EVALUATION OF ORGANIC LOADING AND HYDRAULIC REST PERIOD OF FOOD PROCESSING WASTEWATER IRRIGATION TO PREVENT MOBILIZATION OF TRANSITION METALS

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Biosystems Engineering – Master of Science

2014

ABSTRACT

EVALUATION OF ORGANIC LOADING AND HYDRAULIC REST PERIOD OF FOOD PROCESSING WASTEWATER IRRIGATION TO PREVENT MOBILIZATION OF TRANSITION METALS

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Wastewater generated during food processing is commonly treated using land-application systems which primarily rely on microbes in the soil to treat wastewater by transforming nutrients and organic compounds into benign byproducts. Naturally occurring metals in soil may be chemically reduced via microbially mediated oxidation-reduction reactions as oxygen becomes depleted. Metals such as manganese, iron, and arsenic are water soluble in their reduced forms and may lead to contamination of groundwater.

A column study was conducted at Michigan State University to investigate impacts of land-application of wastewater. Oxygen content and volumetric water data was collected via soil sensors for the duration of the study. The pH, chemical oxygen demand, alkalinity, total iron, and total manganese in the influent and effluent water for each column were evaluated. Average organic loading, organic load per dose, and hydraulic rest period were shown to have statistically significant impacts on effluent water quality using Spearman's Rank Correlation Coefficient. This study verifies that excessive organic loading of land application systems causes mobilization of naturally occurring metals and ineffective wastewater treatment, but also indicates the need for consideration of organic dose load and hydraulic rest period in treatment system design. Findings from this study demonstrate application of water to soil twice daily may encourage soil aeration and allow for increased organic loading while limiting metal mobilization.

ACKNOWLEDGEMENTS

I would like to thank Dr. Safferman, Leila Saber, my undergraduate research assistants, Steve Miller, Steve Marquie, and my committee members for their assistance conducting this research project. I would also like to thank my family and friends for their support. Finally, I would to thank Ashley and my pack for the love and support they've shown me throughout this stage of my life.

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KEY TO ABBREVIATIONS

ac	Acres
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
E_h	Oxidation reduction potential, measured in mV
kg	Kilograms
L	Liters
lbs	Pounds
m	Meters
MDEQ	Michigan Department of Environmental Quality
mg	Milligrams
mL	Milliliters
MSU	Michigan State University
mV	Millivolts
ORP	Oxidation-Reduction Potential
ρ	Spearman's Rank Correlation Coefficient
s	Seconds
SMCL	Secondary Maximum Contaminant Level
STL	Seasonal-Trend Decomposition Procedure Based On Loess
TSS	Total Suspended Solids
USGS	United States Geological Survey
USEPA	United States Environmental Protection Agency
VWC	Volumetric Water Content

Introduction

Land application as a wastewater treatment technology has been a common practice for many years. This technology is especially common for rinse water from fruit and vegetable processing. Wastewater is often used as irrigation water in this process when crops are active. Crops may be cultivated on fields receiving wastewater as irrigation water and used as animal feed. Organic matter from this waste is filtered by soil, degraded via microbially-mediated oxidation-reduction (redox) reactions, and chemically adsorbed. Microbially-mediated redox reactions can occur in either aerobic or anaerobic environments.

Wastewater composition and volume from food processors is highly variable. Biological oxygen demand (BOD), nutrient content, and the volume of wastewater applied are of primary concern in land application design. Microbes carry out redox reactions to achieve cellular respiration. Both an electron donor and an electron acceptor are required to complete such reactions. Organic matter in wastewater encourages microbial growth by acting as an electron donor. Microbial populations will typically shift to utilize the most energetically favorable electron acceptor available.

Naturally occurring transition metals in typical soil such as manganese, iron, and arsenic, exist in oxidized (insoluble) and reduced (soluble) forms. The oxidized forms of these metals may serve as electron acceptors in microbially mediated redox reactions as more favorable electron acceptors such as oxygen become depleted. These metals are chemically reduced in the process causing each to become more soluble in water and become mobilized, resulting in transport from the soil matrix to local groundwater.

Groundwater impacted with high levels of metals resulting from land application sites can create both nuisance and health problems. High concentrations of iron and manganese in drinking water cause nuisance problems including staining of plumbing fixtures and clothing, as well as forming deposits of metals on pipes leading to fouling and blockages. High concentrations of these metals can also result in health problems. Conversely, arsenic is acutely toxic and elevated levels in drinking water can cause cancer and other serious health problems.

There are currently few prescriptive criteria for land application operational strategies that minimize mobilization of these metals. Research was conducted to determine relationships between selected loading criteria and chemical reduction of naturally occurring transition metals.

Literature Review

Land application of wastewater has been utilized for many years and is an effective and economic means of wastewater disposal.(Lance, Whisler et al. 1973, Leeson and Hinchee 1997, Tchbanoglaus, Burton et al. 2003, Mokma 2006, Duan, Sheppard et al. 2010). These systems rely on natural environments to degrade wastes (Leeson and Hinchee 1997, Crites and Tchabanoglaus 1998, Tchbanoglaus, Burton et al. 2003, Duan, Sheppard et al. 2010). Advantages of land application include economic waste disposal, return of water to a local aquifer, and potential for growth and sale of crops (Beggs, Bold et al. 2007). Despite its advantages, land application of wastewater has not been adequately studied (Mokma 2006). Although nutrient requirements of specific crops are well understood, little is known about hydraulic and organic loading rates that promote wastewater treatment without mobilization of metals (Mokma 2006). Poorly managed land application sites have been shown to negatively impact groundwater quality (McDaniel 2006, Beggs, Bold et al. 2007).

Limited scientific information regarding how to control aerobic and anaerobic zones has made formulating guidance that is environmentally protective, yet fair to industry, difficult. Overly-stringent regulations may increase wastewater treatment costs and unnecessarily inhibit business growth. Poorly managed land application practices can cause environmental and health problems (McDaniel 2006, Mokma 2006). Scientifically based data and an understanding of fundamental mechanisms are essential for designing and regulating land application systems.

The goal of this literature review is to provide a comprehensive report regarding current and historical land application systems, impacts of poor treatment system performance on the mobilization of transition metals; namely manganese, iron, and arsenic, and review mechanisms of mobilizing these metals from soil.

Land Application of Wastewater

Land application has been used as a treatment technology for domestic wastewater since before 1880 (Crites and Tchabanoglaus 1998). Wastewater generated from food processing is commonly treated using land application systems (Tchbanoglaus, Burton et al. 2003, Duan, Sheppard et al. 2010). Wastewater in these systems is degraded in the soil, where organic compounds are broken down by physical, chemical, and biological mechanisms (Tchbanoglaus, Burton et al. 2003).

Wastewater Treatment Technologies

Many treatment technologies may be utilized to treat food processing wastewater. Land application offers several advantages including relative simplicity of systems results in increased reliability, return of water to a local aquifer, and potential for growth and sale of crops (United States Environmental Protection Agency Office of Wastewater Management 2004, Beggs, Bold et al. 2007). Wastewater treatment using land application systems can offer significant economic savings over activated sludge treatment plants. The United Nations Economic And Social Commission For Western Asia (2003) estimated operation and maintenance treatment cost of domestic wastewater in a typical activated sludge treatment system to be \$0.22/m^3 and a typical land application system to be \$0.10/m^3 to \$0.20/m^3. Land applications systems also require significantly less maintenance and energy (Crites and Tchabanoglaus 1998), return treated water to the local aquifer(O'Brien 2002, Beggs, Bold et al. 2007, Hillel 2008), and require less infrastructure due to the decentralized nature of these systems(Crites and Tchabanoglaus 1998). An estimated 70% of food processing wastewater in the United States is treated using land-application systems (Beggs, Bold et al. 2007).

Current and Historical Use

Land application of food processing wastewater has been practiced since before 1956 (Mokma 2006). Elevated concentrations of iron, manganese, and arsenic have been identified in groundwater near some treatment sites used by food processing plants since the 1970's (Safferman, Fernandez-Torres et al. 2011). This phenomenon has been identified in Michigan (Mokma 2006).

The California League of Food Processors recently estimated that 70% of wastewater generated by food processing is land applied (Beggs, Bold et al. 2007). Thus, improving understanding of the environmental implications of this practice is critical.

Benefits of land application include inexpensive waste disposal, reduced water consumption for agricultural crops, reduced fertilizer usage, and reduction in carbon emissions (Beggs, Bold et al. 2007, Duan, Sheppard et al. 2010). However, poorly managed land application systems can lead to solubilization of compounds in soil (McDaniel 2006), destruction of crops (McDaniel 2006), and odorous conditions (Beggs, Bold et al. 2007).

Discharge of wastes to surface waters is regulated by the Clean Water Act of 1972. However, implementation of these regulations are generally delegated to individual states by the US Environmental Protection Agency (USEPA) (Beggs, Bold et al. 2007). The Michigan Department of Environmental Quality (MDEQ) regulates land application treatment systems under Cleanup Criteria Requirements for Response Activity (formerly the part 201 Generic Cleanup Criteria and Screening Levels).

Wastewater Characteristics

Site-specific hydraulic, organic, nitrogen, and salt loading rates of a land application treatment system must be considered in the design phase to ensure proper operation (Beggs, Bold et al. 2007). Chemical constituents in food processing wastewater vary significantly depending on the crop processed. These variations must also be considered in design of treatment systems. Characteristics of food processing wastewater vary depending on the crop processed. Table 1 shows water examples of usage and effluent characteristics of a selection of food products processed in California.

Table 1 - Water Use and Effluent Characteristics for Selected Food Products (Mannapperuma, Yates et al. 1993)

Product	Water Usage gallons per ton	BOD lbs per ton	TSS lbs per ton
Apple Sauce	280		
Apricots	3000	39	9.0
Artichokes	770	3.3	3.9
Asparagus	810		
Brussel Sprouts	810		
Cheese	1700	1000	29
Cherries	12000	100	21
Frozen Fruits	1800		
Garlic	2800	1.8	
Meat	4000		
Mushrooms	1800	1.8	0.8
Mushrooms*	780		
Onions	1000		
Pears	4200	11	6.0
Pumpkins	3700		
Raisins	2000	75	15
Seafood	2700	13	7.9
Seafood*	2700		4.0
Specialty	3500		13
Vegetable Oils	2100	1.1	0.3
Yams	6900	8.0	3.0
Yams*	4200	40	22
Zucchini	8000	340	100

*data gathered from multiple processing plants

Organic Loading

Little is known regarding the impacts of organic loading from food processing wastewater (Mokma 2006). Suggested maximum organic loading rates from past articles included 30-100 lbs

BOD ac^{-1} day^{-1} (Mannapperuma 2005), 150 lbs BOD ac^{-1} day^{-1} (Beggs, Bold et al. 2007), 200 lbs BOD ac^{-1} day^{-1} (Carawan and Chambers 1979), 450 to 500 lbs BOD ac^{-1} day^{-1}, (Crites and Tchabanoglaus 1998) and 500 lbs BOD ac^{-1} day^{-1} (Coody, Sommers et al. 1986).

Excessive organic loading can lead to depletion of oxygen in soil and anaerobic conditions (Beggs, Bold et al. 2007). Anaerobic bacteria degrade organic material more slowly than aerobic bacteria and may result in insufficient treatment (McDaniel 2006). Metals naturally occurring in soil may be chemically reduced when subjected to anaerobic conditions for prolonged periods of time and become mobilized (Hillel 2004). Local groundwater can become impacted with inadequately treated wastewater constituents and metals as a result.

Wastewater is physically filtered by soil in land application systems (Crites and Tchabanoglaus 1998). Suspended solids in wastewater can be retained near the surface and limit oxygen transport into the soil, promoting anaerobic conditions (Crites and Tchabanoglaus 1998, Beggs, Bold et al. 2007). Over time the addition of organic matter, especially TSS, can cause a change in soil type (McDaniel 2006). Anaerobic bacteria often produce slime that foul soil pore space, retain water in soil, and reduce oxygen transport (McDaniel 2006).

Hydraulic Loading

Required crop irrigation rates are well studied and typically range from 0.25 to 1.5 cm per day (Mokma 2006). However, the effects of hydraulic loading rates on land application systems are not as well understood.

Controlling hydraulic loading is critical for keeping land application system soil aerobic because anaerobic populations degrade organics at a slower rate (McDaniel 2006). Oxygen is delivered to the soil matrix by gaseous diffusion into soil pore space, carried by water as dissolved oxygen, or as mass transfer drawn in by hydrodynamic forces (McMichael, McKee et al. 1965). Lance, Whisler et al. (1973) estimated that this mass transfer accounts for 30-40% of oxygen present in soil during drainage periods.

Diffusion of oxygen into the soil diminishes as soil pores are flooded with water (Erickson and Tyler 2000) and with depth (Lance, Whisler et al. 1973). Saturated soils are likely to become anaerobic if organic matter and nutrients are present to permit cellular growth(Hillel 2008). Many anaerobic organisms excrete material to form a biofilm that reduces infiltration and further limits oxygen transfer into the soil (King 1986).

Previous column studies have indicated that only soil near the surface can remain aerobic. Lance, Whisler et al. (1973) determined that anaerobic conditions are maintained at a depth of 140 cm. Excessive hydraulic loading of soil can flush organic constituents in the water past this aerobic zone leading to anaerobic degradation (Cook 1995, Beggs, Bold et al. 2007).

Nutrient Loading

Nutrients necessary for cellular growth and respiration must be available for microbially-mediated degradation of organics. Nitrogen and phosphorus are the primary macronutrients required for cellular growth (Chrzanowskil, Kyle et al. 1996, Levy, Fine et al. 2011). Food processing wastewaters often have limited quantities of available nitrogen which can limit bacterial growth and allow fungi to dominate (Mokma 2006). The minimum carbon to nitrogen ratio required for bacterial domination of the soil has been identified as 20:1 (Mokma 2006) and 24:1 (Beggs, Bold et al. 2007). Micronutrients such as manganese, nickel, iron, sodium, sulfur, magnesium, and chloride are also required for cellular growth (Cowan 2012). However, these elements are required in far lower quantities.

Impacts of Elevated Groundwater Concentrations of Selected Metals

Elevated manganese, iron, and arsenic levels in groundwater have been linked to health problems including damage to the neurological and circulatory systems, skin damage, and many forms of cancer. These metals can also cause nuisance problems both in homes and in water distribution systems by causing buildup to form in pipes, unpleasant-tasting water, and staining of piping, fixtures or clothing. The following subsections provide additional detail.

Health Risks and Toxicology

Iron and manganese are necessary micronutrients for humans (Kazantzis 1981, Gurzau, Neagu et al. 2003, Santamaria and Sulsky 2010). However, drinking water is not a primary source for these nutrients.

Manganese, while essential to human health, can pose significant health risk when consumed in high concentrations. Prolonged exposure to elevated doses has been shown to cause neurological problems (World Health Organization 2004, World Health Organization 2006). Animal studies have indicated symptoms including irritability and emotional instability. Prolonged exposure produced muscular weakness, rigidity of lower limbs, and evidence of neural degeneration in rhesus monkeys (World Health Organization 2006). However, assessing the toxic effects of chronic overexposure to manganese on humans has been very difficult as different animals respond differently to manganese (World Health Organization 2006). Case studies where humans have been subjected to high manganese concentrations in drinking water have demonstrated negative health effects such as lethargy, neurological impairment, and tremors (World Health Organization 2004). The USEPA has established a Secondary Maximum Contaminant Level (SMCL) of 0.05 mg/L for manganese in drinking water (United States Environmental Protection Agency 2012).

Iron concentrations in the body are regulated by complex interactions primarily associated with liver enzymes. These interactions are not yet well understood (Gurzau, Neagu et al. 2003). Excessive amounts of iron can cause the production of free-radicals in the body and damage tissue (Gurzau, Neagu et al. 2003). Acute iron overdose occurs with dosages greater than 40 mg/kg of body mass (Fawell, Lund et al. 2003). While acute iron poisoning is dangerous, chronic overexposure is unlikely to cause adverse effects unless the person has another health issue impacting iron uptake by the liver (Fawell, Lund et al. 2003). The USEPA has established a SMCL of 0.3 mg/L for iron in drinking water (United States Environmental Protection Agency 2012).

While recent research indicates arsenic may also be an essential micronutrient (Uthus 2003, Zeng, Uthus et al. 2005), it is dangerous at much lower concentrations than either manganese or iron. Acute arsenic poisoning from drinking contaminated water has been shown to be between 1.2 and 21.0 mg of arsenic/kg body mass depending on redox state (Cotruvo, Fawell et al. 2011). Health problems resulting from chronic exposure to arsenic contaminated water include skin lesions, skin cancer, bladder and kidney cancer, neurological disease, hypertension, pulmonary disease, peripheral vascular disease, and diabetes mellitus (Smith, Lingas et al. 2000). Chronic exposure to arsenic has been shown to cause damage to the skin and circulatory system as well as an increased risk of cancer (United States Environmental Protection Agency Updated November 4th, 2010) and concentrations as low as 500 ppb in drinking water have shown to cause death by cancer in 10% of people exposed (Smith, Lingas et al. 2000). The USEPA has set the Maximum Contaminant Level (MCL) for arsenic at 0.01 ppm (United States Environmental Protection Agency Updated November 4th, 2010). However, the MCL Goal for arsenic is 0.00 mg/L (United States Environmental Protection Agency Updated November 4th, 2010).

Nuisance Problems

In addition to causing several health risks, manganese and iron cause nuisance problems when used domestically. Cho (2005) estimated that chemical removal or prevention of mineral scale formation costs the United States $25-$30 billion annually.

Manganese concentrations as low as 0.1 ppm can give water a foul taste and stain laundry and plumbing fixtures (World Health Organization 2006). At concentrations higher than 0.2 ppm, manganese can cause a black buildup in pipes that occasionally sloughs off (World Health Organization 2006).

Iron concentrations in water of 0.3 ppm have been known to discolor water as well as stain laundry and delivery pipes (World Health Organization 2006). Iron in water also promotes the growth of iron-oxidizing bacteria which cause a slimy buildup in piping (World Health Organization 2006). Iron scale can also be deposited in piping and result in blockages. A pipe fouled with mineral, predominantly iron, scale is shown as Figure 1.

1984).

Figure 1 - Mineral Scale in Pipe

The nuisance effects of arsenic are not as thoroughly studied, since arsenic is toxic at concentrations below those at which it would become a nuisance.

Metal Solubility

Manganese and iron are commonly found in soil in their oxidized states, Fe(III) and Mn(IV), and have very low solubility when pH is neutral (Sposito 2008). Manganese is generally reduced at a redox potential (denoted as Eh) of between 300 and 100 mV, whereas iron is reduced between 100 mV and -100 mV (Chen and Avnimelech 1986). As such, manganese is typically reduced before iron and is depleted when soil is subjected to anaerobic conditions (Sposito 2008). Iron and manganese content in soil vary significantly however, a study conducted by the United States Geological Survey (USGS) found average soil concentrations to be 1.8 percent by mass for iron and 330 ppm for manganese in the contiguous United States (Shacklette and Boerngen 1984).

Arsenic commonly exists in two generic forms in the soil; an oxidized form, As(V) (arsenate) and a reduced form As(III) (arsenite). These ions are most often bound to other chemicals in the soil. Arsenite complexes are four to ten times more soluble and are also more toxic than the oxidized arsenate forms (McLean and Bledsoe 1992). Arsenate compounds replace phosphate in many biological reactions. Arsenite compounds inhibit production of specific enzymes in the body (Hughes 2002). Arsenic in soil is typically found in the arsenate form (Martin, De Burca et al. 2009). A study conducted by the USGS found the average soil concentration of arsenic in the contiguous United States to be 5.2 ppm (Shacklette and Boerngen 1984). Arsenite compounds are rare in soil but can be found in reducing environments where they have been shown to account for 91% of the total arsenic in the soil (Drahota and Filippi 2009).

While groundwater can be directly contaminated by the application of wastewater containing high concentrations of metals, the goal of this review is to investigate the effect of organic material on the solubility of metals found naturally in soil. The solubility of each of these metals depends on complex interactions in the soil. Physical, chemical and biological mechanisms play a role in whether manganese, iron and arsenic exist in either the oxidized (non-soluble) or reduced (soluble) form. If soluble, this can cause the metal to leach into the groundwater. These mechanisms are described in further detail in the following sections.

Soil Conditions

Soil type impacts diffusion rate of oxygen into the soil (McDaniel 2006, Beggs, Bold et al. 2007). Oxygen diffusion rate is limited in soils that are wet, tightly packed, or otherwise have highly tortuous paths for gas diffusion (Moldrup, Olesen et al. 2000).

pH plays a role in metal speciation in soil. Manganese, iron, and arsenic will take their reduced forms and become more soluble in water with a reduced pH even at higher redox levels. For example, iron is insoluble as Fe(III) at pH 7 and oxidation-reduction potential (ORP) of 0 mV but is soluble as Fe(II) at a pH of 4 and ORP of 400 mV (Masscheleyn, Delaune et al. 1991).

Microbially Mediated Redox Reactions

Land application relies primarily on microbial metabolism to chemically oxidize organic wastes (Beggs, Bold et al. 2007). Microbes in soil use organic wastes as a source of carbon and electron donor. Diatomic oxygen is the most common electron acceptor for microbial metabolism in aerobic conditions (Rittman and McCarty 2001). However, other, lower energy, electron acceptors are utilized as oxygen is depleted (Haggblom, Rivera Md Fau - Young et al. , Rittman and McCarty 2001, Spalding 2002, McDaniel 2006, Beggs, Bold et al. 2007). Because manganese and iron are higher energy electron acceptors than arsenic, elevated concentrations of manganese and iron in groundwater near application sites can serve as a potential indicator that arsenic contamination may follow.

Aerobic microorganisms are faster at breaking down organic wastes found in wastewater than anaerobic microbes and typically dominate a population when oxygen in soil is sufficient (Chambers, Willis et al. 1990, Jones, Beyer et al. 1992, McDaniel 2006). The oxygen content in the soil matrix depends on a wide range of factors including soil type, moisture content, soil depth, temperature, and vegetative cover (Craul 1992, Leeson and Hinchee 1997, Hillel 2004, McDaniel 2006).

Excessive organic loading of soil increases oxygen demand and may lead to biofouling of soil pore space, thus limiting oxygen transport into the soil (Hillel 2008). Excessive hydraulic loading saturates the soil porosity limiting the diffusion of air (Hillel 2004, Safferman, Fernandez-Torres et al. 2011). Both conditions may encourage anaerobic conditions and the potential mobilization of metals (McDaniel 2006). Additionally, many anaerobic organisms produce a biofilm that occupies pore space in soil, thus further limiting oxygen diffusion to soil and perpetuating anaerobic conditions (King 1986).

Materials and Methods

A lab-scale experiment was conducted on the campus of Michigan State University (MSU) to analyze the effects of wastewater application on soil on effluent water quality. Concentrations of COD, manganese, and iron were used as specific indicators of water quality. Focus of the study was directed specifically at the impacts of average daily organic load, hydraulic rest period, and organic load per dose on the propensity of soil to mobilize metals, specifically iron and manganese.

Hydraulic loading of each column was limited to 2.4 liters per day to simulate the need of a treatment system to dispose of a constantly generated volume of wastewater. This application volume correlates to an application rate of 1.5 cm/day which was chosen to simulate conditions at field-scale treatment systems and is within the range of treatment systems evaluated by Mokma (2006).

Hydraulic loading frequency of the columns was altered using pumps and timers to deliver a desired volume of water on a desired interval. Average daily organic load was altered by modifying wastewater composition. Combined, these changes modified the organic load per dose delivered to the columns.

Wastewater Composition

Synthetic wastewater was prepared in the lab in accordance with literature (Trulear and Characklis 1982). Table 2 shows ingredients for a solution containing 10 mg glucose/L. This solution contained glucose as a carbon source and micronutrients necessary for microbial growth. Buffer solutions (denoted on Table 2) were used to maintain a neutral pH. This solution was scaled linearly to produce a desired concentration of oxygen demand in the column feed water. Organic loading in the experiment was expressed in units of pounds of BOD per acre per day (lbs BOD ac^{-1} day^{-1}).

Table 2 - Synthetic Wastewater Composition for 10 mg Glucose/L Solution (Trulear and Characklis 1982)

Constituent	Concentration in Dilution	
$FeCl_3$	0.045	mg/L
$MnCl_2*4H_2O$	0.011	mg/L
$ZnCl_2$	0.008	mg/L
$CuCl_2*2H_2O$	0.005	mg/L
$CoCl_2*6H_2O$	0.007	mg/L
$(NH_4)_6Mo_7O_{24}*4H_2O$	0.005	mg/L
$Na_2B_4O_7*10H_2O$	0.003	mg/L
Na_3Citrate	0.408	mg/L
$NaH_2PO_4*H_2O$	0.575	mg/L
$(NH_4)_2SO_4$	0.367	mg/L
NH_4Cl	3.417	mg/L
$CaCl_2$	0.308	mg/L
$MgCl_2*6H_2O$	0.565	mg/L
KH_2PO_4 (Buffer)	0.004	M
Na_2HPO_4 (Buffer)	0.004	M
$C_6H_{12}O_6$	10.0	mg/L

Each column received 2.4 liters of prepared wastewater (1.5 cm) per day for the duration of the experiment. Wastewater was delivered to each column via a peristaltic pump controlled by an electronic timer. The timer and pump for each column were adjusted weekly to ensure delivery of the intended volume of water at prescribed intervals.

Column Construction

The experiment was conducted using eight soil columns. Each column was constructed using 46 cm corrugated polyvinyl chloride (PVC) pipe, using a split PVC end cap as the bottom. Corrugated pipe was used to minimize short-circuiting of water along the column wall. Columns were supported by a wooden structure (Figure 2). The structure held each column 20 cm above the floor. The structure included access beneath the column for drainage and maintenance.

Effluent from each column drained via eleven 3 mm diameter holes and water was collected under the column in a 12 liter clear plastic tub.

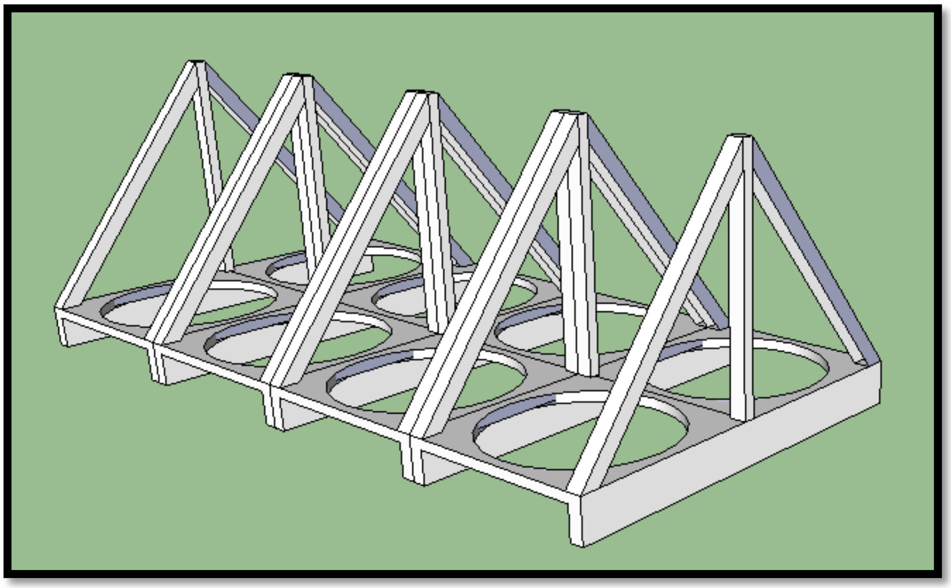

Figure 2 - Column Support Structure Sketch

Pea gravel was added to the bottom of each column to a depth of 1.2 cm. Columns were filled to a specified depth with play sand purchased from a local hardware store. Specifically, six columns had a sand column height of 0.6 m. Two additional columns with a sand column height of 1.2 m were added after the first phase of the experiment to assess effects of a longer treatment zone.

Four columns were modified after the first phase of the experiment to simulate a perched groundwater table. This was accomplished by sealing the drainage holes on the underside of these columns. Rubber patches and epoxy were used to accomplish this. A ½-inch nominal diameter PVC pipe was installed in the side of each of these columns approximately 8 cm from the bottom for drainage. This pipe was installed with a low spot to remain full of water. This acted as an air lock to prevent aeration of the soil column.

Sensor Description

Three types of sensors were installed within the sand columns to monitor soil conditions, described below. These sensors were installed in clusters at specified depths. Each of the sensor clusters was assigned a letter. Table 3 shows depths at which sensors were installed. Figure 3 shows an example of a sensor cluster during construction. Note that only columns with sand 1.2 m deep included sensors at levels D, E, and F.

Table 3 - Column Sensor Depths

Sensor Level	Depth Below Surface (cm)
A	10
B	30
C	51
D	71
E	91
F	112

Figure 3 - Sensor Placement During Column Construction

All sensors were connected to a Campbell Scientific AM16/32 multiplexor for conversion to a digital signal. Data was then stored on a Campbell Scientific CR1000 datalogger. Logged data was accessed using a dedicated desktop computer using Campbell Scientific's PC200W software. Equipment configuration of the datalogger, multiplexors and desktop computer are shown in Figure 4. Data was downloaded monthly from the datalogger and analyzed.

Figure 4 - Sensor Data Collection Setup

Oxygen Sensors

Oxygen in the columns was measured using Apogee Model SO-110 sensors. These sensors contain a fuel that reacts with gaseous oxygen in a galvanic cell. Voltage produced by this cell is linearly proportional to the percentage of oxygen at the sensor. Fuel in the cell is consumed faster when more oxygen is present. The galvanic cell sensor is shipped with enough fuel to last up to 10 years operating continuously at atmospheric oxygen (20.95%). The manufacturer has measured the oxygen consumed by the reaction in the sensor to be "2.2 μmol O_2 per day when the O_2 concentration was 20.95% at 23 C". Oxygen and cell fuel consumed are inversely proportional to the concentration of gaseous oxygen at the sensor(Apogee 2014).

Each sensor requires a multiplier to convert measured voltage into a percent oxygen reading. Output voltages of each sensor were measured in atmospheric conditions (20.95% oxygen) and in a pure nitrogen environment (0% oxygen) as per the instructions in the owner's manual to determine each multiplier before installation in the soil column (Apogee 2014).

Some data collected from the oxygen sensors indicated a malfunction of the sensor. Potential causes include loss of fuel at the sensor, failure of electromagnetic shielding in the sensor cable, and damaged wiring. Sensor data collected was reviewed to identify errant readings. Data gathered by oxygen sensors was excluded from analysis if it met any of the following conditions.

- Oxygen concentrations above 23% or below -1%
- Erratic behavior - likely causes include electrical connectivity issues or loss of fuel at sensor
    - Single points far away from norm (changes of >1% O_2/10 minutes)
    - Several points in a row (>0.5% O_2/10min for more than 30 minutes)

- Known column operational problems, including nutrient feed not delivered to column, column leaking, and sensor filled with chemical precipitate.

The Apogee SO-110 sensor is also equipped with a thermistor to measure ambient temperature. However, this data is not included in this report.

Water Content Reflectometer

Water content reflectometers, which measured volumetric moisture content (VMC) in soil was measured using a Campbell Scientific model CS616 water content reflectometer. This sensor operates by emitting an electronic pulse at an electrode and measuring the transmission time for the signal to travel through the soil matrix and be detected at an adjacent electrode. There is an inverse relationship between moisture content and pulse travel time through the soil. This sensor does not consume any materials and has no prescribed maintenance (Campbell Scientific 2014).

Volumetric water sensors did not experience many of the issues that the oxygen sensors had (no consumable fuel and not susceptible to fouling). These sensors also displayed an error message if the electrical signal was ever lost while a reading was taken. As such, only data with an explicit error message was removed.

These sensors were factory calibrated. However, volumetric water content was measured of column sand with known water content using the reflectometers to verify calibration.

Thermistors

Temperature was logged using Campbell Scientific model T108 thermistors. These sensors measure the resistance of a thermally sensitive BetaTherm 100K6A. The instruction manual provided by the manufacturer states that calibration and maintenance of these probes is not necessary.

The experiment was conducted in a heated indoor space where temperature was held constant. The data collected from these thermistors is therefore not presented in this report.

Experimental Operation

The sand assimilation experiment was carried out using a combination of standard operating procedures (SOPs). These SOPs were conducted either on a routine or when criteria were met to warrant maintenance. These procedures are described in further detail below and attached as Appendix A - Standard Operating Procedure (SOP).

Water application

During all phases of this experiment each column received an average of 2.4 liters per day (15 L $day^{-1}m^{-2}$) of synthetic wastewater to promote microbial growth. Composition of this wastewater is described above and in Table 2. Loading conditions of columns are included in Table 4.

Table 4 - Column Loading Conditions

Unique Identifier	Submerged Bottom?	Column Length (meters)	Average Daily Organic Load (lbs BOD $ac^{-1}day^{-1}$)	Hydraulic Rest Period (hours between doses)	Organic Load per Dose (mg)
C1-1	Yes	0.6	65	6	290
C1-2	Yes	0.6	500	6	2,200
C1-3	Yes	0.6	1000	3	2,200
C2-0	No	0.6	65	6	290
C2-1	No	0.6	65	6	290
C2-2	No	0.6	500	6	2,200
C2-3	No	0.6	1000	3	2,200
C3-1	Yes	0.6	250	12	2,200
C3-2	Yes	0.6	500	12	4,500
C3-3	Yes	0.6	500	24	9,000
C4-0	No	0.6	250	12	2,200
C4-1	No	0.6	250	12	2,200
C4-2	No	0.6	500	12	4,500
C4-3	No	0.6	500	24	9,000
C5-1	Yes	0.6	500	4	1,500
C5-2	Yes	0.6	1000	6	4,500
C5-3	Yes	0.6	1000	56	42,000
C6-0	No	0.6	500	24	9,000
C6-1	No	0.6	500	4	1,500
C6-2	No	0.6	1000	6	4,500
C6-3	No	0.6	1000	24	18,000
C7-1	Yes	1.2	250	12	2,200
C7-2	Yes	1.2	1000	12	9,000
C7-3	Yes	1.2	1000	56	42,000
C8-1	No	1.2	250	12	2,200
C8-2	No	1.2	1000	12	9,000
C8-3	No	1.2	1000	24	18,000

Synthetic wastewater was prepared every Monday, Wednesday and Friday to limit biological growth, chemical degradation, and oxidation before application to the soil. Chemicals used in the feed water were premeasured. Each delivery bucket received dry chemicals from sealed bags and from a pre-mixed liquid stock solution.

Solution remaining in delivery buckets was discarded. Delivery buckets were thoroughly cleaned with phosphate free soap and rinsed before new feed solution was prepared. Wastewater application was automated using Masterflex 07553-80 peristaltic pumps. These pumps were controlled by Cole-Parmer 5010CP digital electronic timers. Pump run times were calibrated weekly to ensure correct wastewater volumes was delivered.

Analytical Data Collected

Influent and effluent water samples were collected from each column analyzed per the SOP for pH, COD, alkalinity, total manganese and total iron. Additional details can be found in Appendix A.

Chemical Oxygen Demand (COD) was measured according to USEPA Reactor Digestion Method 8000 using high-range COD vials (100-1,000 mg/L) for influent water and low-range COD vials (0-150 mg/L) for effluent water. Vials were manufactured by the HACH Corporation.

The pH of samples was measured using Denver Instrument Ultra Basic-10 pH probe. The probe was calibrated before each use using a three-point calibration. Calibration solutions of 4, 7, and 10 were used. The pH probe was inserted into each sample. The reported pH value was recorded after the instrument had reached equilibrium with the sample. The probe was rinsed with deionized water after each reading was collected.

Alkalinity of each sampled was measured weekly using HACH Alkalinity Test Kit, Model AL-DT. Test method 8203 was used. A standard and blank were each measured as a quality control measure with each sampling event.

Influent and effluent samples from each column were collected weekly and analyzed for total iron and manganese by the MSU Plant and Soil Sciences Laboratory using EPA method 6020A via atomic adsorption spectrophotometer.

Maintenance

Soil surfaces were monitored weekly for excessive biological fouling. The columns were scraped with a small garden cultivator when surface ponding persisted 30 minutes after water application to encourage drainage. No soil or biological growth was removed during this process.

Drainage holes on the bottom of each column were visually inspected and mechanically cleaned using a metal pin on a quarterly basis to discourage preferential flow through the end of the columns.

Results and Discussion

Data collected during the study appeared to reveal basic trends between column loading conditions and soil effluent characteristics. Generally speaking, it appeared that columns with very high average daily organic loading led to poor wastewater treatment and excess metals in column effluent. Columns with either the highest and lowest hydraulic rest period also resulted in poor treatment.

Relationships between loading characteristics and treatment appeared to exhibit non-monotonic characteristics. Figures depicting raw data collected for O_2, VWC, effluent manganese concentration, effluent iron concentration, and effluent COD concentration are included as Appendix B - Selected Raw Data Figures. Note that the raw sensor data in these figures has not been censored per the procedures described in the materials and method section of this report. Analytical data collected for effluent manganese concentration, effluent iron concentration, and effluent COD concentration during the study is included as Appendix C - Selected Raw Analytical Data. An objective measure to quantify trends and relationships was required.

Methods of Analysis Considered

Methods initially identified as having potential to examine correlations, but ultimately rejected, are listed below including reasoning for discontinuation of further evaluation.

Principal Component Analysis

Principal Component Analysis (PCA) assumes a linear relationship between each tested variable and that data is normally distributed. A “minimally adequate” sample size of five times the number of variables examined or 100, whichever is larger, is required (O'Rourke and Hatcher 2013). Initial observations of data collected indicated that many relationships were nonlinear. Normality of collected sensor data was tested. Results indicated that data did not have a normal distribution. Only 26 sample results were produced during the study. Therefore the “minimally adequate” sample size was not realized. For these reasons further investigation of PCA was terminated.

Multiple Linear Regression

Multiple Linear Regression (MLR) assumes the relationship between tested variables is linear and that data is distributed normally. MLR also requires that data is homoscedastic, or of constant variance (Greene 2011). Linear relationships between the variables to be tested were not expected and data collected was not normally distributed. Additionally, collected data was not heteroscedastic. Manuals from sensor manufacturers indicated that error varied with readings, not full-scale measurement. Consequently, MLR as a means to analyze data collected during this study was abandoned.

Seasonal-Trend Decomposition Procedure Based on Loess

Seasonal-Trend Decomposition based on Loess (STL) is a data filtering procedure used to decompose a time series into three constituents: an overall trend, a cyclical trend that repeats over a specified interval, and a remainder. The original data set is the sum of these three parts. The “remainder” portion of the data signifies noise. This remainder is separated in STL, allowing underlying trends to be identified in the “trend” and “seasonal” portions of the data. A function for the STL procedure was developed in R, a computing program (Cleaveland, Cleaveland et al. 1990).

Soil sensor data was filtered using the STL function in R. Evaluation of decomposed data revealed that the “remainder” portion of the data exhibited trends indicating that the model did not identify all trend patterns in the data. This demonstrates that STL is likely an inappropriate technique to filter the data set. Further investigation using STL was therefore discontinued.

Analysis Used to Identify Relationships

Censored data collected during the study exhibited visual trends. See appendix B. Figure 5 shows the average daily BOD applied against median effluent total iron concentration. A positive non-monotonic relationship appears to exist between these variables. A simple linear regression through these points yields a low R^2 value of 0.4. However, as discussed above, proving a statistical relationship using conversional techniques has not been effective.

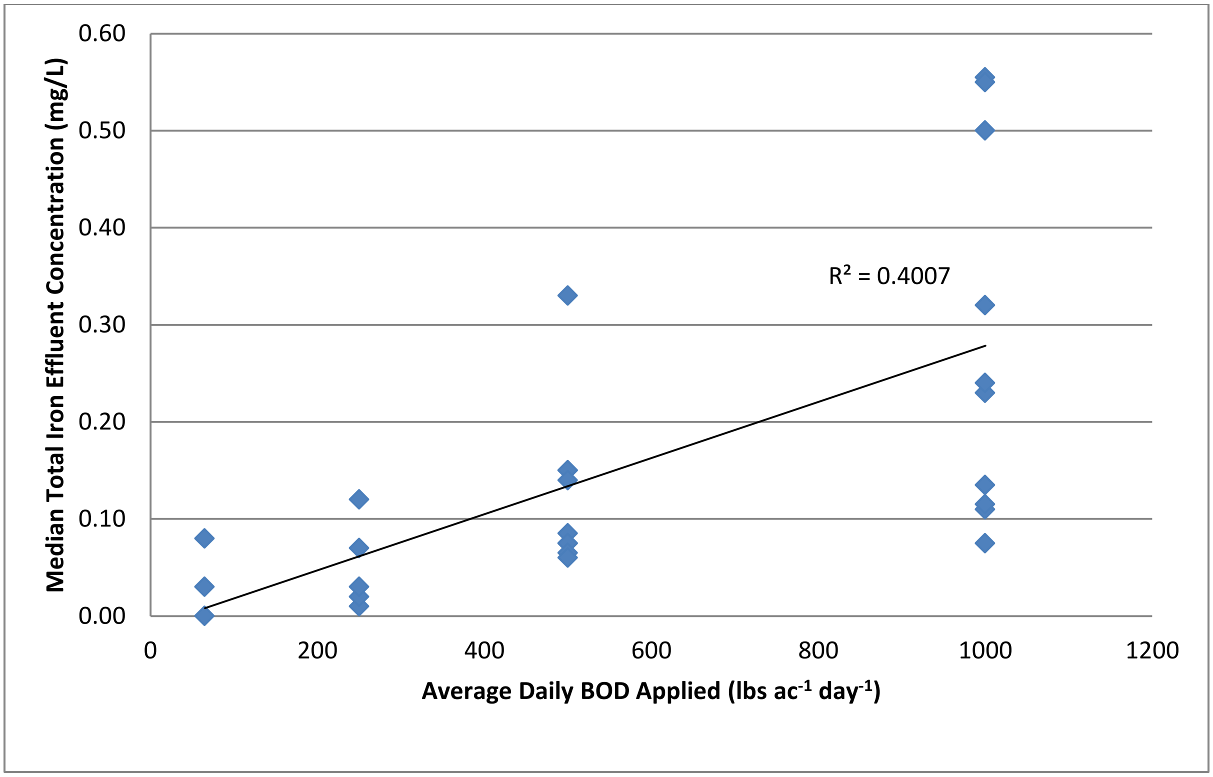

Figure 5 - Average Daily BOD Applied vs. Median Total Iron Effluent Concentration

Spearman's Rank Order Correlation

Spearman's rank order correlation is a modified version of the Pearson product-moment correlation coefficient and is used to indicate whether a statistical correlation exists between two variables. Correlations using Spearman's rank reveal only monotonic relationships in data sets and it does not require that the data be normally distributed or exhibit a linear relationship (McDonald 2014). Spearman's rank is a nonparametric statistical test that is used most extensively in biological studies. The transformation into ranks used in this test limits the impact of strong outliers but may still identify correlations in data.

Table 5 shows raw example data to complete an example Spearman's rank calculation. Note that this data is entirely fabricated. First, both variables must be numerically ranked. For example, the lowest value within a set of one variable is assigned the rank of 1, the second largest 2, and so on. If any values are equal, the ranks that would otherwise be assigned to those values are averaged. See Table 6 for an example.

Table 5 - Spearman's Rank Sample: Raw Example Data

x-values	y-values
2	3
23	2
34	38
53	53
10	41
60	34
52	13
82	96
74	68
74	36

Table 6 - Spearman's Rank Sample: Data Rankings

x-values	y-values	x-rank (x_i)	y-rank (y_i)	$(x_i - y_i)^2$
2	3	1	2	1
23	2	3	1	4
34	38	4	6	4
53	53	6	8	4
10	41	2	7	25
60	34	7	4	9
52	13	5	3	4
82	96	10	10	0
74	68	8.5	9	0.25
74	36	8.5	5	12.25
			Sum	**63.5**

Spearman's rank is denoted as ρ and is defined by the following equation.

$$\rho = 1 - \frac{6\,\Sigma(x_i - y_i)^2}{n^3 - n}$$

Where:

x_i, y_i = respective ranks of data pair

n = number of samples

Using the sample data in Table 5 and Table 6 the Spearman's rank can be calculated for the sample data as:

$$\rho = 1 - \frac{6 * 63.5}{10^3 - 10} = 0.62$$

Spearman's ρ is a relative correlation where $-1 < \rho < 1$, where $\rho = 0$ indicates no correlation and $|\rho| = 1$ indicates a perfect correlation. As ρ approaches 0 the correlation is indicated as weaker.

Figure 6 is a plot of the ranks given to the data in Figure 5. Axes indicate the rank of each value collected rather than the indicating the actual value of the data point. The difference between each of the ranks is not necessarily linear. Figure 6 is included to assist to visualize the transformation to Spearman's rank.

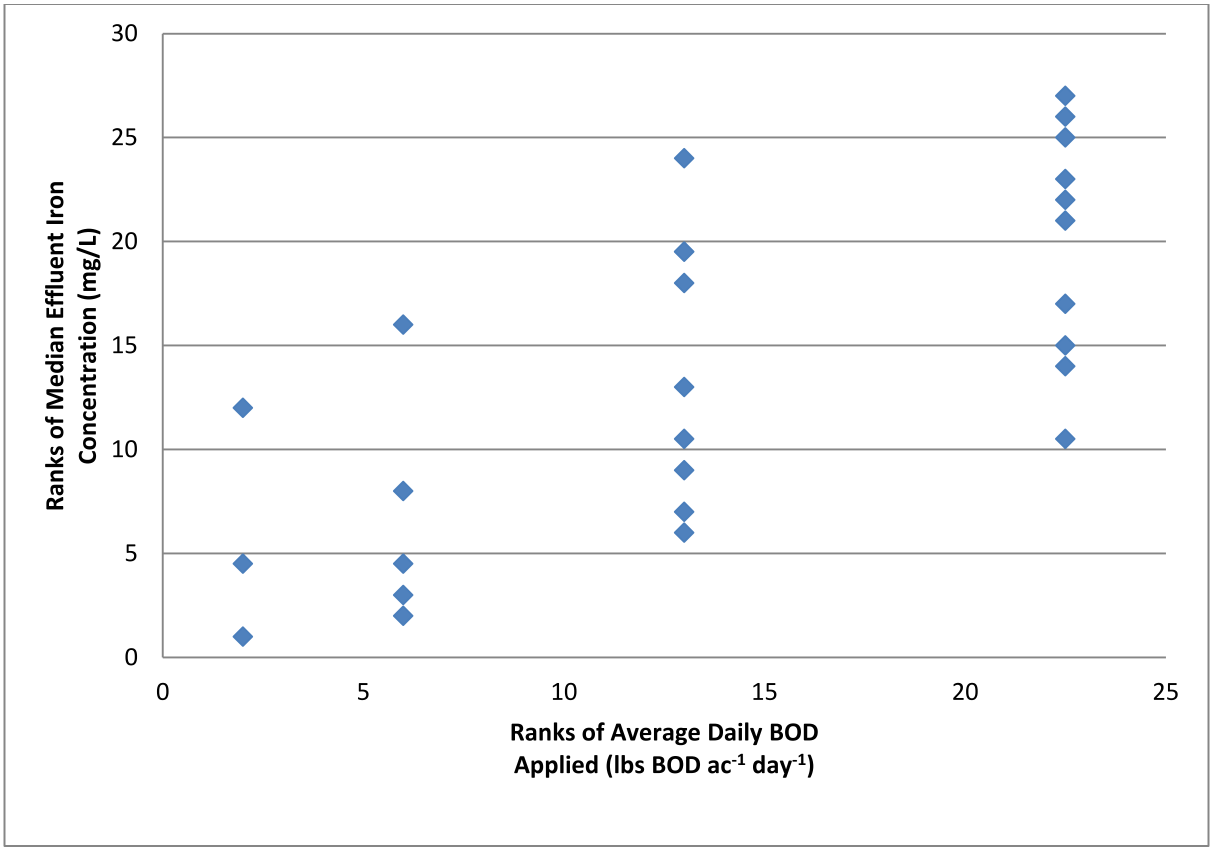

Figure 6 - Ranks of Average Daily Organic Load vs. Ranks of Median Effluent Iron Concentration

Analysis was conducted to determine whether correlations between loading characteristics and treatment conditions existed. Five loading characteristics were studied: Average daily organic load (expressed in lbs BOD ac^{-1} day^{-1}), hydraulic rest period (expressed in hours), organic load per dose (expressed in mg BOD), column length (either 0.6 or 1.2 m), and presence of perched groundwater table.

Because hydraulic loading was held constant during the study, variations in hydraulic rest period caused variations in the volume of water in each application of wastewater. Organic load per dose was calculated based on the concentration of water applied which depended on the average daily organic load, and the volume of wastewater applied per dose which depended on hydraulic rest period.

Treatment conditions studied were total manganese in column effluent, total iron in column effluent, COD in column effluent, oxygen concentration in the column, and volumetric water content of soil in the column.

Spearman's ρ was calculated for these comparisons using Microsoft Excel to determine whether correlations between these parameters were statistically significant. Calculated data and formulas are included as Appendix D - Calculation of Spearman's Correlation Coefficient.

Loading conditions were compared with sensor and analytical data collected for each treatment. Median values of each variable collected during each phase of the experiment were used to rank analytical data to nullify the effect of strong outliers. Data was censored using the procedure outlined in the materials and methods section of this report. Average values collected for O_2 and volumetric VWC were used for ranks.

Spearman's ρ was calculated for comparisons between each of the selected dependent and independent variables. Correlation of the pair was said to be statistically significant if the absolute value of the calculated ρ exceeded the critical value (Zar 1972). A single-tailed approach and p-value of <0.01 were used. Use of this p-value is common practice and indicates that there is less than a 1% chance that the indicated correlation developed due to chance.

A matrix for Spearman's ρ and p-value (if greater than 0.01) between the column loading conditions and the collected data was developed and is shown as Table 7.

Table 7 - Spearman's Rank for Selected Variables

	Spearman's Rank For Selected Variables									
	Mn		Fe		COD		O_2		VWC	
	ρ	p-	ρ	p-	ρ	p-value	ρ	p-value	ρ	p-
Average Daily Organic Load	0.27	> 0.01	0.72	0.005	0.71	0.005	-0.46	0.010	0.59	0.005
Hydraulic Rest Period	0.46	0.01	0.24	> 0.01	0.36	> 0.01	-0.27	> 0.01	- 0.10	> 0.01
Organic Load per Dose	0.41	> 0.01	0.54	0.005	0.61	0.005	-0.52	0.005	0.28	> 0.01
Column Length	0.88	0.01	0.21	> 0.01	0.40	> 0.01	0.31	> 0.01	- 0.36	> 0.01
Presence of Perched Groundwater	0.00	> 0.01	0.24	> 0.01	0.10	> 0.01	-0.20	> 0.01	0.29	> 0.01

Average Daily Organic Loading

Increased average daily organic load has a statistically significant positive correlation with effluent iron concentration, effluent COD concentration, VWC in the soil columns, and a negative correlation with oxygen concentration in the soil columns.

These correlations indicate that soil tends to become anaerobic and create iron reducing conditions as organic loading of the soil increases (Crites and Tchabanoglaus 1998, McDaniel 2006, Beggs, Bold et al. 2007, Hillel 2008). Oxygen required to aerobically degrade organic waste increases as organic application rate is increased. Anaerobic populations will dominate soil if organic application rate exceeds oxygen flux into the soil.

While average daily organic load correlated to poor column performance, several columns with high average daily organic load produced effluent that meeting SMCL criteria from the EPA for manganese (0.05 mg/L) and iron (0.3 mg/L). The success of columns with high average daily organic load to meet these criteria further demonstrates the effects of loading schedule and dosing on the success of a land application treatment system.

Table 8 - Percentage of Columns Meeting SMCL Criteria Organized by Average Daily Organic Load

Average Daily Organic Load lbs BOD ac^{-1} day^{-1}	Percent of Columns Meeting SMCL Criteria for Fe and Mn	Number of Samples
65	67%	3
250	40%	5
500	67%	9
1000	20%	10

Hydraulic Rest Period

Results indicated increased hydraulic rest period had significant positive correlation with effluent manganese concentrations. All other correlations were considered statistically insignificant using Spearman's rank.

Iron requires a more strongly reducing environment to become chemically reduced than manganese. Manganese may be reduced and re-oxidized as soil conditions change. Because the volume of water treated daily was not varied in this study, increased hydraulic rest period increased the volume of individual dose to be treated. It is hypothesized that the volume of water traveling through the column promoted leaching of manganese by temporarily promoting mildly reducing conditions (high water content for a brief time, leading to low oxygen content) and flushing manganese from the soil due to the higher downward velocity of the water.

However, each of the statistically insignificant data sets does not seem to follow a monotonic function. For example, rank of VWC in soil during the study tended to be highest when water applications were either more frequent or more infrequent. The lowest ranked VWC paired with water application frequency between six and twelve hours. Effluent iron concentration and effluent COD concentration follow this same pattern. Average oxygen concentration indicates an inverted pattern. Figure 7 shows the paired rankings of the instantaneous volume of water applied and the rank of VWC in the soil column. Visual inspection of this figure suggests the monotonic requirements of Spearman's rank have been violated. Analysis to objectively quantify whether this relationship was monotonic was not conducted.

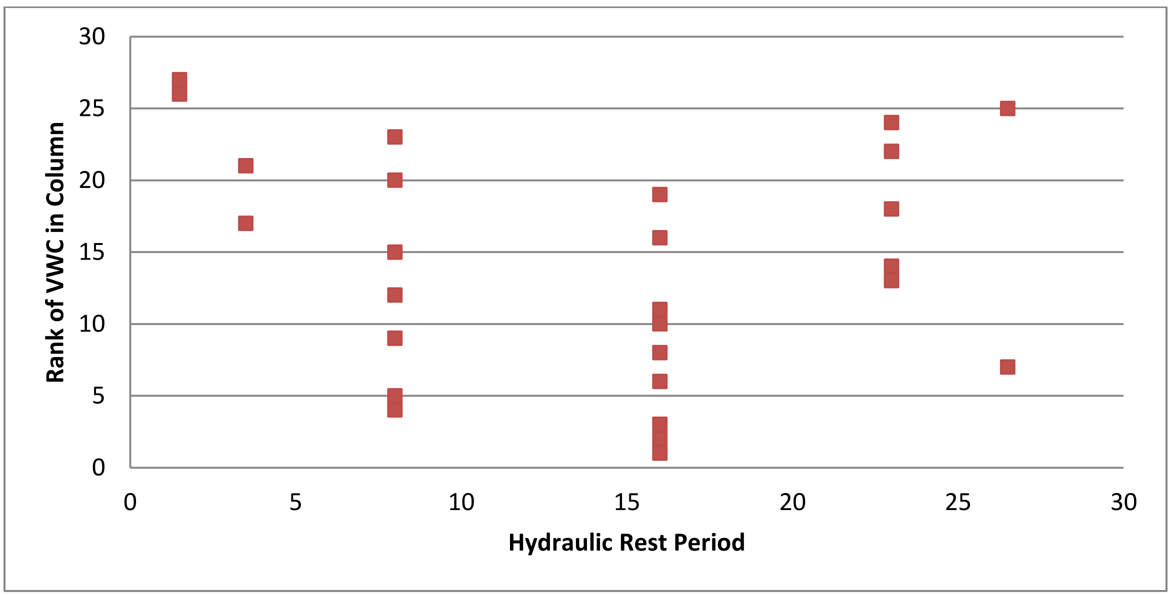

Figure 7 - Rank of Hydraulic Rest Period and Column Water Content

Frequent, low-volume hydraulic dosing may not give soil adequate time to drain, promoting a more saturated soil. As the soil becomes more saturated, downward velocity of the water into the soil decreases and the piston effect that draws oxygen into the soil via low pressure following a substantial hydraulic dose described in previous literature (McMichael, McKee et al. 1965, Lance, Whisler et al. 1973) becomes weaker. Small doses of water may also not draw enough air into the soil to promote an aerobic environment. Conversely, infrequent, high-volume hydraulic dosing draws air into the soil, but the large volume of water in the individual doses may temporarily saturate the soil. This may allow a shift to a predominantly anaerobic microbial population. Anaerobes maintain anaerobic conditions by producing slime in the soil pore space. As such, an ideal dosing frequency appears to exist where soil is allowed to drain sufficiently between water doses, but that provides a piston of air to the soil frequently enough to maintain aerobic conditions. Data from this study suggests a hydraulic rest period of 12 hours will help to maintain an aerobic soil environment. However, denitrification requires an anaerobic environment. As such, denitrification requirements for a site should also be considered.

Organic Load per Dose

Increased instantaneous application of organic material had statistically significant positive correlation with effluent iron concentration, effluent COD concentration, and a negative correlation with oxygen concentration in the soil columns.

These correlations indicate that soil tends to become anaerobic and create iron reducing conditions as organic load from individual dosing events increases. Oxygen demand of the organic load in these doses has the potential to overwhelm oxygen flux into the soil. Anaerobic microbially populations may dominate the soil if oxygen deficient environments are maintained for a long enough period. Biofilms produced by anaerobic bacteria limit oxygen transport into the soil. Aerobic populations will not recover if oxygen flux does not meet oxygen demand. Wastewater treatment efficacy is decreased and potential for metals leaching is increased while anaerobic conditions are maintained.

However, little research specifically investigating effects of individual applications of organic matter on metal mobilization was found. Additionally, statistically significant positive Spearman's correlation between average daily organic load and organic load per dose existed due to the experimental design of this study.

Column Length

Column length was biased by experimental design as long columns used in this study were subjected to higher organic loading than the short columns. This is demonstrated by a significant correlation between column length and average daily organic load.

Spearman's rank for the effect of long columns on the dependent variables was recalculated using a subset of eight loading conditions to nullify this effect. These eight conditions were a combination of four pairs of long soil columns and short soil columns. Loading conditions were duplicated between these pairs. This data subset is shown in Table 9.

Table 9 - Data Subset for Column Length Correlations

Unique Identifier	Submerged Bottom?	Column Length (meters)	Average Daily Organic Load (lbs BOD $ac^{-1}day^{-1}$)	Hydraulic Rest Period (hours between doses)	Organic Load per Dose (mg)
C4-0	No	0.6	250	12	2,200
C4-1	No	0.6	250	12	2,200
C6-3	No	0.6	1000	24	18,000
C5-3	Yes	0.6	1000	56	42,000
C7-1	Yes	1.2	250	12	2,200
C8-1	No	1.2	250	12	2,200
C8-3	No	1.2	1000	24	18,000
C7-3	Yes	1.2	1000	56	42,000

Spearman's rank calculated for these pairs indicated that increased column length had a statistically significant positive correlation with effluent manganese concentration. Short columns were used in the study prior to installation of the long columns. Iron requires a lower redox potential than manganese to be mobilized and is more abundant in typical soils. It may be possible that manganese was depleted from short columns during the initial phase of the experiment. It is hypothesized that this measure is still biased because the long columns in this study were operated for a shorter time than the short columns. No further conclusions were drawn as a result.

Presence of Perched Groundwater Table

The presence of a perched groundwater table had no significant effects on the measured data. This effect validates the experimental setup in that it demonstrates air did not enter the columns from the bottom through drainage holes. It was initially hypothesized that submerged columns would correlate to lower oxygen concentrations in the column if the bottom of unsubmerged columns had allowed significant air to enter the column.

Soil after Experiment

Soil borings were taken of each column following the experiment. Note that soil cores illustrate the changes to the soil due to the cumulative effect of the loading conditions applied to each column. Photographs were taken and visual observations were noted.

Several columns had an organic sludge on the surface. However, because the columns without a sludge layer may have recently been scraped to allow drainage, this sludge was not studied. Sand throughout the columns appeared orange to brown in color. Soil 2.5 cm to 7.6 cm from the surface in each column exhibited a dark band indicating that added organic mass had accumulated in the top layer of soil. Buildup of organic matter in the top layer of the soil limits diffusion rate of air into the soil and can promote anaerobic conditions. A photograph of soil cores taken from one column is included as Figure 8. Organic layer on columns C7 and C8 is less visible. These columns were operated for a shorter time than the other six columns. Photos of all soil columns are included as Appendix E.

Figure 8 - Column 1 Soil Cores Illustrating Accumulation of Organic Matter Near Soil Surface

Conclusions

Organic matter delivered to the soil matrix requires oxygen for aerobic degradation. Anaerobic conditions, characterized by low oxidation-reduction potential, predominate without sufficient oxygen. Naturally occurring metals in the soil may be reduced via microbially mediated redox reactions under anaerobic conditions. Manganese, iron and, arsenic are common in soil and are water soluble in their reduced states. These metals can leach into groundwater when reduced. Additionally, anaerobic populations require more time than aerobic populations to fully degrade organic compounds allowing organic waste to contaminate groundwater.

A lab-scale sand column experiment was conducted to assess impacts of land application of wastewater. Specific goals of the study aimed to evaluate the impacts of several design and operational parameters on groundwater with respect to mobilization of naturally occurring metals from the soil matrix.

Results from the experiment indicated a statistically significant positive correlation between average daily organic loading with effluent iron concentration, effluent COD concentration, and column VWC. Negative correlations with gaseous O_2 concentrations in column were observed. Organic load per dose positively correlated with effluent iron concentration and effluent COD concentration. Negative correlations with gaseous O_2 concentrations in column were observed.

The results of this study concerning average daily organic load validate literature studied. Excessive organic loading of land application systems may cause anaerobic soil conditions resulting in groundwater contamination by metals and incompletely treated wastewater (Crites and Tchabanoglaus 1998, McDaniel 2006, Beggs, Bold et al. 2007).

While the effects of average organic loading have been studied in depth, few studies focus on the impact of organic load per dose as this project did. Results from this study indicate that total oxygen demand of wastewater doses delivered to soil also impact soil conditions and can result in incomplete wastewater treatment and metal mobilization from soil.

Findings from this lab-scale study revealed hydraulic rest period exhibited a statistically significant positive correlation with effluent manganese concentration. Results also indicated that hydraulic loading frequency did not exhibit statistically significant monotonic correlations with effluent iron concentration, effluent COD concentration, soil VWC or soil O_2 concentrations. However, qualitative review of collected data suggests that a non-monotonic relationship with these parameters may exist. Literature indicates water application to soil promotes soil aeration by drawing in air via a hydrodynamic mass transfer "piston-like" effect (McMichael, McKee et al. 1965, Lance, Whisler et al. 1973). Literature regarding effects of small, frequent, dosing of wastewater to land application systems was not found.

The presence of a perched groundwater table was demonstrated to have a negligible effect on effluent water quality and soil conditions during this study. p-values for all comparisons were greater than 0.01.

Length of sand columns showed a statistically significant positive correlation to effluent manganese concentration. However, this correlation is hypothesized to result from experimental design and not necessarily from column length. No significant correlations to iron concentration, COD concentration, oxygen concentration, or VWC were noted.

COD did not have a statistically significant correlation to column length but column effluent typically contained measurable COD (see Appendix C for data). Oxygen concentrations in soil diminish with depth (Lance, Whisler et al. 1973). Anaerobic treatment is slower than aerobic treatment. Anaerobic portions of the soil columns will therefore offer little treatment but will typically cause a reducing environment due to the presence of a carbon source and nutrients (Hillel 2008). Manganese in the column effluent was thereby anticipated because of these reducing conditions. The relatively low concentrations of COD in the lower portions of columns may not have caused redox potential low enough to mobilize iron.

Visual inspect of soil after the experiment revealed deposition of organic matter in the top layer of soil. This deposited organic matter may reduce the oxygen flux into the soil, promoting anaerobic conditions. This layer likely developed over time and had a more significant effect on the last phases of the study than the first. The accumulation of organic matter may introduce bias by reducing oxygen flux into the soil; however, this effect was not specifically studied.

Overall trends indicate that increased average daily organic load and organic load per dose have a negative impact on water quality. Other studies have attempted to determine an average daily organic loading that prevents metal mobilization; however, findings from this study indicate organic dose load and hydraulic rest period are important factors that should be considered in design. General guidance from this study indicates that both organic load per dose and average daily organic load be reduced to ensure a treatment system does not negatively impact groundwater quality. Operational constraints should be considered during the design phase land application treatment systems.

Hydraulic rest period is an important factor and may be used to help aerate soil. Results from this study indicate that a rest period of approximately 12 hours using hydraulic loading events of 0.7 cm can be used to encourage aeration via hydrodynamic mass transfer.

Opportunities for Further Research

Wastewater land application systems offer many benefits. Land application of waste is economical, relatively low-maintenance, and returns water to the local aquifer. Land applied wastewater can serve as nutrient-rich irrigation water for crops. However, poorly managed systems have resulted in crop failure, unpleasant odors, and contamination of soil and groundwater.

Further research is required to gain a more complete understanding of wastewater land application systems. Information acquired through this study can be utilized to further optimize land application design and maintenance strategies as well as direct future research. Specific recommendations developed following the completion of the lab-scale study are listed below.

1) Sample size of column conditions was relatively small in this study due to limited resources. Conducting tests on a larger number of soil columns, including adequate duplication, may allow for more comprehensive analysis using methods such as Multiple Liner Regression.
2) Consideration of soil type in this evaluation would help make this study more immediately applicable to full-scale systems. Soil type plays an important role in available pore space, VWC, and oxygen transfer into soil. Site specific pilot-scale systems may be an appropriate means of assessing the quality of a site for a land application treatment system. Further study using a variety of soil types and soil mixtures will provide a more robust understanding of land application treatment systems and help to develop a prescriptive approach to operation recommendations.
3) Further research is required to better understand the different impacts of average organic load and organic load applied per dose. Land application requires optimization of several competing factors including oxygen flux into soil, biokinetic rate of wastewater degradation (with focus on aerobic versus anaerobic processes), and apparent velocity of water. Computer modeling may prove useful and could be calibrated using data collected during previous studies.
4) Organic material was deposited in the soil throughout the study. Past research has indicated that deposition of organic material on soil limits oxygen transfer into soil. Land application

systems should consider maintenance strategies to reduce surface fouling due to accumulation of organic matter at soil surface.

APPENDICES

APPENDIX A

Standard Operating Procedures

The following is the Standard Operating Procedure for the Sand Assimilation Project. This project is aimed at determining the effect of carbon loading on soil on the leeching of metals from the soil.

The barn behind Farrall Hall houses the sand columns. These columns receive a mix of synthetic wastewater from a system of pumps operated on timers. The pumps and timers allow for a more precise delivery of the wastewater, both in terms of timing and volume, and help to reduce the amount of time spent on the project. Below, in Figure 1, the pump configuration can be seen. This configuration was planned out to keep the columns from the previous stage of the experiment in their current positions and add Columns 7 and 8 with the smallest amount of confusion.

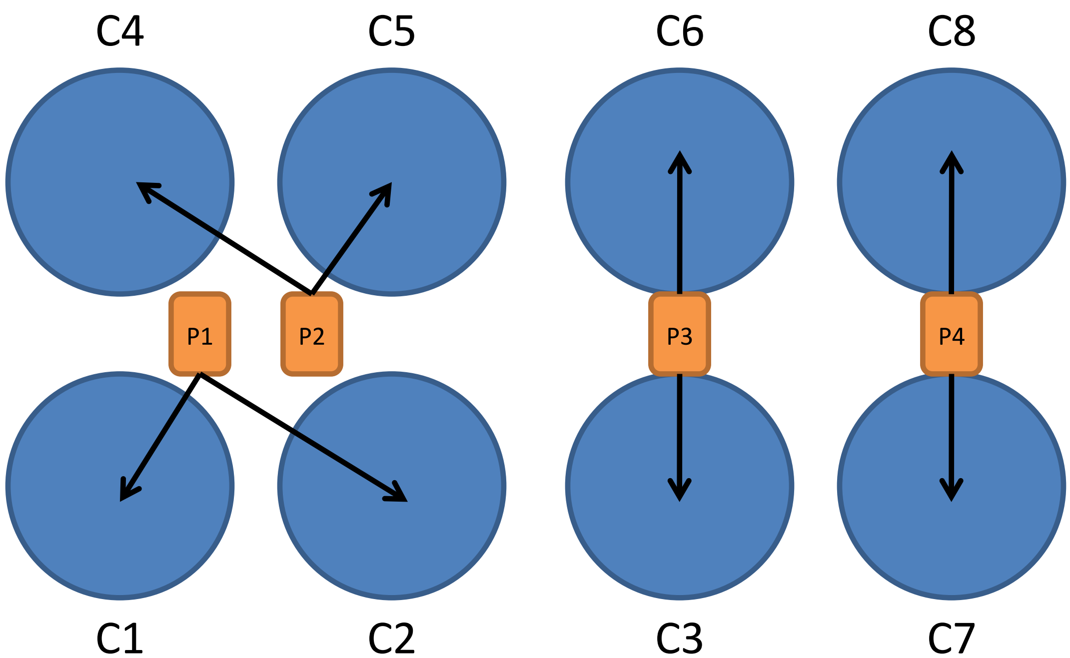

Figure 9 - Pump Configuration

Synthetic wastewater is produced by measuring out several chemicals to achieve a certain chemical oxygen demand (COD) based on a well-respected article (Trulear, 1982). There are eight columns being studied, each receiving a particular COD loading. Each column has a counterpart; one will allow water to exit the column as it reaches the bottom and another with a closed bottom and a water trap to simulate a high groundwater table. As such, wastewater will be prepared in four buckets, one for each pair of conditions, and then split into eight buckets, one for each column. Conditions and bucket assignments can be seen below in Table 1.

Table 10 - Column Loading Schedule

	Organic Loading	Hydraulic Loading	Loading Frequency	Submerged	Bucket
Column 1	65 lbs BOD/day	2.4 L/day	4x/day	Submerged	B1
Column 2	65 lbs BOD/day	2.4 L/day	4x/day	Unsubmerged	
Column 3	250 lbs BOD/day	2.4 L/day	2x/day	Submerged	B2
Column 4	250 lbs BOD/day	2.4 L/day	2x/day	Unsubmerged	
Column 5	500 lbs BOD/day	2.4 L/day	6x/day	Submerged	B3
Column 6	500 lbs BOD/day	2.4 L/day	6x/day	Unsubmerged	
Column 7	250 lbs BOD/day	2.4 L/day	2x/day	Submerged	B4
Column 8	250 lbs BOD/day	2.4 L/day	2x/day	Unsubmerged	

Therefore, B1 will feed C1 and C2. However, both columns will have a separate bucket for influent. So, B1 will be prepared, split evenly into F1 and F2 which will feed C1 and C2 respectively. Testing will be done on B1-4 and not F1-8, as the samples would have the same concentrations and yield redundant data.

Lab tests will be done to determine the pH, COD, Alkalinity and concentrations of manganese and iron of both the influent and effluent water (from buckets and columns).

Data will be collected, input into a master spreadsheet and then analyzed.

Scheduled Operations

Preparation and Sampling

Prepare Sample Cups

Clean sample cups can be found in a drawer labeled "Sample Cups" on the right-hand side of the fume hood in Lab 128. For a typical day's operation 12 cups will be needed; four for bucket samples, eight for column samples. Be sure to grab the correct type of lid for each cup as there are two styles of threading.

Affix a small piece of painter's tape to each cup and write the date and sample location on that tape. Cups will be needed to sample each of the mixing buckets (B1-B4) and each of the columns (C1-C8).

Prepare Nutrient Solution

Nutrient solution is stored in a 2L screw-cap bottle in a cupboard directly across from the door to lab 128. Also in this cupboard is a glass pipette and a sheet of paper explaining the necessary amount of nutrients for each bucket/column. Use the pipette and the cordless pipetter normally found on the countertop to fill the sample cups B1-B4 with the prescribed amount of the nutrient solution (indicated on nutrient loading sheet). When finished clean the pipette tip out by flushing it with deionized (DI) water. Place all materials back where they were found.

Measure Remaining Influent

In order to complete a mass balance of metals and nutrients the amount of water actually applied to the columns must be calculated. This is done by measuring the volume of influent water that is left over after application and subtracting that from the volume of water prepared and using information about the concentration of nutrients in the solution.

When first arriving in the barn each day, prepare an Influent/Effluent sheet. This is simply a large post-it note (blank ones on the computer desk in the barn) with the date, time, temperature and volumes of influent and effluent water recorded on it. The temperature should be recorded from the digital thermometer located on top of the computer.

Measure the volume of influent remaining in each bucket either by using the graduations marked on the sides of each feed bucket or by pouring the remaining influent into the graduated cylinder near the columns. If using the graduated cylinder, make sure to keep it clean and avoid contaminating one bucket with another's nutrient solution. Record the volume on the Influent/Effluent sheet.

Clean Buckets

After measuring the remaining effluent, each bucket must be cleaned thoroughly using phosphorus-free soap and a sponge. Only use the sponge that has been labeled for this project as any other one could be contaminated with chemicals that will interfere with the experiment. This will be done the easiest in the shop sink (out the back door of Lab 129). A key into the shop can be found in the drawer where the sample cups are stored.

Prepare Nutrient Buckets

As stated previously, each column will be receiving water from its own bucket. This will allow a mass balance to be done for each column. However, synthetic wastewater will be prepared for each pair of buckets and need to be split into two different buckets. This saves time and makes measuring nutrients easier.

To prepare each bucket, pour the nutrient solution measured earlier into the proper bucket as well as the correct baggie of dry nutrients. These baggies will be stored in the same cupboard as the nutrient solution.

Water must be added to each bucket. Each column will have 3000 mL available each day. Although they are only meant to receive 2400 mL per day, the extra water allows for some error correction and makes measuring the remaining influent easier. So, when preparing the nutrients, B1 (which feeds both C1 and C2) will need 12 L of water on Mondays and Wednesdays. Because the columns will be left alone for an extra day over the weekend, 18 L of water is needed.

After mixing the water and required nutrients together, carefully rinse out the B1-B4 sample cups to reduce the residue left from the concentrated nutrient solution. Do this by scooping and pouring out some of the solution to be sampled. This helps ensure that the bucket has all of the nutrients from the sample cup and that the sample cup has a representative sample of the solution.

Each nutrient mixing bucket will then be split in half into the respective nutrient feed buckets.

Each bucket will then need to be placed on a shelf near its respective column in the barn. Wipe the hose and PVC pipe connected to it with paper towel and replace the lid on each bucket. This helps prevent bacterial growth in each bucket and helps ensure that nutrients are delivered to the columns instead of consumed before application.

Measure/Sample Effluent

The effluent from each column will also need to be measured to complete the mass balance. Under each column there is a clear plastic tub. Take a sample of each of these tubs using the correctly labeled sample cup. Again, rinse the sample cup with the sample by scooping up water and pouring it out (do this three times for each sample). After sampling the water measure the effluent volume by pouring the contents of the tub into the graduated cylinder. Be sure to account for the volume of the sample (typically 50-100 mL). Record this on the Influent/Effluent Sheet (post-it note).

Cleaning Spray Nozzles

Every week the spray nozzles that distribute the synthetic wastewater onto the soil columns must be cleaned to ensure an even distribution and prevent clogs and buildup. Do this by pulling out the dirty nozzles from their enclosure and allowing them to sit in an H_2O_2 solution. There is an extra set of nozzles so that the clean ones can immediately be placed into the enclosure and the dirty nozzles can sit overnight in the Hydrogen Peroxide solution.

The easiest way to do this has been to replace one nozzle each day of the week until all nozzles have been cleaned. For example, replace C1 and C2 on Monday, C3 and C4 on Tuesday and so on. Do not replace any nozzles on Friday.

Cleaning Effluent Tubs

After measuring the volume of effluent produced take the empty effluent tubs to the sink in the shop to wash. Wash them in the same way as the buckets. That is, scrub each out with phosphorus-free soap using the sponge for this project.

Dry the tubs out by wiping the inside of each of them with paper towel and replace them under the columns to continue catching effluent water.

Clean the Sink

Each week the sink in the shop will need to be cleaned to prevent any bacterial buildup. To do this, use the other sponge, not the one for the sand assimilation project, and the Comet cleaning powder to wipe down the entire sink. Report any problems to Ryan Julien or Phil Hill.

Collect Sensor Data

Once a week sensor data must be collected and input into the sensor data spreadsheet.

Observe Pumps

Pumping of water onto columns should be observed once a week to ensure that the pumps are operating properly and not leaking. This observation also serves to check that the columns are draining properly. If all water has not infiltrated the soil surface 30 minutes after the water was applied, the top of the column needs to be scraped. This can be done by running a small garden rake over the top of the column to break up any bacterial growth and allow for proper drainage.

Lab Tests

After collecting the samples and ensuring that the columns will have a continuous supply of water until the next sampling period different laboratory tests must be run. All lab tests have Standard Operating Procedures that can be found in the Sand Assimilation Project Book.

pH

pH of each sample must be tested as soon after collection as possible (within 1 hour). This will be done using the pH meter in Lab 128. Follow the standard procedures for using the pH meter and be sure to calibrate the meter before every test using the pH buffer solutions, found in the same cupboard as the nutrient mixes.

COD

Chemical oxygen demand is measured using HACH COD test kits. There are both high and low range test kits for 1500mg O_2/L and 150mg O_2/L respectively. Typically the bucket samples will require the use of the high range (HR) kits and the column samples can be measured using the low range (LR) kits. Both types require 2mL of sample to be added to the prepared test tube. However, the HR kits will normally be diluted with a 1 to 4 ratio. This means that 1.5mL of DI water and 0.5mL of sample water will be added to each test tube. The LR tests are generally not diluted and simply receive 2mL of sample water.

Both the HR and LR tests will be run with a blank to calibrate the spectrophotometer that the tests are read in. This blank is prepared by adding 2 mL of DI water to a prepared test tube.

A HR standard is also prepared. This is done using a standard 1000mg/L solution from the HACH Company. Although this is a high range test, it is not meant to be diluted and 2mL of the solution is to be added to a prepared vial.

Be sure to label each sample vial with the sample location (B1, HR Blank, Standard, etc.) and the date. This is easiest to do before adding the sample to each vial as the reaction between the prepared solution and the sample is exothermic and can be too hot to handle easily.

After preparing the solutions appropriately, overturn the vials 10 times to ensure the contents are entirely mixed and place them in the oven under the fume hood for 2 hours at 150C as per the HACH instructions. For any additional information see the HACH COD Kit SOP (Method 8000).

Alkalinity

The alkalinity test is performed using pH indicator powder packets and a digital titrator. Follow the SOP provided by HACH (method 8203).

Metals

Metal testing will be done by the plant and soil sciences department. However, before a sample is brought in for testing it must be acidified.

As-Needed Operations

Several tasks do not adhere to a strict schedule and must be completed on an as-needed basis. Below are the main tasks, but keep in mind this is not an exhaustive list.

Prepare Nutrient Baggies

Nutrient baggies are to be prepared using the formulas on the nutrient mixing spreadsheet found in the cupboard in Lab 128. Use the zip-top baggies (found on top of cabinets in Lab 128) and label each bag with an appropriate label. This label includes the bucket number and whether the baggie is for two or three days. It is best to have baggies in the cupboard for at least one week in advance to allow for any changes in schedule that may occur.

Prepare Nutrient Solution

As the concentrated nutrient solution runs out more will need to be prepared. There is another sheet describing all of the chemicals included in this mixture in the cupboard and the Sand Assimilation Binder. The 2L mixture generally lasts for about one month.

Prepare Clean H_2O_2 Solution

The hydrogen peroxide solution used to clean the spray nozzles often gets dirty and becomes less effective. When this happens it is time to prepare a clean solution.

In the cabinet under the computer in Lab 128 there is a bottle of 50% H_2O_2. This should be diluted to at least 25% before being used to clean the nozzles. Pour an amount of 50% H_2O_2 into a sample cup and add an equal volume of water. Use this as the new H_2O_2 solution.

Clean O_2 Sensors

Occasionally oxygen sensors in the sand columns get plugged up with crystals; presumably precipitates from the nutrient solution. If sensor data shows that an oxygen sensor is reading 0% O_2, it is likely that the sensor has been overwhelmed with this precipitate.

To clean the sensors they must be carefully removed from the columns to reduce the influence of opening the column to the atmosphere and cleaned according to the instructions provided by Apogee, the producer of the sensors. These instructions can be found in the Apogee O_2 sensor brochures in the Sand Assimilation Book.

Checklist

To ensure that each task is completed, a checklist has been developed. After completing a task initial the corresponding box. This will allow all working on the project to easily see what tasks have been completed and which, if any, need attention. See a copy of the weekly checklist below.

Table 11 - Weekly Checklist

Week **to**

Task	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Prepare Nutrient Mix							
Measure Influent/Effluent							
Clean Nozzles							
Clean Effluent Tubs							
Observe Pumps							
Clean Sink							
Collect Sensor Data							

Task Log

Any work or results that are out of the ordinary should be in the Task Log section of the Sand Assimilation Data Book. This should be done every day.

APPENDIX B

Selected Raw Data Figures

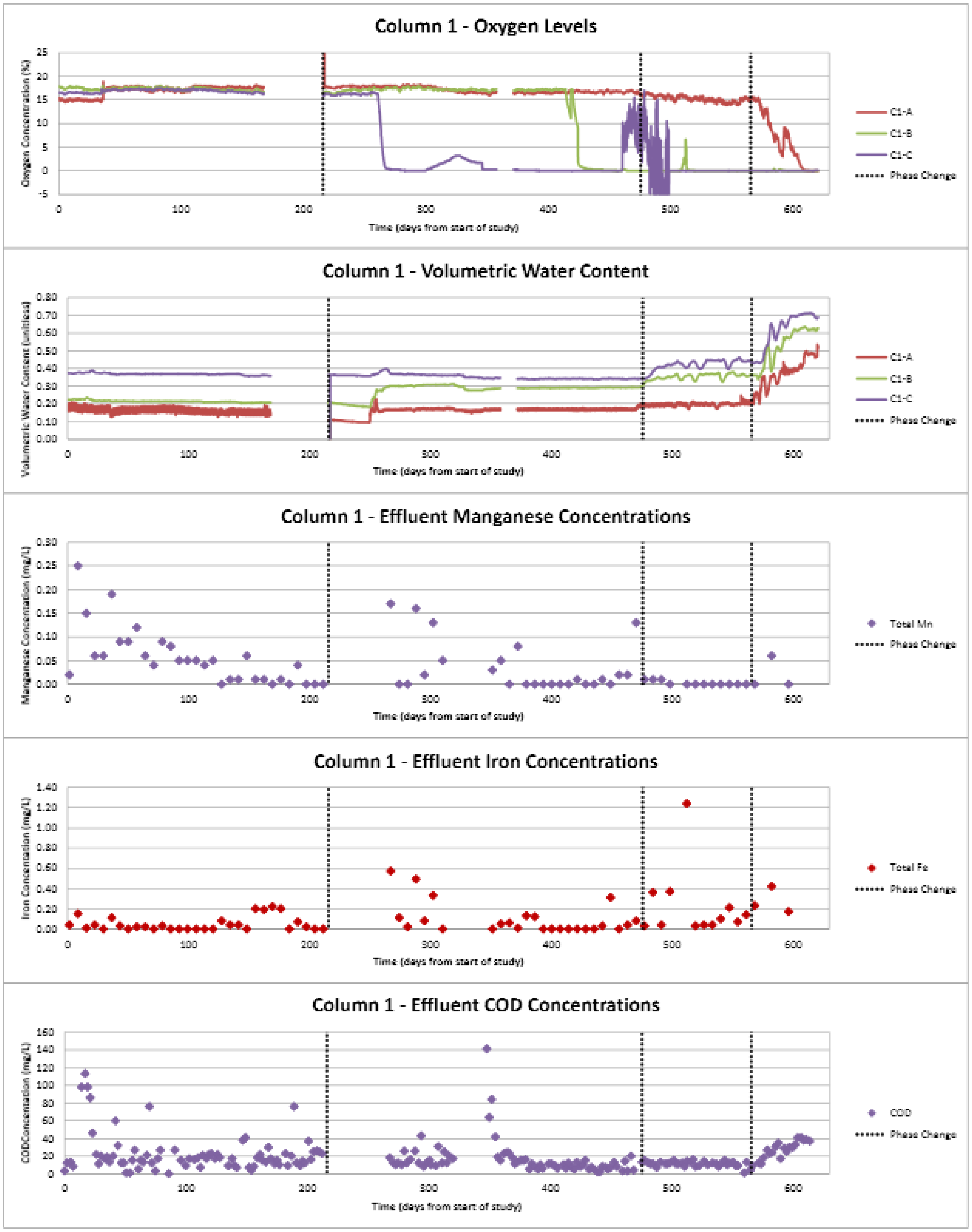

Figure 10 - Column 1 Raw Data

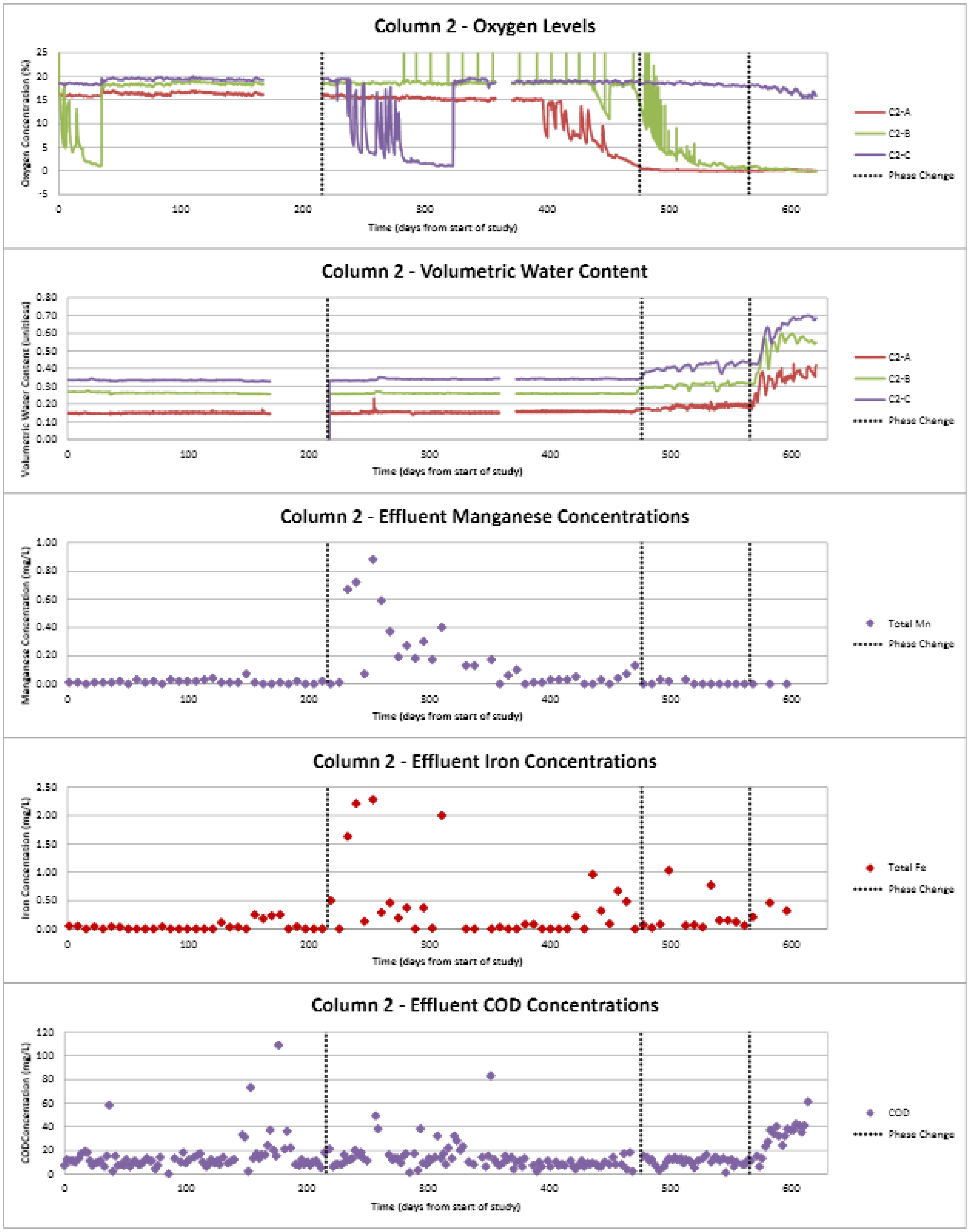

Figure 11 - Column 2 Raw Data

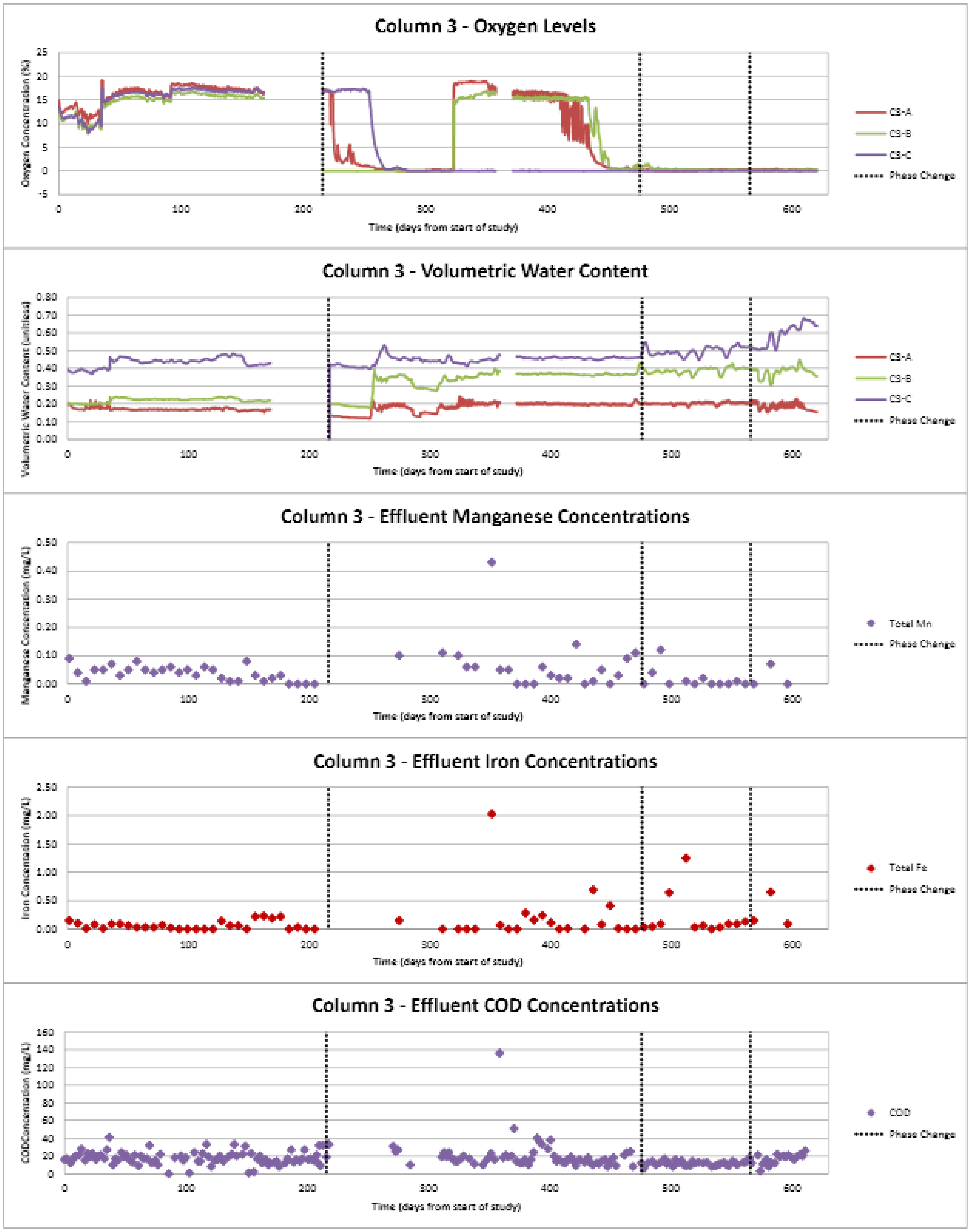

Figure 12 - Column 3 Raw Data

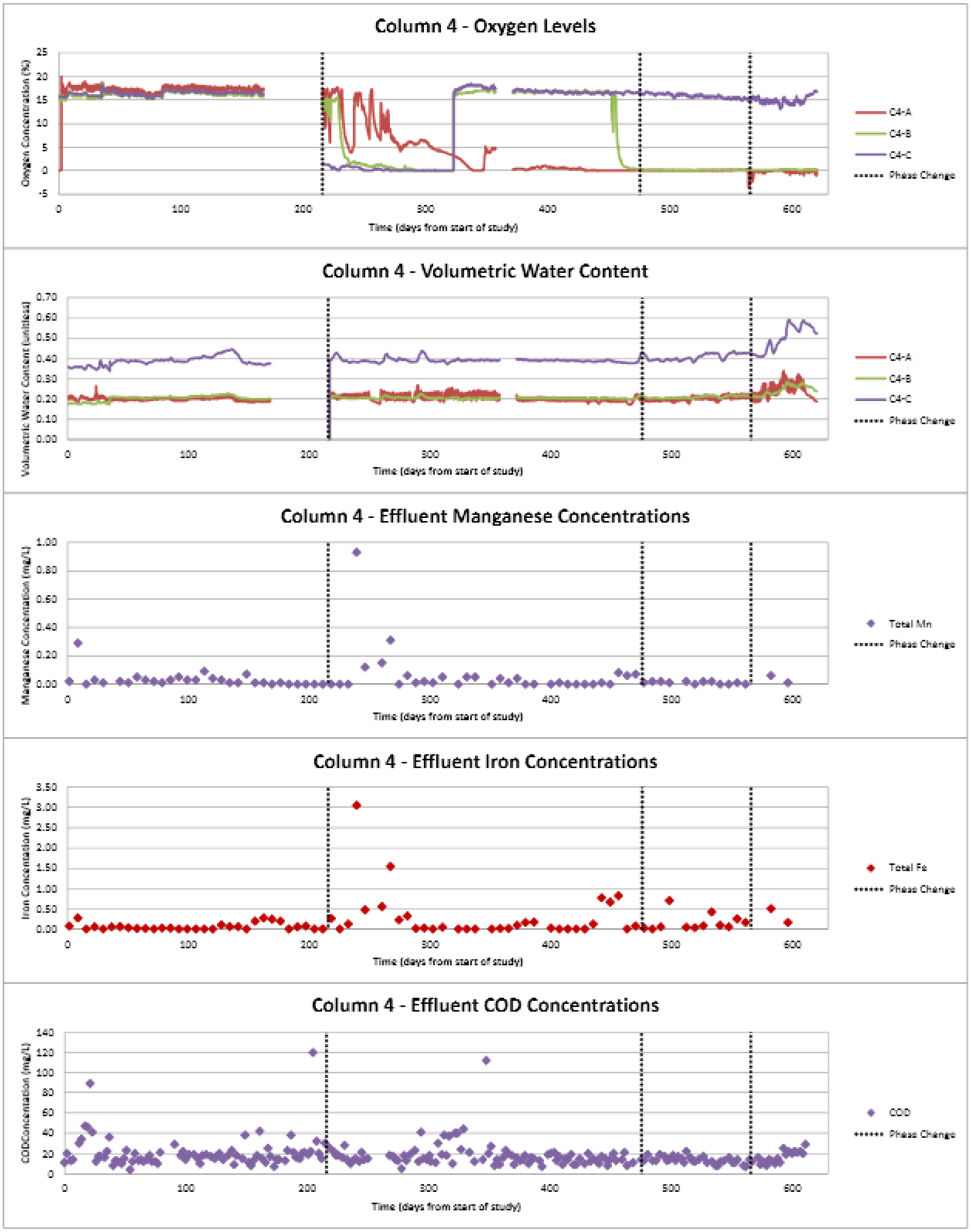

Figure 13 - Column 4 Raw Data

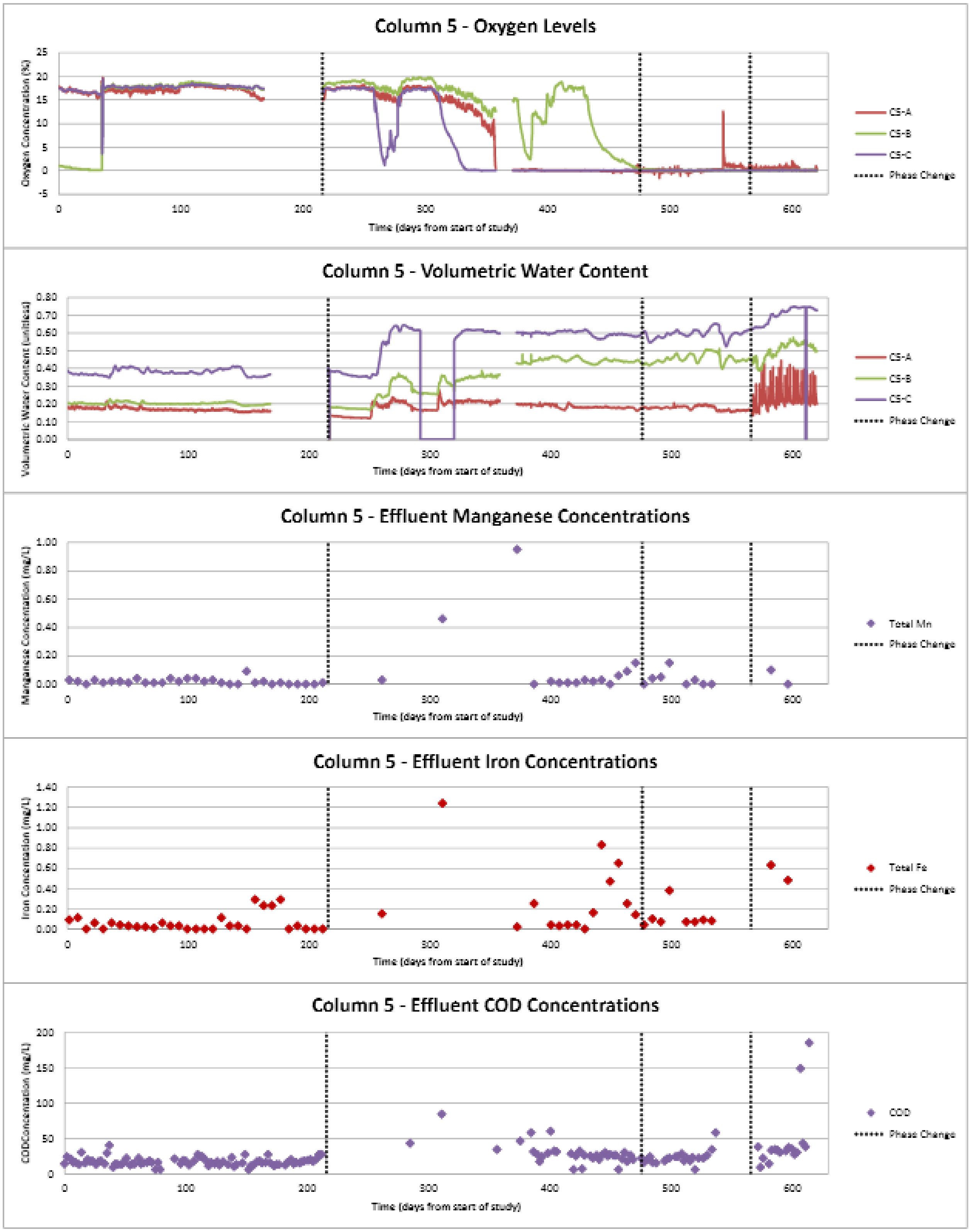

Figure 14 - Column 5 Raw Data

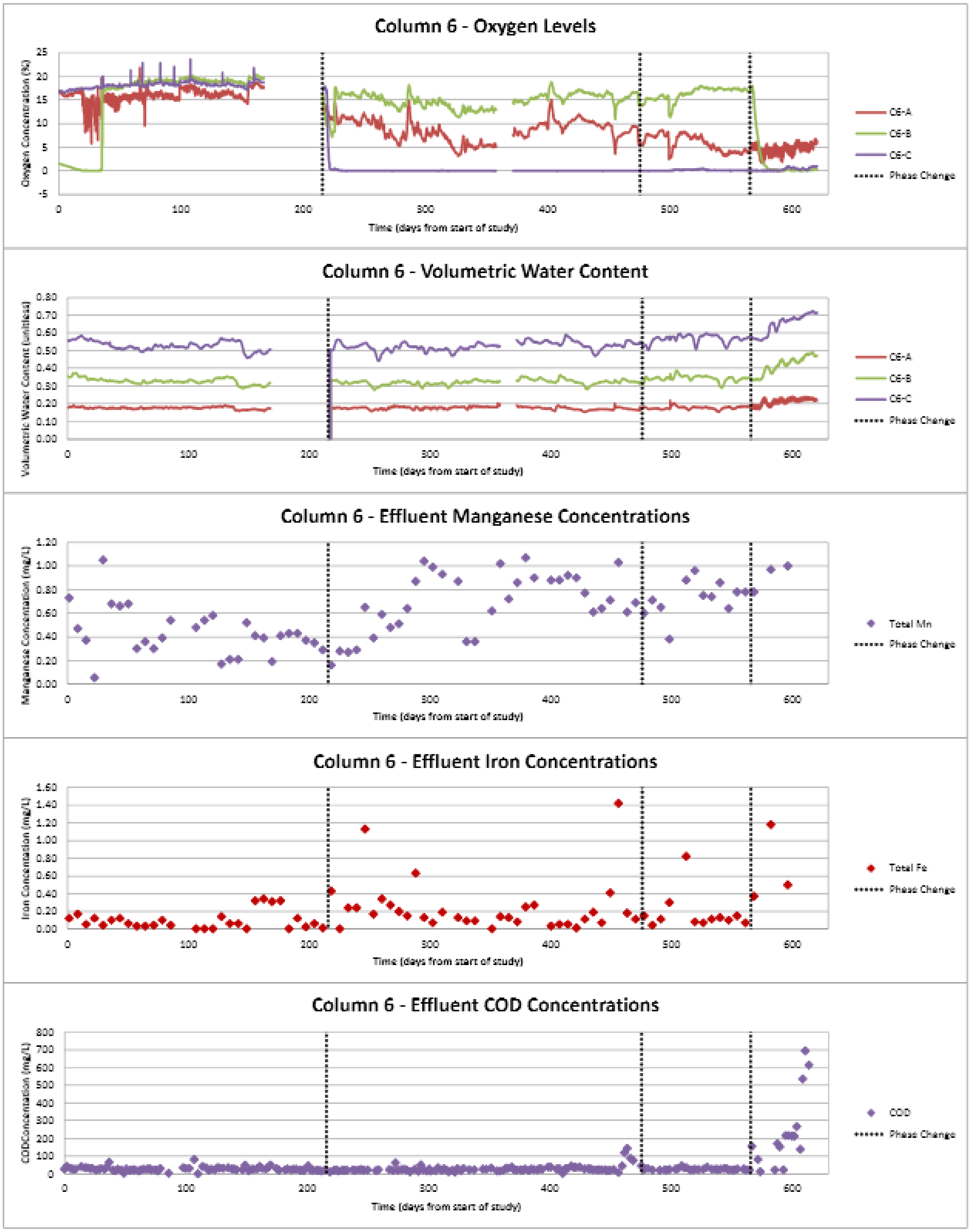

Figure 15 - Column 6 Raw Data

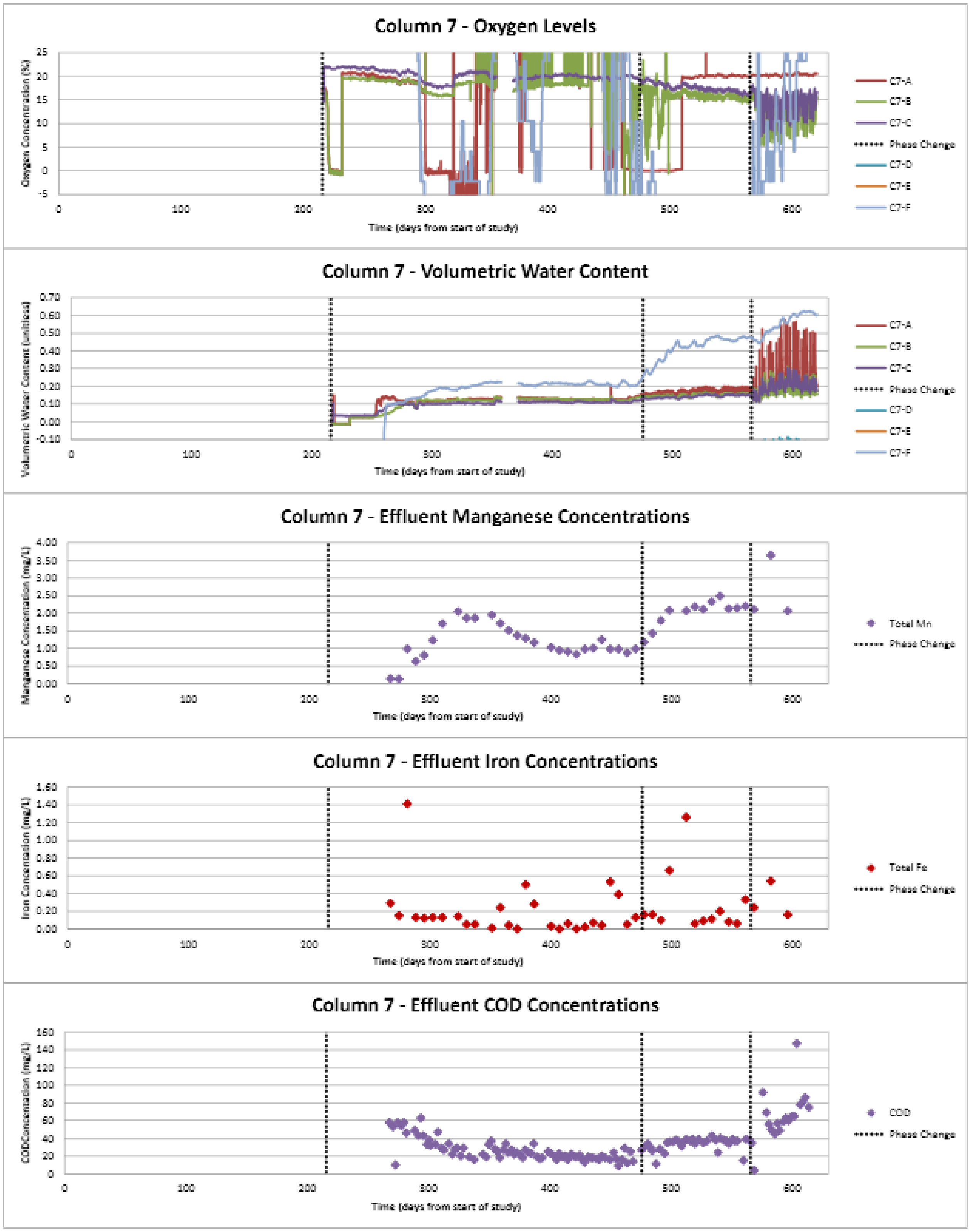

Figure 16 - Column 7 Raw Data

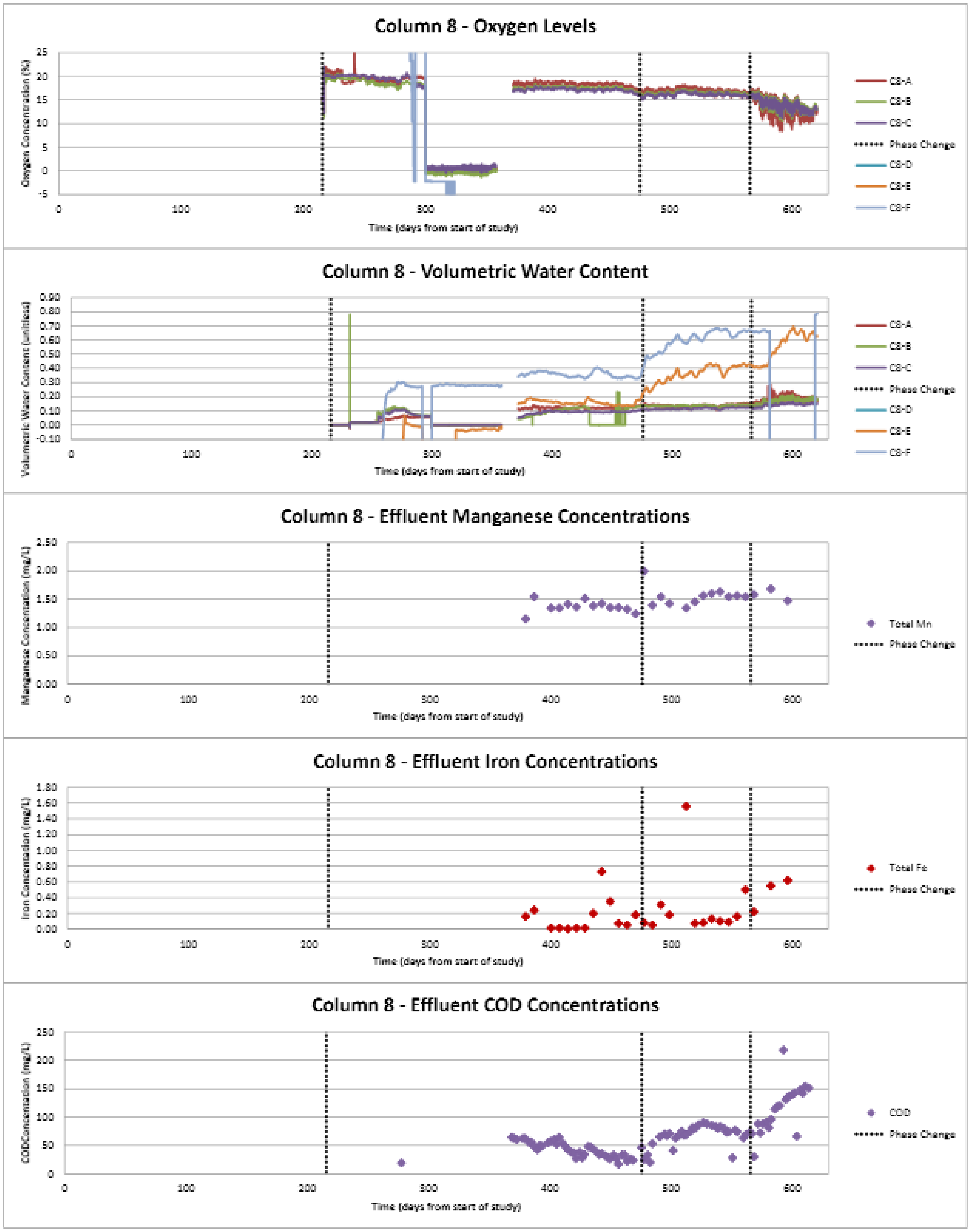

Figure 17 - Column 8 Raw Data

APPENDIX C

Raw Analytical Data

Table 12 - Raw Analytical Data

Date	C1					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
8/30/2010	588					
9/1/2010	536					
9/3/2010	544		0.25		0.55	
9/6/2010	580					
9/8/2010	520					
9/10/2010	532		0.33		1.62	
9/13/2010	520					
9/15/2010	528					
9/17/2010	524		0.21		1.18	
9/20/2010	536					
9/22/2010	524					
9/24/2010	532		0.40		1.47	
9/27/2010	544					
9/29/2010						
10/1/2010			0.82		1.52	
10/4/2010	504					
10/6/2010	552					
10/8/2010			0.32		2.05	
10/11/2010						
10/13/2010						
10/15/2010	524	18	0.82	0.17	2.06	0.57
10/18/2010	564	12				
10/20/2010	488	10				
10/22/2010	524	12	0.19	0.00	1.17	0.11
10/25/2010	592	10				
10/27/2010	668	26				
10/29/2010	576	12	0.19	0.00	0.90	0.02
11/1/2010	504	16				
11/3/2010						
11/5/2010	528	26	0.73	0.16	2.70	0.49
11/8/2010	504	12				
11/10/2010	204	43				
11/12/2010	524	8	0.20	0.02	0.76	0.08
11/15/2010	528	13				

Table 12 (cont'd)

Date	C1					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
11/17/2010	288	15				
11/19/2010			0.29	0.13	1.20	0.33
11/22/2010	564	9				
11/24/2010	844	31				
11/26/2010						
11/29/2010	536	25				
12/1/2010	520	12				
12/3/2010	544	20				
12/6/2010	472	17				
12/8/2010	524					
12/10/2010	744					
12/13/2010	548					
12/15/2010	504					
12/17/2010					0.79	
12/20/2010	552					
12/22/2010						
12/24/2010	1288		0.26		0.98	
12/27/2010						
12/29/2010						
12/31/2010	548					
1/3/2011	556	141				
1/5/2011	532	64				
1/7/2011	520	84	0.26	0.03	4.41	0.00
1/10/2011	256	42				
1/12/2011	552	19				
1/14/2011	524	15	0.30	0.05	2.71	0.05
1/17/2011	488	23				
1/19/2011	512	24				
1/21/2011		24	0.37	0.00	1.72	0.06
1/24/2011	556	18				
1/26/2011	540	11				
1/28/2011	528	13	0.22	0.08	1.44	0.01
1/31/2011	588	15				
2/2/2011	528	15				

Table 12 (cont'd)

Date	C1					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
2/4/2011	552	16	0.21	0.00	1.94	0.13
2/7/2011	632	5				
2/9/2011	536	11				
2/11/2011	512	8	0.17	0.00	1.82	0.12
2/14/2011	536	5				
2/16/2011	544	10				
2/18/2011	392	6	0.22	0.00	2.40	0.00
2/21/2011						
2/23/2011	520	11				
2/25/2011	536	11	0.19	0.00	1.54	0.00
2/28/2011	544	9				
3/2/2011	552	6				
3/4/2011	520		0.31	0.00	1.83	0.00
3/7/2011	468	10				
3/9/2011	516	6				
3/11/2011	440	12	0.27	0.00	1.82	0.00
3/14/2011	568	7				
3/16/2011	488	5				
3/18/2011	492	13	0.20	0.01	1.88	0.00
3/21/2011	544	8				
3/23/2011	564	10				
3/25/2011	516	15	0.22	0.00	1.71	0.00
3/28/2011	508	5				
3/30/2011	540	7				
4/1/2011	556	5	0.21	0.00	2.21	0.00
4/4/2011	544	2				
4/6/2011	528	2				
4/8/2011	572	8	0.21	0.01	2.35	0.03
4/11/2011	564	7				
4/13/2011	520	5				
4/15/2011	532	7	0.19	0.00	2.44	0.31
4/18/2011	564	13				
4/20/2011	484	8				
4/22/2011	536		2.50	0.02	1.45	0.00

Table 12 (cont'd)

Date	C1					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
4/25/2011	540	3				
4/27/2011	492	14				
4/29/2011	596	3	0.23	0.02	1.21	0.04
5/2/2011	524	20				
5/4/2011	2040	4				
5/6/2011	2008		0.62	0.13	2.33	0.08
5/9/2011						
5/11/2011	2092	13				
5/13/2011	2060	15	0.52	0.01	1.51	0.03
5/16/2011	2024	12				
5/18/2011	2116	11				
5/20/2011	2080	11	0.68	0.01	3.93	0.36
5/23/2011	2012	7				
5/25/2011						
5/27/2011			0.67	0.01	3.56	0.04
5/30/2011	1856	11				
6/1/2011	2072	11				
6/3/2011	2128	12	0.45	0.00	2.51	0.37
6/6/2011	2328	15				
6/8/2011	2036	11				
6/10/2011	1852	11				
6/13/2011	2012	12				
6/15/2011	2092	8				
6/17/2011	2024	14	0.49	0.00	2.80	1.24
6/20/2011	2028	13				
6/22/2011	1916	16				
6/24/2011	2036	8	0.65	0.00	3.47	0.03
6/27/2011	3096	9				
6/29/2011						
7/1/2011	2156	14	0.63	0.00	3.26	0.04
7/4/2011	2104	10				
7/6/2011						
7/8/2011	2184	12	0.49	0.00	2.68	0.04
7/11/2011	336	11				

Table 12 (cont'd)

Date	C1					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
7/13/2011	2008	8				
7/15/2011	2092	11	0.62	0.00	3.30	0.10
7/18/2011	936	15				
7/20/2011	932	10				
7/22/2011	2184	12	0.63	0.00	3.53	0.21
7/25/2011	2020	13				
7/27/2011	2084	9				
7/29/2011	2052	9	0.64	0.00	3.04	0.07
8/1/2011						
8/3/2011	528	1				
8/5/2011	1952	13	0.60	0.00	3.54	0.14
8/8/2011	2048	4				
8/10/2011	4128	9				
8/12/2011	3668		1.06	0.00	5.94	0.23
8/15/2011		12				
8/17/2011		11				
8/19/2011	8310	18				
8/22/2011		27				
8/24/2011		23				
8/26/2011		24	1.27	0.06	6.15	0.42
8/29/2011	7940	31				
8/31/2011	8290	35				
9/2/2011	7660	17				
9/5/2011	8020	29				
9/7/2011	8720	25				
9/9/2011	7100	30	1.42	0.00	7.90	0.17
9/12/2011	8340	30				
9/14/2011	8020	33				
9/16/2011	7560	41				
9/19/2011	8360	41				
9/21/2011	8320	38				
9/23/2011	8350	39				
9/26/2011	8520	37				
9/28/2011						

Table 12 (cont'd)

Date	C2					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
8/30/2010	588	6				
9/1/2010	536	8				
9/3/2010	544	8	0.25	0.01	0.55	0.00
9/6/2010	580	8				
9/8/2010	520	16				
9/10/2010	532	11	0.33	0.67	1.62	1.63
9/13/2010	520	12				
9/15/2010	528	13				
9/17/2010	524	20	0.21	0.72	1.18	2.21
9/20/2010	536	16				
9/22/2010	524	18				
9/24/2010	532	13	0.40	0.07	1.47	0.13
9/27/2010	544	11				
9/29/2010						
10/1/2010			0.82	0.88	1.52	2.28
10/4/2010	504	49				
10/6/2010	552	38				
10/8/2010			0.32	0.59	2.05	0.29
10/11/2010						
10/13/2010						
10/15/2010	524	16	0.82	0.37	2.06	0.46
10/18/2010	564	12				
10/20/2010	488	13				
10/22/2010	524	13	0.19	0.19	1.17	0.19
10/25/2010	592	9				
10/27/2010	668	15				
10/29/2010	576	17	0.19	0.27	0.90	0.37
11/1/2010	504	1				
11/3/2010						
11/5/2010	528	17	0.73	0.18	2.70	0.00
11/8/2010	504	3				
11/10/2010	204	38				
11/12/2010	524	9	0.20	0.30	0.76	0.37
11/15/2010	528	8				

Table 12 (cont'd)

Date	C2					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
11/17/2010	288	13				
11/19/2010			0.29	0.17	1.20	0.01
11/22/2010	564	14				
11/24/2010	844	32				
11/26/2010						
11/29/2010	536	17				
12/1/2010	520	8				
12/3/2010	544	22				
12/6/2010	472	13				
12/8/2010	524	32				
12/10/2010	744	28				
12/13/2010	548	20				
12/15/2010	504	23				
12/17/2010			0.24	0.17	0.79	0.00
12/20/2010	552	10				
12/22/2010						
12/24/2010	1288	8	0.26	0.13	0.98	0.00
12/27/2010						
12/29/2010						
12/31/2010	548	14				
1/3/2011	556	6				
1/5/2011	532	15				
1/7/2011	520	83	0.26	0.17	4.41	0.00
1/10/2011	256	12				
1/12/2011	552	9				
1/14/2011	524	7	0.30	0.00	2.71	0.03
1/17/2011	488	9				
1/19/2011	512	15				
1/21/2011		12	0.37	0.06	1.72	0.00
1/24/2011	556	14				
1/26/2011	540	4				
1/28/2011	528	10	0.22	0.10	1.44	0.00
1/31/2011	588	11				
2/2/2011	528	6				

Table 12 (cont'd)

Date	C2					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
2/4/2011	552	13	0.21	0.00	1.94	0.08
2/7/2011	632					
2/9/2011	536					
2/11/2011	512	7	0.17	0.01	1.82	0.08
2/14/2011	536	2				
2/16/2011	544	10				
2/18/2011	392	6	0.22	0.01	2.40	0.00
2/21/2011						
2/23/2011	520	11				
2/25/2011	536	6	0.19	0.03	1.54	0.00
2/28/2011	544					
3/2/2011	552	10				
3/4/2011	520	7	0.31	0.03	1.83	0.00
3/7/2011	468	8				
3/9/2011	516	7				
3/11/2011	440		0.27	0.03	1.82	0.00
3/14/2011	568	11				
3/16/2011	488	6				
3/18/2011	492	4	0.20	0.05	1.88	0.22
3/21/2011	544	8				
3/23/2011	564	11				
3/25/2011	516	6	0.22	0.00	1.71	0.00
3/28/2011	508	9				
3/30/2011	540	8				
4/1/2011	556	9	0.21	0.00	2.21	0.96
4/4/2011	544	8				
4/6/2011	528	6				
4/8/2011	572	6	0.21	0.03	2.35	0.32
4/11/2011	564	10				
4/13/2011	520					
4/15/2011	532	8	0.19	0.00	2.44	0.09
4/18/2011	564	14				
4/20/2011	484	8				
4/22/2011	536		2.50	0.04	1.45	0.67

Table 12 (cont'd)

Date	C2					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
4/25/2011	540	8				
4/27/2011	492	17				
4/29/2011	596	4	0.23	0.07	1.21	0.48
5/2/2011	524	18				
5/4/2011	2040	2				
5/6/2011	2008		0.62	0.13	2.33	0.00
5/9/2011						
5/11/2011	2092					
5/13/2011	2060	15	0.52	0.00	1.51	0.07
5/16/2011	2024	14				
5/18/2011	2116	11				
5/20/2011	2080	12	0.68	0.00	3.93	0.02
5/23/2011	2012	7				
5/25/2011						
5/27/2011			0.67	0.03	3.56	0.08
5/30/2011	1856	6				
6/1/2011	2072	10				
6/3/2011	2128	13	0.45	0.02	2.51	1.03
6/6/2011	2328	12				
6/8/2011	2036	14				
6/10/2011	1852	12				
6/13/2011	2012	13				
6/15/2011	2092	9				
6/17/2011	2024	12	0.49	0.03	2.80	0.06
6/20/2011	2028	11				
6/22/2011	1916	9				
6/24/2011	2036	5	0.65	0.00	3.47	0.07
6/27/2011	3096	11				
6/29/2011						
7/1/2011	2156	13	0.63	0.00	3.26	0.03
7/4/2011	2104	16				
7/6/2011						
7/8/2011	2184	10	0.49	0.00	2.68	0.77
7/11/2011	336	14				

Table 12 (cont'd)

Date	C2					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
7/13/2011	2008	13				
7/15/2011	2092	11	0.62	0.00	3.30	0.15
7/18/2011	936	13				
7/20/2011	932	1				
7/22/2011	2184	11	0.63	0.00	3.53	0.15
7/25/2011	2020	12				
7/27/2011	2084	6				
7/29/2011	2052	10	0.64	0.00	3.04	0.12
8/1/2011						
8/3/2011	528	8				
8/5/2011	1952	8	0.60	0.00	3.54	0.06
8/8/2011	2048	12				
8/10/2011	4128	11				
8/12/2011	3668		1.06	0.00	5.94	0.21
8/15/2011		15				
8/17/2011		6				
8/19/2011	8310	13				
8/22/2011		23				
8/24/2011		27				
8/26/2011		37	1.27	0.00	6.15	0.46
8/29/2011	7940	34				
8/31/2011	8290	40				
9/2/2011	7660	32				
9/5/2011	8020	24				
9/7/2011	8720	32				
9/9/2011	7100	38	1.42	0.00	7.90	0.32
9/12/2011	8340	37				
9/14/2011	8020	37				
9/16/2011	7560	42				
9/19/2011	8360	41				
9/21/2011	8320	35				
9/23/2011	8350	41				
9/26/2011	8520	61				
9/28/2011						

Table 12 (cont'd)

Date	C3					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
8/30/2010						
9/1/2010						
9/3/2010					0.55	
9/6/2010						
9/8/2010						
9/10/2010					1.62	
9/13/2010						
9/15/2010						
9/17/2010					1.18	
9/20/2010						
9/22/2010						
9/24/2010					1.47	
9/27/2010	2028					
9/29/2010						
10/1/2010			0.80		1.52	
10/4/2010	2020					
10/6/2010	2036					
10/8/2010			0.63		2.05	
10/11/2010						
10/13/2010						
10/15/2010	1356		0.62		2.06	0.57
10/18/2010	2044	31				
10/20/2010	2028	25				
10/22/2010	2132	27	0.63	0.10	1.17	0.11
10/25/2010	2156					
10/27/2010	2016					
10/29/2010	1928		0.60		0.90	0.02
11/1/2010	2000	10				
11/3/2010						
11/5/2010	1796		0.30		2.70	0.49
11/8/2010	1508					
11/10/2010	1724					
11/12/2010	1884		0.65		0.76	0.08
11/15/2010	1928					

Table 12 (cont'd)

Date	C3					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
11/17/2010	1768					
11/19/2010			0.69		1.20	0.33
11/22/2010	1976					
11/24/2010	1372					
11/26/2010						
11/29/2010	1676	24				
12/1/2010	2016	19				
12/3/2010	2080	24				
12/6/2010	1984	17				
12/8/2010	1956	14				
12/10/2010	1628	14				
12/13/2010	2016	17				
12/15/2010	1972	20				
12/17/2010			0.65	0.05	0.79	
12/20/2010	2092	17				
12/22/2010						
12/24/2010	5012	11	0.58	0.06	0.98	
12/27/2010						
12/29/2010						
12/31/2010	1804	10				
1/3/2011	2064	15				
1/5/2011	2040	18				
1/7/2011	2000	23	0.68	0.43	4.41	0.00
1/10/2011	1768	16				
1/12/2011	1912					
1/14/2011	2068	136	0.75	0.05	2.71	0.05
1/17/2011	1820	18				
1/19/2011	1844	21				
1/21/2011	528	19	0.73	0.05	1.72	0.06
1/24/2011	1812	20				
1/26/2011	2156	51				
1/28/2011	1860	14	0.64	0.00	1.44	0.01
1/31/2011	2144	12				
2/2/2011	1952	12				

Table 12 (cont'd)

Date	C3					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
2/4/2011	2072	16	0.58	0.00	1.94	0.13
2/7/2011	1816	10				
2/9/2011	2044	16				
2/11/2011	2024	24	0.51	0.00	1.82	0.12
2/14/2011	2092	40				
2/16/2011	2172	36				
2/18/2011	1960	33	0.57	0.06	2.40	0.00
2/21/2011						
2/23/2011	1984	28				
2/25/2011	1968	38	0.42	0.03	1.54	0.00
2/28/2011	2064	20				
3/2/2011	2052	14				
3/4/2011	1952	16	0.64	0.02	1.83	0.00
3/7/2011	1928	13				
3/9/2011	1968	12				
3/11/2011	2148	16	0.66	0.02	1.82	0.00
3/14/2011	2064	19				
3/16/2011	2044	14				
3/18/2011	2004	9	0.56	0.14	1.88	0.00
3/21/2011	2056	16				
3/23/2011	2136					
3/25/2011	2048	13	0.56	0.00	1.71	0.00
3/28/2011	2068	18				
3/30/2011	1964	12				
4/1/2011	2152	10	0.56	0.01	2.21	0.00
4/4/2011	2176	12				
4/6/2011	1972	11				
4/8/2011	2164	14	0.79	0.05	2.35	0.03
4/11/2011	2020	16				
4/13/2011	2052	8				
4/15/2011	2160	13	0.59	0.00	2.44	0.31
4/18/2011	2208	18				
4/20/2011	1964	9				
4/22/2011	1952		0.53	0.03	1.45	0.00

Table 12 (cont'd)

Date	C3					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
4/25/2011	2048					
4/27/2011	2200	21				
4/29/2011	2208	24	0.65	0.09	1.21	0.04
5/2/2011	2340	25				
5/4/2011	3220	8				
5/6/2011	1944		0.63	0.11	2.33	0.08
5/9/2011						
5/11/2011	2088	12				
5/13/2011	2120	6	0.68	0.00	1.51	0.03
5/16/2011	2072	12				
5/18/2011	2128					
5/20/2011	2028	14	0.68	0.04	3.93	0.36
5/23/2011	2368	10				
5/25/2011						
5/27/2011			0.72	0.12	3.56	0.04
5/30/2011	1900	17				
6/1/2011	2044	11				
6/3/2011	1848	12	0.41	0.00	2.51	0.37
6/6/2011	2072	8				
6/8/2011	2028	16				
6/10/2011	2076	12				
6/13/2011	2056	15				
6/15/2011	2020	10				
6/17/2011	2004	9	0.71	0.01	2.80	1.24
6/20/2011	2204	9				
6/22/2011	1940	14				
6/24/2011	1952	12	0.77	0.00	3.47	0.03
6/27/2011	3044	13				
6/29/2011						
7/1/2011	2064	12	0.61	0.02	3.26	0.04
7/4/2011	2084	13				
7/6/2011						
7/8/2011	872	8	0.50	0.00	2.68	0.04
7/11/2011	276	9				

Table 12 (cont'd)

Date	C3					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
7/13/2011	2052	10				
7/15/2011	2032	11	0.60	0.00	3.19	0.03
7/18/2011	980	13				
7/20/2011	924	10				
7/22/2011	2000	9	0.56	0.00	3.29	0.09
7/25/2011	1888	14				
7/27/2011	2080	13				
7/29/2011	2008	10	0.63	0.01	2.95	0.09
8/1/2011						
8/3/2011	240	13				
8/5/2011	2036	13	0.65	0.00	3.56	0.13
8/8/2011	2000	18				
8/10/2011	1816	12				
8/12/2011	1940		0.66	0.00	4.55	0.15
8/15/2011	4144	21				
8/17/2011	4288	3				
8/19/2011	3930	11				
8/22/2011	3980	16				
8/24/2011	3860	8				
8/26/2011		13	0.88	0.07	4.75	0.65
8/29/2011	3890	12				
8/31/2011	4210	22				
9/2/2011	3910	19				
9/5/2011	4260	20				
9/7/2011	4120	19				
9/9/2011	4260	21	0.78	0.00	5.74	0.09
9/12/2011	3660	18				
9/14/2011	4150	16				
9/16/2011	3520	19				
9/19/2011	4430	22				
9/21/2011	4320	20				
9/23/2011	4120	26				
9/26/2011	4100					
9/28/2011						

Table 12 (cont'd)

Date	C4					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
8/30/2010	2056	22				
9/1/2010	2064	18				
9/3/2010	1840	18		0.00		0.00
9/6/2010	1512	16				
9/8/2010	1964	28				
9/10/2010	2000	14		0.00		0.12
9/13/2010	1824	10				
9/15/2010	1940	13				
9/17/2010	1904	15		0.93		3.05
9/20/2010	1896	12				
9/22/2010	1880	21				
9/24/2010	2068	14		0.12		0.47
9/27/2010	2028	15				
9/29/2010						
10/1/2010			0.80		3.62	
10/4/2010	2020					
10/6/2010	2036					
10/8/2010			0.63	0.15	3.67	0.55
10/11/2010						
10/13/2010						
10/15/2010	1356	18	0.62	0.31	2.71	1.54
10/18/2010	2044	17				
10/20/2010	2028	14				
10/22/2010	2132	13	0.63	0.00	2.73	0.22
10/25/2010	2156	5				
10/27/2010	2016	18				
10/29/2010	1928	13	0.60	0.06	2.60	0.32
11/1/2010	2000	19				
11/3/2010						
11/5/2010	1796	23	0.30	0.01	1.21	0.01
11/8/2010	1508	12				
11/10/2010	1724	41				
11/12/2010	1884	15	0.65	0.02	2.34	0.02
11/15/2010	1928	14				

Table 12 (cont'd)

Date	C4					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
11/17/2010	1768	18				
11/19/2010			0.69	0.01	2.82	0.00
11/22/2010	1976	11				
11/24/2010	1372	30				
11/26/2010						
11/29/2010	1676	38				
12/1/2010	2016	18				
12/3/2010	2080	37				
12/6/2010	1984	10				
12/8/2010	1956	40				
12/10/2010	1628	40				
12/13/2010	2016	24				
12/15/2010	1972	44				
12/17/2010			0.65	0.02	1.26	0.01
12/20/2010	2092	21				
12/22/2010						
12/24/2010	5012	12	0.58	0.05	2.29	0.00
12/27/2010						
12/29/2010						
12/31/2010	1804	14				
1/3/2011	2064	112				
1/5/2011	2040	20				
1/7/2011	2000	27	0.68	0.00	5.13	0.00
1/10/2011	1768	8				
1/12/2011	1912	14				
1/14/2011	2068	9	0.75	0.04	3.72	0.01
1/17/2011	1820	16				
1/19/2011	1844	23				
1/21/2011	528	20	0.73	0.01	3.19	0.01
1/24/2011	1812	18				
1/26/2011	2156	9				
1/28/2011	1860	16	0.64	0.04	3.29	0.09
1/31/2011	2144	13				
2/2/2011	1952	14				

Table 12 (cont'd)

Date	C4					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
2/4/2011	2072	18	0.58	0.00	2.74	0.16
2/7/2011	1816	10				
2/9/2011	2044	16				
2/11/2011	2024	15	0.51	0.00	3.00	0.17
2/14/2011	2092					
2/16/2011	2172	13				
2/18/2011	1960	7	0.57		3.40	
2/21/2011						
2/23/2011	1984	19				
2/25/2011	1968	20	0.42	0.00	2.23	0.02
2/28/2011	2064	21				
3/2/2011	2052	13				
3/4/2011	1952	17	0.64	0.01	3.13	0.00
3/7/2011	1928	9				
3/9/2011	1968	15				
3/11/2011	2148	14	0.66	0.00	3.85	0.00
3/14/2011	2064	19				
3/16/2011	2044	9				
3/18/2011	2004	9	0.56	0.00	3.35	0.00
3/21/2011	2056	15				
3/23/2011	2136					
3/25/2011	2048	10	0.56	0.00	2.69	0.00
3/28/2011	2068	20				
3/30/2011	1964	12				
4/1/2011	2152	15	0.56	0.00	2.86	0.12
4/4/2011	2176	13				
4/6/2011	1972	10				
4/8/2011	2164	17	0.79	0.01	3.55	0.77
4/11/2011	2020	15				
4/13/2011	2052	8				
4/15/2011	2160	14	0.59	0.00	3.02	0.66
4/18/2011	2208	20				
4/20/2011	1964	13				
4/22/2011	1952		0.53	0.08	2.49	0.82

Table 12 (cont'd)

Date	C4					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
4/25/2011	2048	14				
4/27/2011	2200	21				
4/29/2011	2208	8	0.65	0.06	3.08	0.00
5/2/2011	2340					
5/4/2011	3220	11				
5/6/2011	1944		0.63	0.07	2.14	0.07
5/9/2011						
5/11/2011	2088	14				
5/13/2011	2120	13	0.68	0.01	3.30	0.02
5/16/2011	2072	19				
5/18/2011	2128					
5/20/2011	2028	13	0.68	0.02	4.13	0.00
5/23/2011	2368	13				
5/25/2011						
5/27/2011			0.72	0.02	3.62	0.05
5/30/2011	1900	17				
6/1/2011	2044	13				
6/3/2011	1848	14	0.41	0.01	2.35	0.70
6/6/2011	2072	18				
6/8/2011	2028	13				
6/10/2011	2076	17				
6/13/2011	2056	15				
6/15/2011	2020	11				
6/17/2011	2004	22	0.71	0.02	0.70	0.04
6/20/2011	2204	16				
6/22/2011	1940	13				
6/24/2011	1952	12	0.77	0.00	3.98	0.03
6/27/2011	3044	14				
6/29/2011						
7/1/2011	2064	17	0.61	0.02	3.28	0.08
7/4/2011	2084	11				
7/6/2011						
7/8/2011	872	12	0.50	0.02	3.32	0.42
7/11/2011	276	8				

Table 12 (cont'd)

Date	C4					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
7/13/2011	2052	8				
7/15/2011	2032	12	0.60	0.00	3.90	0.09
7/18/2011	980	13				
7/20/2011	924					
7/22/2011	2000	16	0.56	0.00	3.29	0.05
7/25/2011	1888	11				
7/27/2011	2080	11				
7/29/2011	2008	14	0.63	0.01	2.95	0.25
8/1/2011						
8/3/2011	240	8				
8/5/2011	2036	7	0.65	0.00	3.56	0.16
8/8/2011	2000	14				
8/10/2011	1816	12				
8/12/2011	1940		0.66		4.55	
8/15/2011	4144	16				
8/17/2011	4288	9				
8/19/2011	3930	12				
8/22/2011	3980	8				
8/24/2011	3860	14				
8/26/2011		13	0.88	0.06	4.75	0.50
8/29/2011	3890	10				
8/31/2011	4210	15				
9/2/2011	3910	11				
9/5/2011	4260	25				
9/7/2011	4120	19				
9/9/2011	4260	22	0.78	0.01	5.74	0.16
9/12/2011	3660	20				
9/14/2011	4150	22				
9/16/2011	3520	21				
9/19/2011	4430	22				
9/21/2011	4320	20				
9/23/2011	4120	29				
9/26/2011	4100					
9/28/2011						

Table 12 (cont'd)

Date	C5					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
8/30/2010	2056					
9/1/2010	2064					
9/3/2010	1840		0.58		1.56	
9/6/2010	1512					
9/8/2010	1964					
9/10/2010	2000		0.11		1.34	
9/13/2010	1824					
9/15/2010	1940					
9/17/2010	1904		0.79		4.31	
9/20/2010	1896					
9/22/2010	1880					
9/24/2010	2068		1.33		4.63	
9/27/2010	4068					
9/29/2010						
10/1/2010			1.25		5.79	
10/4/2010	3956					
10/6/2010	4104					
10/8/2010			1.28	0.03	5.27	0.15
10/11/2010						
10/13/2010						
10/15/2010	2716		1.12		4.62	
10/18/2010	4056					
10/20/2010	3920					
10/22/2010	3468		1.12		2.81	
10/25/2010	4044					
10/27/2010	4016					
10/29/2010	4172		1.27		5.65	
11/1/2010	3892	43				
11/3/2010						
11/5/2010	3468		1.48		5.21	
11/8/2010	4032					
11/10/2010	3560					
11/12/2010	4136		1.21		4.57	
11/15/2010	4080					

Table 12 (cont'd)

Date	C5					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
11/17/2010	3604					
11/19/2010			1.31		4.90	
11/22/2010	4096					
11/24/2010	2664					
11/26/2010						
11/29/2010	3880					
12/1/2010	3860					
12/3/2010						
12/6/2010	4036					
12/8/2010	3884					
12/10/2010	3860					
12/13/2010	3968					
12/15/2010	4328					
12/17/2010			1.11		2.23	
12/20/2010	4016					
12/22/2010						
12/24/2010	5208		1.11		4.77	
12/27/2010						
12/29/2010						
12/31/2010	3932					
1/3/2011	3968					
1/5/2011	3984					
1/7/2011	3984		1.19		7.15	
1/10/2011	3684					
1/12/2011	3380	34				
1/14/2011	4032		1.31		6.01	
1/17/2011	2948					
1/19/2011	1748					
1/21/2011	1724		0.85		1.45	
1/24/2011	3628					
1/26/2011	3184					
1/28/2011	4076		1.25	0.95	5.74	0.02
1/31/2011	4136	46				
2/2/2011	3940					

Table 12 (cont'd)

Date	C5					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
2/4/2011	4092		1.05		4.28	
2/7/2011	4152					
2/9/2011	4020	58				
2/11/2011	3776	31	0.95	0.00	4.66	0.25
2/14/2011	4124	27				
2/16/2011	4136	17				
2/18/2011	4252	24	1.13		5.89	
2/21/2011						
2/23/2011	3900	29				
2/25/2011	3848	60	0.52	0.02	1.54	0.04
2/28/2011	4004	32				
3/2/2011	4012	31				
3/4/2011	4044		1.12	0.01	5.81	0.03
3/7/2011	3772					
3/9/2011	3648					
3/11/2011	3964		0.97	0.01	4.25	0.04
3/14/2011	4016	28				
3/16/2011	4108	6				
3/18/2011	3836	25	0.95	0.01	5.20	0.04
3/21/2011	4220	32				
3/23/2011	4044	7				
3/25/2011	3924	26	1.08	0.03	5.43	0.00
3/28/2011	4076					
3/30/2011	4060	25				
4/1/2011	4156	22	1.03	0.02	3.27	0.16
4/4/2011	4068	26				
4/6/2011	4040	20				
4/8/2011	4120	26	1.11	0.03	4.28	0.83
4/11/2011	3948	30				
4/13/2011	4004	25				
4/15/2011	4160	27	1.05	0.00	3.18	0.47
4/18/2011	4260	26				
4/20/2011	3816	26				
4/22/2011	3740	6	0.83	0.06	2.76	0.65

Table 12 (cont'd)

Date	C5					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
4/25/2011	144	21				
4/27/2011	4148	30				
4/29/2011	4024	17	1.16	0.09	5.65	0.25
5/2/2011	4732	26				
5/4/2011	3952	20				
5/6/2011	4028		1.15	0.15	4.52	0.14
5/9/2011						
5/11/2011	4144	22				
5/13/2011	4040	16	1.18	0.00	5.69	0.04
5/16/2011	4096	21				
5/18/2011	4208	24				
5/20/2011	3736	16	1.14	0.04	6.22	0.10
5/23/2011	4052	15				
5/25/2011						
5/27/2011			1.26	0.05	6.31	0.07
5/30/2011	4108	18				
6/1/2011	4304	21				
6/3/2011	3968	22	0.81	0.15	4.03	0.38
6/6/2011	4316					
6/8/2011	4008	24				
6/10/2011	3500	24				
6/13/2011	4052	28				
6/15/2011	4072	18				
6/17/2011	4288	23	1.27	0.00	6.86	0.07
6/20/2011	4024	18				
6/22/2011	3960	23				
6/24/2011	4060	6	1.28	0.03	6.49	0.07
6/27/2011	5996	22				
6/29/2011						
7/1/2011	4220	22	1.22	0.00	6.41	0.09
7/4/2011	3544	26				
7/6/2011						
7/8/2011	4136	34	0.83	0.00	4.45	0.08
7/11/2011	328	58				

Table 12 (cont'd)

Date	C5					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
7/13/2011	4076					
7/15/2011	3940		1.13		5.70	
7/18/2011	1888					
7/20/2011	1892					
7/22/2011	4188		1.09		2.10	
7/25/2011	3928					
7/27/2011	4184					
7/29/2011	3976		1.27		4.26	
8/1/2011						
8/3/2011	728					
8/5/2011	3976		1.16		6.05	
8/8/2011	3832					
8/10/2011	4024					
8/12/2011	4020		1.19		7.10	
8/15/2011		38				
8/17/2011		9				
8/19/2011	7780	22				
8/22/2011						
8/24/2011		14				
8/26/2011		33	1.34	0.10	7.15	0.63
8/29/2011	8020	34				
8/31/2011	8080	33				
9/2/2011	7710	30				
9/5/2011	8260					
9/7/2011	7980	32				
9/9/2011	7350	37	1.43	0.00	8.94	0.48
9/12/2011	8690	35				
9/14/2011	8210	27				
9/16/2011	8360	30				
9/19/2011	8520	149				
9/21/2011	8220	43				
9/23/2011	7410	38				
9/26/2011	8590	185				
9/28/2011						

Table 12 (cont'd)

Date	C6					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
8/30/2010	3828	18				
9/1/2010	4236	23				
9/3/2010	2916	16	0.58	0.28	1.56	0.00
9/6/2010	3348	20				
9/8/2010	3936	19				
9/10/2010	3920	19	0.11	0.27	1.34	0.24
9/13/2010	3816					
9/15/2010	3876	21				
9/17/2010	4092	19	0.79	0.29	4.31	0.24
9/20/2010	4124	23				
9/22/2010	3808	24				
9/24/2010	2068	19	1.33	0.65	4.63	1.13
9/27/2010	4068	21				
9/29/2010						
10/1/2010			1.25	0.39	5.79	0.17
10/4/2010	3956	17				
10/6/2010	4104	23				
10/8/2010			1.28	0.59	5.27	0.34
10/11/2010						
10/13/2010						
10/15/2010	2716	24	1.12	0.48	4.62	0.27
10/18/2010	4056	18				
10/20/2010	3920	62				
10/22/2010	3468	19	1.12	0.51	2.81	0.20
10/25/2010	4044	24				
10/27/2010	4016	25				
10/29/2010	4172	22	1.27	0.64	5.65	0.15
11/1/2010	3892	12				
11/3/2010						
11/5/2010	3468	25	1.48	0.87	5.21	0.63
11/8/2010	4032	14				
11/10/2010	3560	50				
11/12/2010	4136	22	1.21	1.04	4.57	0.13
11/15/2010	4080	16				

Table 12 (cont'd)

Date	C6					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
11/17/2010	3604	27				
11/19/2010			1.31	0.99	4.90	0.07
11/22/2010	4096	17				
11/24/2010	2664	34				
11/26/2010						
11/29/2010	3880	28				
12/1/2010	3860	21				
12/3/2010		11				
12/6/2010	4036	20				
12/8/2010	3884	9				
12/10/2010	3860	29				
12/13/2010	3968	17				
12/15/2010	4328	30				
12/17/2010			1.11	0.61	2.23	0.10
12/20/2010	4016	23				
12/22/2010						
12/24/2010	5208	22	1.11	0.36	4.77	0.09
12/27/2010						
12/29/2010						
12/31/2010	3932	26				
1/3/2011	3968	25				
1/5/2011	3984					
1/7/2011	3984	32	1.19	0.62	7.15	0.00
1/10/2011	3684					
1/12/2011	3380	16				
1/14/2011	4032	15	1.31	1.02	6.01	0.14
1/17/2011	2948	20				
1/19/2011	1748	31				
1/21/2011	1724	31	0.85	0.72	1.45	0.13
1/24/2011	3628	37				
1/26/2011	3184	22				
1/28/2011	4076	21	1.25	0.86	5.74	0.08
1/31/2011	4136	23				
2/2/2011	3940	20				

Table 12 (cont'd)

Date	C6					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
2/4/2011	4092	26	1.05	1.07	4.28	0.25
2/7/2011	4152	18				
2/9/2011	4020	26				
2/11/2011	3776	24	0.95	0.90	4.66	0.27
2/14/2011	4124	22				
2/16/2011	4136	29				
2/18/2011	4252	25	1.13		5.89	
2/21/2011						
2/23/2011	3900	38				
2/25/2011	3848	37	0.52	0.88	1.54	0.03
2/28/2011	4004					
3/2/2011	4012	26				
3/4/2011	4044	29	1.12	0.88	5.81	0.05
3/7/2011	3772	2				
3/9/2011	3648	28				
3/11/2011	3964	30	0.97	0.92	4.25	0.05
3/14/2011	4016	43				
3/16/2011	4108	36				
3/18/2011	3836	36	0.95	0.90	5.20	0.01
3/21/2011	4220	37				
3/23/2011	4044					
3/25/2011	3924	27	1.08	0.77	5.43	0.11
3/28/2011	4076	29				
3/30/2011	4060	26				
4/1/2011	4156	23	1.03	0.61	3.27	0.19
4/4/2011	4068	23				
4/6/2011	4040	22				
4/8/2011	4120	23	1.11	0.64	4.28	0.07
4/11/2011	3948	23				
4/13/2011	4004	17				
4/15/2011	4160	19	1.05	0.71	3.18	0.41
4/18/2011	4260	24				
4/20/2011	3816					
4/22/2011	3740	7	0.83	1.03	2.76	1.42

Table 12 (cont'd)

Date	C6					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
4/25/2011	144	44				
4/27/2011	4148	119				
4/29/2011	4024	143	1.16	0.61	5.65	0.18
5/2/2011	4732	87				
5/4/2011	3952	74				
5/6/2011	4028		1.15	0.69	4.52	0.11
5/9/2011						
5/11/2011	4144	45				
5/13/2011	4040	23	1.18	0.60	5.69	0.15
5/16/2011	4096	30				
5/18/2011	4208					
5/20/2011	3736	21	1.14	0.71	6.22	0.04
5/23/2011	4052					
5/25/2011						
5/27/2011			1.26	0.65	6.31	0.11
5/30/2011	4108	22				
6/1/2011	4304	21				
6/3/2011	3968	24	0.81	0.38	4.03	0.30
6/6/2011	4316					
6/8/2011	4008	26				
6/10/2011	3500	29				
6/13/2011	4052	44				
6/15/2011	4072	34				
6/17/2011	4288	34	1.27	0.88	6.86	0.82
6/20/2011	4024	23				
6/22/2011	3960	23				
6/24/2011	4060	25	1.28	0.96	6.49	0.08
6/27/2011	5996	24				
6/29/2011						
7/1/2011	4220	25	1.22	0.75	6.41	0.07
7/4/2011	3544	37				
7/6/2011						
7/8/2011	4136	25	0.83	0.74	4.45	0.11
7/11/2011	328	25				

Table 12 (cont'd)

Date	C6					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
7/13/2011	4076	24				
7/15/2011	3940	25	1.13	0.86	5.70	0.13
7/18/2011	1888	30				
7/20/2011	1892	29				
7/22/2011	4188	22	1.09	0.64	2.10	0.10
7/25/2011	3928	21				
7/27/2011	4184	23				
7/29/2011	3976	26	1.27	0.78	4.26	0.15
8/1/2011						
8/3/2011	728	26				
8/5/2011	3976	22	1.16	0.78	6.05	0.07
8/8/2011	3832	21				
8/10/2011	4024	155				
8/12/2011	4020		1.19	0.78	7.10	0.37
8/15/2011		81				
8/17/2011		12				
8/19/2011	7780					
8/22/2011						
8/24/2011						
8/26/2011			1.34	0.97	7.15	1.18
8/29/2011	8020	21				
8/31/2011	8080	170				
9/2/2011	7710	152				
9/5/2011	8260	22				
9/7/2011	7980	215				
9/9/2011	7350	215	1.43	1.00	8.94	0.50
9/12/2011	8690	214				
9/14/2011	8210	212				
9/16/2011	8360	267				
9/19/2011	8520	138				
9/21/2011	8220	535				
9/23/2011	7410	693				
9/26/2011	8590	613				
9/28/2011						

Table 12 (cont'd)

Date	C7					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
8/30/2010						
9/1/2010						
9/3/2010			1.15		4.33	
9/6/2010						
9/8/2010						
9/10/2010			1.46		5.26	
9/13/2010						
9/15/2010						
9/17/2010			1.35		7.04	
9/20/2010						
9/22/2010						
9/24/2010	3900		0.87		4.56	
9/27/2010	2152					
9/29/2010						
10/1/2010			0.75		3.23	
10/4/2010	1944					
10/6/2010	2016					
10/8/2010			0.77		3.59	
10/11/2010						
10/13/2010						
10/15/2010	2036	58	0.97	0.15	4.99	0.29
10/18/2010	1992	53				
10/20/2010	1888	10				
10/22/2010	1680	58	0.59	0.14	2.67	0.15
10/25/2010	1904	54				
10/27/2010	1828	58				
10/29/2010		46		0.99		1.41
11/1/2010	1912					
11/3/2010						
11/5/2010		49		0.64		0.13
11/8/2010		43				
11/10/2010		63				
11/12/2010		43		0.81		0.12
11/15/2010		33				

Table 12 (cont'd)

Date	C7					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
11/17/2010		38				
11/19/2010				1.23		0.13
11/22/2010	1964	33				
11/24/2010	2612	47				
11/26/2010						
11/29/2010	1604	27				
12/1/2010	1972					
12/3/2010	4056	34				
12/6/2010	1976	22				
12/8/2010	2016	28				
12/10/2010	2016	29				
12/13/2010	1976	20				
12/15/2010	2100	29				
12/17/2010			0.60	1.78	0.91	0.14
12/20/2010	2044	19				
12/22/2010						
12/24/2010	4496	16	0.67	1.86	2.93	0.05
12/27/2010						
12/29/2010						
12/31/2010	1924	22				
1/3/2011	1880	19				
1/5/2011	1964	33				
1/7/2011	1568	37	0.67	1.95	4.19	0.01
1/10/2011	1736	28				
1/12/2011	1524	25				
1/14/2011	2080	18	0.67	1.71	4.01	0.24
1/17/2011	1432	27				
1/19/2011	1760	34				
1/21/2011	228	24	0.75	1.51	2.77	0.04
1/24/2011	1968	27				
1/26/2011	2072	22				
1/28/2011	1676	24	0.62	1.37	3.87	0.00
1/31/2011	2108	21				
2/2/2011	2004	18				

Table 12 (cont'd)

Date	C7					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
2/4/2011	2108	27	0.57	1.29	2.95	0.50
2/7/2011	2128	24				
2/9/2011	2072	23				
2/11/2011	1992	34	0.58	1.17	2.90	0.28
2/14/2011	2072	19				
2/16/2011	2148	17				
2/18/2011	1924	18	1.04		2.96	
2/21/2011						
2/23/2011	2012	25				
2/25/2011	2064	23	0.24	1.03	0.95	0.03
2/28/2011	1992	20				
3/2/2011	2152	16				
3/4/2011	2088	23	0.67	0.95	3.36	0.00
3/7/2011	1892	19				
3/9/2011	1920	20				
3/11/2011	1804	16	0.51	0.91	2.56	0.06
3/14/2011	1968	22				
3/16/2011	2028	20				
3/18/2011	2080	19	0.56	0.84	3.56	0.00
3/21/2011	1984	21				
3/23/2011	2056	16				
3/25/2011	1980	13	0.59	0.98	3.37	0.02
3/28/2011	2036	19				
3/30/2011	1912	18				
4/1/2011	2128	18	0.59	1.01	2.97	0.07
4/4/2011	2048	17				
4/6/2011	2028	16				
4/8/2011	2156	20	0.71	1.25	3.73	0.04
4/11/2011	2032	18				
4/13/2011	1996					
4/15/2011	1928	16	0.56	0.98	3.26	0.53
4/18/2011	2100	24				
4/20/2011	1944	17				
4/22/2011	2004	9	0.57	0.98	2.79	0.39

Table 12 (cont'd)

Date	C7					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
4/25/2011	60	16				
4/27/2011	4088	29				
4/29/2011	4136	12	0.65	0.88	2.70	0.05
5/2/2011	4048	25				
5/4/2011	4092	14				
5/6/2011	3836		1.11	0.99	4.42	0.13
5/9/2011						
5/11/2011	4136	27				
5/13/2011	3856	30	1.13	1.18	5.50	0.16
5/16/2011	4164	34				
5/18/2011	4184	30				
5/20/2011	3908	26	1.19	1.43	6.46	0.16
5/23/2011	4176	11				
5/25/2011						
5/27/2011			1.27	1.79	6.57	0.10
5/30/2011	4320	23				
6/1/2011	4000	35				
6/3/2011	3940	36	0.82	2.08	4.14	0.66
6/6/2011	4264	36				
6/8/2011	3760	38				
6/10/2011	3852	37				
6/13/2011	4104	31				
6/15/2011	4000	36				
6/17/2011	4040	39	1.41	2.07	7.19	1.26
6/20/2011	3836	37				
6/22/2011	3940	39				
6/24/2011	4160	34	1.28	2.19	3.55	0.06
6/27/2011		39				
6/29/2011						
7/1/2011	4288	35	1.15	2.11	6.05	0.09
7/4/2011	4216	37				
7/6/2011						
7/8/2011	4040	43	0.84	2.33	7.02	0.11
7/11/2011	340	38				

Table 12 (cont'd)

Date	C7					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
7/13/2011	3932	24				
7/15/2011	3912	40	1.42	2.46	1.33	0.20
7/18/2011	2000	38				
7/20/2011	1896	37				
7/22/2011	4352	34	1.04	2.13	1.04	0.08
7/25/2011	3900	39				
7/27/2011	3980	37				
7/29/2011	4032	37	1.13	2.15	3.25	0.06
8/1/2011						
8/3/2011	640	15				
8/5/2011	3800	39	1.18	2.20	6.54	0.33
8/8/2011	4104	38				
8/10/2011	4096	35				
8/12/2011	4024	4	1.18	2.11	7.07	0.24
8/15/2011						
8/17/2011						
8/19/2011	8050	92				
8/22/2011		69				
8/24/2011		56				
8/26/2011		50	1.64	3.64	8.82	0.54
8/29/2011	8000	45				
8/31/2011	8330	57				
9/2/2011	7760	49				
9/5/2011	8090	59				
9/7/2011	8690	63				
9/9/2011	8110	60	2.01	2.06	9.55	0.16
9/12/2011	8390	65				
9/14/2011	8090	65				
9/16/2011	8230	147				
9/19/2011	8750	78				
9/21/2011	8100	81				
9/23/2011	7770	86				
9/26/2011	7920	75				
9/28/2011						

Table 12 (cont'd)

Date	C8					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
8/30/2010						
9/1/2010						
9/3/2010			1.15		4.33	
9/6/2010						
9/8/2010						
9/10/2010			1.46		5.26	
9/13/2010						
9/15/2010						
9/17/2010			1.35		7.04	
9/20/2010						
9/22/2010						
9/24/2010	3900		0.87		4.56	
9/27/2010	2152					
9/29/2010						
10/1/2010			0.75		3.23	
10/4/2010	1944					
10/6/2010	2016					
10/8/2010			0.77		3.59	
10/11/2010						
10/13/2010						
10/15/2010	2036		0.97		4.99	
10/18/2010	1992					
10/20/2010	1888					
10/22/2010	1680		0.59		2.67	
10/25/2010	1904	19				
10/27/2010	1828					
10/29/2010						
11/1/2010	1912					
11/3/2010						
11/5/2010						
11/8/2010						
11/10/2010						
11/12/2010						
11/15/2010						

Table 12 (cont'd)

Date	C8					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
11/17/2010						
11/19/2010						
11/22/2010	1964					
11/24/2010	2612					
11/26/2010						
11/29/2010	1604					
12/1/2010	1972					
12/3/2010	4056					
12/6/2010	1976					
12/8/2010	2016					
12/10/2010	2016					
12/13/2010	1976					
12/15/2010	2100					
12/17/2010			0.60		0.91	
12/20/2010	2044					
12/22/2010						
12/24/2010	4496		0.67		2.93	
12/27/2010						
12/29/2010						
12/31/2010	1924					
1/3/2011	1880					
1/5/2011	1964					
1/7/2011	1568		0.67		4.19	
1/10/2011	1736					
1/12/2011	1524					
1/14/2011	2080		0.67		4.01	
1/17/2011	1432					
1/19/2011	1760					
1/21/2011	228		0.75		2.77	
1/24/2011	1968	64				
1/26/2011	2072	62				
1/28/2011	1676	60	0.62		3.87	
1/31/2011	2108					
2/2/2011	2004	62				

Table 12 (cont'd)

Date	C8					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
2/4/2011	2108	62	0.57	1.15	2.95	0.16
2/7/2011	2128	56				
2/9/2011	2072	56				
2/11/2011	1992	49	0.58	1.54	2.90	0.24
2/14/2011	2072	42				
2/16/2011	2148	50				
2/18/2011	1924	49	1.04		2.96	
2/21/2011						
2/23/2011	2012	55				
2/25/2011	2064	57	0.24	1.34	0.95	0.01
2/28/2011	1992	60				
3/2/2011	2152	52				
3/4/2011	2088	64	0.67	1.34	3.36	0.01
3/7/2011	1892	54				
3/9/2011	1920	48				
3/11/2011	1804	43	0.51	1.41	2.56	0.00
3/14/2011	1968	38				
3/16/2011	2028	37				
3/18/2011	2080	27	0.56	1.36	3.56	0.01
3/21/2011	1984	38				
3/23/2011	2056	28				
3/25/2011	1980	34	0.59	1.51	3.37	0.01
3/28/2011	2036	48				
3/30/2011	1912	47				
4/1/2011	2128	44	0.59	1.38	2.97	0.20
4/4/2011	2048	38				
4/6/2011	2028	34				
4/8/2011	2156	35	0.71	1.42	3.73	0.73
4/11/2011	2032	32				
4/13/2011	1996	29				
4/15/2011	1928	26	0.56	1.35	3.26	0.35
4/18/2011	2100	33				
4/20/2011	1944	27				
4/22/2011	2004	17	0.57	1.35	2.79	0.07

Table 12 (cont'd)

Date	C8					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
4/25/2011	60	33				
4/27/2011	4088	33				
4/29/2011	4136	22	0.65	1.32	2.70	0.05
5/2/2011	4048	26				
5/4/2011	4092	24				
5/6/2011	3836		1.11	1.24	4.42	0.18
5/9/2011						
5/11/2011	4136	46				
5/13/2011	3856	25	1.13	1.99	5.50	0.08
5/16/2011	4164	33				
5/18/2011	4184	20				
5/20/2011	3908	53	1.19	1.39	6.46	0.05
5/23/2011	4176					
5/25/2011						
5/27/2011			1.27	1.54	6.57	0.31
5/30/2011	4320	70				
6/1/2011	4000	67				
6/3/2011	3940	71	0.82	1.42	4.14	0.18
6/6/2011	4264	41				
6/8/2011	3760	63				
6/10/2011	3852	66				
6/13/2011	4104	75				
6/15/2011	4000	68				
6/17/2011	4040	69	1.41	1.34	7.19	1.56
6/20/2011	3836	74				
6/22/2011	3940	81				
6/24/2011	4160	80	1.28	1.45	3.55	0.07
6/27/2011		86				
6/29/2011						
7/1/2011	4288	90	1.15	1.56	6.05	0.08
7/4/2011	4216	88				
7/6/2011						
7/8/2011	4040	85	0.84	1.60	7.02	0.13
7/11/2011	340	83				

Table 12 (cont'd)

Date	C8					
	Influent COD (mg/L)	Effluent COD (mg/L)	Influent Mn (mg/L)	Effluent Mn (mg/L)	Influent Fe (mg/L)	Effluent Fe (mg/L)
7/13/2011	3932	80				
7/15/2011	3912	83	1.42	1.63	1.33	0.10
7/18/2011	2000	80				
7/20/2011	1896	73				
7/22/2011	4352	74	1.04	1.54	1.04	0.09
7/25/2011	3900	28				
7/27/2011	3980	77				
7/29/2011	4032	74	1.13	1.56	3.25	0.16
8/1/2011						
8/3/2011	640	63				
8/5/2011	3800	69	1.18	1.54	6.54	0.50
8/8/2011	4104	73				
8/10/2011	4096	71				
8/12/2011	4024	30	1.18	1.58	7.07	0.22
8/15/2011		88				
8/17/2011		72				
8/19/2011	8050	88				
8/22/2011		91				
8/24/2011		81				
8/26/2011		96	1.64	1.68	8.82	0.55
8/29/2011	8000	114				
8/31/2011	8330	119				
9/2/2011	7760	120				
9/5/2011	8090	218				
9/7/2011	8690	131				
9/9/2011	8110	136	2.01	1.47	9.55	0.62
9/12/2011	8390	139				
9/14/2011	8090	142				
9/16/2011	8230	66				
9/19/2011	8750	148				
9/21/2011	8100	142				
9/23/2011	7770	154				
9/26/2011	7920	151				
9/28/2011						

APPENDIX D

Calculation Of Spearman's Correlation Coefficient

Table 13 - Results Including Ranks for Calculation of Spearman's Rank

Sand Column Study Data

Results Including Ranks for Calculation of Spearman's Rank Correlation Coefficient

	A	E	F	G	H	J	K	L	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
4		Column Design				Loading Conditions						Sensors				Analytical Results					
5	Unique Identifier	Presence of Perched Groundwater Table (2 = Y, 1 = N)	Presence of Perched Groundwater Table Rank	Column Length (meters)	Column Length Rank	Average Daily Organic Load (lbs BOD ac^{-1}day^{-1})	Average Daily Organic Load Rank	Hydraulic Dosing Frequency (hours between doses)	Hydraulic Dosing Frequency Rank	Organic Load per Dose (mg)	Organic Load per Dose Rank	Average O_2 (%)	Average O_2 Rank	Average VWC	Average VWC Rank	Median Effluent Mn (mg/L)	Median Effluent Mn Rank	Median Effluent Fe (mg/L)	Median Effluent Fe Rank	Median Effluent COD (mg/L)	Median Effluent COD Rank
6	C1-1	2	21.5	0.6	11	65	2	6	8	290	2	16.74	22	0.27	9	0.01	8.5	0.03	4.5	12	5.5
7	C1-2	2	21.5	0.6	11	500	13	6	8	2,200	10	15.30	17	0.33	15	0.00	3.5	0.09	13	11	2.5
8	C1-3	2	21.5	0.6	11	1000	22.5	3	1.5	2,200	10	2.08	5	0.54	27	0.00	3.5	0.23	21	30	19
9	C2-0	1	8	0.6	11	65	2	6	8	290	2	18.14	26	0.25	4	0.01	8.5	0.00	1	11	2.5
10	C2-1	1	8	0.6	11	65	2	6	8	290	2	17.53	24	0.25	5	0.07	17	0.08	12	11	2.5
11	C2-2	1	8	0.6	11	500	13	6	8	2,200	10	6.75	6	0.30	12	0.00	3.5	0.08	10.5	11	2.5
12	C2-3	1	8	0.6	11	1000	22.5	3	1.5	2,200	10	17.21	23	0.52	26	0.00	3.5	0.32	23	35	21
13	C3-1	2	21.5	0.6	11	250	6	12	16	2,200	10	10.37	10	0.34	16	0.05	15.5	0.01	2	17	9.5
14	C3-2	2	21.5	0.6	11	500	13	12	16	4,500	16.5	0.13	1.5	0.36	19	0.00	3.5	0.08	9	12	5.5
15	C3-3	2	21.5	0.6	11	500	13	24	23	9,000	21	0.13	1.5	0.39	22	0.00	3.5	0.15	19.5	19	11.5
16	C4-0	1	8	0.6	11	250	6	12	16	2,200	10	16.70	21	0.26	6	0.03	12.5	0.02	3	17	9.5
17	C4-1	1	8	0.6	11	250	6	12	16	2,200	10	11.90	15	0.27	8	0.01	8.5	0.03	4.5	15	8
18	C4-2	1	8	0.6	11	500	13	12	16	4,500	16.5	15.93	19	0.27	10	0.01	8.5	0.07	7	13	7
19	C4-3	1	8	0.6	11	500	13	24	23	9,000	21	7.49	7	0.33	14	0.04	14	0.33	24	19	11.5
20	C5-1	2	21.5	0.6	11	500	13	4	3.5	1,500	4.5	11.81	13	0.38	21	0.03	12.5	0.15	19.5	26	17.5
21	C5-2	2	21.5	0.6	11	1000	22.5	6	8	4,500	16.5			0.41	23	0.02	11	0.08	10.5	22	13
22	C5-3	2	21.5	0.6	11	1000	22.5	56	26.5	42,000	26.5	0.17	3	0.48	25	0.05	15.5	0.56	27	33	20
23	C6-0	1	8	0.6	11	500	13	24	23	9,000	21	17.72	25	0.34	18	0.44	18	0.06	6	26	17.5
24	C6-1	1	8	0.6	11	500	13	4	3.5	1,500	4.5	8.07	9	0.34	17	0.71	19	0.14	18	23	14.5
25	C6-2	1	8	0.6	11	1000	22.5	6	8	4,500	16.5	7.65	8	0.36	20	0.75	20	0.11	14	25	16
26	C6-3	1	8	0.6	11	1000	22.5	24	23	18,000	24.5	1.70	4	0.44	24	0.97	21	0.50	25	191	27
27	C7-1	2	21.5	1.2	24.5	250	6	12	16	2,200	10	15.97	20	0.16	1	1.01	22	0.12	16	23	14.5
28	C7-2	2	21.5	1.2	24.5	1000	22.5	12	16	9,000	21	11.26	11	0.22	3	2.12	27	0.14	17	36	22
29	C7-3	2	21.5	1.2	24.5	1000	22.5	56	26.5	42,000	26.5	11.80	12	0.26	7	2.11	26	0.24	22	63	24
30	C8-1	1	8	1.2	24.5	250	6	12	16	2,200	10	15.73	18	0.17	2	1.35	23	0.07	8	42	23
31	C8-2	1	8	1.2	24.5	1000	22.5	12	16	9,000	21	13.81	16	0.27	11	1.54	24	0.12	15	72	25
32	C8-3	1	8	1.2	24.5	1000	22.5	24	23	18,000	24.5	11.82	14	0.32	13	1.58	25	0.55	26	119	26

Table 14 - Spearman's Rank Resulting Calculated Data

	AB	AC	AE	AF	AG	AH	AI
30–32	**Spearman's Rank** Resulting Calculated Data						
33			Spearman's Rank				
34			**Mn**	**Fe**	**COD**	**O2**	**VWC**
35		*Offset*	*0*	*2*	*4*	*-4*	*-2*
36	Daily Average Organic Load	*7*	0.27	0.72	0.71	-0.46	0.59
37	Instantaneous Water Applied	*10*	0.46	0.24	0.36	-0.15	-0.10
38	Instantaneous Organic Load Applied	*12*	0.41	0.54	0.61	-0.44	0.28
39	Length of Sand Column	*4*	0.77	0.41	0.66	0.34	-0.15
40	Presence of Perched Groundwater Table	*2*	0.00	0.24	0.10	-0.21	0.29

Table 15 - Spearman's Rank Excel Formulas Used

	AJ	AK	AL	AM	AN	AO	AP
30			**Spearman's Rank**				
31							
32			Formulas used in Excel to calculate ρ				
33			**Spearman's Rank**				
34			**Mn**	**Fe**	**COD**	**O2**	**VWC**
35		*Offset*	*0*	*2*	*4*	*-4*	*-2*
36	Daily Average Organic Load	*7*	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC36)-OFFSET($V$6:$V$32,0,AL$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC36)-OFFSET($V$6:$V$32,0,AM$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC36)-OFFSET($V$6:$V$32,0,AN$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC36)-OFFSET($V$6:$V$32,0,AN$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC36)-OFFSET($V$6:$V$32,0,AP$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))
37	Instantaneous Water Applied	*10*	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC37)-OFFSET($V$6:$V$32,0,AL$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC37)-OFFSET($V$6:$V$32,0,AM$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC37)-OFFSET($V$6:$V$32,0,AN$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC37)-OFFSET($V$6:$V$32,0,AN$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC37)-OFFSET($V$6:$V$32,0,AP$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))
38	Instantaneous Organic Load Applied	*12*	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC38)-OFFSET($V$6:$V$32,0,AL$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC38)-OFFSET($V$6:$V$32,0,AM$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC38)-OFFSET($V$6:$V$32,0,AN$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC38)-OFFSET($V$6:$V$32,0,AN$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC38)-OFFSET($V$6:$V$32,0,AP$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))
39	Length of Sand Column	*4*	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC39)-OFFSET($V$6:$V$32,0,AL$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1)), (recalculated by hand. See "Spearman's Rank Order Correlation" in text)	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC39)-OFFSET($V$6:$V$32,0,AL$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1)), (recalculated by hand. See "Spearman's Rank Order Correlation" in text)	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC39)-OFFSET($V$6:$V$32,0,AL$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1)), (recalculated by hand. See "Spearman's Rank Order Correlation" in text)	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC39)-OFFSET($V$6:$V$32,0,AL$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1)), (recalculated by hand. See "Spearman's Rank Order Correlation" in text)	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC39)-OFFSET($V$6:$V$32,0,AL$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1)), (recalculated by hand. See "Spearman's Rank Order Correlation" in text)
40	Presence of Perched Groundwater Table	*2*	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC40)-OFFSET($V$6:$V$32,0,AL$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC40)-OFFSET($V$6:$V$32,0,AM$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC40)-OFFSET($V$6:$V$32,0,AN$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC40)-OFFSET($V$6:$V$32,0,AN$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))	=1-(6*SUM((OFFSET($D$6:$D$32,0,$AC40)-OFFSET($V$6:$V$32,0,AP$35))^2))/(COUNT($V$6:$V$32)*(COUNT($V$6:$V$32)^2-1))

APPENDIX E

Photos Of Soil Column Cores Following Study

Figure 18 - Photos of Soil Cores from Columns One Through Four

Figure 19 - Photos of Soil Cores from Columns Five Through Eight

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