation of simulated FGD wastewater.

Table 14. Sediment toxicity results in terms of survival and growth measurements of *Hyaella azteca* for wetland treatments and controls.

Treatment	Rep	Survival	Average Percent Survival	Total H.a. Wt(g)	Weight per Org. (g)	Average Wt/Org (g)
Control	1	10/10	100%	0.00237	0.00024	0.00023
	2	10/10		0.00231	0.00023	
	3	10/10		0.00211	0.00021	
1st Wetland Cell	1	10/10	100%	0.00339	0.00003	0.00060
	2	10/10		0.00975	0.00010	
	3	10/10		0.00488	0.00005	
2nd Wetland Cell	1	10/10	100%	0.00296	0.00003	0.00093
	2	10/10		0.0109	0.00011	
	3	10/10		0.01409	0.00014	
4th Wetland Cell	1	10/10	100%	0.00841	0.00008	0.00062
	2	10/10		0.00297	0.00003	
	3	10/10		0.00711	0.00007	

Chironomus tentans

In review of results, control organisms averaged 90% survival, while the first treatment cell averaged 80% survival. Both treatment cells 2 and 4 averaged 96.7% survival. Average weight per organism was observed as 0.00089 g for controls, 0.00133 g for wetland cell 1, 0.0117 g for wetland cell 2, and 0.00138 g for wetland cell 4. The average weight per organism was greater in the three sediment treatments compared to the control (Table 14). From these results, there is no statistical evidence to conclude that growth of *C. tentans* is impaired by exposure to sediments/hydrosol from constructed wetland treatment systems used in the remediation of simulated FGD wastewater.

Table 15. Sediment toxicity results in terms of survival and growth measurements of *Chironomus tentans* for wetland treatments and controls.

Treatment	Rep	Survival	Average Percent Survival	Total C.t. Wt (g)	Weight per Org. (g)	Average Wt/Org (g)
Control	1	9/10	90%	0.00976	0.00108	0.00089
	2	8/10		0.00580	0.00073	
	3	10/10		0.00872	0.00087	
1st Wetland Cell	1	10/10	80%	0.00957	0.00096	0.00133
	2	6/10		0.01028	0.00171	
	3	8/10		0.01049	0.00131	
2nd Wetland Cell	1	10/10	96.7%	0.01152	0.00115	0.00117
	2	9/10		0.00962	0.00107	
	3	10/10		0.01300	0.00130	
4th Wetland Cell	1	10/10	96.7%	0.01386	0.00139	0.00138
	2	9/10		0.01447	0.00161	
	3	11/11		0.01272	0.00116	

DISCUSSION

In the constructed wetland treatment systems, the targeted constituents (As, Hg, and Se) decreased from the inflow of the system to the outflow of the system for both samples of simulated FGD wastewater. Due to complete mortality of both *C. dubia* and *P. promelas* in both samples of simulated FGD wastewater, dilutions of these samples were used for toxicity experiments. Dilutions allowed for determination of upper and lower thresholds of toxicity. In the dilutions of simulated FGD wastewater used for toxicity experiments both the acute and reproductive toxicity to *C. dubia* decreased from the inflow to final outflow of this treatment system. The pilot-scale wetland treatment system also decreased the acute toxicity to *P. promelas* in dilutions of simulated FGD wastewater from inflow to final outflow samples. Understanding that chloride concentrations through the system remain relatively unaffected, it can be hypothesized that decreases in toxicity for dilution experiments between inflow and outflow samples can be correlated with removal of toxic soluble elements (arsenic, mercury, and selenium) by this treatment system.

Aqueous Toxicity Experiments

Observed responses of the two species were different as literature suggests (Spehar and Fiandt, 1986, USEPA, 1987, Mount *et al.*, 1997), and the observed differences in species sensitivity may be attributed to chloride, as the two species respond at different concentrations of the two main forms of chloride present. As CaCl_2 , chloride has a 48-hr LC_{50} of 1.83 g/L for *C. dubia* and a 96-hr LC_{50} 4.63 g/L for *P. promelas*. Chloride as MgCl_2 has a 48-hr LC_{50} of 0.88 g/L for *C. dubia* and a 96-hr LC_{50} of 2.12 g/L for *P. promelas* (Mount *et al.*, 1997)

When comparing *C. dubia* survival between treatment weeks (Figure 29) only the dilutions of 3.125% were statistically different from each other, in which greater survival was observed for Sample One. When comparing *P. promelas* survival only, the dilutions

of 25% were statistically different (Figure 30), and the dilutions of 12.5% were close to being statistically different with a p-value of 0.0573. For Sample One, the concentration of chlorides was approximately 4150 mg/L while in Sample Two, the concentration of chlorides was approximately 5250 mg/L.

Bulk Sediment Toxicity Experiments

Hyalella azteca

Toxicity endpoints of survival and growth for *H. azteca* did not differ significantly between sediment treatments (exposed sediment from wetland cells 1, 2, and 4) and control organisms. No mortality occurred during the experimental duration of 10-d and organism weights were greater for treatment sediments in comparison to controls. In this situation, it is plausible to hypothesize that non-toxic food sources (i.e. detritus) were in greater abundance than was available in the control sediment.

Chironomus tentans

Toxicity endpoints of survival and growth for *C. tentans* did not differ significantly between sediment treatments (exposed sediment from wetland cells 1, 2, and 4) and control organisms. Minimal mortality occurred during the experimental duration of 10-d and midge weights were greater for treatment sediments in comparison to controls. In this situation, it is plausible to hypothesize that non-toxic food sources (i.e. detritus) were in greater abundance than in the control sediment. Average survival was observed as 90% for controls, 80% for wetland cell 1, and 96.7% for wetland cells 2 and 4.

CONCLUSIONS

For efficient implementation of FGD scrubber units at fossil-fuel fired power plants, an effective and reliable wastewater treatment system is required. Large volumes of FGD wastewater will be produced from scrubber systems within smoke stacks, and this variable aqueous matrix must be treated to eliminate contaminants in order to achieve discharge limitations established under the National Pollution Discharge Elimination System (NPDES) and Clean Water Act. Specifically designed constructed wetland treatment systems have been used to treat each of these elements independently, (Hansen *et al.*, 1998; Kaplan, *et al.*, 2002; Thompson, *et al.*, 2003) but this concept or technology had not been “proven” for FGD wastewaters. Wetlands possess unique reactions not occurring in other aquatic or terrestrial systems (Jacob and Otte, 2002). This pilot study was conducted in order to develop confidence in the ability of a constructed wetland treatment system to treat FGD wastewater.

While the undiluted outflow from this constructed wetland treatment system was toxic in terms of reproduction to *C. dubia* at dilutions as low as 0.78%, this toxicity is likely due to the elevated concentration of chlorides (in excess of 4000 mg/L) and not the constituents which were targeted for removal by this treatment system. Based on

inorganic analysis of pre- and post-treatment wastewater from the pilot-scale constructed wetland treatment system, aqueous constituents of concern (As, Hg, and Se) were significantly decreased as well as organism responses of toxicity for *C. dubia* and *P. promelas*. Bulk sediment toxicity, in terms of survival and reproduction, were not observed with exposed hydrosol from any wetland cell treatments and is consistent with the sequential extraction data from Task Two. Bioavailability of these elements should correlate to estimate binding strengths (sequential extractions). Under this assumption, responses of *H. azteca* and *C. tentans* indicate that As, Hg, and Se are transferred into non-bioavailable forms within the sediment and should not pose a risk unless disturbed. Overall, pilot-scale constructed wetland treatment systems decreased aqueous concentrations of toxic inorganics and toxic responses of *C. dubia* and *P. promelas* with co-management of dilution water. These systems can provide scaling coefficients for full-scale design, in which actual FGD wastewater can be treated to meet NPDES restrictions of discharge wastewater.

OVERALL CONCLUSIONS

Observations from this research indicate that constructed wetland treatment systems specially designed for FGD wastewater are both practical and efficient in removal of soluble elements of concern (As, Hg, and Se).

Future research should include continued monitoring of these systems with simulated and actual FGD wastewaters for a more comprehensive understanding of temporal variations in removal rates and extents of these elements. Also, research should focus on minor manipulations of these systems for greater removal of all elements including changes in HRTs, organic matter and composition, speciation of iron within selected cells, and sulfide concentrations. These data allow a first-order assessment of the chemical properties of these precipitated elements within the sediment.

In conclusion, constructed wetland treatment systems can be utilized for many FGD wastewaters. These systems have many advantages in comparison to other treatment processes including: public perception (“green” chemistry), low maintenance and simple monitoring processes, efficiency in removal rates and extents of elements commonly observed in FGD wastewater, minimal capital and operating costs, and spatial requirements.

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