Project Number: JYP-1002

Water Quality Assessment and Manganese Treatment for the Russell F. Tenant Water Treatment Facility

A Major Qualifying Project

submitted to the Faculty

of

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

By

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Date: March 9, 2011

Approved:

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1. Drinking water
2. Manganese
3. Potassium permanganate

Abstract

The goal of this project was to design an effective manganese control process for the Russell F. Tenant Drinking Water Treatment Facility in Attleboro, MA. Water quality in Orrs Pond, the primary source water for the facility, was analyzed over a five month period. Treatment options were assessed using a criteria matrix. Oxidation with potassium permanganate was selected for a detailed design including chemical dosing, operational considerations, alkalinity consumption, and cost. The process was laboratory tested and oxidized up to 99% of manganese using theoretical permanganate dosing. Recommendations for the continuation of this project include a year-round water quality assessment of the intake water and full-scale testing the design.

Executive Summary

Elevated levels of iron and manganese in potable water can cause aesthetic issues such as metallic taste and discoloration. Raw water at the Russell F. Tenant Water Treatment Facility in Attleboro, MA has iron and manganese concentrations that exceed the Environmental Protection Agency's (EPA) secondary maximum contaminant levels, 0.3 mg/L and 0.05 mg/L respectively, during the summer and early fall. Iron can typically be treated conventionally within the treatment facility. Manganese, however, frequently requires more involved control measures, such as chemical oxidation. Manganese is currently treated with ozone in the facility. Ozone oxidation is energy intensive and has the potential to produce the byproduct bromate, a suspected carcinogen. The health risks associated with this treatment method are undesirable for the facility and another control strategy should be implemented.

The goal of this project was to develop an effective manganese control strategy that does not have negative environmental or human health impacts. Major objectives included:

- Bimonthly sampling events to analyze water quality characteristics of the source water, Orrs Pond
- Comparing different iron and manganese control strategies
- Laboratory testing the recommended treatment process

Water quality characteristics were assessed bimonthly in Orrs Pond at the approximate location of the raw water intake from the surface to a depth of 25 feet at 5 foot intervals. The collected water was used for testing relevant water quality parameters including iron, manganese, organic carbon, pH, turbidity, temperature, and dissolved oxygen. Peak measurements for dissolved iron and manganese were observed on September 23, 2010, and were 3.85 mg/L and 13.12 mg/L, respectively. Dissolved organic carbon levels peaked at 13.41 mg/L and were taken into consideration during the development of the control strategy.

Iron and manganese control strategies were compared using a criteria matrix that included effectiveness, environmental impact, and safety. Each criteria was assigned a value 1-5 and the two highest scoring control strategies, greensand filtration and oxidation with potassium permanganate, were selected for preliminary designs. A basic cost analysis and design comparison was performed and it was determined that oxidation with potassium permanganate was the recommended treatment. A detailed design for this process was completed.

The potassium permanganate oxidation system was designed using stoichiometric dosing of 0.94 mg $KMnO_4$ per mg of dissolved iron and 1.92 mg $KMnO_4$ per mg of dissolved manganese. The potassium permanganate would be added at the raw water intake, which provides adequate reaction time (greater than 10 minutes) through the piping and rapid mixing. Alkalinity consumption of 1.47 mg as $CaCO_3$ per mg of iron and 1.21 mg as $CaCO_3$ per mg of manganese was calculated. The alkalinity consumption was determined in order to ensure that no additional process modifications would be required.

The design was laboratory tested and shown to oxidize 99% of manganese, 94% of iron, and 25% of organic carbon with theoretical dosing and a dissolved organic carbon concentration of 3 mg/L. Additional intake sampling and full-scale testing of the design are recommended prior to the treatment system going on-line.

Estimated capital costs for a potassium permanganate system are $27,000 for the chemical storage tank and accessories. Estimated operational costs are $79,386 annually based on historical and observed iron, manganese, and organic carbon concentrations. Operational considerations for adjusting the chemical dose based on raw water quality and maintaining the treatment system are also provided.

Acknowledgements

The project team would like to thank the following individuals for their contributions:

- Professor Jeanine Plummer of Worcester Polytechnic Institute for technical recommendations and review of the design and the report as well as guidance throughout the duration of the project
- Christine Millhouse of the Russell F. Tenant Water Treatment Facility for the opportunity to work on this project
- Kourtney Wunschel and Michael Rebelo of the Russell F. Tenant Water Treatment Facility for assistance with pond sampling and design recommendations
- Donald Pellegrino, Daniel Roop, and Abigail Charest of Worcester Polytechnic Institute for laboratory assistance
- Jeff Burkle of Pristine Water Solutions; Peter Vendzules of Hungerford and Terry; Rick Wells of Carus Corporation; and Ron Mastrogiacomo of AECOM for assistance with cost estimation
- Professor Paul Mathisen of Worcester Polytechnic Institute for loaning our team his depth sampler

The success of this project would not have been possible without these and many other contributions by personnel in the water treatment profession.

Capstone Design Statement

The purpose of this Major Qualifying Project was to design a manganese control strategy for the Russell F. Tenant Water Treatment Facility in Attleboro, MA. Orrs Pond, the primary source water for the treatment facility, has elevated levels of iron and manganese, peaking at 3.85 mg/L and 13.12 mg/L respectively, during the summer and early fall. The current treatment process, preozonation, is undesirable because it has the potential to form the suspected carcinogenic byproduct bromate and is energy intensive. Different treatment options, including modifying the source water, modifying the treatment facility, and changing the source water, were analyzed based on different parameters using a criteria matrix. The two highest scoring control strategies, greensand filtration and oxidation with potassium permanganate, were chosen for preliminary designs. After a comparison of the estimated costs and effectiveness of the two designs, potassium permanganate oxidation was selected for further development and laboratory tested.

The project addressed the following ABET design considerations:

- Economic
    - Oxidation with potassium permanganate was determined to have significantly lower capital and operational costs than greensand filtration
    - Cost estimation for the oxidation design include $27,000 for capital costs and annual operational costs of $79,386 based on observed and historical water quality results

- Environmental
    - Environmental impact was one of the criteria used in determining the two control strategies to receive preliminary design
    - The design produces no harmful byproducts

- Health and Safety
    - Health and safety was one of the criteria used in determining the two control strategies to receive preliminary design
    - The design replaces ozone, providing safer potable water
    - No outstanding operational risks are associated with the design

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1 Russell F. Tenant Water Treatment Facility

The Russell F. Tennant Water Treatment Facility, located in Attleboro, Massachusetts, supplies drinking water to over 40,000 people in Attleboro, North Attleboro, and Mansfield. The facility went online in June 1995. Depending on water demand, the facility produces between three and six million gallons per day (MGD) for both residential and industrial use. Orrs Pond is the primary water source for the treatment facility. In the summer of 2011, water from the Manchester Reservoir was drawn into the treatment facility as a temporary solution to high levels of iron and manganese exceeding the Environmental Protection Agency (EPA) water quality guidelines (Millhouse personal communication, 2010). This chapter introduces the water bodies and watersheds that feed the treatment facility, water demand for Attleboro, North Attleboro, and Mansfield, the treatment facility's processes, and relevant historical data.

1.1 Attleboro Reservoir System

The treatment facility is fed water from water bodies located within the Ten Mile River Watershed. These water bodies are Manchester Reservoir, Orrs Pond, Luther Pond, Hoppin Hill Reservoir, Lake Mirimichi and Blakes Pond. Water from Hoppin Hill Reservoir in North Attleboro flows into the Seven Mile River. This water spills into Luther Reservoir and then can be pumped to Manchester Reservoir or to Orrs Pond. Manchester Reservoir and Orrs Pond are located in Attleboro. The land uses within the watershed consist of a mix of undeveloped forested land, residential development, businesses, agriculture, recreation and protected lands. Protected open space accounts for 28% of the total area for the Ten Mile River Watershed. Figure 1-1 is a map denoting the relevant water bodies, corresponding sub watersheds, and the watershed boundary. Details of the six water supplies can be seen in Table 1-1.

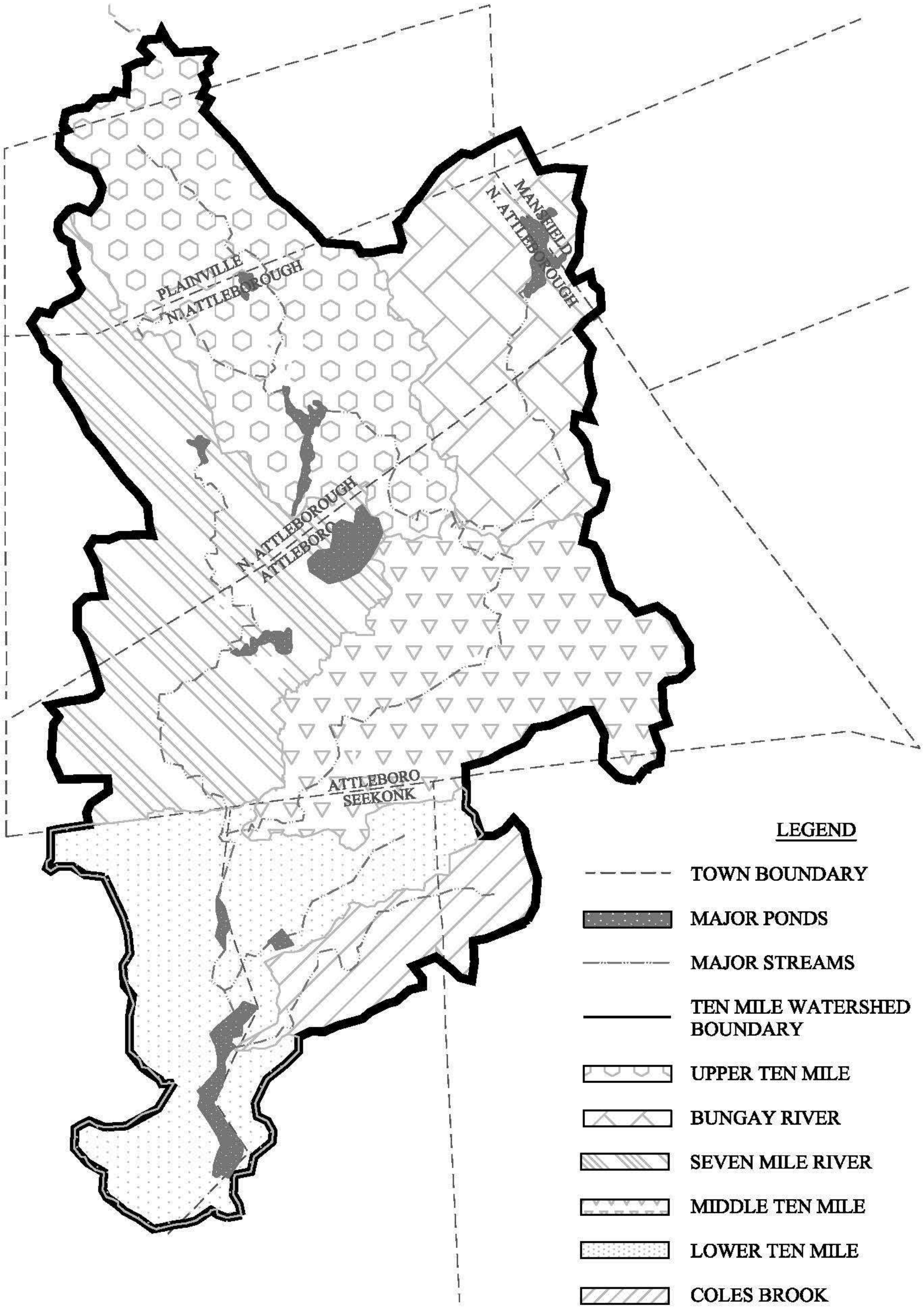

Figure 1-1: Map of Ten Mile River Watershed

Table 1-1: Water Supply Information

Name	Built	Maximum Storage (Gallons)	Surface Area (acres)
Orrs Pond*	Early 1900	100 million	47
Manchester Reservoir*	1963	1.1 billion	252
Luther Pond*	Mid 1970	33 million	17
Hoppin Hill Reservoir*	1911	200 million	36.7
Lake Mirimichi	1926	495 million	160
Blakes Pond**	1930, 1959	5 million	4

*Denotes that water body is fed by Ten Mile River Basin
** Denotes that the body is fed by Taunton River Basin

1.2 Treatment Processes

The Russell F. Tenant Water Treatment Facility operates as a conventional water treatment plant. Processes include preozonation, coagulation, flocculation, sedimentation, filtration, disinfection, and storage. The layout of the treatment facility is shown is Figure 1-2. Refer to Appendix A for a full set of treatment facility data from the Attleboro Water Department.

1.2.1 Raw Water Intake

The raw water intake is located in Orrs Pond at approximately 41°55.651’N, 71°20.107W at a depth of 25 ft. The water passes through a Venturi meter before reaching the rapid mix tanks. A Venturi meter is a mechanism for measuring water flow while expending relatively little head loss (Viessman et al., 2009).

1.2.2 Preozonation

During the summer months, ozone is added as a pretreatment measure between the raw water intake and rapid mix tanks for the oxidation of manganese. Typically ozone is added when there is noticeable water discoloration or when the facility is unable to keep a chlorine residual. Ozone dosages range from 1 mg/L of 4% to 5 mg/L of 6% (Wunschel personal communication, 2010). Ozone oxidation is discussed in greater detail in Chapter 2 of this report.

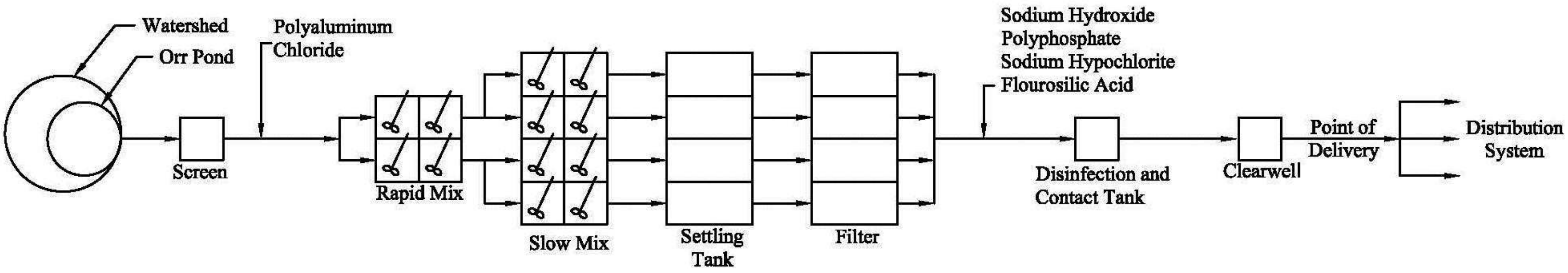

Figure 1-2: Process Flow Chart for the Russell F. Tenant Water Treatment Facility

1.2.3 Coagulation and Flocculation

Many particles contain repulsive forces that keep them suspended in water. Coagulation chemically reduces these repulsive forces so that colloidal particles form flocs, which are aggregates of coagulated particles. These flocs are then separated from the water in subsequent processes. A coagulating chemical is added to water in a rapid mix tank so that it can come into maximum contact with colloidal particles before it is able to react with water molecules instead (Droste, 1997). Polyaluminum chloride is used in the treatment facility as a coagulant and dosed at 20-60 mg/L. Dosages are typically higher during the summer. The Russell F. Tenant Water Treatment Facility's rapid mix process operates at 45 rpm in four 29,700 gallon tanks (Wunschel personal communication, 2010). The coagulated particles are then further mixed, or flocculated, in the slow mix basins to aggregate flocs without breaking them apart. The slow mix operates at 30 rpm in eight 268,000 gallon tanks (Wunschel personal communication, 2010).

1.2.4 Sedimentation

After coagulation and flocculation, the flocs become large enough to be removed through sedimentation. Ultimately, these processes reduce color, odor, and pathogens in addition to removing inorganic particles (Viessman et al., 2009). Sedimentation basins rely on gravity to remove the heaviest particles present in a water inflow. The fluid travels along a constant horizontal flow from one end of the tank to the other. Meanwhile, particles displace downward according to their density and size. Larger flocs will reach the bottom of the basin before the end of the tank, while water molecules and smaller contaminants pass through uninhibited. Particles that gather at the bottom of a sedimentation basin are referred to as sludge and are removed from the treatment process and handled as waste (Viessman et al., 2009). There are four sedimentation basins at the treatment facility. Each one is 129 ft long, 17 ft wide, and 15.25 ft tall (Wunschel personal communication, 2010).

1.2.5 Filtration

Filtration removes those particles that pass through sedimentation, but can be effectively intercepted by a porous media (Viessman et al., 2009). Filtration reduces turbidity, which is an aggregate measure of particulates in the water, as well as bacterial concentrations. The removal efficiency is dependent on the effective surface area of media particles as well as the depth of the filter (Droste, 2001). Filtration performance is monitored through effluent turbidity as well as development of head loss. When either parameter reaches a predefined value, the filter is cleaned through backwash (Droste, 2001). There are four mixed media filters at the treatment facility each with a depth of 16 feet and a volume of 209,000 gallons, comprised of activated carbon, to treat organic particles, and sand (Wunschel personal communication, 2010).

1.2.6 Disinfection and Distribution

Disinfection is the inactivation of pathogenic microorganisms. The EPA Surface Water Treatment Rule requires the inactivation of different pathogens to ensure consumer safety from waterborne diseases (Droste, 2001). The Russell F. Tenant facility disinfects with sodium hypochlorite from 1.5-3 mg/L. After the application of chemical disinfectants, drinking water is retained in a contact tank long enough for the inactivation of microorganisms to take place. There is a 1.15 million gallon contact tank for holding disinfected drinking water. After the contact tank, the expected chlorine residual is 0.8-0.9 mg/L (Wunschel personal communication, 2010). Chemical residual in drinking water treatment is the excess chemical added to actively continue disinfection of microorganisms as treated water passes through the distribution system.

In addition to the disinfectant, several chemicals are added prior to distribution. Sodium hydroxide is added at a dose of 11-20 mg/L to stabilize the pH between 7.5 and 8.0. Polyphosphate is added at 1.3 mg/L as a corrosion inhibitor in the distribution system. Fluorosilicic acid is added at 1.0 mg/L for dental purposes. The finished water to be distributed to the resident population is stored in a 398,000 gallon clearwell (Wunschel personal communication, 2010).

1.3 Historical Water Quality Information

Since 2004, the Russell F. Tennant Water Treatment Facility has experienced difficulties with high levels of iron and manganese in their main source water, Orrs Pond. Although the installation of the ozone pretreatment system has helped to reduce the levels in the finished water, the costs and risks of forming byproducts from this treatment method are undesirable (Wunschel personal communication, 2010).

1.3.1 Historical Manganese Data

Historical data from 2004-2010 have shown an increase in both total and dissolved manganese, particularly in the raw water. As shown in Appendix B, the majority of the manganese is found in the dissolved form. Figure 1-3 shows the total manganese for both raw and finished water from January 2004 until August 2010. It should be noted that the treatment facility switched from Orrs Pond to Manchester Reservoir in May 2010 and drew water into the treatment facility from then until the beginning of September 2010.

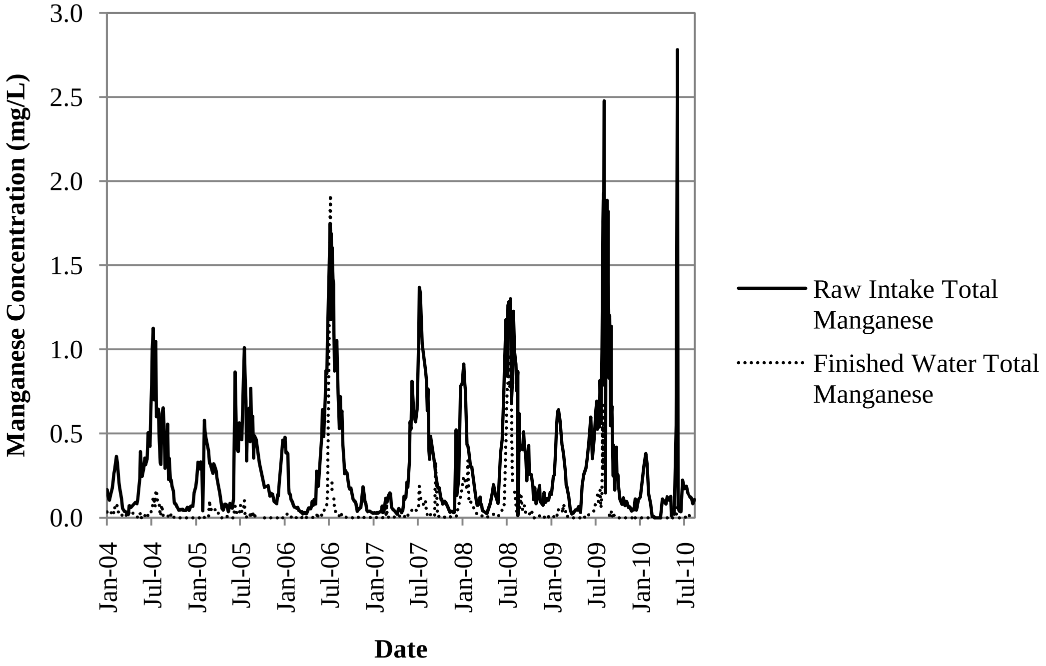

Figure 1-3: Historical Total Manganese for Raw and Finished Water

The elevated levels of manganese appear to be a seasonal issue, with the highest yearly levels observed during the May-August time frame. There is a slight upward trend in the seasonal peaks. The highest raw water manganese concentration in 2007 was 1.37 mg/L, compared to 2.48 mg/L and 2.78 mg/L in 2009 and 2010, respectively. These concentrations suggest that this issue is getting worse over time. Although preozonation currently reduces the levels of manganese in finished water, the treatment facility is concerned with the adverse effects this treatment technique can cause.

1.3.2 Other Historical Water Quality Parameters

Many different water quality parameters are tested daily, weekly, or monthly within the Russell F. Tenant Treatment Facility. Daily tests include alkalinity, temperature, pH, and turbidity. Total and dissolved manganese in both raw and finished water as well as alkalinity in finished water are measured weekly. Lastly, sodium and total organic carbon are both measured monthly.

Turbidity is an aggregate measure of particulates in the water. Figure 1-4 shows the measured daily turbidity from January 2006 until December 2009. The turbidity data follows a similar trend to the total manganese data, with peak measurements occurring during the summer months. However, some peaks are also observed in the winter months. Levels are lowest in the spring and fall. Turbidity levels also show a general upward trend from 2006 until 2009. The maximum turbidity recorded in 2006 was 3.37 ntu, compared to 4.13 ntu and 6.08 ntu, observed in 2008 and 2009 respectively.

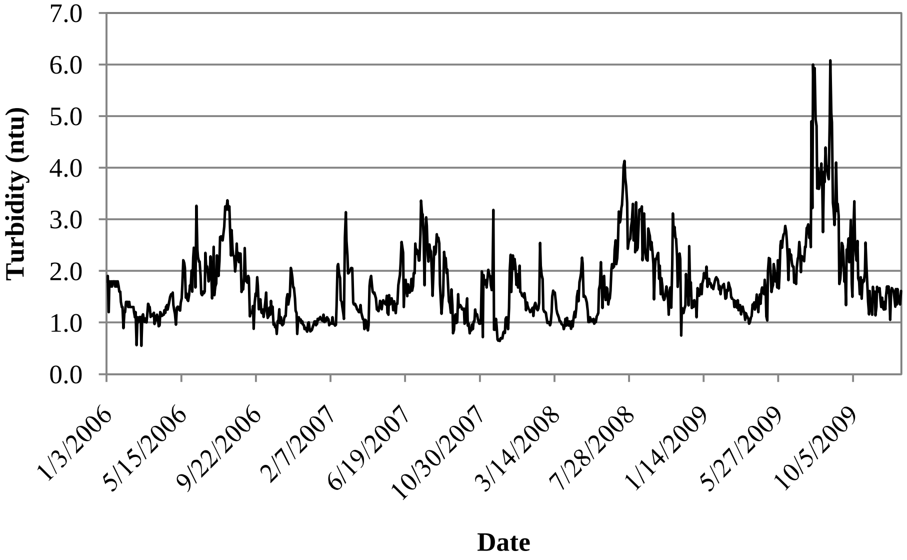

Figure 1-4: Historical Turbidity Measurements

Appendix B presents additional monitoring data from the treatment facility. Total organic carbon showed seasonal variations, with the lowest value (1.9 mg/L) observed in February 2010 and the highest value (7.0 mg/L) observed in August 2009. Temperature ranged from a winter low of 1°C to a summer high of 26 °C. pH remained relatively constant year round, averaging 6.86.

2 Background

Iron and manganese in drinking water can cause aesthetic issues such as discoloration, metallic taste, and pipe staining (U.S. EPA, 2010). The Environmental Protection Agency provides guidelines on the allowable levels of these metals in potable water. This chapter provides background on the causes of elevated levels of iron and manganese, issues surrounding these metals in drinking water, and water quality recommendations. Next, an overview of water quality parameters that affect iron and manganese and options to reduce the concentrations, including source treatment and removal in a treatment plant, is provided. Lastly, a case study documenting elevated iron and manganese levels in a reservoir in Massachusetts is examined.

2.1 Iron and Manganese in Water Sources

Iron and manganese issues typically arise when high levels of the insoluble forms of these metals are found in finished drinking water. Both metals are naturally soluble in water. However, the metals react with chemicals such as chlorine in treatment systems and form precipitates, which consequently cause issues such as discoloration. The insoluble and easily oxidized forms of iron and manganese are desired for treatment purposes.

2.1.1 Causes of Iron and Manganese in Water

Iron and manganese are metallic elements found in many types of rocks. These metals can get into surface and ground water. Concentrations of iron and manganese are often higher in groundwater than surface water. As water percolates through soil and rock, it can dissolve minerals containing iron and manganese and hold them in solution. The dissolved iron and manganese can then leach into the ground water. For surface waters, rainfall runoff picks up iron and manganese and deposits them in to water bodies and soil. Dissolved iron and manganese is more readily found in surface waters that are stratified due to lack of oxygen at the bottom of the water body (Wisconsin DNR, 2010). Corrosion and deterioration of old iron pipes may also be a source of iron in water.

2.1.2 Iron and Manganese Chemistry and Reactivity in Water

The most common forms of manganese (Mn) found in water are manganese (II) and manganese (VII), which are both soluble, and manganese (IV), which is insoluble. Mn^{4+} results from the oxidation of Mn^{2+} by air (Deblois, 2002). Less oxygen implies more Mn^{2+} because less of the manganese is being oxidized into Mn^{4+}. Therefore, aerobic water body conditions produce greater amounts of insoluble manganese, which is easier to treat than soluble manganese (AWWARF, 2006).

Iron (Fe) is usually found in water as iron (II) and iron (III), known as ferrous and ferric iron, respectively. Ferric iron is more prevalent because it is of a higher oxidation state and oxygen is plentiful in earth's atmosphere. It is more desirable to have ferric iron in a water body because its precipitate form traps other particles and removes them from the process as well during pretreatment (Newton, 2010). Dissolved ferrous iron appears clear in a water sample, but reddish brown particles appear and settle to the bottom of the sample after it is exposed to air. Insoluble ferric iron appears rusty, red, or yellow in a water sample and settles to the bottom over time (Illinois DPH, 2010).

2.1.3 Health and Aesthetic Issues

Taste and odor become noticeable above a threshold odor number (TON) of 3 and color becomes visible above 15 color units (EPA, 2010). Water quality recommendations set by the EPA for iron and manganese address these limits. While iron and manganese often appear together and cause similar aesthetic concerns, iron is a bigger concern when in compounds versus its elemental form and manganese ions can be a cause for neurological concerns. Additionally, certain bacteria are able to grow in the presence of iron and manganese. These bacteria are not pathogenic to humans but can clog pipes and become difficult to remove once layers of slime form on the inner walls of pipes (Connecticut DPH, 2009).

Iron produces a metallic taste, a rusty color in water, and a reddish/orange staining of plumbing fixtures and laundered clothes at concentrations above 0.3 mg/L (U.S. EPA, 2010). Fe^{2+} oxidizes more readily than Fe^{3+} and therefore causes more rusting in pipes (Newton, 2010). The compound iron chloride has a greater effect on human health than the element iron. This compound is toxic above concentrations of 200 mg and lethal at 10-50 g (Lenntech, 2010). Iron chloride can form in water treatment systems because of the prevalence of chlorine as a disinfectant and within the distribution system.

Oxidized manganese (Mn^{4+}) produces black staining, gives water a bitter metallic taste, and turns water blackish brown above 0.05 mg/L (U.S. EPA, 2010). There are no adverse short term health effects associated with manganese. Chronic exposure to manganese has been observed to cause mild neurological damage. Table 2-1 shows the maximum allowable consumption by age and gender as recommended by the EPA (U.S EPA, 2004).

Table 2-1: Maximum Consumption of Manganese to Avoid Neurological Damage (U.S EPA, 2009)

Classification	Age (years)	Male (g/day)	Female (g/day)
Infants	0-1	3.0	3.0
Children	1-8	1.2 – 1.5	1.2 – 1.5
Young Adults	9-18	1.9 – 2.2	1.6
Adults, 19+ years	19+	2.3	1.8

2.1.4 Regulations

The Safe Drinking Water Act of 1974 gave the EPA authority to set primary and secondary drinking water standards. Primary drinking water standards are federally enforceable while secondary drinking water standards are guidelines. Primary standards are set for contaminants that may negatively impact human health, while secondary standards are set for aesthetically unpleasant or nuisance contaminants (Davis et al., 2009). Primary standards specify maximum contaminant levels (MCL) in treated drinking waters and/or treatment techniques (TT) for reducing contaminant concentrations. Secondary standards specify secondary maximum contaminant levels (SMCL) that treatment plants should strive to meet in order to produce water with an acceptable appearance, taste, and smell (U.S. EPA, 2010). While aesthetic properties are not directly associated with health concerns, consumers often rely on aesthetics to judge the quality of drinking water.

As discussed in Section 2.1.3, iron and manganese are generally not harmful to ingest (Droste, 1997). The principal concerns associated with iron and manganese in drinking water are aesthetic. Therefore, the EPA has set secondary maximum contaminant levels for iron and manganese (SMCL). The SMCL for iron and manganese are 0.3 mg/L and 0.05 mg/L, respectively (U.S. EPA, 2010).

2.2 Water Quality Parameters Affecting Iron and Manganese

There are several water quality parameters that are related to iron and manganese in bodies of water. The parameter that most directly affects the solubility of iron and manganese is dissolved oxygen. As the dissolved oxygen concentration decreases, the percentage of iron and manganese that is dissolved increases. Temperature, pH, turbidity, and total and dissolved organic carbon all have an impact on the dissolved oxygen concentration which consequently affects the concentration of iron and manganese.

2.2.1 Dissolved Oxygen

Dissolved oxygen enters surface waters naturally by mass transfer from the surrounding air and as a byproduct of photosynthesis. Measurements of dissolved oxygen can be used to determine the health or cleanliness of a lake or stream. These concentrations also have an effect on iron and manganese. If the oxygen concentrations are low, the iron and manganese will dissolve more readily, especially if the pH of the water is less than 7.

There are many factors that affect dissolved oxygen concentrations: how much oxygen is being produced and used, how well mixed the water is, and temperature. Oxygen is depleted by microbial organisms that consume organic matter in the water through aerobic respiration. When sunlight is present, algae will produce oxygen from undergoing photosynthesis. Photosynthesis stops during the night and algae use the oxygen for respiration. Once the algae die, they sink to the bottom of the body of water. At the bottom they are decomposed by bacteria, which use oxygen. This causes the bottom layer of water bodies to have lower dissolved oxygen concentrations. If the water is poorly mixed, or stratified, the bottom layer of water will have significantly lower dissolved oxygen concentrations and can become hypoxic or anoxic (Murphy, 2010). To increase the concentration of oxygen in a water body, it can be aerated to improve the circulation of the water.

2.2.2 Temperature

Temperature is a relevant parameter to measure because it influences water chemistry. A higher temperature generally increases the rate of chemical and biological reactions (Perlman, 2010). Temperature also impacts dissolved oxygen in surface waters due to stratification. During the summer months, the top of the lake becomes warmer then the lower layers. The warm water stays on the top of the lake because it is less dense. As air temperature cools in autumn, the surface water also cools, resulting in uniform temperature conditions throughout the water body. This causes the water at different depths to mix in a process called overturn. Turning of a lake causes it to become mixed and results in the dissolved oxygen levels to increase at the bottom (Perlman, 2010). The higher dissolved oxygen levels will increase the rate at which iron and manganese oxidize.

2.2.3 pH

pH is defined as the negative logarithm of the hydrogen ion concentration, represented as $[H^+]$ in moles/liter, as shown in Equation 3-1.

$$pH = -\log [H^+] \qquad \text{(Equation 3-1)}$$

The pH value is used to represent the acidity of a solution and it ranges from 0 to 14. A pH of 7.0 is considered neutral, while below 7.0 is acidic and above 7.0 is basic. This is particularly important in water because it determines the solubility of chemical elements and heavy metals. The water solubility of some iron and manganese compounds increases at lower pH levels (Seelig et al., 2010).

2.2.4 Turbidity

All water contains suspended matter which can be removed from water through solid-liquid separation processes. Suspended matter can be clay, silt, finely divided organic and inorganic matter, insoluble organic compounds, plankton and microscopic organisms. Water that is flowing fast will contain more suspended matter because the particles do not have time to settle out. Ponds and lakes with a high volume to flow ratio tend to be clear because the particulate matter settles to the bottom.

Turbidity is an aggregate measurement of particulate matter that is suspended in water. A turbidimeter measures the scattering effect that light has on suspended solids in Nephelometric Turbidity Units (NTU). For this measurement, water is placed into a clear, unscratched vial and a light beam is passed through the sample. Two sensors measure the light intensity. The first sensor is directly across from the beam and the second sensor at a right angle to the beam. The ratio between the light intensities at the two sensors is calculated and results in the turbidity in NTU (U.S. EPA, 1999).

High turbidity in lakes can be caused by many factors including soil erosion from agricultural practices, domestic and industrial wastewater discharge, runoff from roads, parking lots and other impervious surfaces, flooding, algae growth, and removing vegetation from the banks (U.S. EPA, 1998). The higher the turbidity, the more particulate matter is in the water. This can interfere with sunlight penetration to plants in the water that need light for photosynthesis. If the turbidity is high enough, it decreases photosynthetic activity which reduces the amount of oxygen produced which will consequently cause iron and manganese to stay in their soluble forms.

2.2.5 Total and Dissolved Organic Carbon

Total organic carbon is the measure of the organic molecules present in the water measured as carbon. Dissolved organic carbon is the organic matter that is able to pass through a filter. Organic carbon enters water through both natural and anthropogenic sources. Naturally occurring organic carbon comes from the decomposition of plants and animals and runoff from forested lands. Anthropogenic sources of organic carbons include spills and runoff from urban and agricultural land (Environmental Agency, 2011).

Knowing the amount of organic carbon is important for several reasons. Organic carbon serves as a primary food source for aquatic organisms. A high organic content means an increase in the growth of microorganisms which contribute to the depletion of oxygen supplies. Particulate organic carbon can also reduce the penetration of sunlight into water, limiting photosynthesis. Therefore, high concentrations of organic carbon can reduce oxygen concentration, which increases solubility of iron and manganese (Beristain, 2005). Additionally, organic carbon readily oxidizes with some oxidizing agents (Knocke personal communication, 2010).

2.3 Iron and Manganese Control Strategies

There are several control strategies that may be employed to ensure that finished drinking water meets EPA guidelines for iron and manganese. Control strategies that can be applied in the water source include aeration and sequestration. Although many treatment options for iron and manganese are considered difficult and costly, implementing control strategies to treat iron and manganese in situ, or within the source water, is considered to be an easier, more cost effective solution for treating these metals. By treating the source water directly, the water treatment facility is not faced with the process of modifying the treatment system (Viessman et al., 2009). Treatment options within the water treatment facility include chemical oxidation, aeration-filtration, and greensand filtration. These options can prove to be more advantageous when the facility is capable of utilizing them without making major modifications to the treatment system.

Adsorptive or catalytic media filtration in the plant can also retain manganese, iron, and other metals using special filter media with the ability to retain metals. This treatment technique is not covered in this report because the media may be susceptible to fouling when total organic carbon (TOC) is present at concentrations above 1.0 mg/L (HDR Engineering, 2001). As shown in Chapter 1, the TOC levels at the home facility can reach as high as 7 mg/L in the summer months, therefore this treatment technique is not applicable to this project. Biological oxidation is also excluded from this report because the theories and practices are still being modified (Sharma, 2001). Sequestration, a treatment technique used to alleviate staining issues associated with iron and manganese by holding the metals in solution, is excluded because it requires water with less than 1.0 mg/L iron and less than 0.3 mg/L manganese and the levels that occur in Orrs Pond exceed these values.

2.3.1 Aeration

Aeration involves the addition of oxygen into a water body through physical means to increase dissolved oxygen levels. Increasing dissolved oxygen levels decreases dissolved iron and manganese levels by oxidizing the metals into their insoluble forms, as shown in Reactions 2-1 and 2-2. This will allow for the metals to be settled and filtered out of the water in the existing treatment system.

$$4Fe(HCO_3)_2 + O_2 + 2H_2O \longrightarrow 4Fe(OH)_3 + 8CO_2 \qquad \text{(Reaction 2-1)}$$

$$2Mn(HCO_3)_2 + O_2 \longrightarrow 2MnO_2 + 4CO_2 + 2H_2O \qquad \text{(Reaction 2-2)}$$

Whole lake artificial circulation is one option for mixing and aerating a water body. This technique is effective in relatively shallow (typically less than 20 feet) water bodies that are stratified, meaning that conditions from the surface to the bottom are not uniform and temperature and dissolved oxygen typically decrease with depth. Artificial mixing creates uniform conditions within the water body, introducing higher levels of dissolved oxygen at the bottom where iron and manganese levels are typically higher. The recommended air flow rate is 1.3 cubic feet per minute per acre of lake (Mattson et al., 2004).

Full lift aeration (see Figure 2-1) involves using a pump to draw hypoxic water from the bottom of a reservoir to the surface where it is exposed to oxygen. The oxygenated water is then returned to the bottom (Mattson et al., 2004).

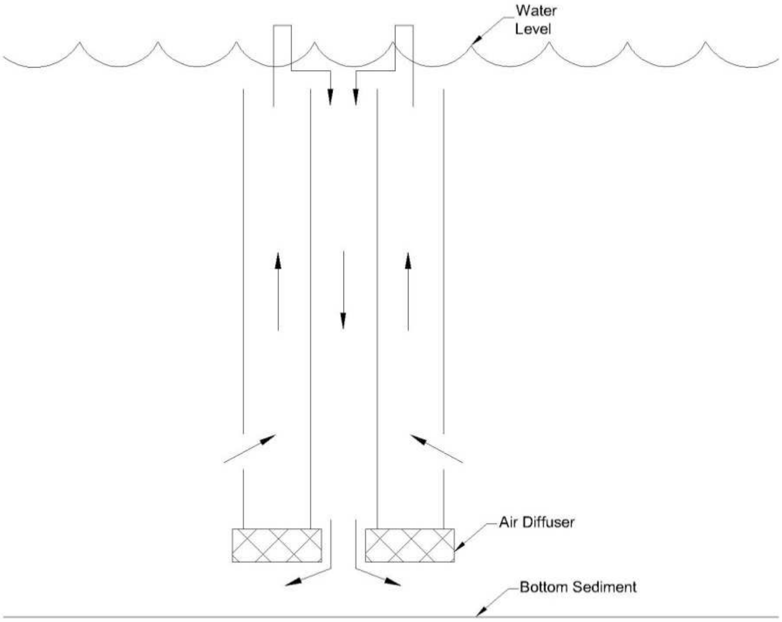

Figure 2-1: Full Lift Aeration Schematic

Partial lift aeration is another option for mixing surface waters (see Figure 2-2). In this scenario, air is pumped through a submerged chamber to the bottom of the water body. This treatment technique requires a compressor housed on the shoreline. Unlike full lift aeration, this technique does not interfere with regular pond or lake use (Mattson et al., 2004).

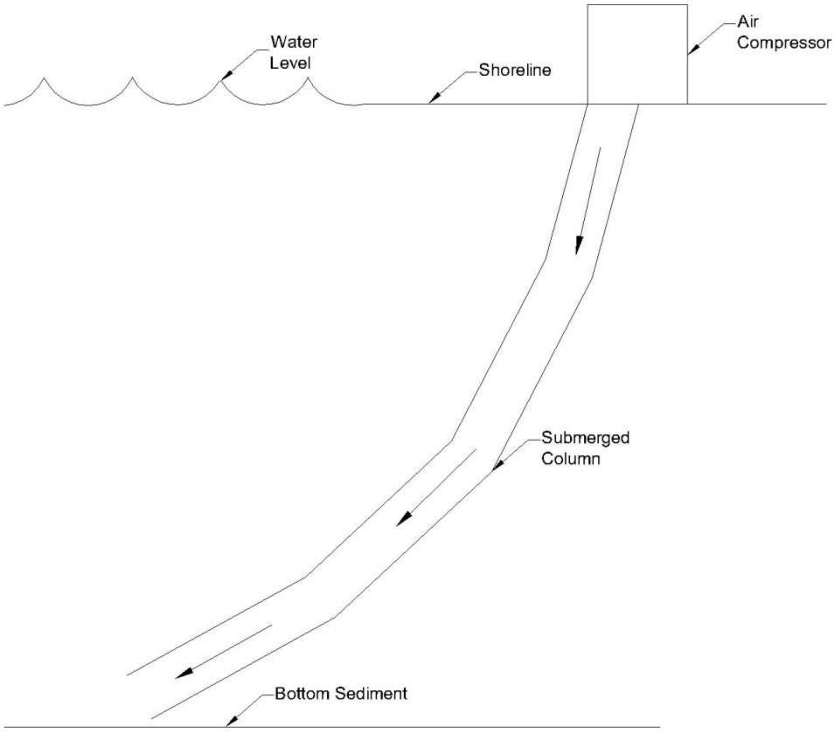

Figure 2-2: Partial Lift Aeration Schematic

2.3.2 Precipitation by Chemical Oxidation

Chemical oxidation can be used to treat high levels of iron and manganese (greater than 10 mg/L). Since iron (Fe^{2+}) and manganese (Mn^{2+}) are soluble in neutral water, oxidation is required in order to precipitate the metals so they can subsequently be removed through settling and filtration. Oxidation involves the transfer of electrons from the iron and manganese to the oxidizing agent. There is a direct correlation between the concentration of iron and manganese in the water and the concentration of oxidizing chemicals required. Chemicals used to oxidize iron and manganese include potassium permanganate, chlorine, chlorine dioxide, and ozone (Land, 2010). The relevant reactions and dosages are shown in Tables 2-2 and 2-3.

Table 2-2: Chemical Reactions and Dosages for the Oxidation of Iron

Oxidant	Chemical Reaction	Dosage (mg/ mg Fe^{2+})	Comments
Potassium permanganate	$3Fe(HCO_3)_2+KMnO_4+2H_2O \rightarrow 3Fe(OH)_3+MnO_2+KHCO_3+5CO_2$	0.94	Essentially instantaneous
Chlorine	$2Fe(HCO_3)_2 + Ca(HCO_3)_2 + Cl_2 \rightarrow 2Fe(OH)_3 + CaCl_2 + 6CO_2$	0.64	Reaction is pH and temperature dependent
Chlorine dioxide	$Fe(HCO_3)_2 + NaHCO_3 + ClO_2 \rightarrow Fe(OH)_3 + NaClO_2 + 3CO_2$	1.21	Reaction is pH and temperature dependent
Ozone	$2Fe(HCO3)_2 +O_3 + 2H_2O \rightarrow 2Fe(OH)_3 +O_2 + 4CO_2 +H_2O$	0.43	Essentially instantaneous

Table 2-3: Chemical Reactions and Dosages for the Oxidation of Manganese

Oxidant	Chemical Reaction	Dosage (mg/ mg Mn^{7+})	Comments
Potassium permanganate	$3Mn(HCO_3)_2 + 2KMnO_4 \rightarrow 5MnO_2 + 2KHCO_3 + 2H_2O + 4CO_2$	1.92	Reaction is very rapid
Chlorine	$Mn(HCO_3)_2+Ca(HCO_3)_2+Cl_2 \rightarrow MnO_2+CaCl_2+2H_2O+4CO_2$	1.29	Reaction is very slow at neural pH, speeds up as pH increases
Chlorine dioxide	$Mn(HCO_3)_2+2NaHCO_3+2ClO_2 \rightarrow MnO_2+2NaClO_2+2H_2O+4CO_2$	2.46	Reaction is slow at neural pH, speeds up as pH increases
Ozone	$Mn(HCO_3)_2 + O_3 + 2H_2O \rightarrow MnO_2 + 2CO_2 + 3H_2O$	0.88	Reaction is very rapid

Potassium permanganate ($KMnO_4$) is strong oxidant that does not generate any toxic byproducts. Potassium permanganate is a dry chemical and a solution is created by adding the chemical directly to the water. Typically it is added to the raw water intake. This process does not require any special mixing equipment. The retention time needed for complete oxidation is between 5 and 10 minutes if the pH is over 7.0. The oxidized forms of iron and manganese precipitate as ferric hydroxide and manganese hydroxide respectively, as shown Tables 2-2 and 2-3. Once the precipitates are formed, they can be filtered out (U.S. EPA, 2010).

Iron and manganese in water can be oxidized by chlorine. Chlorine converts iron and manganese to ferric hydroxide and manganese dioxide which can then be removed by filtration. The ideal pH conditions for chlorine to oxidize iron and manganese are 7 and 9.5, respectively. Chlorination is not the best method for manganese control because of the high pH required. The contact time and rate of chlorine addition can be determined by a jar test. If there is a high concentration of organic material, chlorine has the potential to produce byproducts, such as trihalomethanes (U.S. EPA, 2010).

Chlorine dioxide (ClO_2) can be used as an oxidant for treating high levels of iron and manganese. Chlorine dioxide reacts quickly with the soluble forms of iron and manganese when the pH is above 7.0, forming precipitates that can be removed by sedimentation and filtration (U.S. EPA, 2010). Iron (III) precipitates in the form of iron hydroxide, as shown in Table 2-2. For pH conditions above 5, 1.21 mg/L of chlorine dioxide is needed to oxidize each 1.0 mg/L of iron (U.S. EPA, 2010).When chlorine dioxide reacts with manganese, manganese dioxide is formed. This process is most effective when the pH is above 7. For a pH above 7, 2.46 mg/L of chlorine dioxide is needed to oxidize each 1.0 mg/L of manganese (U.S. EPA, 2010).

Ozone (O_3), also known as “activated oxygen”, is a powerful oxidant. An ozone generator is used to make ozone on-site, which is then fed by pump or by an air injector into the water. Ozone oxidizes iron (II) to iron (III) which hydrolyzes to form insoluble iron (III) hydroxide. The oxidation reaction requires 0.43 mg of ozone per mg of iron (II) and the pH needs to be in the range of 6 to 9. Ozone oxidizes manganese (II) to insoluble manganese (IV) dioxide, requiring 0.88 mg of ozone per mg of manganese (II). Excess ozone beyond this ratio will form permanganate. The permanganate can be reduced back to manganese (IV) dioxide if there is organic material that is easily oxidized in the water and enough contact time. Manganese oxidation is most effective around a pH of 8 (AWWARF, 2006). One of the drawbacks to using ozone is that if more than 100 mg/L of bromide ion is present, the formation of bromate is possible. This can be a serious issue, particularly to childbearing women and children, as bromate is a suspected carcinogen and has been known to cause gastrointestinal issues when ingested (New York State Department of Health, 2006).

2.3.3 Precipitation with a Base

Adding lime, caustic, or soda ash removes iron and manganese in surface waters by raising the pH, which causes precipitation of the metals. The recommended pH for effective iron removal is 7.5 (Faust et al., 1998). The recommend pH for manganese removal is higher. Precipitation is most efficient when the ratio between iron and manganese is two to one (or greater) and lime ($Ca(OH)_2$) is considered to be the most effective reactant. This is because iron reacts rapidly with lime, and manganese gets "dragged" into the precipitate (Lovett, 2010).

2.3.4 Aeration-Filtration

Aeration-filtration treatment is a two or three step process within the water treatment plant is to oxidize the metals and precipitate them. First, the water is aerated to oxidize the metals. This is typically done using a physical process such as using trays and vertical risers. Because manganese is not as easily oxidized as iron, aeration by itself is not an effective means of removal for both metals. Chemical agents, such as lime or soda ash, are introduced the water to increase the pH to a level where manganese will precipitate. This process, combined with the use of coke beds coated in oxides used during aeration, will successfully oxidize the manganese. Once the metals are oxidized and have formed precipitates, they are removed using sedimentation and filtration (Viessman et al., 2009).

2.3.5 Greensand Filtration

Greensand filtration is a filtration process that combines oxidation and removal of precipitates. Oxides located on the surface of the filter media oxidize the metals, rendering them insoluble such that they can be captured in the filter. Pre-oxidation may be required in the presence of high iron and manganese. This process is conducted in a pressure filter where permanganate is added either continuously or periodically to seize the oxidized iron and manganese. Permanganate is also useful in regenerating the greensand. Since greensand is often used as the second part of a dual media filtration system, it is important to have a top layer of media effective in removing most of the particles before reaching the greensand. Anthracite is commonly used as the top layer in this process (Viessman et al., 2009).

2.4 Case Study: Cambridge, MA

In the summer of 1998, the Cambridge Water Department in MA began a 14-month sampling period on the three reservoirs that are used as source waters for the water treatment facility serving Cambridge, Massachusetts. These reservoirs are Hobbs Brook and Stony Brook, which are both fed by basins from surrounding cities and towns, and Fresh Pond, a kettle-hole lake. The major contaminants of concern within these water bodies included elevated levels of dissolved iron, manganese, organic carbon, and sodium (Waldron et al., 2001). Eutrophication, a decrease in dissolved oxygen as a direct result of increased organic matter in a water body (USGS, 2010), was believed to be a key factor in these elevated levels. Sampling events were designed to develop a basic model of the health of the water bodies, using physical, chemical, and biological parameters, within the 14-month period (Waldron et al., 2001).

The methods for data collection were standardized for the three reservoirs and included sampling at the deepest point of each of the water bodies as well as additional points in the Hobbs Brook Reservoir. Sampling events ranged from 4 week to 13 week intervals and occurred from September 1997 until November 1998. The samples were taken at different depths: every meter for Hobbs and Stony Brook Reservoirs and every two meters for Fresh Pond. These samples were preserved using coolers and ice and were tested in a laboratory setting for dissolved manganese, iron, organic carbon, phosphorous, nitrogen, and trihalomethane formation potential. Parameters measured on-site included dissolved oxygen, temperature, pH, and specific conductivity (Waldron, 2001).

The results for all three reservoirs varied by season. Dissolved oxygen was either fully depleted or reduced during the warmer months. This resulted in elevated levels of nitrogen, dissolved organic carbon, phosphorous, and manganese. The reduction of dissolved oxygen is believed to be related to the decrease of temperature with depth, or stratification, which occurred during the summer months. Both Hobbs and Stony Brook Reservoirs were anoxic by the late summer months, yielding levels of dissolved manganese as high as 6.27 mg/L at the bottom of Stony Brook Reservoir. Although Fresh Pond did not have fully depleted dissolved oxygen at the bottom, the water was still hypoxic, causing dissolved manganese levels to spike up to 12.7 mg/L in August 1998. This relationship between dissolved manganese levels in anoxic and hypoxic waters may infer “that manganese is released under hypoxic conditions from various points in the sediments” (Waldron et al., 2001). It is likely that manganese was reduced under these conditions (Waldron et al., 2001).

Aeration was successfully implemented in Fresh Pond (as well as Stony Brook Reservoir) to improve water quality. An aeration system was put into place to increase dissolved oxygen and destratify the water, consequently decreasing the manganese and iron levels. It was run during the elevated manganese and iron period that spanned from May until September. This system was effective: while in operation, dissolved oxygen levels did not drop below 3.2 mg/L and manganese levels did not exceed the EPA standard of 0.05 mg/L. In contrast, when the system was shut down temporarily, the dissolved oxygen levels dropped below 1 mg/L and manganese levels rose to a high of 2 mg/L (Mattson et al., 2004).

3 Methodology

The goal of this project was to quantify the iron and manganese concentrations in Orrs Pond, the primary source water for Attleboro, MA, and design a control strategy for these contaminants. As described in this chapter, the project team developed a sampling plan and measured relevant water quality parameters in the field and laboratory. Then, the team evaluated options for controlling iron and manganese, designed a treatment system, and laboratory tested the recommended treatment option.

3.1 Orrs Pond Water Sampling

The project team developed a sampling plan to collect water from Orrs Pond and measure various water quality parameters. There were nine sample events throughout the duration of the project, eight occurring every two weeks from August 3, 2010 until November 1, 2010, and one on December 3, 2010.

3.1.1 Sampling Location

All samples were collected at the approximate location of the raw water intake in Orrs Pond in order to obtain samples with similar characteristics to the water that enters the treatment facility. On the first sampling date, August 3, 2010, the intake location was found using a method predetermined by the water treatment facility staff. Two project team members used a row boat to paddle to the middle of the pond, guided by a premeasured string. The string was 225 ft in length, the distance from the shore to the intake. Using a TomTom xl n14644 handheld global positioning system (GPS), the coordinates of the approximate location of the raw water intake were recorded as 41°55.651’N, 71°20.107’W. On all subsequent sampling dates, the project team used the GPS to navigate to this location to ensure consistent positioning.

3.1.2 Sampling Technique

Water samples were collected in Orrs Pond to quantify iron and manganese concentrations as well as the general quality of the water body. The project team sampled at six different depths, from the surface to 25 feet deep at 5 foot intervals. The approximate depth of the raw water intake is 25 ft and the total depth of the pond is approximately 32 ft. On two occasions, intake samples were collected from inside of the raw water intake.

The surface sample was collected by submerging the sample bottles in the water, 25 ft above the approximate location of the raw water intake. In order to collect water below the surface, a depth sampler was used. No depth sampler was used on the first sample event. The second through fifth sampling events utilized the depth sampler shown in Figure 3-1. This depth sampler worked by securing the two hinged sidewalls open and submerging the depth sampler to the desired collection depth, where it filled with water at that depth. Then, a weight was dropped onto the sampler that triggered the sampler to close, and the full depth sampler was raised out of the water.

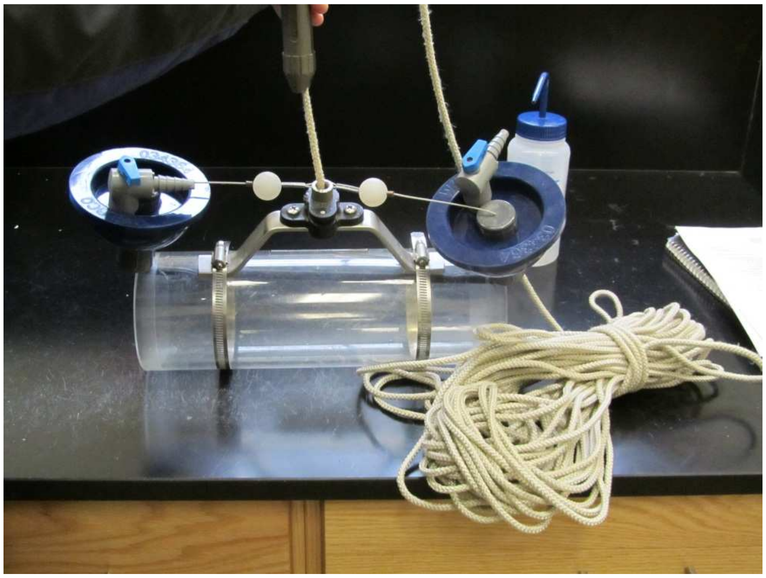

Figure 3-1: WPI Depth Sampler

The sixth through twelfth events utilized the depth sampler shown in Figure 3-2. This depth sampler worked by placing the rubber stopper into the sampler opening, and submerging the sampler to the desired collection depth. Once at the correct depth, the rubber stopper was removed from the opening of the sampler by tugging upward. This allowed the sampler to fill, and it was then pulled out of the water.

Figure 3-2: Attleboro Depth Sampler

Once the sample was collected, it was dispensed into four containers: (1) a 1 liter (L) screw cap plastic sample bottle, (2) two 40 milliliter (mL) organic-free amber glass vials with Teflon lined septa and screw caps, and (3) a 500 mL plastic beaker. Each sample was given a unique sample identification number which was labeled on the corresponding containers. The sample in the beaker was used for field testing (see Section 3.2.1) and then discarded. The sample bottles and vials were put into a cooler with ice packs until they were brought to the WPI laboratory and stored in the refrigerator until all laboratory tests were complete.

3.2 Water Testing Methods

All of the samples from Orrs Pond were analyzed for water quality. The tests were divided into two categories, field and laboratory testing. Dissolved oxygen and temperature were measured in the field. pH, turbidity, TOC, DOC, iron, and manganese were measured in a laboratory. All of the results were recorded and added to a Microsoft Excel spreadsheet.

3.2.1 Field Testing: Dissolved Oxygen and Temperature

Dissolved oxygen and temperature were measured on the row boat on Orrs Pond immediately after each sample was collected. To measure the dissolved oxygen and temperature, a YSI85 Dissolved Oxygen and Conductivity Meter, manufactured by YSI Incorporated located in Yellow Springs, Ohio, was used. The meter was calibrated by soaking a small sponge with reagent grade water and placing it into the calibration storage chamber. The meter was turned on and the MODE button pressed until dissolved oxygen was displayed on the screen. Approximately fifteen minutes was allowed for the DO and temperature readings to stabilize. After the readings stabilized, the calibration was completed by pressing the upward and downward arrows simultaneously and then entering an elevation input of 200 feet into the device. To measure DO and temperature, the probe was inserted into the plastic beaker containing the sample, and continuously stirred. Once the measured values stabilized, the dissolved oxygen and temperature were recorded in a field notebook.

3.2.2 Laboratory Testing

Laboratory testing was conducted at the Worcester Polytechnic Institute Environmental Engineering Laboratory located in Kaven Hall. Samples were stored in a 4°C refrigerator and analyzed within one week after the samples were collected. pH and turbidity were analyzed on the same day as sample collection.

3.2.2.1 pH

pH was measured with an Accumet Basic AB15 pH Meter, manufactured by Fisher Scientific located in Pittsburgh, Pennsylvania. First, the meter was calibrated. The calibration was performed using the following steps:

1. Turn on the meter
2. Press the standardize button
3. Clean the probe with Epure water
4. Immerse the probe into a buffer with a pH of 4 until the meter indicated that the value was stabilized
5. Press “standardize” to set the pH 4 value, and
6. Repeat steps 3-5 twice, once with the pH 7 buffer and once with the pH 10 buffer.

After the calibration, the pH was measured by rinsing the probe with Epure water and inserting the probe into each individual sample bottle until the meter indicated the reading was stable. The results were then recorded into a laboratory notebook.

3.2.2.2 Turbidity

The turbidity was measured in the laboratory by using a 2100N HACH Turbidimeter, manufactured by Hach, located in Loveland, Colorado. The 1L plastic bottle containing the water sample was inverted several times to mix the sample. A portion of the sample was then poured into a turbidity vial until the sample water reached the line on the vial. The turbidity vial was capped and inverted two times. The outside of the vial was rinsed with Epure water and wiped with a Kimwipe. The vial was then placed in the turbidimeter. The average turbidity was recorded after ten seconds. The vial was then cleaned by rinsing three times with Epure water and dried with Kimwipes. The turbidity vial was then refilled and the turbidity was measured again for the same sample. The average of the two turbidity readings was recorded in the laboratory notebook. This procedure was repeated for all of the water samples.

3.2.2.3 Organic Carbon

Total and dissolved organic carbon were measured on a Shimadzu TOC-5000A, manufactured by Shimadzu located in Columbia, Maryland. The Shimadzu TOC-5000A is calibrated using standards developed from a stock standard of 1,000 mg/L potassium hydrogen phthatlate. Using the stock standard, an intermediate standard of 100 mg/L TOC was created which was used to create the three working standards of 0 mg/L, 5 mg/L, and 10 mg/L for the calibration. These standards were created by adding 100 μL of 6 N HCl to a 100 mL volumetric flask, adding the desired level of TOC to the flask, and filling the flask with Epure water until the volume is 100 mL. For example, the 10 mg/L standard was created by adding 10 mL of the intermediate stock. The working standards were then transferred from the volumetric flasks into Shimadz TOC vials and sealed with parafilm. The working standards were placed in order of increasing concentration into the "S" slots in the autosampler tray and the prepared TOC and DOC samples were placed in slots 1-16, with the placement of samples recorded on a sheet of paper. Before running the analysis, the TOC analyzer was turned on and warmed up for approximately one hour until all status indicators read "OK". The calibration information, sample group numbers, and type of analysis are then input into the instrument and the start button is pressed. After the instrument analysis, the printed results, provided by a graduate student, were stored in the laboratory notebook.

One of the samples collected in a 40 mL glass vial was used for TOC analysis. Upon arrival at the laboratory, the sample was preserved using 40 microliters (µL) of 6N hydrochloric acid (HCl). This acidified sample was then stored in the refrigerator for up to one week prior to analysis. For analysis, each sample was poured into a Shimadz TOC vial. The vials were then sealed with parafilm, and capped.

The DOC was measured in a similar manner as TOC except that the samples were filtered. The samples were filtered utilizing the following procedure:

1. Unscrew the filter holder of a 50 mL syringe,
2. Use tweezers to place a Whatman GF/C glass fiber filter on the holder,
3. Dampen the filter with Epure water,
4. Screw the filter holder back onto the syringe,
5. Fill the syringe with 30 mL of Epure water,
6. Filter the contents of the syringe into the sink,
7. Fill the syringe with the contents of the 40 mL acid washed sample vial dedicated to the DOC test, and
8. Filter the contents of the syringe into a 40 mL acid washed vial.

The procedures to preserve the sample, calibrate the Shimadzu TOC-5000A, and record the results, as described for TOC were then followed.

3.2.2.4 Total and Dissolved Iron and Manganese

Total concentrations of iron and manganese were measured in the laboratory using a Perkin Elmer AAnalyst 300 Atomic Spectrometer, manufactured by Perkin Elmer located in Waltham, Massachusetts. Assistance was provided by Don Pellegrino, the WPI Civil Engineering laboratory manager. Using the samples obtained in the 1 L plastic bottles, the following steps were performed to prepare each sample for measurement:

1. Mix the bottle by inverting it several times
2. Pour 25 mL of the mixed sample into a 100 mL glass beaker
3. Add 10 mL of 70% nitric acid to the glass beaker with the sample under a fume hood
4. Place the sample on a hot plate with a watch cover on top of each beaker
5. Digest the samples on the hot plate on low heat overnight
6. Remove the samples from the hot plate and add Epure water to each sample until the volume reaches 25 mL
7. Transfer the digested sample into a 50 mL plastic centrifuge tube

Dissolved iron and manganese samples were prepared using disposable 20 mL syringe driven filter units with a filter pore size of 45 µm. The syringe was filled and then flushed with sample water before drawing 20 mL of water from the plastic sample bottle. The filter was then attached by screwing the filter onto the tip of the syringe. The full syringe was then expelled into a 50 mL centrifuge tube. These samples were not digested and measurements were taken immediately after preparation.

The procedure the laboratory manager followed to calibrate the instrument and measure the total and dissolved iron and manganese included:

1. Ignite the flame that corresponds with the metal to be measured

2. Enter the values of the standards (0.1, 0.5, 1, 3, 10 mg/L) used to calibrate the instrument into the computer
3. Insert the capillary tube into each standard until the flame changes color and the reading is measured
4. Enter the sample ID numbers into the computer
5. Insert the capillary tube into the first prepared sample until the flame changes color and the reading is measured
6. Repeat step 5 until all samples have been measured
7. Print the results.

In some instances, the concentration of a metal exceeded the highest standard used to calibrate the spectrometer flame. This was resolved by diluting the sample with 50% Epure water, then doubling the measurement indicated by the spectrometer. The printed results were stored in a laboratory notebook.

3.3 Determining Design Options

A criteria matrix was developed to determine the most applicable iron and manganese treatment options for the Russell F. Tenant Water Treatment Facility. First, potential source water and treatment facility alternatives were identified based on background research. Then, criteria for evaluating each alternative were developed. The criteria included viability, environmental impact, long term applicability, byproducts formation, user friendliness, and effectiveness, as described below.

- Viability: the cohesiveness with the current treatment process with regard to ease of construction and implementation.
- Environmental impact: the degree to which the treatment alternative has a negative effect on the environment.

- Long term applicability: how well the treatment alternative is projected to work in five years.
- Byproducts formation: the likelihood of forming harmful byproducts from the treatment alternative.
- User friendliness: the ease of use and safety of the treatment alternative.
- Effectiveness: how effective the alternative is in reducing manganese concentrations.

A numerical value of 1-5, with 1 being the lowest rating and 5 being the highest, was assigned to each treatment alternative for each of the criteria. These ratings were determined based on research on each alternative and were agreed upon by all team members. Two options with the highest total rating were selected for preliminary designs.

After completion of the preliminary designs, a qualitative comparative analysis between the two selected treatment options was performed. The criteria investigated were cost and cohesiveness with the current treatment process. The estimated cost was determined by contacting Peter Vendzules of Hungerford and Terry, Rick Wells of Carus Corporation, and Ron Mastrogiacomo, a cost estimator from AECOM Water. Using the preliminary design figures, the peak monthly cost was estimated for each design. Cohesiveness with the current treatment processes was determined based on the amount of new construction and equipment required to implement the design. The design that ranked highest based on these parameters was the recommended alternative, and a detailed design was completed for this alternative.

3.4 Personal Communications

Iron and manganese treatment experts, potassium permanganate and greensand manufacturers, engineering consultants, and town and water treatment facility staff were contacted to assist with the design portion of the project. Table 3-1 summarizes the personal communications utilized in the project.

Table 3-1: Summary of Personal Communications

Contact Person	Title	Company	Location	Contact Method	Reason for contact
Aaron Ambler	Superintendent	City of Marshall	Marshall, MI	Email	Operational experience with green sand filtration
Andy Reid	Project Engineer	AECOM Water	Concord, MA	Phone	Design experience with iron and manganese treatment
Jeff Burkle	Sales Representative	Pristine Water Solutions	Waukegan, IL	Phone	Chemical sales representative
Peter Vendzules	Sales Representative	Hungerford and Terry, Inc	Clayton, NJ	Phone	Cost estimation of manganese greensand
Rick Wells	Sales Representative	Carus Corporation	Peru, IL	Phone	Cost estimation of permanganate products
Stephen Cronin	WTP Manager	Town of Westford	Westford, MA	Email	Operational experience with greensand filtration
David Rindal	Community Water Systems	Minnesota Department of Health	Lakeville, MN	Email	Operational experience with greensand filtration
Paul Roy	WTP Operations Supervisor	Town of Exeter	Exeter, NH	Phone	Operational experience with chemical oxidation
Kourtney Wunschel	Assistant Superintendent	City of Attleboro	Attleboro, MA	Email/Phone	General assistance for sampling and treatment design
Christine Milhouse	Superintendent	City of Attleboro	Attleboro, MA	Email/Phone	General assistance for sampling and treatment design
Ron Mastrogiacomo	Head of Cost Estimation	AECOM Water	Wakefield, MA	Email	Cost estimation of chemical feed and storage tank

3.5 Laboratory Testing of the Potassium Permanganate Oxidation Design

Chemical oxidation with potassium permanganate was tested in the laboratory to verify its effectiveness in oxidizing manganese and examine the impact of water quality on dosing. Five liters of water was collected from the intake of the Russell F. Tenant Water Treatment Facility on January 20, 2010. The water was brought to the WPI Environmental Engineering Laboratory and stored at 4°C. Total and dissolved iron, manganese, and organic carbon were measured using the methods described in section 3.2.2. Using the results from these tests, a spreadsheet was made in Microsoft Excel to demonstrate the relationship between the water conditions on January 20, 2010 and the desired water conditions for the laboratory testing.

The collected water had the following characteristics: 0.42 mg/L Mn, 0.21 mg/L Fe, and 3.04 mg/L DOC. The desired conditions for the testing were 3 mg/L Mn and DOC values of 3.04, 5, and 7 mg/L. The manganese concentration of 3 mg/L was preselected based on historical data to create the conditions that would require the highest dose. The dissolved iron concentration was not raised in the laboratory tests because iron is naturally insoluble in water, as supported in our sampling results, and is not a significant treatment concern. In order evaluate how organic carbon impacts the reaction between potassium permanganate and manganese, three DOC concentrations were tested. The values included: 3.04 mg/L (the observed DOC in the intake water), 5 mg/L (the intermediate concentration), and 7 mg/L (the highest observed TOC value historically).

The water conditions were obtained by adding manganese and/or organic carbon to samples of the water, as detailed in Section 3.5.1 and 3.5.2. Due to a laboratory error, each sample had 1.51 mg/L of manganese instead of the desired 3 mg/L. The organic carbon values that were achieved were 3.04, 5.60 and 5.94 mg/L. In total, twelve samples were created, nine demonstrating unique scenarios with permanganate dosing and organic carbon content, and three samples that were not treated but used to verify water quality conditions. Table 3-2 summarizes the testing conditions.

Table 3-2: Laboratory Testing for Potassium Permanganate Design

Test #	Total Manganese (mg/L)	Total Iron (mg/L)	Dissolved Organic Carbon (mg/L)	Potassium Permanganate Dose (mg/L)
1	1.51	0.21	3.04	5.83
2	1.51	0.21	5.00	2.92
3	1.51	0.21	7.00	11.67
4	1.51	0.21	5.00	5.83
5	1.51	0.21	7.00	2.92
6	1.51	0.21	3.04	11.67
7	1.51	0.21	7.00	5.83
8	1.51	0.21	3.04	2.92
9	1.51	0.078	5.00	11.67

The potassium permanganate dosing was determined based on concentrations of 0.078 mg/L dissolved iron and 3 mg/L manganese. The iron level is the concentration that was measured when the water was tested on January 20. The water was retested on January 26 when the experiment was performed, and measured 0.21 mg/L. It is not known why there was a discrepancy in the measurements. Three different doses of permanganate were used in the laboratory: 5.83 mg/L (the theoretical dose required to oxidize the iron and manganese), 2.92 mg/L (half the theoretical dose), and 11.67 (double the theoretical dose). The experiments were set up in a factorial design.

Accounting for the laboratory errors, the dosing values were recalculated to determine the percentage of the theoretical dosing that was used. These results are shown in Table 3-3. Therefore, doses from 94% to 376% were tested.

Table 3-3: Comparison of Theoretical and Actual Stoichiometric Dosing

Actual Mn (mg/L)	Actual Fe (mg/L)	KMnO4 Dose (mg/L)		% of theoretical KMnO4 dose	
		Applied*	Theoretical+	Intended	Actual
1.51	0.21	5.83	3.10	100	188
1.51	0.21	2.93	3.10	50	94
1.51	0.21	11.67	3.10	200	376

*Based on desired Mn concentration of 3 mg/L and iron concentration of 0.078 mg/L
+Based on actual Mn concentration of 1.51 mg/L and iron concentration of 0.21 mg/L as measured in experiments

3.5.1 Adjusting Manganese Concentration

The total manganese concentration in the intake water was low (0.72 mg/L) because the sample was collected in January. To achieve a higher level (reflective of high summertime conditions), manganese sulfate was added to the water. The required additional manganese was calculated by subtracting the observed average dissolved concentration from the intake from the desired 3 mg/L. Using the molar relationship between manganese and manganese sulfate, the amount of manganese sulfate required to reach the desired manganese concentration was calculated (see Appendix E).

3.5.2 Adjusting Organic Carbon Concentration

Humic acid manufactured by ICN Biomedicals, Inc. in Aurora, OH was used to adjust the organic carbon concentration in the test waters. The organic carbon concentration in humic acid was unknown therefore a solution was developed by measuring 50 mg of humic acid and adding it to 500 mL of Epure water. A weighing boat was placed on the analytical balance and tared. Then humic acid was added to the boat using a spatula until the scale read 0.05 grams. The measured amount of humic acid was transferred into a 500 mL beaker. Epure water, measured in a 500 mL volumetric flask, was used to clean any residual humic acid out of the tray and added to the beaker. The remaining amount of the 500 mL of Epure water was then slowly added to the beaker. The dissolved and total organic carbon in the solution were measured in duplicate to the methods described in Section 3.2.2.

Using the results of the DOC and TOC for the humic acid solution, the percentage of organic carbon in the humic acid was determined to be approximately 33%. The additional amounts of organic carbon required for the oxidation experiments were calculated by subtracting the observed DOC in the intake sample from the desired level. Using these values, the amounts of humic acid required to achieve the desired levels of organic carbon for the tests were calculated.

3.5.3 Stock Solutions

Stock solutions for potassium permanganate, manganese sulfate, and medium and high concentrations of humic acid were developed. Each stock solution was developed using the same methodology. Equation 3-1 was used to determine the concentration of the stock solution.

$$C_{stock}*V_{stock}=C_{experiment}*V_{experiment} \qquad \text{Equation 3-1}$$

$C_{experiment}$ = Concentration in experimental water
C_{stock} = Stock concentration of chemical
$V_{experiment}$ = Volume of experimental water
V_{stock} = Stock solution volume

The experiments were all conducted using a 200 mL volume ($V_{experiment}$ = 200 mL). For the dosing of each stock solution, with the exception of potassium permanganate, a 1 mL volume of stock solution (V_{stock}) was selected as a convenient volume that could be transferred with a mircopipet. Depending on the desired concentration of potassium permanganate, the volume of the stock solution was selected as 0.5 mL, 1 mL, or 2 mL.

Then, the required C_{stock} was calculated. Equation 3-2 shows a sample calculation for potassium permanganate for the 5.38 mg/L dose:

$$(C_{stock\text{-}KMnO4})*(1\text{ mL}) = (5.83\text{ mg/L})*(200\text{ mL}) \qquad \text{Equation 3-2}$$

$$C_{stock\text{-}KMnO4} = 1.17\text{ g/L}$$

Detailed calculations for the development of all stock solutions can be found in Appendix E.

After the stock concentrations were determined, the required amount of the chemical to make a 100 mL stock solution was calculated. This weight was measured on an analytical balance and transferred into a 250 mL jar. 100 mL of Epure water was measured in a 100 mL volumetric flask and poured into the jar with the measured chemical. A stir bar was then placed in the jar and the jar was placed on a stir plate and mixed at medium speed for five minutes. The jar was then removed from the stir plate, the stir bar was removed from the jar using tweezers, and the jar was capped.

3.5.4 Testing Procedures

Each sample was run in numerical order starting with the first and ending with the ninth. Samples 10-12 were prepared to represent the desired starting organic carbon and manganese levels and did not receive oxidation treatment. Using the water collected from the intake, 200 mL of water was measured in a volumetric flask and then poured into a 250 mL beaker. In all samples, 1 mL of the manganese sulfate stock was added to the beaker to increase the manganese concentration. Depending on the required level of organic carbon for each test, no stock solution or 1 mL of either the medium or high concentration humic acid stock solution was added to the beaker. A stir bar was then placed in the beaker and the beaker was placed on a stir plate where it was mixed on slow. The potassium permanganate stock solution was then added to correspond with the three doses. The solution was allowed to react for 10 minutes. The reacted sample was then taken off of the stir plate and the stir bar was removed from the beaker with tweezers. The sample was transferred from the beaker into a 250 mL jar and the cap was screwed on. Each jar was labeled with the corresponding test number. Following the reaction, pH was tested and the DOC and TOC samples were prepared. Samples were then stored at 4°C. Total and dissolved iron and manganese and TOC and DOC tests were run 6 days after the testing event. These tests were run using the methods outlined in section 3.2.2.

4 Results and Analysis

This chapter summarizes water quality sampling results from Orrs Pond, the source water for the Russell F. Tenant Water Treatment Facility in Attleboro, MA, which has experienced problems with elevated manganese in the summer months. Next, a quantitative and qualitative assessment of nine different treatment options to control manganese is provided. A preliminary design is presented for greensand filtration. Based on cost and the effective implementation at surface water treatment facilities, chemical oxidation using potassium permanganate is the recommended treatment method and a detailed design is provided.

4.1 Orrs Pond Sampling Data

Water quality was analyzed using the methodologies described in Chapter 3. Samples were collected at 5 foot intervals from the surface to 25 feet deep in Orrs Pond at the approximate location of the raw water intake for the treatment facility. Sampling events occurred from August 3, 2010 to December 3, 2010 at approximately 2 week intervals. The full results for all sampling events are presented in Appendix C. Notable results are presented and discussed in the following sections.

4.1.1 Overall Water Quality

A summary of the results for all tested parameters at the 25 foot depth at the approximate location of the raw water intake is shown in Table 4-1.

Table 4-1: Summary of Results at 25 foot Depth at Orrs Pond Intake Location

Parameter	Value or Concentration		
	Minimum (Date)	Average	Maximum (Date)
Temperature (°C)	5.40 (12/3)	16.0	23.6 (9/9)
pH	5.98 (10/7)	6.40	7.33 (11/1)
Turbidity (ntu)	11.4 (10/19)	36.8	86.7 (9/23)
Dissolved Oxygen (mg/L)	0.45 (8/30)	5.30	12.0 (12/3)
Total Iron (mg/L)	2.30 (12/3)	1.50	42.8 (9/23)
Dissolved Iron (mg/L)	0.13 (12/3)	14.1	3.55 (9/9)
Total Manganese (mg/L)	0.29 (12/3)	4.90	17.5 (9/23)
Dissolved Manganese (mg/L)	0.14 (12/3)	6.10	13.1 (9/23)
Total Organic Carbon (mg/L)	4.23 (12/3)	13.1	31.8 (9/23)
Dissolved Organic Carbon (mg/L)	3.24 (12/3)	9.10	26.5 (9/23)

The table indicates seasonal variations for all of the parameters observed except for pH, which showed no relationship with time. The September 23, 2010 sampling event yielded the maximum values for six of the nine parameters: turbidity, total iron, total and dissolved manganese and both measures of organic carbon. These high concentrations are due in part to the water treatment facility switching from drawing water from Manchester Reservoir where they draw water from during the summer months to Orrs Pond on September 8, 2010. The samples taken prior to these date indicate the health of the water quality in Orrs Pond when it is not used as a water source. The initial draw of the water in Orrs Pond caused mixing that stirred up the sediments at the bottom of the water body. Since sediments often have traces of metals and organics, these high concentrations were expected during the September 2010 sampling events.

On two occasions, October 19, 2010 and December 3, 2010, an intake sample was collected in addition to the pond samples. These samples were collected, prepared, and analyzed using the same methodologies as the pond samples and were used to compare the conditions of the pond at the approximate location of the raw water intake and the water in the intake. Table 4-2 summarizes a comparison of the 25 ft sample and intake sample for relevant water quality parameters.

Table 4-2: Comparison of 25 ft Sample to Raw Water Intake

Date	Turbidity (ntu)		Dissolved Fe (mg/L)		Dissolved Mn (mg/L)		Dissolved Organic Carbon (mg/L)	
	25 ft Depth	Intake	25 ft Depth	Intake	25 ft Depth	Intake	25 ft Depth	Intake
10/19/2010	11.4	2.20	0.25	0.18	0.14	0.18	3.35	3.36
12/3/2010	22.7	9.76	0.13	0.06	0.14	0.11	3.24	3.04

With the exception of dissolved manganese on October 19, the 25 ft depth samples had higher concentrations for all water quality parameters than the intake samples. It is likely that the water quality changes from the pond to the intake. However, the data is inconclusive due to the low number of samples. Additionally, the levels of iron, manganese, and organic carbon had already dropped from the seasonal peak in September. Differences between the pond and intake samples may be greater during the summer months due to the higher concentrations of iron, manganese, organic carbon, and turbidity.

4.1.2 Dissolved Oxygen

Field measurements of dissolved oxygen were taken at depths of 0 to 25 feet. Results from five of the sampling events are shown in Figure 4-1. The dissolved oxygen measurements show an increase from late summer through late fall. The lowest DO concentration at a 25 foot depth was 0.45 mg/L on August 30 and the highest was 12.0 mg/L on December 3. This trend is commonly found in surface waters in temperate climates. Dissolved oxygen content is directly related to temperature, with colder water able to hold more oxygen than warmer water. Consequently, as the water temperature decreases due to lower sun exposure and air temperatures, the water body becomes more oxygen rich (City of Manchester, 2011). However, the August 30, 2010 reading may be erroneous due to incorrect use of the YSI field meter which may have resulted in lower readings for the DO. The project team was retrained in use of the field meter prior to the subsequent sampling events.

The dissolved oxygen levels for all sample events except the December 3, 2010 sample event show a trend of decreasing concentration with depth. For example, on September 23, the surface concentration of DO was 6.30 mg/L and the 25 ft concentration was 2.75 mg/L. This is due to the consumption of oxygen at the bottom of the pond by biological processes and the lack of reaeration due to stratification (City of Manchester, 2011).

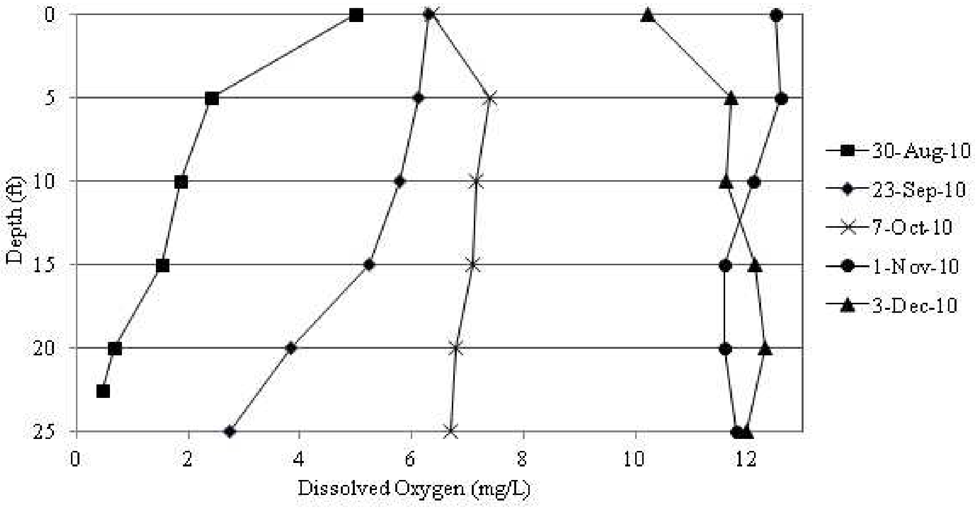

Figure 4-1: Dissolved Oxygen vs. Depth of Reading

4.1.3 Organic Carbon

Organic carbon is naturally occurring in water bodies and needs to be taken into consideration when determining different manganese treatment options. This is especially true with oxidation, since organic carbon will readily react with certain oxidants, causing the required dose to be greater than theoretical. Figure 4-2 shows a comparison between total and dissolved organic carbon at a depth of 25 ft for each sampling event. The figure indicates the majority of the organic carbon was in the dissolved phase, with DOC representing 48 to 110 % of the total organic carbon. The 110% is due to instrument error, as DOC cannot exceed TOC. Levels peaked at 31.82 mg/L and 26.50 mg/L for TOC and DOC, respectively.

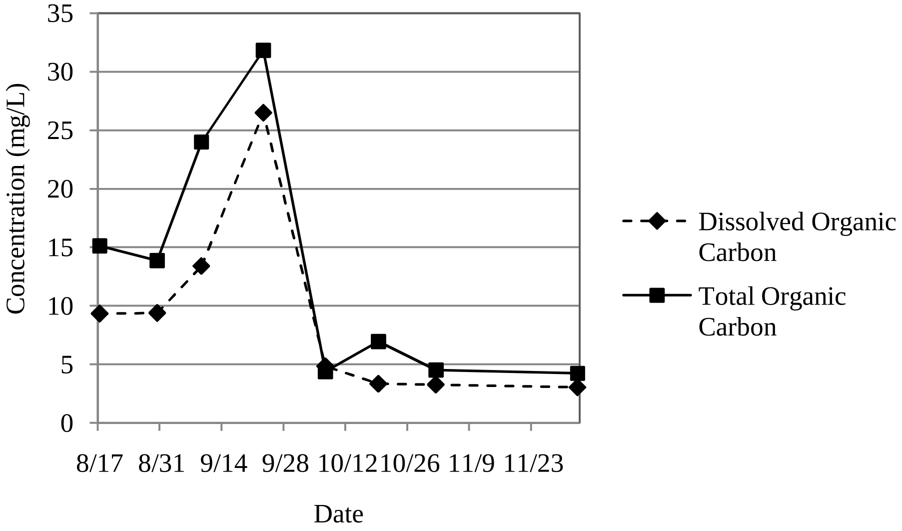

Figure 4-2: Dissolved Organic Carbon vs. Time

4.1.4 Iron

Figure 4-4 shows total and dissolved iron for the maximum depth for each sampling event. This figure demonstrates a large difference between the amount of total and dissolved iron in the samples for August and September, with dissolved iron levels less than 5 mg/L for all sampling events and total iron levels peaking at 43 mg/L on September 23. This indicates that the majority of the iron measured in Orrs Pond is insoluble, which is consistent with the natural insolubility of iron in water. Insoluble iron is advantageous when looking into treatment design options because it can be treated conventionally with sedimentation and filtration. Dissolved iron may cause problems with chemical dosing when trying to treat manganese because iron is more easily oxidized than manganese. The dissolved levels need to be taken into account when calculating chemical dosing for oxidation.

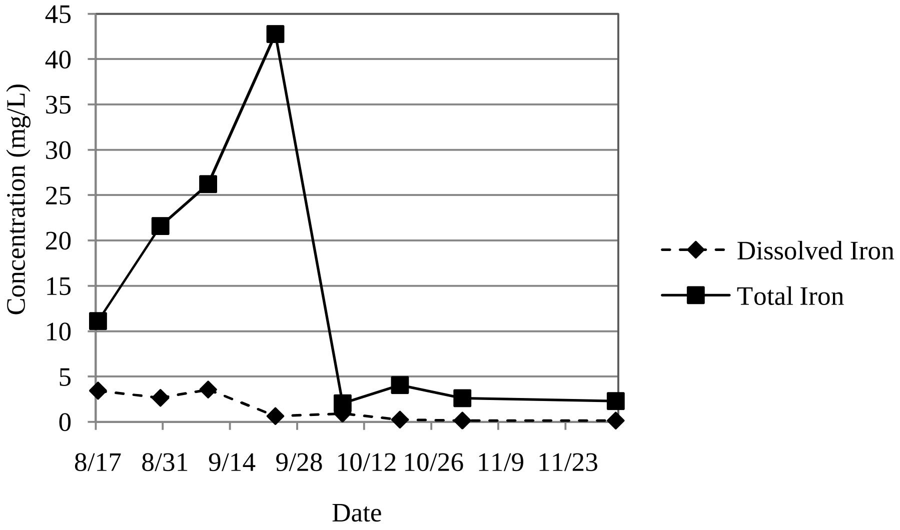

Figure 4-3: Iron Concentrations in Orrs Pond at 25 foot Depth

4.1.5 Manganese

Total and dissolved manganese concentrations at a depth of 25 feet taken at the approximate location of the raw water intake are shown in Figure 4-4. Unlike iron, there is not a significant difference between measured total and dissolved manganese. This indicates that the majority of the manganese measured in Orrs Pond is in soluble form, which is typical of manganese at a neutral pH in water. The peak total and dissolved manganese levels, both observed on September 23, are 17.5 mg/L and 13.1 mg/L, respectively. These values also represent the largest difference between total and dissolved manganese concentrations. The graph indicates seasonal variance, with the four highest values occurring during the summer and early fall. Dissolved manganese is more difficult to treat than insoluble manganese, and also more difficult to remove than iron.

Therefore, dissolved manganese was taken into careful consideration during the design process.

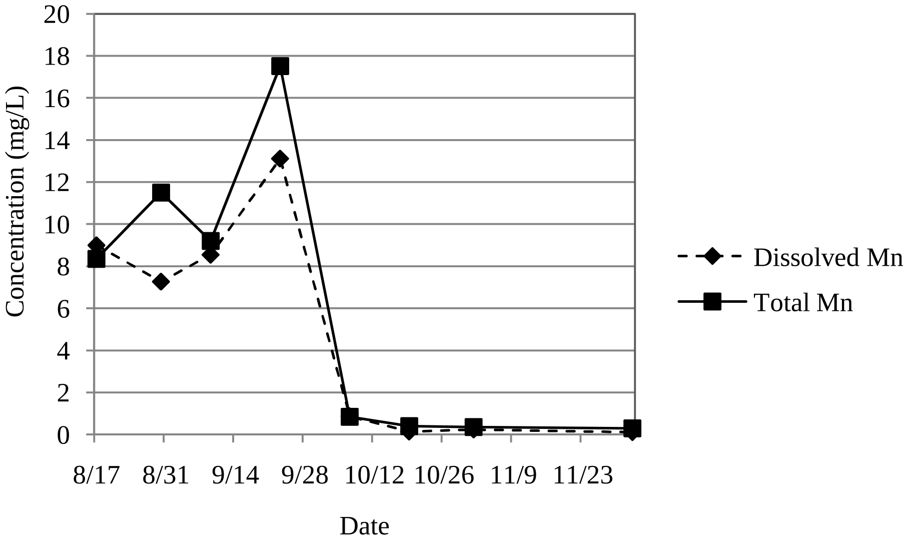

Figure 4-4: Manganese Concentrations in Orrs Pond at 25 foot Depth

4.2 Selection of Alternatives for Manganese Control

A qualitative review of applicable iron and manganese treatment options was performed by the project team to determine two alternatives for control of manganese.

4.2.1 Rating of Treatment Options

A criteria matrix developed by the project team, shown in Table 4-3, was used to select two preliminary treatment option designs. The treatment options evaluated fall into three categories: modification to source water, modification to treatment facility, and changing the water source. The two treatment options that involved modifying the source water are aeration and sequestration. There were three different treatment options researched that involved modifying the treatment facility: chemical oxidation, greensand filtration, and aeration-filtration. Multiple chemical oxidation options are available, each with its own dosing requirement, contact time requirements, and effectiveness. Four oxidation options were compared: potassium permanganate, chlorine dioxide, chlorine, and ozone. As described in Section 3-3, each alternative was rated based on 6 criteria on a scale from 1 (lowest) to 5 (highest). Thus, the total ratings could range from 6 to 30.

Table 4-3: Criteria Matrix for Evaluating Manganese Control Options

Treatment	**Viability**	**Environmental Impact**	**Long Term Applicability**	**Byproduct Formation**	**User Friendly**	**Effectiveness**	**Total**
Modification to Source Water							
Aeration (air diffusion)	3	3	5	4	3	2	**20**
Sequestration	1	1	5	2	4	1	**14**
Modification to Treatment Plant							
Potassium Permanganate Oxidation	4	3	5	4	3	4	**23**
Chlorine Dioxide Oxidation	4	3	5	4	2	3	**21**
Chlorine Oxidation	5	3	5	2	4	2	**21**
Ozone Oxidation	5	4	5	2	3	4	**23**
Aeration-Filtration	3	4	5	4	4	2	**21**
Greensand Filtration	4	4	5	4	3	3	**23**
Change Water Source							
Switch to Manchester Reservoir*	3	4	3*	5*	5	3*	**22**

*Some parameters have insufficient data

Three treatment options received the highest score of 23 out of 30: greensand filtration, potassium permanganate oxidation, and ozone oxidation. Greensand filtration scored well in all of the criteria. Chemical oxidation using potassium permanganate got a score of 23 points, receiving consistent marks because it is an effective, viable treatment option and doesn’t have harmful byproducts. Chlorine dioxide did not score as well as oxidation with potassium permanganate because it is not user friendly, it uses an explosive chemical that needs to be monitored, and is not as effective as potassium permanganate for oxidizing manganese. Chlorine oxidation scored lower than potassium permanganate because chlorine can form of harmful halogenated disinfection byproducts, such as trihalomethanes and halogenated acetic acids. Additionally, chlorine is not effective for oxidizing manganese. Ozone received good scores across the criteria matrix except it received a score of 2 for byproducts for the potential to form the suspected carcinogen bromate. Because ozone oxidation is the current treatment system in place at the Russell F. Tenant Water Treatment Facility and has the potential to form harmful byproducts, potassium permanganate oxidation and greensand filtration were selected for the preliminary design.

Other notable criteria matrix results include the ratings for sequestration, aeration-filtration, and drawing water from Manchester Reservoir during the summer months. Sequestration received the lowest total score of 14. Sequestration involves adding chemicals into the source water to keep the metals in solution. Consequently, this option received a 1 for effectiveness since it does not remove the manganese. Additionally, the facility's superintendent Christine Millhouse expressed disinterest in adding chemicals to the source water due to negative environmental impact, causing sequestration to receive a score of 1 each for viability and environmental impact. Aeration-filtration received a score of 21 points. This treatment option scored 4 points each for environmental impact, byproducts and user friendliness. However, it is not effective as a stand-alone treatment for manganese and received a score of 2 for effectiveness. During the summer in 2010, the water treatment facility switched the source water from Orrs Pond to the Manchester Reservoir. This was the first time this has been done, so the project team concluded that there was insufficient data to determine accurate scores for long term applicability, byproducts, and effectiveness. The two treatment options that received the highest rankings, greensand filtration and chemical oxidation with potassium permanganate, were further evaluated and received preliminary designs.

4.2.2 Comparison of Selected Alternatives

The two highest rated alternatives, greensand filtration and oxidation with potassium permanganate, were compared based on cost, effectiveness at treating manganese as a standalone solution, and observed uses in other treatment facilities. Each alternative was assigned a score from 1-5 for each criteria, with 5 as the highest (best) score. Table 4-4 shows the comparative ratings of the two treatment alternatives.

Table 4-4: Comparison of Selected Treatment Alternatives

Treatment Process	Cost	Effectiveness	Experience	Total
Greensand Filtration	2	3	1	6
Oxidation with $KMnO_4$	3	4	4	11

Greensand filtration typically requires pre-oxidation at iron concentrations greater than 10 mg/L, which are observed in Orrs Pond (Viessman et al., 2009). For this reason, the treatment received a 3 in effectiveness and therefore peroxidation with potassium permanganate would be recommended as a pretreatment in conjunction with the greensand filtration design. Greensand filtration received a 2 for cost because the design requires the replacement of filter media and greensand recharge, which would cause greater capital and operational costs than chemical oxidation alone. Lastly, the project team found no known applications of greensand filtration for the treatment of manganese in surface waters, consequently earning it a score of 1 in this category. Although potassium permanganate is expensive, both capital and operational costs are lower for the oxidation design and thus it received a score of 3. Oxidation with potassium permanganate received a score of 4 in both effectiveness and experience, which were determined based on research and discussion with treatment facility operators.

Based on this analysis, the recommended treatment option for the Russell F. Tenant Treatment Facility is oxidation with potassium permanganate. Greensand filtration is a second alternative. Section 4.3 provides a detailed design for potassium permanganate oxidation, including incorporation of theoretical dosing requirements and bench-scale testing of treatment effectiveness. Section 4.4 provides a preliminary design for a greensand filtration system.

4.3 Potassium Permanganate Oxidation Design

A potassium permanganate oxidation system was designed for control of iron and manganese at the Russell F. Tenant Water Treament Facility. Resources used to complete the design included: personal communications with Rick Wells, a permanganate salesperson from Carus Corporation; personal communications with Paul Roy, the operations supervisor of the Exeter, New Hampshire water treatment plant, which operates a potassium permanganate oxidation system; an iron and manganese treatment lecture by iron and manganese treatment expert Professor William Knocke, at Virginia Polytechnic Institute; and personal communications with Ron Mastrogiacomo, the head of cost estimation at AECOM Water. The critical design parameters included chemical dosing and reaction time. A cost analysis was also completed. After the design was completed, it was tested at the bench-scale to confirm effectiveness.

Chemical dosing was calculated based on theoretical stoichiometric requirements. As shown in reactions 4-1 and 4-2, the iron and manganese requirements are molar ratios of 0.94 mg $KMnO_4$ per 1 mg Fe and 1.92 mg $KMnO_4$ per 1 mg Mn, respectively.

$$3Fe(HCO_3)_2 + KMnO_4 + 2H_20 \rightarrow 3Fe(OH)_3 + MnO_2 + KHCO_3 + 5CO_2 \qquad \text{Reaction 4-1}$$

$$3Mn(HCO_3)_2 + 2KMnO_4 \rightarrow 5MnO_2 + 2KHCO_3 + 2H_2O + 4CO_2 \qquad \text{Reaction 4-2}$$

For the design, the peak historical total manganese concentration, 2.78 mg/L was used because the raw water was sampled directly from the intake, providing more representative results of the water quality entering the facility. The peak observed dissolved iron concentration, 3.85 mg/L was used for the design because no historical data on iron concentrations were available. Based on these values, the required permanganate dose is 8.96 mg/L for peak conditions. Median and low concentrations were also calculated and a full set of calculations can be found in Appendix D. Table 4-5 summarizes the selected low, median, and peak concentrations of iron and manganese as well as the total alkalinity consumption and required potassium permanganate dose based off of the selected values.

Table 4-5: Design Specifications for Potassium Permanganate Oxidation Design

Iron and Manganese Conditions	Historical Manganese Concentration (mg/L)	Observed Dissolved Iron Concentration (mg/L)	Potassium Permanganate Dose Required (mg/L)	Total Alkalinity Consumed (mg/L as $CaCO_3$)
Low	0.01	0.03	0.05	0.06
Median	0.21	0.19	0.58	0.54
Peak	2.78	3.85	8.96	9.10

Alkalinity is the measurement of the ability to neutralize acids in water. This is important in water treatment because highly alkaline waters, exceeding 20 mg/L, may produce undesirable taste (EPA, 1999). Historical finished water alkalinity measurements for the Russell F. Tenant range from 15 mg/L as $CaCO_3$ to 44 mg/L as $CaCO_3$. The rates at which alkalinity is consumed are 1.49 mg $CaCO_3$ per mg Fe and 1.21 mg $CaCO_3$ per mg Mn. As show in table 4-5, the alkalininty consumed during peak conditions is 9.10 mg/L and the alkalinity consumed during low conditions is 0.06 mg/L. Appendix D shows full calculations for determining these values. Due to the large range in alkalinity observed in the facility as well as the low amount of alkalinity being consumed, no process modifications regarding finished water alkalinity are recommended.

The reaction time required for full oxidation of iron and manganese is 5-10 minutes with a pH of greater than 6.5 was (Knocke personal communication, 2010). The historical pH at the raw water intake ranges from 6.33 to 7.72, with an average of 6.86. The project team determined that the pH would not need to be adjusted prior to the addition of potassium permanganate. The average flow at the treatment facility is 4.5 million gallons per day (MGD). As shown in Appendix D, piping from the raw water intake to rapid mix is 28,361 gallons the rapid mix basin has a volume of 24,681 gallons. If the potassium permanganate is applied at the raw water intake, this provides a total volume of 53,042 gallons, allowing for a 17 minute reaction time prior to flocculation. This result is desirable because precipitated manganese is colloidal and would require flocculation prior to being settled and filtered (Knocke personal communication, 2010). Additionally, the detention time for a peak flow of 9.5 MGD was calculated to be 8 minutes, which is in the range of 5-10 minutes required for full iron and manganese oxidation. Because both average and peak flow conditions provide sufficient reaction time from the raw water intake to flocculation, no additional storage is required.

4.3.1 Oxidation with Potassium Permanganate Bench-Scale Results

Laboratory testing of chemical oxidation with potassium permanganate was conducted using the methodologies described in Chapter 3. Sample water was collected directly from the intake of the Russell F. Tenant Water Treatment Facility on January 20, 2011. The raw water was tested for initial concentrations of dissolved manganese, dissolved iron, and DOC. For the testing, additional manganese was added to the water to achieve an initial concentration of 1.51 mg/L. Then, nine tests were performed with varying organic carbon concentrations that were created by adding humic acid to some samples and varying potassium permanganate doses of 94%, 188%, and 376% of the theoretical stoichiometric dosing. The samples were allowed to react for 10 minutes and were then filtered and the filtrate was analyzed for dissolved iron, manganese, and organic carbon. Table 4-6 presents the laboratory testing results.

Table 4-6: Water Quality Results for Potassium Permanganate Oxidation

Sample Conditions		KMnO4 Dose (mg/L)	Manganese			Iron			DOC		
KMnO4 Dose % Stoichiometry	Organic Concentration		Initial (mg/L)	Final (mg/L)	% Oxidized	Initial (mg/L)	Final (mg/L)	% Oxidized	Initial (mg/L)	Final (mg/L)	% Oxidized
94	Low	2.92	1.51	0.02	98.9	0.21	0.04	80.6	3.61	2.70	25.1
94	Medium	2.92	1.51	0.16	89.6	0.21	0.03	83.5	5.60	4.13	26.3
94	High	2.92	1.51	2.31	-53.5	0.21	0.24	-16.7	5.94	5.99	-0.84
188	Low	5.83	1.51	0.02	98.6	0.21	0.01	93.7	3.61	2.70	25.4
188	Medium	5.83	1.51	0.08	94.6	0.21	0.03	83.5	5.60	4.12	26.5
188	High	5.83	1.51	1.34	10.9	0.21	0.14	32.4	5.94	5.85	1.52
376	Low	11.67	1.51	0.01	99.2	0.21	0.04	79.1	3.61	2.60	28.0
376	Medium	11.67	1.51	0.05	96.7	0.21	0.04	80.1	5.60	5.21	6.96
376	High	11.67	1.51	0.31	79.5	0.21	0.04	80.6	5.94	6.10	-2.69

All nine treated waters displayed some slight color change, from the purple of the potassium permanganate solution to a faint pinkish orange color, prior to filtration. Higher dosages of potassium permanganate correlated with higher oxidation percentages for iron and manganese. The following sample conditions oxidized manganese to meet the EPA's secondary maximum contaminant level of 0.05 mg/L:

- 95% stoichiometric dose with low organic carbon
- 190% stoichiometric dose with low organic carbon
- 378% stoichiometric dose with low organic carbon
- 378% stoichiometric dose with medium organic carbon

The initial dissolved organic carbon level was inversely related to the percent of manganese oxidized. It is likely that potassium permanganate reacted with organic carbon, leaving less available oxidant to react with iron and manganese. All three samples with low organic carbon resulted in treated manganese concentrations at or below the EPA SMCL. Samples treated with 94% of the stoichiometric dose yielded manganese values ranging from 0.02 mg/L to 2.31 mg/L. Samples treated with 188% of the stoichiometric dose yielded manganese values ranging from 0.02 mg/L to 1.34 mg/L. Samples treated with 376% of the stoichiometric dose yielded manganese values ranging from 0.01 mg/L to 0.31 mg/L. The result for the 94% $KMnO_4$ dose with high organic carbon is notable because it underwent a 53.5% increase in dissolved manganese, 16.6% increase in dissolved iron, and approximately no oxidation of organic carbon. It is possible that this outlier is the result of laboratory error.

For concentrations of organic carbon less than 3 mg/L, dosing approximately the theoretical stoichiometric amount is sufficient for the oxidation of manganese to 0.05 mg/L. However, at organic carbon concentrations greater than this value, it is recommended that the dose be adjusted to a value greater than the stoichiometric dose for iron and manganese. Due to laboratory error, there is little difference between the medium and high organic carbon samples, measured as initial concentrations of 5.60 mg/L and 5.94 mg/L, respectively. 190% of the stoichiometric dose with a concentration of 5.60 mg/L DOC reduced the dissolved manganese to a concentration of 0.08 mg/L and

378% of the stoichiometric dose with a concentration of 5.60 mg/L DOC reduced the dissolved manganese concentration to 0.05 mg/L. Because this difference in manganese reduction is so small, the project team recommends overdosing potassium permanganate to a value no greater than 200% of the stoichiometric dose due to the cost of the chemical.

4.3.2 Estimated Design Costs for the $KMnO_4$ Treatment System

Operational costs for the quantity of potassium permanganate were estimated based on correspondence with Rick Wells, a permanganate salesperson at Carus Corporation for low, median, and peak dissolved iron and manganese levels. A unit price of $4.50/lb was determined for potassium permanganate. This unit price was converted into daily and yearly costs, based off of the low, median, and peak iron and manganese concentrations.

Using the historical data, it was determined that concentrations of Mn less than the EPA SMCL of 0.05 mg/L represent 29% of the year, low concentrations less than 0.1 mg/L and greater than 0.05 mg/L of Mn represent 13% of the year, median concentrations between 0.1 mg/L of Mn and 0.5 mg/L of Mn represent 38% of the year, and peak concentrations greater than 0.5 mg/L of Mn represent 20% of the year. The historical concentrations were averaged based on the provided manganese concentration ranges and a low concentration of 0.07 mg/L, a medium concentration of 0.26 mg/L, and a high concentration of 0.86 mg/L were used to determine chemical dosing for each portion of the year.

Iron concentrations were selected based off of observed concentrations in Orrs Pond with a low concentration of 0.13 mg/L (the lowest observed dissolved iron concentration at 25 feet) and a high concentration of 1.46 mg/L (the average dissolved iron concentration at 25 feet for the duration of the project). A medium concentration of 0.80 mg/L of iron was selected because it is the average of the low and high concentrations.

Dosage adjustments are recommended based off of the bench-scale testing for DOC concentrations greater than 5 mg/L. In order to account for the additional cost, a double dose of potassium permanganate was applied for 21 days at the high iron and manganese concentrations, the equivalent amount of days when TOC historically exceeded 5 mg/L.

Electricity costs were considered to be negligible for operation (Roy personal communication, 2011). Capital costs for the chemical storage tank and accessories were estimated based on correspondence with Ron Mastrogiacomo, who referred the project team to a quote for the purchase of a 2,000 gallon fiberglass chemical storage tank with applicable accessories. The yearly capital cost was calculated based on a 20 year loan period at 5% annual interest. Table 4-7 summarizes estimated design costs.

Table 4-7: Estimated Costs for Potassium Permanganate Oxidation Design

Category	Fixed & Daily Cost		Annual Cost
Capital	$27,000		$2,167
$KMnO_4$	Daily	Days/year	
No treatment required	$0	106	$0
Low Mn	$44	47	$2,064
Medium Mn	$211	139	$29,344
High Mn, low DOC	$510	52	$26,522
High Mn, high DOC	$1,022	21	$21,457
$KMnO_4$ Annual			$79,386
Total Annual			$81,553

4.4 Greensand Filtration Preliminary Design

A preliminary design for greensand filtration was completed as a second alternative for control of manganese. The design used research and personal communications with Aaron Ambler, Stephen Cronin, David Rindal, Peter Vendzules, and Rick Wells. The following design considerations were determined: surface loading rate (SLR), filter media type and depth, greensand recharge rate, and cost.

Appropriate SLRs were determined from EPA's book *Removal of Arsenic from Drinking Water Supplies by Iron Removal Processes* (Hoffman, 2006). This reference notes that

SLRs should range from 3-5 gpm/ft^2. For greensand filtration, dual media with anthracite and manganese coated greensand is recommended by the EPA and has been used in full-scale manganese treatment systems. The different SLRs and amounts of anthracite and greensand used by different water treatment facilities are displayed in Table 4-8.

Table 4-8: Water Treatment Facilities Greensand Filter Specifications

Location	SLR (gpm/ft^2)	Media and Amount (in.)	
Westford, MA	2.17	Anthracite	18
		Greensand	28
Lakeville, MN	6.89	Anthracite	17
		Greensand	13
Marshall, MN	1.09	Anthracite	12
		Greensand	18
Raymond, NH	1.98	Anthracite	18
		Greensand	28

The Westford, MA and Raymond, NH treatment facilities each use a SLR of approximately 2 gpm/ft^2, while the Lakeville, MN facility uses a significantly higher SLR of 6.89 gpm/ft^2. The current surface loading rate for filters in the Russell F. Tenant Water Treatment Facility is 3.58 gpm/ft^2, which is within recommended SLR values. Therefore, it is recommended that this rate be used to minimize treatment modifications and maintain the same overall filter surface area.

The Westford, MA and Raymond, NH water treatment facilities have 18 inches of anthracite on top of 28 inches of greensand. This provides a ratio in which the anthracite accounts for approximately 40% of the filter media and the greensand accounts for 60% of the media. The media amounts for the preliminary design were determined to be consistent with those ratios as well as to minimize the amount of filter modifications by keeping the same amount of freeboard and gravel and leaving the underdrain unmodified. The design called for 25 inches of anthracite on top of 38 inches of greensand.

The capital costs for the filter media were estimated by Peter Vendzules, a sales representative from Hungerford and Terry. The unit cost for anthracite is $9.70/cu-ft and the unit cost for greensand is $54.99/cu-ft. There is only a capital cost for the media costs because the filters already exist. Operational costs regarding potassium permanganate were based off of a recharge rate of 0.18 lb/cu-ft with one filter being backwashed per day. Preoxidation with potassium permanganate is recommended for this design due to the high levels of dissolved iron and manganese. Capital and operational costs regarding the chemical storage tank and cost for peroxidation were determined using the same procedures outlined in Section 4-3. Table 4-9 shows the estimated fixed, daily, and yearly costs considered for preliminary design.

Table 4-9: Estimated Yearly Costs for Greensand Filtrations Preliminary Design

Category		Fixed & Daily Cost		Annual Cost
Capital	Chemical storage tank	$27,000		$2,167
	Anthracite	$8,831		$709
	Greensand	$76,097		$6,106
		Daily	Days/year	
Preoxidation with $KMnO_4$	No treatment required	$0	106	$0
	Low Mn	$44	47	$2,064
	Medium Mn	$211	139	$29,344
	High Mn, low DOC	$510	52	$26,522
	High Mn, high DOC	$1,022	21	$21,457
$KMnO_4$ for recharge		$1,100	365	409,000
Total Annual Operating Costs				$488,386
Total Annual				$497,368

Table 4-10 summarizes design information and specifications for the greensand filtration preliminary design. Figure 4-5 shows a cross-section of the filter. Design calculations are provided in Appendix D.

Table 4-10: Design Specifications for Greensand Filtration Design

	Existing Sand and Activated Carbon Filter	Proposed Greensand Filtration Design
Dimensions (ft)	23x19x16	23x19x16
SLR (gpm/ft^2)	3.58	3.58
Number of Units	4	4
First Media	48” Activated Carbon	25” Anthracite
Second Media	15” Silica Sand	38” Greensand

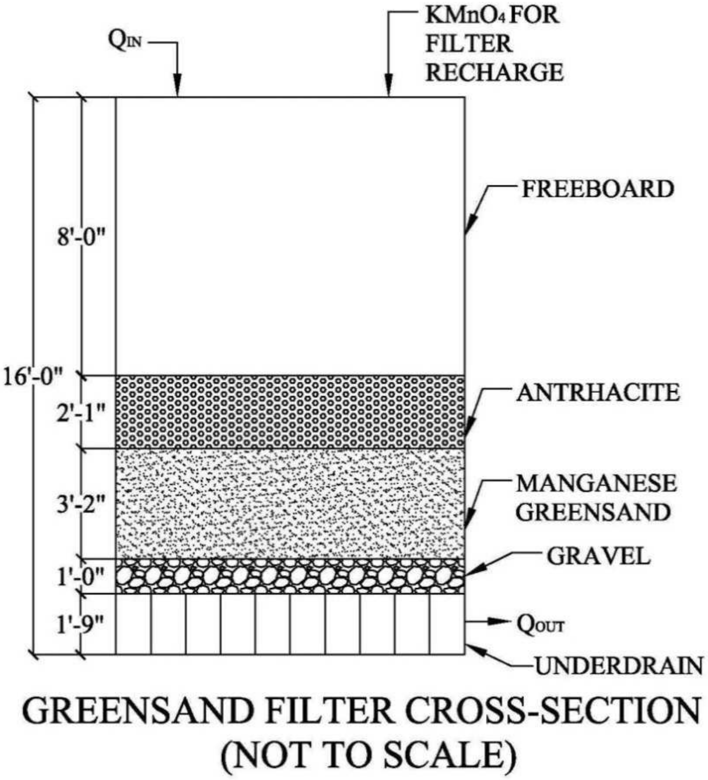

Figure 4-5: Greensand Filter Cross-Section

5 Conclusions and Recommendations

The goal of this project was to design an effective iron and manganese control strategy for the Russell F. Tenant Water Treatment Facility. Bimonthly sampling in Orrs Pond was used to analyze the source water quality. After comparing different treatment options, a potassium permanganate oxidation was selected, designed, and tested at the bench scale. This chapter summarizes the water quality in Orrs Pond, provides design recommendations, and provides recommendations for the continuation of this study.

5.1 Orrs Pond Water Quality

Manganese concentrations up to 3 mg/L are observed during the summer months in the raw water of the Russell F. Tenant Water Treatment Facility. These high concentrations yield undesirable water discoloration. Currently the water is treated with preozonation on an as-needed basis. However, ozone has the potential to develop the suspected carcinogenic byproduct bromate. Therefore, the project team reviewed historical water quality data from Orrs Pond and conducted sampling from August-December 2010 to evaluate source water conditions and gain an understanding of the causes of the high levels of manganese. Dissolved and total iron, manganese, and organic carbon, as well as turbidity, pH, dissolved oxygen, and temperature were all tested at depths 0-25 feet, in five foot intervals, at the approximate location of the raw water intake.

The concentrations of total and dissolved manganese in Orrs Pond ranged from 0.3 mg/L to 17.5 mg/L and 0.1 mg/L to 13.1 mg/L, respectively, at a depth of 25 feet. The concentrations of total and dissolved iron ranged from 2.1 mg/L to 42.8 mg/L and 0.1 mg/L to 3.6 mg/L, respectively. These levels exceed the EPA’s secondary maximum contaminant levels for iron and manganese, which are 0.3 mg/L and 0.05 mg/L, and control strategies need to be implemented to meet these recommendations. The primary difference between iron and manganese concentrations was that most of the iron was insoluble and most of the manganese was soluble. Because the soluble forms of the metals are more difficult to remove during treatment, these dissolved concentrations were of greater concern and taken into account during the treatment system design.

The temperature and dissolved oxygen readings showed decreasing levels with depth for most sample events. These results indicate that Orrs Pond observes seasonal stratification, which is common for lakes and ponds in New England. It is not uncommon for stratified water bodies to have elevated levels of manganese because manganese is more soluble in the absence of oxygen.

The water quality results collected by the project team are not consistent with the historical data, likely due to the location of the sampling. Historical data reflects raw water from the treatment plant at the plant intake, whereas the project team sampled directly in the pond. On two occasions, the project team collected water from the intake in addition to the pond and ran the same tests. A comparison of intake samples to pond samples reflected the same inconsistencies. Therefore, the iron and manganese results in the pond samples are higher than what is representative of the intake.

5.2 Comparison of Ozone and Potassium Permanganate Treatment Systems

Oxidation with ozone is energy intensive and has the potential to develop the carcinogenic byproduct bromate. Although bromate was only detected on one occasion, the potential to form this byproduct is undesirable. For these reasons, oxidation with potassium permanganate was designed in as an alternative manganese control strategy. The current operational costs for the ozone treatment system are $76/day for ozone and $200/day for electricity costs associated with the process (Wunschel personal communication, 2011). Using these values, the estimated yearly cost of operation for ozone was calculated, assuming that the treatment system would operate on as many days as the potassium permanganate system. Table 5-1 compares these costs to the estimated annual cost of the potassium permanganate treatment system and the calculations can be found in Appendix F.

Table 5-1: Ozone and Potassium Permanganate Treatment System Annual Costs

Cost	Ozone	Potassium Permanganate
Electricity	$51,800	Negligible
Chemical	$19,684	$81,553
Total	$71,484	$81,553

The annual cost for the potassium permanganate treatment system is approximately $10,000 more than the ozone treatment system. However, it is likely that the differential between the annual costs is greater. The ozone treatment system was installed in 1995 and it is likely that, within the 20 year payback period for the potassium permanganate treatment system, equipment replacements and maintenance will be required incurring greater annual costs. Additionally, a significant portion of the operating costs for the ozone treatment system are electricity costs, which is a less sustainable practice and the costs for electricity are subject to change.

5.3 Potassium Permanganate Design

The recommended treatment option involves the addition of potassium permanganate at the raw water intake. The current layout of the facility allows for the 5-10 minute required reaction time to oxidize iron and manganese at average and peak flows. The design is estimated to cost $81,553 annually to implement.

The peak historical manganese value was selected because the raw water was sampled directly from the intake, providing more representative results of the water quality entering the facility. Because no historical data on iron concentrations was provided, the peak dissolved iron value observed in this study was taken into account for the dosing because it is easily oxidized by permanganate. The design specifications in this report are based on the highest historical manganese concentration recorded by the facility, 2.78 mg/L, the highest iron concentration observed by the project team, 3.85 mg/L, and an average flow of 4.5 million gallons per day.

The project team recommends daily monitoring of iron and manganese levels to allow for potassium permanganate dosage adjustments. Raw water intake levels will need to be monitored for these metals, as well as organic carbon. Dissolved organic carbon levels above 5 mg/L will react with potassium permanganate and limit manganese precipitation, so these conditions will require dosage adjustments. The color of the potable water should also be monitored daily because adding too much potassium permanganate will give the water an undesirable pink tint. Regular backwashing of the filters and sedimentation basin cleanings to prevent buildup of oxidized manganese from reentering solution is recommended. Upkeep of the chemical storage tank is also recommended. Potassium permanganate, as with other chemicals currently utilized by the facility, will need to be replenished within the tank.

5.4 Future Work

Sampling for this project was completed from August-December 2010. In order to gain a further understanding of the yearly manganese control requirements, a yearly investigation of the relevant water quality parameters should be performed. These parameters include pH, temperature, dissolved oxygen, turbidity, TOC, DOC, iron, and manganese. Water should be collected bimonthly at the intake. The yearly sampling will allow for the development of seasonal dosage adjustments.

Design testing performed by professional engineers is also recommended for the continuation of this project. In particular, additional laboratory tests should be performed to refine the potassium permanganate dosing in the presence of organic carbon in concentrations greater than 3 mg/L. Full-scale testing of the chemical oxidation design should also be performed within the facility before the treatment system goes online to ensure that the oxidizing reactions do not negatively impact any of the other treatment processes within the facility. Additionally, full-scale tests should reveal that there are no issues with the required equipment, such as the storage tank and chemical feed valves, in generating the potassium permanganate solution.

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Appendix A: Treatment Data from the Attleboro Water Department

A.1 List of Treatment Processes and Dimensions

Stage	Number of Units	Dimensions (ft)	Volume (gallons)
Scum Removal	4	8x8x15.5	29,681
Rapid Mix	4	8x8x15.5	29,681
Flocculations	8	17x17x15.5	268,053
Sed Basins	4	129x17x15.25	1,000,622
Filters	4	23x19x16	209,201
Contact Tank	1	140x10	1,150,873
Clearwell	1	78x31x22	397,906
Raw Water (Before Venturi)	1	2x690	16,206
Raw Water (After Venturi)	1	3x190	10,041
Split at Pretreatment	2	2x45	2,114
Settled Water Effluent Flume	1	3x250	13,212
Filter Effluent to Contact Tank	1	3x460	24,309
From Contact Tank to Clearwell	1	3x660	34,878
Total Plant Volume (gallons)	3,186,776		

A.2 Retention Times of Various Plant Flows

Plant Flow (MGD)	Total Plant Retention Time (days)	Total Plant Retention Time (hours)	Total Plant Retention Time (hours, minutes)
3.00	1.06	25.49	25hr 29min
3.25	0.98	23.53	23hr 32min
3.50	0.91	21.85	21hr 51min
3.75	0.85	20.40	20hr 24min
4.00	0.80	19.12	19hr 7min
4.25	0.75	18.00	18hr
4.50	0.71	17.00	17hr
4.75	0.67	16.10	16hr 6min
5.00	0.64	15.30	15hr 18min
5.25	0.61	14.57	14hr 34min
5.50	0.58	13.91	13hr 55min
5.75	0.55	13.30	13hr 18min
6.00	0.53	12.75	12hr 45min
6.25	0.51	12.24	12hr 14min
6.50	0.49	11.77	11hr 46min
6.75	0.47	11.33	11hr 20min
7.00	0.46	10.93	10hr 56min
7.25	0.44	10.55	10hr 33min
7.50	0.42	10.20	10hr 12min
7.75	0.41	9.87	9hr 52min
8.00	0.40	9.56	9hr 34min
8.25	0.39	9.27	9hr 16min
8.50	0.37	9.00	9hr
8.75	0.36	8.74	8hr 44min
9.00	0.35	8.50	8hr 30min

A.3 Chemical Dosages

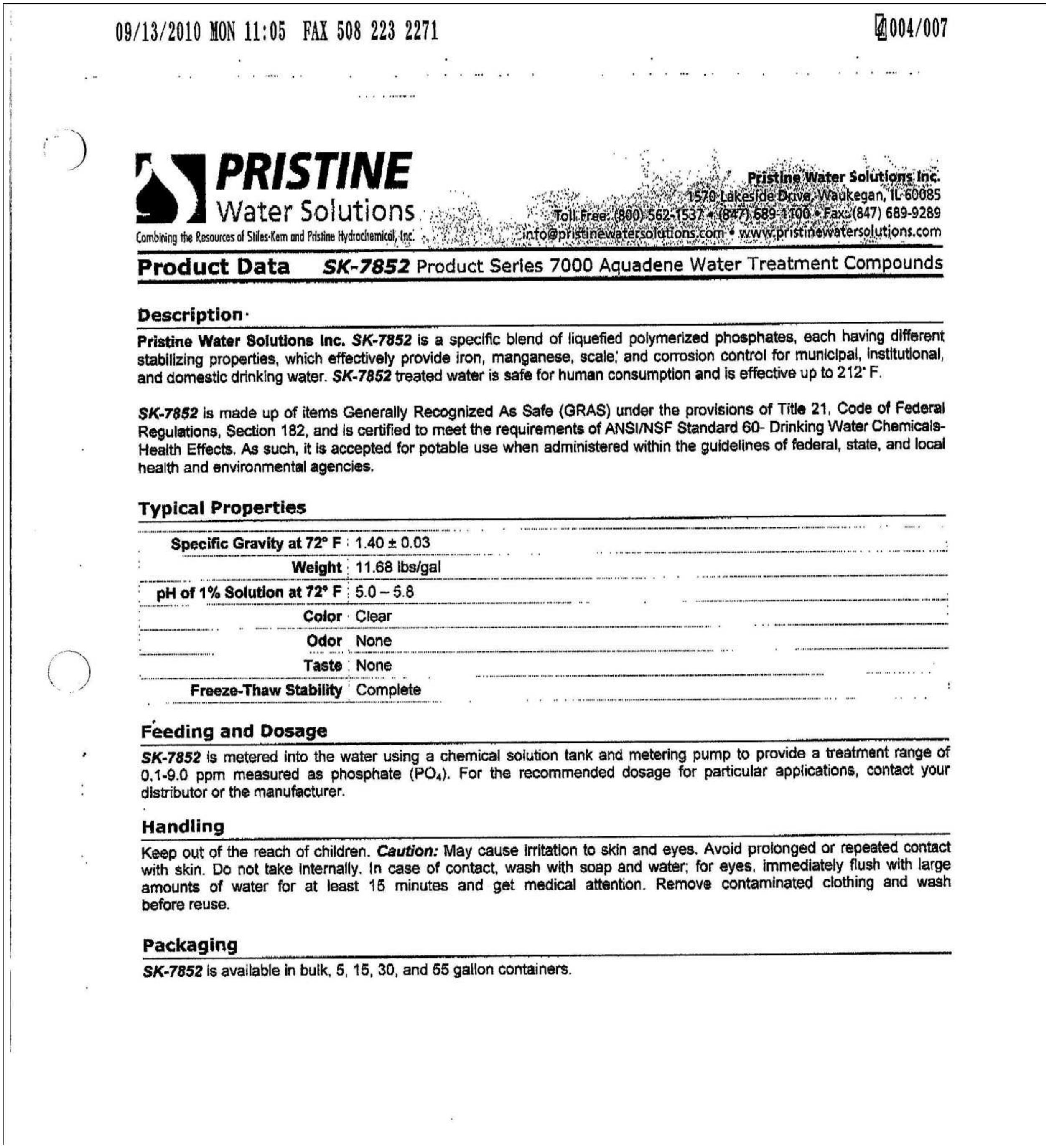
Chemical	Dosage	Use
Fluosilicic Acid	1.0 mg/L yearround	Dental purposes
Ozone Gas	1 mg/L of 4% O3 to O2, through 5 mg/L of 6% O3 to O2	Manganese removal (seasonal)
Polyaluminum Chloride	~20-60 mg/L, depending on raw water quality, lower in the winter and higher in the summer	Coagulant for pretreatment
Polyphosphate	~1.3 mg/L yearround	Corrosion inhibitor for distribution system
Sodium Hydroxide	11-20 mg/L	pH adjustment, ideal finish water pH of 7.5-8.0
Sodium Hypochlorite	1.5-3 mg/L, demand fluctuates along with raw water quality and temperature	Disinfectant, ideal chlorine residual 0.8-0.9 mg/L

A.4 Mixer speeds

Mixer	Speed
Rapid Mix	45 RPM
Slow Mix	30 RPM

A.5 Various Manufacturer Certificates

A.5.1 Pristine Water Solutions Inc., SK-7852



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info@pristinewatersolutions.com • www.pristinewatersolutions.com

Product Data ***SK-7852*** Product Series 7000 Aquadene Water Treatment Compounds

Description

Pristine Water Solutions Inc. ***SK-7852*** is a specific blend of liquefied polymerized phosphates, each having different stabilizing properties, which effectively provide iron, manganese, scale, and corrosion control for municipal, institutional, and domestic drinking water. ***SK-7852*** treated water is safe for human consumption and is effective up to 212° F.

SK-7852 is made up of items Generally Recognized As Safe (GRAS) under the provisions of Title 21, Code of Federal Regulations, Section 182, and is certified to meet the requirements of ANSI/NSF Standard 60- Drinking Water Chemicals-Health Effects. As such, it is accepted for potable use when administered within the guidelines of federal, state, and local health and environmental agencies.

Typical Properties

Specific Gravity at 72° F	1.40 ± 0.03
Weight	11.68 lbs/gal
pH of 1% Solution at 72° F	5.0 – 5.8
Color	Clear
Odor	None
Taste	None
Freeze-Thaw Stability	Complete

Feeding and Dosage

SK-7852 is metered into the water using a chemical solution tank and metering pump to provide a treatment range of 0.1-9.0 ppm measured as phosphate (PO_4). For the recommended dosage for particular applications, contact your distributor or the manufacturer.

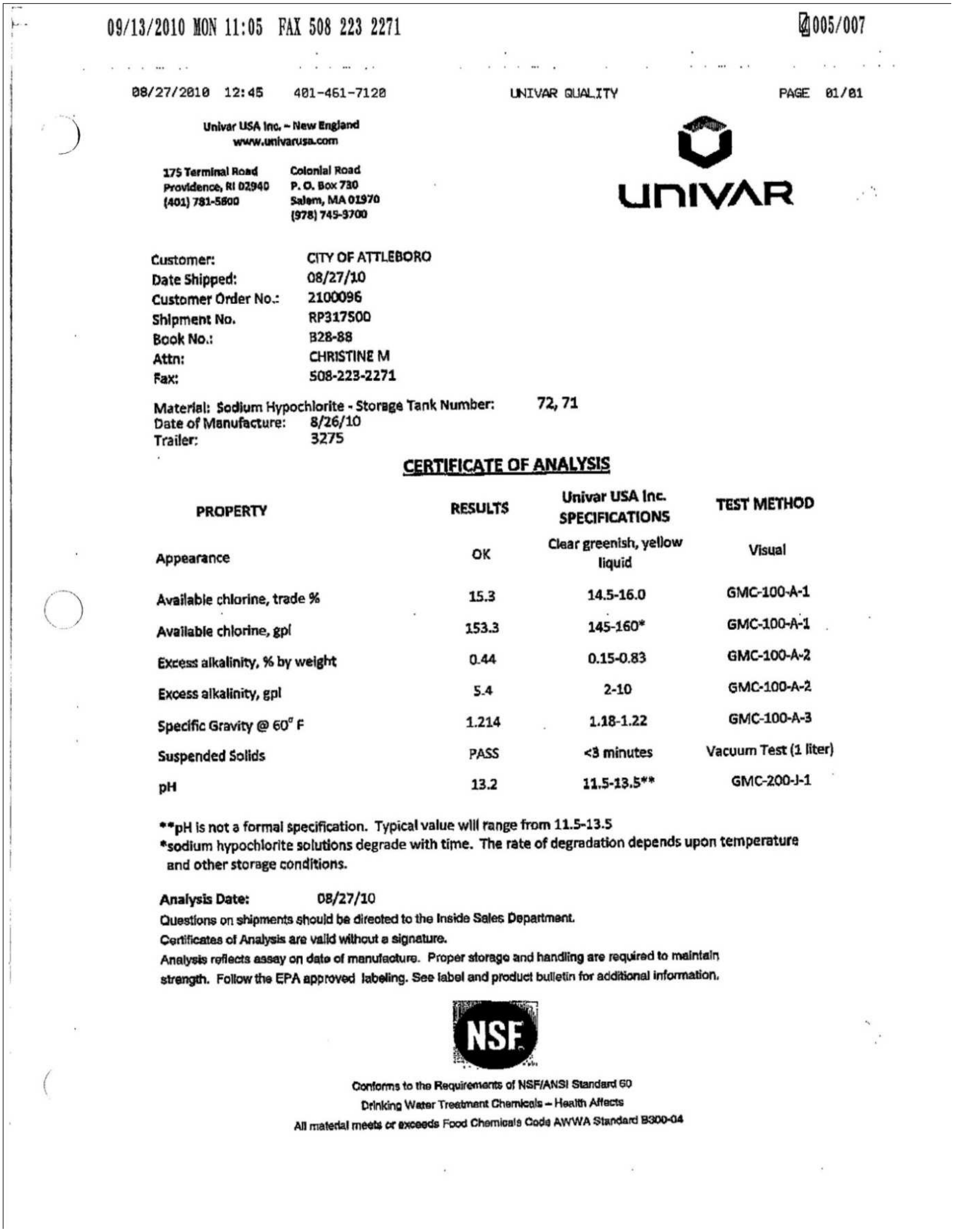
Handling

Keep out of the reach of children. ***Caution:*** May cause irritation to skin and eyes. Avoid prolonged or repeated contact with skin. Do not take internally. In case of contact, wash with soap and water; for eyes, immediately flush with large amounts of water for at least 15 minutes and get medical attention. Remove contaminated clothing and wash before reuse.

Packaging

SK-7852 is available in bulk, 5, 15, 30, and 55 gallon containers.

A.5.2 Univar, Sodium Hypochlorite Certificate of Analysis



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08/27/2010 12:45 401-461-7120 UNIVAR QUALITY PAGE 01/01

Univar USA Inc. – New England
www.univarusa.com

175 Terminal Road
Providence, RI 02940
(401) 781-5800

Colonial Road
P. O. Box 730
Salem, MA 01970
(978) 745-3700

UNIVAR

Customer:	CITY OF ATTLEBORO
Date Shipped:	08/27/10
Customer Order No.:	2100096
Shipment No.	RP317500
Book No.:	B28-88
Attn:	CHRISTINE M
Fax:	508-223-2271

Material: Sodium Hypochlorite - Storage Tank Number: 72, 71
Date of Manufacture: 8/26/10
Trailer: 3275

CERTIFICATE OF ANALYSIS

PROPERTY	RESULTS	Univar USA Inc. SPECIFICATIONS	TEST METHOD
Appearance	OK	Clear greenish, yellow liquid	Visual
Available chlorine, trade %	15.3	14.5-16.0	GMC-100-A-1
Available chlorine, gpl	153.3	145-160*	GMC-100-A-1
Excess alkalinity, % by weight	0.44	0.15-0.83	GMC-100-A-2
Excess alkalinity, gpl	5.4	2-10	GMC-100-A-2
Specific Gravity @ 60° F	1.214	1.18-1.22	GMC-100-A-3
Suspended Solids	PASS	<3 minutes	Vacuum Test (1 liter)
pH	13.2	11.5-13.5**	GMC-200-J-1

**pH is not a formal specification. Typical value will range from 11.5-13.5
*sodium hypochlorite solutions degrade with time. The rate of degradation depends upon temperature and other storage conditions.

Analysis Date: 08/27/10

Questions on shipments should be directed to the Inside Sales Department.

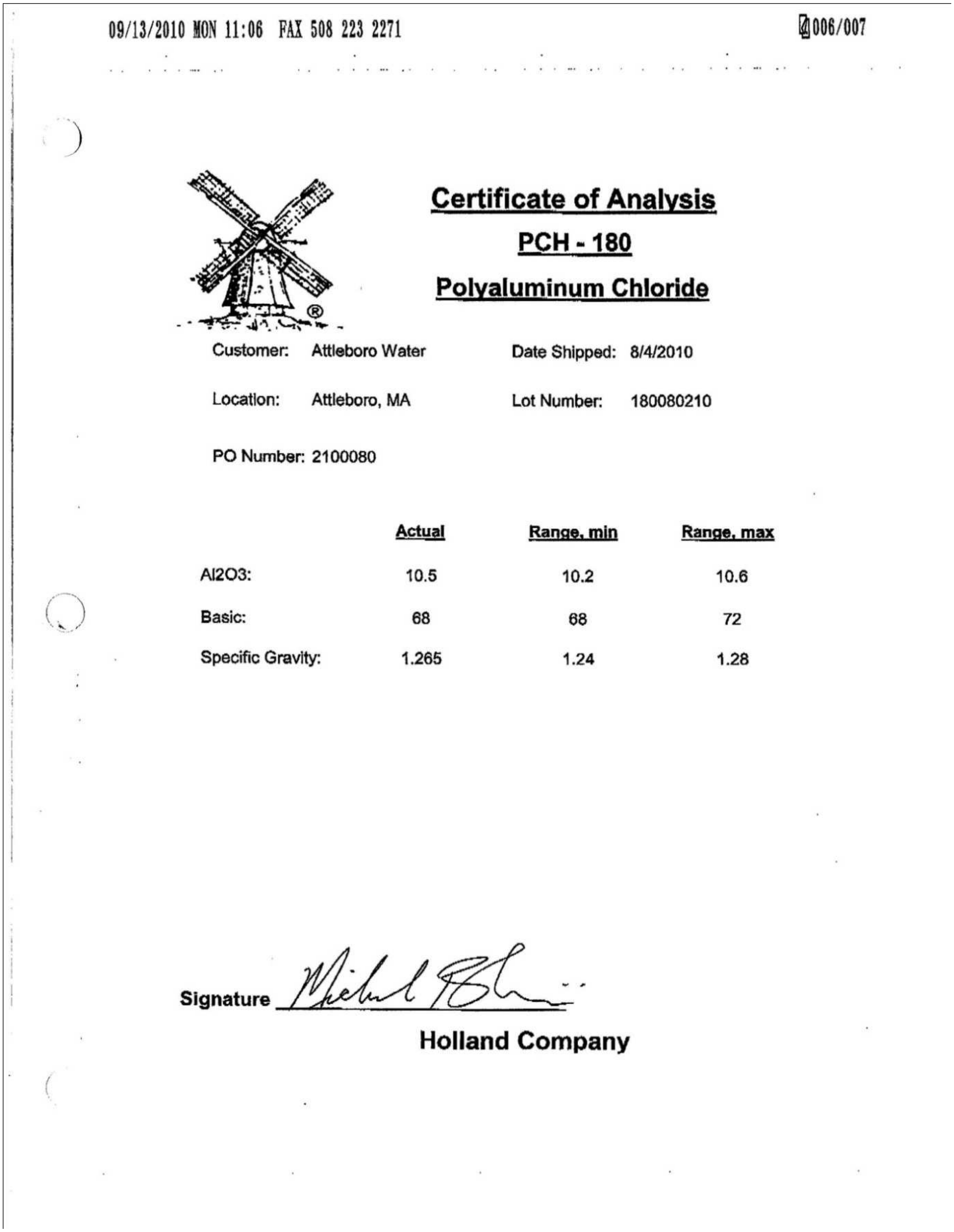
Certificates of Analysis are valid without a signature.

Analysis reflects assay on date of manufacture. Proper storage and handling are required to maintain strength. Follow the EPA approved labeling. See label and product bulletin for additional information.

NSF

Conforms to the Requirements of NSF/ANSI Standard 60
Drinking Water Treatment Chemicals – Health Affects
All material meets or exceeds Food Chemicals Code AWWA Standard B300-04

A.5.3 Univar, Sodium Hydroxide Certificate of Analysis



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006/007

Certificate of Analysis

PCH - 180

Polyaluminum Chloride

Customer: Attleboro Water

Date Shipped: 8/4/2010

Location: Attleboro, MA

Lot Number: 180080210

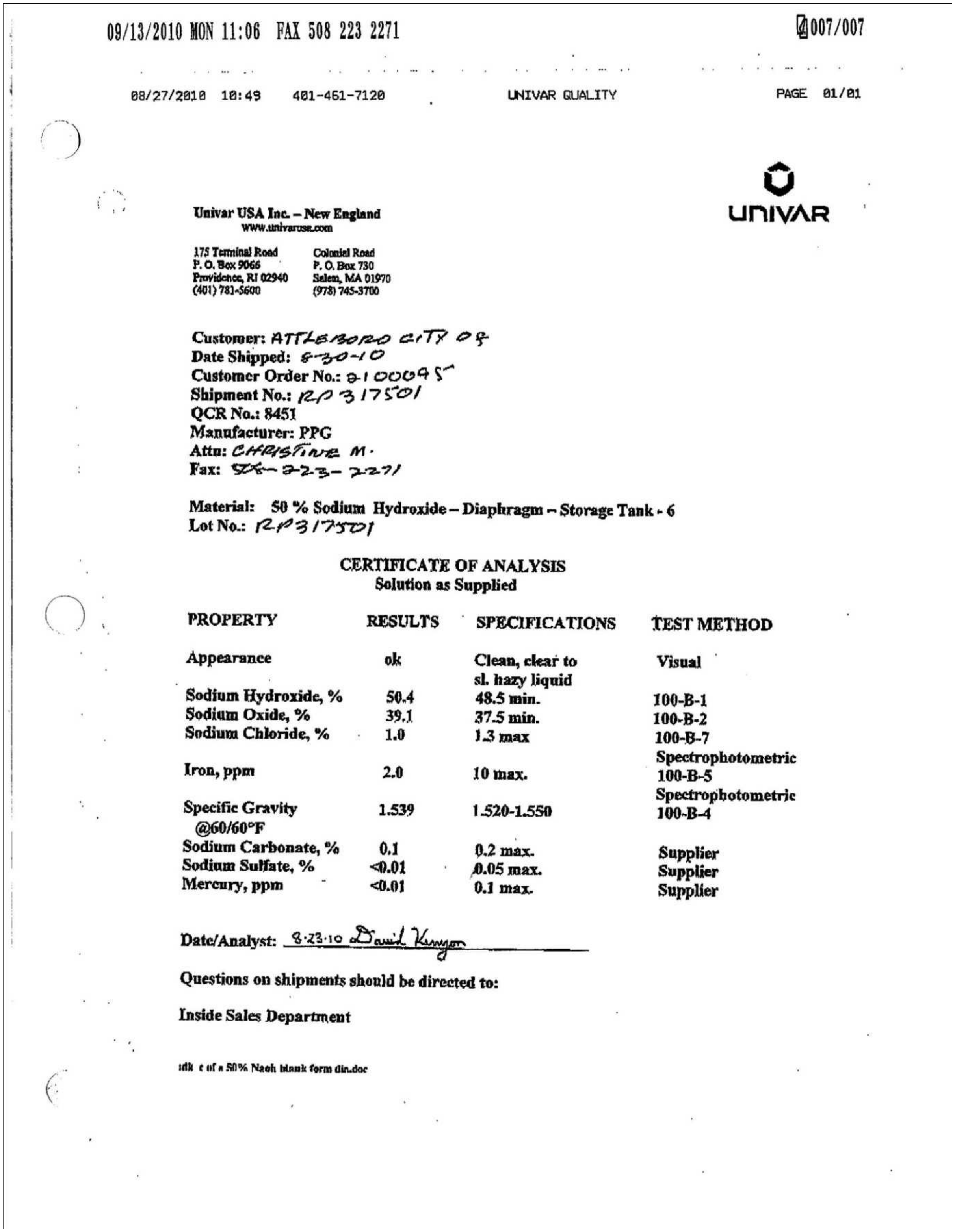
PO Number: 2100080

	Actual	Range, min	Range, max
Al2O3:	10.5	10.2	10.6
Basic:	68	68	72
Specific Gravity:	1.265	1.24	1.28

Signature ____________________

Holland Company

A.5.4 Holland Company, Polyaluminum Chloride Certificate of Analysis



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08/27/2010 10:49 401-461-7120 UNIVAR QUALITY PAGE 01/01

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P. O. Box 730
Salem, MA 01970
(978) 745-3700

Customer: ATTLEBORO CITY OF
Date Shipped: 8-30-10
Customer Order No.: 2100095
Shipment No.: RP317501
QCR No.: 8451
Manufacturer: PPG
Attn: CHRISTINE M.
Fax: 508-223-2271

Material: 50 % Sodium Hydroxide – Diaphragm – Storage Tank - 6
Lot No.: RP317501

CERTIFICATE OF ANALYSIS
Solution as Supplied

PROPERTY	RESULTS	SPECIFICATIONS	TEST METHOD
Appearance	ok	Clean, clear to sl. hazy liquid	Visual
Sodium Hydroxide, %	50.4	48.5 min.	100-B-1
Sodium Oxide, %	39.1	37.5 min.	100-B-2
Sodium Chloride, %	1.0	1.3 max	100-B-7
Iron, ppm	2.0	10 max.	Spectrophotometric 100-B-5
Specific Gravity @60/60°F	1.539	1.520-1.550	Spectrophotometric 100-B-4
Sodium Carbonate, %	0.1	0.2 max.	Supplier
Sodium Sulfate, %	<0.01	0.05 max.	Supplier
Mercury, ppm	<0.01	0.1 max.	Supplier

Date/Analyst: 8·23·10 David Kenyon

Questions on shipments should be directed to:

Inside Sales Department

idk c of a 50% Naoh blank form din.doc

Appendix B: Historical Data and Graphs

B.1 Tabular Representation of Historical Data

B.1.1 Raw Intake Water Quality

Date	Temp (°C)	pH	Turbidity (ntu)	Alkalinity >20/<20 Method
1/3/2006	4	6.58	1.8	16.1
1/4/2006	5	6.53	1.9	15.9
1/5/2006	5	6.58	1.2	15.6
1/6/2006	5	6.5	1.8	16.4
1/9/2006	5	6.52	1.7	15.6
1/10/2006	4	6.43	1.8	15.3
1/11/2006	4	6.48	1.7	15.3
1/12/2006	5	6.47	1.8	15.4
1/13/2006	5	6.53	1.8	15.6
1/17/2006	5	6.61	1.8	14.2
1/18/2006	5	6.51	1.7	14.9
1/19/2006	4	6.65	1.8	12.9
1/20/2006	5	6.77	1.7	12.4
1/23/2006	5	6.67	1.8	11.7
1/24/2006	4	6.78	1.7	11.9
1/25/2006	5	6.78	1.6	12
1/26/2006	5	6.84	1.6	12.3
1/27/2006	5	6.77	1.4	12.4
1/30/2006	4	6.84	1.3	12.6
1/31/2006	4	6.9	1.3	12.6
2/1/2006	4	6.86	0.89	12.6
2/2/2006	4	6.81	1.2	12
2/3/2006	5	6.9	1.2	13.2
2/6/2006	5	7.01	1.4	11.9
2/7/2006	5	7.03	1.4	12.4
2/8/2006	4	7	1.4	12.3
2/9/2006	5	7.01	1.3	12.5
2/10/2006	4	6.98	1.4	12.3
2/13/2006	3	7.02	1.3	12.8
2/14/2006	3	6.97	1.3	12.8
2/15/2006	4	6.98	1.3	12.7
2/17/2006	5	7	1.3	13
2/21/2006	4	7.13	1.2	13.7
2/22/2006	4	7.08	1.1	14.1

2/23/2006	4	7.03	1.2	13.7
2/24/2006	3	6.96	0.56	13.8
2/27/2006	5	7.09	1.1	14.4
2/28/2006	4	7.04	1	14.6
3/1/2006	4	6.94	1.03	14.6
3/2/2006	4	6.92	1.11	14.8
3/3/2006	5	6.33	1.1	14.8
3/6/2006	4	6.97	0.55	14.7
3/7/2006	4	6.94	1.12	14.6
3/8/2006	4	6.93	1.16	15.9
3/9/2006	5	6.93	1.05	15.2
3/10/2006	4	6.92	1.01	15.5
3/13/2006	5	7.14	1.08	13.8
3/14/2006	6	7.15	1	14.7
3/15/2006	6	7.13	1.13	14.6
3/16/2006	6	7.28	1.36	14.9
3/17/2006	6	7.27	1.33	15
3/20/2006	6	7.4	1.3	13.8
3/21/2006	5	7.41	1.11	14.7
3/22/2006	5	7.34	1.13	14.2
3/23/2006	6	7.38	1.16	14.8
3/24/2006	7	7.3	1.13	14.8
3/27/2006	7	7.4	1.19	14.5
3/28/2006	7	7.37	0.97	14.7
3/29/2006	6	7.39	1.13	15.2
3/30/2006	5	7.37	1.04	14.8
3/31/2006	7	7.36	1.15	15
4/3/2006	7	7.36	1.08	14.2
4/4/2006	8	7.3	0.93	14.8
4/5/2006	8	7.26	0.95	15
4/6/2006	9	7.3	1.2	15.2
4/7/2006	8	7.28	1.16	15.8
4/10/2006	8	7.29	1.13	15.6
4/11/2006	8	7.21	1.14	15.4
4/12/2006	9	7.23	1.15	15.9
4/13/2006	10	7.25	1.24	16
4/18/2006	12	7.42	1.31	15.7
4/19/2006	11	7.37	1.34	16
4/20/2006	11	7.27	1.25	15.8
4/21/2006	13	7.24	1.34	16.2
4/24/2006	12	7.25	1.4	17

4/25/2006	13	7.08	1.5	16.8
4/26/2006	12	7.11	1.55	17
4/27/2006	12	7.07	1.55	16.8
4/28/2006	12	7.06	1.58	16.8
5/1/2006	12	7.14	1.34	17.4
5/2/2006	13	7.31	1.23	17.6
5/3/2006	12	7.21	1.17	17.9
5/4/2006	12	7.12	0.96	18
5/5/2006	12	7.12	1.29	17.2
5/8/2006	13	7.09	1.31	17
5/9/2006	13	7.08	1.3	17.2
5/10/2006	13	7.14	1.25	17.4
5/11/2006	14	7.17	1.23	17.7
5/12/2006	13	7.14	1.38	17.4
5/15/2006	12	7.16	1.47	21.2
5/16/2006	12	6.98	1.73	17.8
5/17/2006	12	6.91	2.21	15.8
5/18/2006	12	6.9	2.15	16.6
5/19/2006	13	6.98	2.05	16.7
5/22/2006	12	6.85	1.48	17.5
5/23/2006	12	6.81	1.56	17.6
5/24/2006	12	6.83	1.44	18
5/25/2006	12	6.81	1.42	17.6
5/26/2006	13	6.83	1.53	16.6
5/30/2006	15	6.93	1.72	16.4
5/31/2006	15	6.95	1.67	16.6
6/1/2006	16	6.9	2.01	16.5
6/2/2006	17	7	1.6	16.9
6/5/2006	16	6.88	2.26	17.8
6/6/2006	16	6.84	2.45	17
6/7/2006	15	6.79	2.42	16.7
6/8/2006	15	6.75	1.68	20.2
6/9/2006	14	6.56	3.26	13.3
6/12/2006	16	6.68	2.42	13.2
6/14/2006	14	6.5	2.18	13.6
6/15/2006	15	6.41	2.18	13.5
6/16/2006	15	6.46	1.91	13.8
6/19/2006	16	6.56	1.57	15
6/20/2006	16	6.49	1.53	16
6/21/2006	17	6.52	1.6	16.1
6/22/2006	17	6.54	1.57	16.7

6/23/2006	18	6.58	1.61	17.2
6/26/2006	19	6.76	2.35	21
6/27/2006	20	6.55	2.03	16.5
6/28/2006	20	6.53	2.09	16.6
6/29/2006	20	6.47	1.94	17.1
6/30/2006	20	6.5	1.8	16
7/3/2006	20	6.63	1.87	20.9
7/5/2006	21	6.56	2.28	21.8
7/6/2006	20	6.63	2.05	22.6
7/7/2006	20	6.66	1.47	22.7
7/10/2006	21	6.47	1.78	24.1
7/11/2006	22	6.67	2.47	25.1
7/12/2006	21	6.52	1.53	25
7/13/2006	21	6.57	1.7	26
7/14/2006	21	6.83	1.76	26.2
7/17/2006	22	6.79	2.3	26.1
7/18/2006	22	6.63	2.13	26.6
7/19/2006	22	6.59	1.9	26.4
7/20/2006	22	6.81	2.19	26.2
7/21/2006	23	6.81	2.66	26.3
7/24/2006	23	6.69	2.67	26.1
7/25/2006	23	6.78	2.66	25
7/26/2006	23	6.78	2.59	25.1
7/27/2006	24	6.99	2.75	23.8
7/28/2006	23	6.75	2.86	23.1
7/31/2006	24	6.7	3.25	22.8
8/1/2006	24	6.69	3.18	22
8/2/2006	25	6.71	3.26	22
8/3/2006	25	6.67	3.37	21.8
8/4/2006	24	6.92	3.18	21.8
8/7/2006	25	6.72	3.25	23.4
8/8/2006	25	6.75	2.83	24.6
8/10/2006	25	6.79	2.79	25.3
8/11/2006	24	6.8	2.41	24.8
8/14/2006	22	6.81	2.3	21.6
8/15/2006	22	6.97	2.29	21.1
8/16/2006	22	6.76	1.99	17.8
8/17/2006	22	6.76	2.11	20.4
8/18/2006	22	6.71	2.53	20.4
8/21/2006	22	6.63	2.22	20.4
8/22/2006	23	6.69	2.35	20.9

8/23/2006	22	6.76	2.17	20.7
8/24/2006	22	6.71	2.33	20
8/25/2006	22	6.71	2.34	20.3
8/28/2006	20	6.78	1.59	20.2
8/29/2006	20	6.78	1.66	18
8/30/2006	20	6.77	1.64	20.2
8/31/2006	20	6.8	1.88	17.9
9/1/2006	20	6.73	2.44	17.6
9/5/2006	19	6.76	1.84	17.4
9/6/2006	19	6.72	1.8	17.2
9/7/2006	19	6.73	1.77	16.9
9/8/2006	19	6.71	1.9	17.4
9/11/2006	19	6.73	1.86	17
9/12/2006	18	6.82	1.12	18
9/13/2006	18	6.79	1.19	21
9/14/2006	18	6.75	1.19	21
9/15/2006	18	6.7	1.18	21.2
9/18/2006	18	6.66	1.32	20.9
9/19/2006	18	6.65	0.88	21.4
9/20/2006	18	6.64	1.38	20.2
9/21/2006	18	6.64	1.56	20
9/22/2006	18	6.71	1.52	17.8
9/25/2006	18	6.69	1.88	15.6
9/26/2006	19	6.78	1.71	15.9
9/27/2006	18	6.78	1.26	16.3
9/28/2006	18	6.75	1.33	16.5
9/29/2006	17	6.71	1.45	15.8
10/2/2006	17	6.77	1.21	16.2
10/3/2006	16	6.7	1.18	16.3
10/4/2006	16	6.75	1.25	15.9
10/6/2006	16	6.67	1.28	16
10/10/2006	15	6.77	1.39	14.8
10/11/2006	15	6.76	1.58	14.8
10/12/2006	15	6.69	1.22	14.9
10/13/2006	15	6.75	1.09	15.2
10/16/2006	13	6.8	1.12	14.8
10/17/2006	13	6.77	1.29	14.6
10/18/2006	12	6.71	1.15	14.9
10/19/2006	12	6.68	1.42	14.8
10/20/2006	13	6.64	1.19	14.9
10/23/2006	12	6.73	1.31	14.6

10/24/2006	12	6.75	0.96	14.8
10/25/2006	11	6.74	0.98	15.2
10/26/2006	10	6.76	0.91	15
10/27/2006	10	6.8	0.93	15.1
10/30/2006	10	6.76	0.78	14.3
10/31/2006	9	6.81	1.03	15.1
11/1/2006	8	6.8	1.03	14.8
11/2/2006	9	6.84	1.26	15
11/3/2006	8	6.81	0.99	14.9
11/6/2006	7	6.76	1.1	14.8
11/7/2006	7	6.73	0.97	14.9
11/8/2006	8	6.74	0.95	14.6
11/9/2006	9	6.76	0.97	14.8
11/13/2006	8	6.68	1.08	15
11/14/2006	8	6.64	1.13	15
11/15/2006	8	6.63	1.13	14.9
11/16/2006	9	6.61	1.46	15.2
11/17/2006	9	6.63	1.55	15.7
11/20/2006	9	6.68	1.35	15.6
11/21/2006	9	6.68	1.46	17.4
11/22/2006	10	6.79	1.52	17.7
11/27/2006	7	6.71	2.06	15.2
11/28/2006	7	6.62	2	14.6
11/29/2006	7	6.61	1.86	15
11/30/2006	7	6.61	1.7	15.2
12/1/2006	8	6.59	1.66	15.1
12/4/2006	7	6.74	1.47	15.4
12/5/2006	7	6.75	1.23	15.5
12/7/2006	7	6.7	0.78	15.2
12/8/2006	5	6.8	1.05	15.4
12/11/2006	7	6.99	1.1	15.4
12/12/2006	4	6.84	1.04	16
12/13/2006	4	6.79	1.06	15.9
12/14/2006	5	6.79	0.99	16
12/15/2006	4	6.8	1.02	15.9
12/18/2006	5	6.88	0.96	16.4
12/19/2006	5	6.87	0.95	16.4
12/20/2006	5	6.89	0.87	16.2
12/21/2006	5	6.94	0.9	16.4
12/22/2006	4	7.06	0.87	17.2
12/26/2006	7	7.05	0.82	16.7

12/27/2006	5	6.98	0.98	17.1
12/28/2006	4	7	1	16.9
12/29/2006	3	7.05	0.86	17.3
1/2/2007	4	7.03	0.83	17.2
1/3/2007	4	6.98	0.85	17.2
1/4/2007	3	7	0.86	17.1
1/5/2007	4	6.99	0.92	17.2
1/8/2007	5	6.99	0.98	16.8
1/9/2007	5	6.93	1.02	16.8
1/10/2007	5	7	1.02	16.7
1/11/2007	5	7.04	0.95	16.8
1/12/2007	4	7.05	0.97	16.7
1/16/2007	3	7.01	1.07	16.5
1/17/2007	3	7.01	1.05	16.8
1/18/2007	3	6.98	1.08	16.5
1/19/2007	3	6.88	1.11	17.2
1/22/2007	3	6.89	1.06	17.7
1/23/2007	3	6.75	1.04	17.8
1/24/2007	4	6.8	1.03	18.2
1/25/2007	4	6.78	1.15	18.1
1/26/2007	3	6.76	1.01	18.2
1/29/2007	4	6.79	1.08	21
1/30/2007	3	6.74	1.03	20.9
1/31/2007	4	6.72	1.1	21.1
2/1/2007	4	6.64	1.08	20.9
2/2/2007	4	6.67	1.06	21.1
2/6/2007	4	6.75	0.97	21.8
2/7/2007	4	6.73	0.99	21.8
2/8/2007	4	6.75	0.98	21.8
2/9/2007	4	6.74	1.1	21.7
2/12/2007	4	6.78	0.97	22
2/13/2007	4	6.75	0.96	22.2
2/14/2007	5	6.68	0.94	22
2/15/2007	4	6.63	0.96	21.6
2/16/2007	5	6.74	1.32	20.6
2/20/2007	7	6.69	2.09	16.4
2/21/2007	5	6.75	2.13	18.1
2/22/2007	5	6.67	1.94	17.8
2/23/2007	4	6.7	1.86	17
2/26/2007	5	6.68	1.43	16.3
2/27/2007	5	6.64	1.4	17.3

2/28/2007	4	6.56	1.3	17.4
3/1/2007	4	6.51	1.18	17.5
3/2/2007	5	6.61	1.07	17.2
3/5/2007	5	6.48	2.65	14.8
3/6/2007	5	6.62	3.14	15
3/7/2007	4	6.45	2.58	15.2
3/8/2007	5	6.45	2.3	15.1
3/9/2007	5	6.46	1.95	15
3/12/2007	5	6.51	1.97	13.6
3/13/2007	5	6.48	2	13.1
3/14/2007	5	6.43	2.03	13
3/15/2007	5	6.48	2.06	12.8
3/16/2007	5	6.46	2.05	12.9
3/19/2007	4	6.83	1.39	12.8
3/20/2007	4	6.83	1.35	12.7
3/21/2007	5	6.84	1.36	12.2
3/22/2007	5	6.86	1.34	12.5
3/23/2007	5	6.86	1.3	12.7
3/26/2007	6	6.84	1.26	12.5
3/27/2007	8	6.89	1.24	12.5
3/28/2007	7	6.82	1.2	12.5
3/29/2007	7	6.83	1.2	12.4
3/30/2007	7	6.84	1.34	12.6
4/2/2007	8	6.84	1.2	13
4/4/2007	8	6.84	1.07	13.2
4/5/2007	8	6.9	1.05	13.8
o4/6/2007	8	6.93	0.87	14.8
4/9/2007	7	7.07	1.05	14.5
4/10/2007	7	7.02	1.01	14.6
4/11/2007	7	6.91	0.91	14.4
4/12/2007	8	6.9	0.85	14.2
4/13/2007	8	6.97	0.95	14.1
4/17/2007	7	7.12	1.71	14.3
4/18/2007	8	7.08	1.83	14
4/19/2007	7	7.02	1.9	13.6
4/20/2007	8	6.97	1.7	13.5
4/23/2007	8	6.91	1.59	12.8
4/24/2007	9	6.88	1.56	13
4/25/2007	9	6.94	1.58	13.1
4/26/2007	9	6.9	1.51	13
4/27/2007	9	7.07	1.47	13.4

4/30/2007	10	7	1.25	12.8
5/1/2007	10	6.96	1.26	13.2
5/2/2007	11	6.99	1.22	13.2
5/3/2007	11	6.93	1.32	13.4
5/4/2007	11	6.91	1.42	13.5
5/7/2007	13	6.86	1.39	14.2
5/8/2007	13	6.91	1.26	15.4
5/9/2007	14	6.97	1.4	16.2
5/10/2007	14	6.96	1.43	16.2
5/11/2007	14	6.96	1.38	16.3
5/14/2007	15	6.96	1.36	16.5
5/15/2007	15	6.94	1.35	16.9
5/16/2007	16	6.93	1.52	16.9
5/17/2007	16	7	1.18	17.4
5/18/2007	17	6.95	1.15	20.2
5/21/2007	14	6.94	1.53	20.2
5/22/2007	13	6.87	1.35	17.3
5/23/2007	14	6.91	1.46	17.5
5/24/2007	15	7.01	1.47	17.6
5/25/2007	14	6.82	1.38	17.5
5/29/2007	16	7.04	1.24	20.8
5/30/2007	16	6.96	1.41	21.4
6/1/2007	17	6.89	1.18	22
6/4/2007	19	6.84	1.36	22.6
6/5/2007	19	6.89	1.36	22.7
6/6/2007	18	6.84	1.73	22.1
6/7/2007	18	6.78	1.81	21.1
6/8/2007	18	6.79	1.92	21.4
6/11/2007	20	6.92	2.14	22.5
6/12/2007	18	6.7	2.56	23.5
6/13/2007	18	6.69	2.48	23
6/14/2007	19	6.9	2.35	23.2
6/15/2007	18	6.9	1.3	22.8
6/18/2007	19	7.02	1.78	22.8
6/19/2007	19	6.99	1.83	23.4
6/20/2007	20	6.92	1.65	23.2
6/21/2007	20	6.83	1.51	23.8
6/25/2007	21	6.98	1.74	24.4
6/26/2007	21	6.77	1.62	23.9
6/27/2007	21	6.76	1.58	24.6
6/28/2007	21	6.75	1.62	25.1

6/29/2007	21	6.75	1.85	25.6
7/2/2007	22	6.75	1.62	26.3
7/3/2007	22	7.06	1.71	21
7/5/2007	21	6.86	1.96	16.7
7/6/2007	22	6.78	1.95	21
7/9/2007	22	6.71	2.53	24.3
7/10/2007	22	6.74	2.33	24.9
7/11/2007	22	6.68	2.41	25.3
7/12/2007	22	6.76	2.38	25.5
7/13/2007	22	6.7	2.2	26.2
7/16/2007	23	6.98	2.21	22.6
7/17/2007	24	6.87	2.7	23.2
7/18/2007	24	6.8	3.36	24.7
7/19/2007	25	6.81	3.11	25.8
7/20/2007	24	6.74	3.09	25.9
7/23/2007	24	6.83	2.68	21.3
7/24/2007	23	6.86	1.72	24.4
7/25/2007	24	6.87	2.59	24.6
7/26/2007	23	6.74	3.04	24.7
7/27/2007	23	6.74	2.88	24.8
7/31/2007	24	6.67	2.18	23.7
8/1/2007	24	6.67	2.51	24.2
8/2/2007	25	6.66	2.41	24.2
8/3/2007	25	6.66	2.37	23.9
8/6/2007	26	6.68	1.92	20.6
8/7/2007	25	6.75	1.52	17.2
8/8/2007	25	6.75	2.02	16.8
8/9/2007	25	6.71	2.47	20.8
8/10/2007	25	6.73	2.32	22.3
8/13/2007	23	6.72	2.37	20.9
8/14/2007	23	6.7	2.71	22.1
8/15/2007	23	6.68	2.58	22.3
8/16/2007	24	6.77	2.64	21.7
8/17/2007	24	6.67	2.53	21.7
8/20/2007	22	6.75	1.75	16.8
8/21/2007	22	6.91	1.4	16.8
8/22/2007	21	6.87	1.17	17.3
8/23/2007	21	6.85	1.45	16.3
8/24/2007	21	6.87	1.53	15.8
8/27/2007	21	6.69	2.37	20.1
8/28/2007	22	6.67	2.2	17.8

8/29/2007	22	6.67	2.25	17.7
8/30/2007	23	6.69	1.96	17.6
8/31/2007	23	6.72	2.03	17.7
9/4/2007	23	7	1.65	15.6
9/5/2007	22	6.84	1.41	16.2
9/6/2007	22	6.85	1.36	15.8
9/7/2007	22	6.93	1.19	15.4
9/10/2007	22	6.73	1.64	17.1
9/11/2007	22	6.78	1.33	16.7
9/12/2007	21	6.9	0.79	17.1
9/13/2007	21	6.92	0.86	16.3
9/14/2007	20	6.78	1.09	17.4
9/17/2007	20	6.8	1.16	17.1
9/18/2007	19	6.9	0.99	16.8
9/19/2007	19	6.88	1.01	16.1
9/20/2007	19	6.97	1.55	15.9
9/21/2007	20	6.95	1.29	16.9
9/24/2007	19	6.73	1.34	16.4
9/26/2007	19	6.78	1.31	16.9
9/27/2007	20	6.76	1.26	16.8
9/28/2007	20	6.73	1.25	16.9
10/1/2007	19	6.93	1.27	15.7
10/2/2007	19	6.98	0.98	15.4
10/3/2007	20	6.91	1.02	16.1
10/4/2007	20	6.87	1.26	17.6
10/5/2007	20	6.84	1.47	17.5
10/9/2007	20	6.98	0.94	14.9
10/10/2007	18	6.99	0.98	15.5
10/11/2007	19	6.93	0.79	15.8
10/12/2007	18	6.89	0.87	15.9
10/15/2007	15	6.88	0.85	16.1
10/16/2007	15	6.94	0.96	16.9
10/17/2007	15	6.87	0.87	17.3
10/18/2007	16	6.91	1	16.5
10/19/2007	15	6.88	1.04	20
10/22/2007	15	6.95	1.25	17.3
10/23/2007	15	6.78	1.14	17.4
10/24/2007	15	6.78	1.16	17.3
10/25/2007	15	6.72	1.09	17.2
10/26/2007	15	6.87	1.01	17.7
10/29/2007	14	6.91	0.98	20.1

10/30/2007	13	6.97	0.98	17.7
10/31/2007	13	6.97	1.07	17.4
11/1/2007	15	6.68	1.99	14.9
11/2/2007	15	6.72	0.72	14.8
11/5/2007	13	6.8	1.92	16.4
11/6/2007	13	6.76	1.74	16.9
11/7/2007	13	6.75	1.74	17
11/8/2007	12	6.77	1.82	17
11/9/2007	12	7.92	1.68	29
11/13/2007	10	6.76	1.88	15.2
11/14/2007	10	6.78	2.02	15.3
11/15/2007	11	6.73	1.93	15
11/16/2007	11	6.78	1.9	15.4
11/19/2007	10	6.84	1.72	16.1
11/20/2007	9	6.68	1.63	16
11/21/2007	9	6.87	1.68	15.8
11/27/2007	9	6.79	0.86	15.4
11/28/2007	9	6.81	0.86	15.6
11/29/2007	9	6.78	1.07	16.1
11/30/2007	9	6.8	0.95	16.1
12/3/2007	5	7.21	0.67	21.1
12/4/2007	5	7.31	0.65	21.1
12/5/2007	3	7.23	0.67	21.4
12/6/2007	3	7.17	0.64	21.6
12/7/2007	3	7.13	0.7	21.6
12/10/2007	4	7.02	0.69	23.3
12/11/2007	4	7.03	0.69	23.9
12/12/2007	5	6.86	0.8	24.5
12/13/2007	4	6.93	0.82	22.8
12/14/2007	4	6.92	0.8	22.3
12/17/2007	4	6.78	1.06	26.4
12/18/2007	5	6.77	1.1	25.8
12/19/2007	4	6.65	1.01	25.2
12/20/2007	4	6.81	0.87	22.6
12/21/2007	3	6.96	1.28	22.1
12/24/2007	4	6.8	2	23.1
12/26/2007	3	6.75	2.31	21.6
12/27/2007	5	6.76	1.59	22.1
12/28/2007	3	6.71	2.16	22.6
12/31/2007	6	6.7	2.3	20.1
1/2/2008	3	6.49	2.04	17

1/3/2008	2	6.56	2.23	17.7
1/4/2008	3	6.56	2.08	17.4
1/7/2008	4	6.52	1.73	20.1
1/8/2008	4	6.53	1.94	20.7
1/9/2008	4	6.48	1.68	21
1/10/2008	4	6.44	1.69	20.8
1/11/2008	4	6.49	2.1	21
1/14/2008	4	6.48	1.59	20.1
1/15/2008	5	6.59	1.58	17.6
1/16/2008	4	6.42	1.52	20.4
1/17/2008	4	6.45	1.51	20
1/18/2008	5	6.56	1.49	17.7
1/22/2008	6	6.63	1.57	17
1/23/2008	5	6.42	1.43	17.4
1/25/2008	5	6.58	1.39	17.6
1/28/2008	5	6.42	1.32	17
1/29/2008	5	6.54	1.27	18
1/30/2008	5	6.42	1.24	20.4
1/31/2008	4	6.43	1.2	20.1
2/1/2008	5	6.57	1.22	20
2/4/2008	5	6.47	1.25	20.1
2/5/2008	6	6.55	1.29	17.8
2/6/2008	5	6.49	1.13	20.7
2/7/2008	5	6.47	1.32	20.1
2/8/2008	5	6.49	1.38	17
2/11/2008	7	6.6	1.33	16.8
2/12/2008	5	6.44	1.26	17
2/13/2008	5	6.45	1.24	16.9
2/14/2008	5	6.4	1.28	16.4
2/15/2008	5	6.48	1.38	16.4
2/19/2008	6	6.61	2.54	11.4
2/20/2008	4	6.58	2.1	11.4
2/21/2008	4	6.75	1.92	11.4
2/22/2008	3	6.79	1.84	11.6
2/25/2008	4	6.78	1.26	11.7
2/26/2008	4	6.82	1.21	12
2/27/2008	5	6.79	1.21	12
2/28/2008	3	6.78	1.19	12.2
2/29/2008	4	6.92	1.1	11.9
3/3/2008	4	6.94	0.99	12.4
3/4/2008	6	7.03	1.01	12.8

3/5/2008	5	6.95	1.01	12.2
3/6/2008	5	7.01	0.95	12.6
3/7/2008	5	7.05	0.99	13
3/10/2008	6	7.06	1.2	12
3/11/2008	6	7.12	1.51	12.2
3/12/2008	6	7.02	1.62	11.7
3/13/2008	6	6.98	1.57	11.7
3/14/2008	6	7.02	1.58	11.3
3/17/2008	5	7.02	1.41	11.4
3/18/2008	6	7.09	1.26	12
3/19/2008	6	7.05	1.17	12.3
3/20/2008	6	7.01	1.14	12.4
3/24/2008	6	7.22	1.03	12.7
3/25/2008	6	7.2	1.02	12.8
3/26/2008	7	7.27	0.97	12.6
3/27/2008	7	7.27	0.96	12.8
3/28/2008	8	7.26	0.95	12.7
3/31/2008	7	7.32	0.87	12.6
4/1/2008	8	7.27	0.94	13
4/2/2008	8	7.25	1.07	13.3
4/3/2008	8	7.3	0.94	12.7
4/4/2008	8	7.28	1.09	13.2
4/7/2008	8	7.36	0.96	14
4/8/2008	8	7.32	0.94	14.4
4/9/2008	8	7.3	1.02	13.8
4/10/2008	8	7.37	0.95	14.3
4/11/2008	9	7.39	0.88	14.6
4/14/2008	9	7.21	1.03	13.6
4/15/2008	9	7.32	0.92	14.2
4/16/2008	10	7.25	1.11	14
4/17/2008	10	7.25	1.21	14.1
4/18/2008	11	7.29	1.1	14.2
4/22/2008	12	7.34	1.27	13.8
4/23/2008	11	7.32	1.5	14.7
4/24/2008	13	7.35	1.61	15.2
4/25/2008	14	7.33	1.41	15.5
4/28/2008	14	7.13	1.78	15.6
4/29/2008	15	7.23	1.84	16.8
4/30/2008	14	7.08	1.95	17.2
5/1/2008	13	7.03	2.258	15.2
5/2/2008	13	7.04	2.15	14.7

5/5/2008	13	7.01	1.5	14.2
5/6/2008	12	7.02	1.52	14.5
5/7/2008	12	6.97	1.5	14.6
5/8/2008	12	6.94	1.46	14.7
5/9/2008	13	7.03	1.39	15
5/12/2008	13	6.95	1.22	15.6
5/13/2008	13	7.16	1.01	16.9
5/14/2008	14	7.18	1.01	16.4
5/15/2008	14	7.18	1.1	17.2
5/16/2008	14	7.18	1.03	16.3
5/20/2008	14	7.08	1.02	16.7
5/21/2008	15	7.08	1.07	17
5/22/2008	15	7.26	0.98	16.5
5/23/2008	15	7.23	1.02	16.9
5/27/2008	15	7.28	1.01	17.6
5/28/2008	15	7.32	1.12	17.5
5/29/2008	16	7.28	1.14	17.6
5/30/2008	16	7.31	1.19	17.4
6/2/2008	18	7.26	1.64	20.2
6/3/2008	18	7.12	1.73	21.1
6/4/2008	18	7.19	2.17	21.5
6/5/2008	19	7.17	1.84	20.8
6/6/2008	18	7.04	1.28	21.4
6/9/2008	18	7.08	1.88	22.7
6/10/2008	19	6.95	1.9	22.9
6/11/2008	19	6.94	1.56	23.2
6/12/2008	19	6.94	1.44	23.6
6/13/2008	20	7.02	1.68	22.7
6/16/2008	22	7.03	1.66	20.6
6/17/2008	21	7.01	1.35	20.9
6/18/2008	21	6.98	1.44	20.7
6/19/2008	22	7	1.48	17.7
6/20/2008	21	6.96	1.61	21.3
6/23/2008	21	6.88	2.04	23
6/24/2008	21	6.89	2.13	24.2
6/25/2008	21	6.92	2.06	23.8
6/26/2008	21	6.97	2.08	22.5
6/27/2008	22	6.86	2.41	24.8
7/2/2008	22	6.83	2.59	24.5
7/3/2008	21	6.92	2.13	25
7/7/2008	22	7.02	2.25	20.5

7/8/2008	24	7.01	2.48	22
7/9/2008	23	6.85	3.15	23
7/10/2008	23	6.79	2.94	22.7
7/11/2008	23	6.75	2.98	22.6
7/14/2008	24	6.92	3.22	22.7
7/15/2008	23	6.95	3.28	21.5
7/16/2008	23	6.89	3.62	22.3
7/17/2008	24	6.89	4.03	21.5
7/21/2008	25	7.02	3.81	23.9
7/22/2008	24	6.97	3.64	24.1
7/23/2008	24	6.89	3.32	21.3
7/24/2008	25	7.01	2.43	17.8
7/25/2008	24	6.94	2.57	20.2
7/28/2008	23	6.9	2.6	21
7/29/2008	23	6.96	2.62	21.7
7/30/2008	23	6.84	2.84	21.6
7/31/2008	23	6.85	2.97	22.1
8/1/2008	23	6.84	3.3	23.5
8/5/2008	24	6.92	2.59	23.9
8/7/2008	25	-	-	-
8/8/2008	24	6.76	2.36	23.5
8/11/2008	22	6.39	3.33	24.6
8/12/2008	24	6.91	2.4	23
8/13/2008	23	7.03	2.45	21.3
8/14/2008	22	6.98	2.76	21.1
8/15/2008	22	6.95	3.19	20.6
8/18/2008	22	6.99	3.2	21.2
8/19/2008	23	6.85	3.17	21.6
8/20/2008	22	6.89	3.25	21.5
8/21/2008	22	6.95	2.21	22.1
8/22/2008	22	6.95	2.48	22.8
8/25/2008	22	6.82	3.11	21
8/26/2008	22	6.94	2.46	17.3
8/27/2008	22	6.96	2.25	16.9
8/28/2008	22	7	2.22	17.1
8/29/2008	22	7.08	2.2	20.4
9/2/2008	22	6.97	2.82	17.4
9/3/2008	21	6.91	2.73	17.6
9/4/2008	22	6.65	2.67	14.6
9/5/2008	21	6.97	2.41	16.8
9/8/2008	21	7.04	2.56	17.5

9/9/2008	22	6.87	2.38	20.1
9/10/2008	22	7.02	2.14	21.4
9/11/2008	22	7.06	1.45	21.2
9/12/2008	21	6.95	2.07	21
9/15/2008	20	6.98	2.24	20.4
9/16/2008	20	6.94	2.23	21.6
9/18/2008	19	6.99	2.35	21
9/19/2008	19	7.16	1.85	22
9/22/2008	18	7.07	2.1	20
9/23/2008	17	7.09	1.55	20.6
9/24/2008	17	7.07	1.86	20.8
9/25/2008	16	7.06	1.71	21.4
9/26/2008	16	6.97	1.5	21.2
9/29/2008	16	7.04	1.44	22.7
9/30/2008	16	6.95	1.46	22.8
10/1/2008	17	6.91	1.57	22.9
10/2/2008	17	6.83	1.7	23
10/3/2008	16	6.89	1.58	23
10/6/2008	15	6.96	1.43	20.8
10/7/2008	15	6.87	1.15	20.3
10/8/2008	14	6.92	1.63	21.3
10/9/2008	15	6.9	1.68	21.4
10/10/2008	14	6.92	1.29	22.2
10/14/2008	14	6.73	2.12	21.6
10/15/2008	15	6.86	3.11	21.4
10/16/2008	16	6.85	2.69	22
10/17/2008	15	6.9	2.85	22.2
10/20/2008	12	7.12	2.64	22.2
10/21/2008	12	7.09	2.62	22.4
10/22/2008	11	7.13	2.28	23.1
10/23/2008	11	7.09	1.69	21.9
10/24/2008	10	7.12	2.27	22.4
10/27/2008	10	7.11	2.34	22.7
10/28/2008	10	7.03	2.23	22.9
10/29/2008	10	7.04	0.75	21.7
10/30/2008	9	7.18	1.28	22.2
10/31/2008	9	7.15	1.27	22.7
11/3/2008	8	7.21	1.18	22.4
11/4/2008	8	7.1	1.27	22.8
11/5/2008	8	7.09	1.33	23.6
11/6/2008	10	7.14	1.94	23.5

11/7/2008	8	6.96	1.54	22.3
11/10/2008	9	7.01	1.71	21.8
11/12/2008	9	7.09	1.33	23.9
11/13/2008	8	7.05	2.48	23
11/17/2008	8	6.99	1.78	23.1
11/18/2008	9	7.16	1.28	22.9
11/19/2008	7	7.24	1.41	23.5
11/20/2008	6	7.23	1.3	23
11/21/2008	5	7.16	1.43	23.1
11/24/2008	3	7.38	1.33	22.6
11/25/2008	4	7.34	1.38	22.9
11/26/2008	4	7.37	1.1	22.6
1/2/2009	2	6.6	1.67	14
1/5/2009	2	6.78	1.6	15.2
1/6/2009	3	6.67	1.52	15.6
1/7/2009	2	6.8	1.58	16.1
1/8/2009	2	6.71	1.74	16.1
1/9/2009	3	6.78	1.55	16.4
1/12/2009	3	6.75	1.76	16.3
1/13/2009	3	6.48	1.83	15.6
1/14/2009	2	6.49	1.96	15.6
1/15/2009	2	6.51	1.88	16.4
1/16/2009	2	6.54	1.86	16.6
1/20/2009	3	6.48	2.08	17
1/21/2009	3	6.55	1.69	17.4
1/22/2009	2	6.43	1.8	17.6
1/23/2009	3	6.45	1.85	17.4
1/26/2009	2	6.51	1.75	20.8
1/27/2009	3	6.5	1.76	20
1/28/2009	2	6.46	1.68	20.4
1/29/2009	3	6.5	1.71	20.6
1/30/2009	3	6.51	1.65	21
2/2/2009	3	6.45	1.71	21.4
2/3/2009	3	6.54	1.8	21
2/4/2009	3	6.58	1.84	21
2/5/2009	2	6.52	1.88	20.6
2/6/2009	2	6.43	1.85	20.6
2/9/2009	4	6.63	1.81	20.1
2/10/2009	3	6.38	1.64	20.2
2/11/2009	4	6.4	1.71	20.1
2/12/2009	4	6.58	1.55	20.2

2/13/2009	4	6.58	1.65	20.8
2/17/2009	4	6.65	1.68	16.2
2/19/2009	4	6.52	1.75	17
2/20/2009	4	6.51	1.62	16.8
2/23/2009	5	6.61	1.46	16.8
2/24/2009	4	6.53	1.48	16.4
2/25/2009	5	6.58	1.63	17
2/26/2009	5	6.55	1.62	17.2
2/27/2009	5	6.47	1.77	16.2
3/2/2009	4	6.52	1.7	16.4
3/3/2009	5	6.58	1.64	16
3/4/2009	4	6.55	1.5	16.6
3/5/2009	4	6.58	1.46	16.2
3/6/2009	5	-	-	-
3/9/2009	5	6.67	1.44	16.2
3/10/2009	4	6.5	1.3	16
3/11/2009	5	6.59	1.42	16.4
3/12/2009	5	6.6	1.35	16
3/13/2009	5	6.6	1.29	15.8
3/16/2009	5	6.6	1.43	15
3/17/2009	6	6.73	1.24	14.4
3/18/2009	6	6.74	1.26	14.4
3/19/2009	6	6.79	1.34	14
3/20/2009	7	6.9	1.16	14
3/23/2009	6	6.83	1.25	14.4
3/24/2009	6	6.98	1.31	14.4
3/25/2009	6	7.1	1.22	16
3/26/2009	6	7.02	1.19	14.8
3/27/2009	6	6.98	1.05	15
3/30/2009	7	7.06	1.18	14.6
3/31/2009	7	7.07	1.13	14.8
4/1/2009	7	7.17	1.1	15.4
4/2/2009	9	7.05	1.07	14.8
4/3/2009	8	7.08	0.98	14.6
4/6/2009	8	7.15	1.02	16
4/7/2009	8	7.13	1.1	16.2
4/8/2009	9	7.15	1.12	16.4
4/9/2009	9	7.15	1.35	16.8
4/10/2009	9	7.1	1.29	16.4
4/13/2009	8	7.06	1.39	15.4
4/14/2009	9	7.14	1.25	16

4/16/2009	9	7.08	1.54	15.4
4/17/2009	9	7.14	1.39	15.8
4/21/2009	10	7.15	1.2	14.4
4/22/2009	10	7.14	1.43	15.2
4/23/2009	10	7.15	1.54	14.6
4/24/2009	11	7.1	1.36	14.8
4/27/2009	12	7.12	1.63	14.4
4/28/2009	13	7.11	1.68	15.2
4/29/2009	12	7.18	1.63	15.2
4/30/2009	12	7.16	1.55	14.8
5/1/2009	12	7.14	1.83	14.8
5/4/2009	13	7.06	1.61	14.8
5/5/2009	13	7.02	1.12	15.8
5/6/2009	14	7.09	1.04	18.8
5/7/2009	13	7	1.99	17.6
5/8/2009	14	7.06	2.25	17.8
5/11/2009	14	6.87	2.24	17.4
5/12/2009	14	6.89	2	17.6
5/13/2009	14	6.86	1.59	17.8
5/14/2009	14	6.87	1.67	17.6
5/15/2009	14	6.99	1.73	20.2
5/18/2009	14	6.95	2.13	20.2
5/19/2009	15	7	2.01	21
5/20/2009	15	7.01	1.8	21.6
5/21/2009	15	7.04	1.95	21.6
5/22/2009	15	7.01	1.68	21.2
5/26/2009	16	7.07	2.21	22.4
5/27/2009	16	7.1	1.66	22.4
5/28/2009	16	7.07	1.89	23.2
5/29/2009	16	7.17	2.5	23
6/1/2009	16	7.05	2.58	23.2
6/2/2009	16	6.95	2.45	23.4
6/3/2009	16	6.94	2.65	23.4
6/4/2009	16	7	2.71	23.6
6/5/2009	16	7.04	2.74	24
6/8/2009	16	6.97	2.87	24
6/9/2009	19	6.99	2.76	23.4
6/10/2009	18	6.84	2.6	23.2
6/11/2009	17	7	2.23	24.2
6/15/2009	17	6.84	2.42	23.8
6/16/2009	17	6.99	2.23	24

6/17/2009	17	6.95	2.32	23.4
6/18/2009	18	6.98	2.15	22
6/19/2009	18	7.07	2.09	21.8
6/22/2009	18	6.96	2.08	21.4
6/23/2009	18	6.93	1.77	23
6/24/2009	18	6.94	1.92	23
6/25/2009	18	6.89	1.75	22.8
6/26/2009	18	7.02	2.06	23
6/29/2009	18	6.71	2.23	22
6/30/2009	18	6.81	2.27	23.4
7/1/2009	18	6.75	2.56	23.2
7/2/2009	18	6.99	2.43	24
7/6/2009	19	6.93	1.98	24.4
7/7/2009	19	6.8	2.29	24.4
7/8/2009	19	6.8	2.27	24.2
7/9/2009	19	6.88	2.21	24.6
7/10/2009	19	6.82	2.19	24.4
7/13/2009	20	6.74	2.47	23.4
7/14/2009	20	6.65	2.46	23
7/15/2009	20	6.79	2.83	23.2
7/16/2009	20	6.74	2.84	22.8
7/17/2009	20	6.9	2.9	23.2
7/20/2009	21	6.77	2.64	23.4
7/21/2009	21	6.78	2.84	23.4
7/22/2009	21	6.84	2.46	23.6
7/23/2009	21	6.9	4.9	24.3
7/24/2009	21	6.79	3.22	22.8
7/27/2009	20	6.72	6	20
7/28/2009	21	6.58	5.14	16.2
7/29/2009	20	6.69	5.93	20
7/30/2009	20	6.67	4.94	20
7/31/2009	20	6.67	4.81	21.4
8/3/2009	20	6.56	3.6	24
8/4/2009	20	6.64	3.99	24.4
8/5/2009	21	6.63	3.59	25.1
8/6/2009	20	6.61	3.69	25.6
8/7/2009	21	6.88	3.77	26.8
8/11/2009	22	6.78	3.57	24.6
8/12/2009	21	6.78	2.75	25.8
8/13/2009	21	6.64	3.92	25
8/14/2009	21	6.75	3.72	25.8

8/17/2009	22	6.65	4.39	26.2
8/18/2009	22	6.56	4.05	26.1
8/19/2009	22	6.55	3.99	26.4
8/20/2009	22	6.59	3.86	26.8
8/21/2009	22	6.49	3.78	27.2
8/24/2009	23	6.62	4.88	25.3
8/25/2009	24	6.67	6.08	28.2
8/26/2009	25	6.78	5.06	25.5
8/27/2009	24	6.67	4.88	25.7
8/28/2009	24	6.77	3.32	26
8/31/2009	23	6.7	3.2	22
9/1/2009	21	6.73	2.89	23.2
9/2/2009	21	6.698	3.3	23.4
9/3/2009	20	6.8	4.1	23.8
9/4/2009	20	6.81	3.16	23.4
9/8/2009	19	6.88	3.3	22.4
9/9/2009	19	6.92	3.07	22.2
9/10/2009	19	6.92	1.75	22.6
9/11/2009	19	7	1.85	22
9/14/2009	18	6.97	2.1	20.6
9/15/2009	18	6.71	2.54	20.8
9/16/2009	18	6.79	2.48	21.2
9/17/2009	18	6.8	2.27	21.2
9/18/2009	18	6.88	1.79	21.5
9/21/2009	17	6.97	1.99	20.2
9/22/2009	17	6.9	1.34	17
9/23/2009	17	6.95	2.41	17.6
9/24/2009	18	6.9	2.4	20
9/25/2009	16	6.75	2.63	17.4
9/28/2009	17	6.87	2.17	21.2
9/29/2009	17	6.72	2.6	22.2
9/30/2009	17	6.67	2.98	22.2
10/1/2009	16	6.98	1.75	21.6
10/2/2009	15	6.92	1.5	21
10/5/2009	15	6.89	2.77	20
10/7/2009	15	6.86	2.58	21.2
10/8/2009	15	7.11	2.31	20.4
Date	Temp (°C)	pH	Turbidity (ntu)	Alkalinity >20/<20 Method
10/9/2009	15	6.97	2.2	20.4
10/13/2009	13	6.99	2.58	13.9

10/14/2009	12	6.82	1.86	17.8
10/15/2009	12	7.04	1.8	17.8
10/16/2009	10	6.95	1.55	17.6
10/19/2009	9	6.99	1.88	16.2
10/20/2009	9	6.91	1.46	17
10/21/2009	9	6.9	1.74	17
10/22/2009	9	6.83	1.82	16.8
10/23/2009	8	6.9	1.8	17
10/26/2009	9	6.75	1.95	15.4
10/27/2009	9	6.89	2.55	17
10/28/2009	9	6.83	2.08	17.2
10/29/2009	9	6.94	1.68	16.4
10/30/2009	10	6.9	1.4	17.8
11/2/2009	10	6.9	1.16	17.4
11/3/2009	10	6.92	1.61	17
11/4/2009	10	6.9	1.25	17.2
11/5/2009	10	7.04	1.29	17.4
11/6/2009	10	6.87	1.15	16.8
11/9/2009	9	6.85	1.69	16.4
11/10/2009	10	6.8	1.41	17.6
11/12/2009	8	6.77	1.6	17.2
11/13/2009	9	6.97	1.14	17.8
11/16/2009	9	7.12	1.3	20
11/17/2009	8	6.81	1.69	17.2
11/18/2009	8	6.95	1.62	17.6
11/19/2009	8	6.84	1.6	17.6
11/20/2009	9	6.87	1.67	18
11/23/2009	9	6.97	1.42	17.8
11/24/2009	9	6.75	1.3	17.6
11/25/2009	8	6.7	1.48	17.6
11/30/2009	7	6.84	1.3	15.8
12/1/2009	7	6.94	1.25	17.4
12/2/2009	6	6.85	1.4	17.2
12/3/2009	7	6.73	1.26	16.8
12/4/2009	7	6.88	1.51	16.5
12/8/2009	6	6.8	1.58	16
12/9/2009	5	6.82	1.7	16
12/10/2009	4	6.82	1.44	15.8
12/11/2009	3	6.79	1.05	16
12/14/2009	2	6.75	1.6	15.8
12/15/2009	3	6.62	1.67	15.4

12/16/2009	3	6.75	1.63	15.8
12/17/2009	1	6.62	1.6	15
12/18/2009	1	6.7	1.49	15.6
12/21/2009	1	6.68	1.31	16.2
12/22/2009	1	6.55	1.65	15.8
12/23/2009	2	6.65	1.35	16.6
12/28/2009	2	6.61	1.65	15.2
12/29/2009	2	6.62	1.45	17.8
12/30/2009	2	6.52	1.43	17.8
12/31/2009	2	6.56	1.35	17.8

B.1.2 Alkalinity

Date	Raw Water Result (mg/L)	Finished Water Result (mg/L)	Location
4/8/2010	9.4	21.6	Manchester
1/6/2010	17.4	36.6	West St
1/24/2002	15.6	NM	West St
1/30/2002	NM	24.4	West St
2/6/2002	14.2	22	West St
3/6/2002	13.8	15.4	West St
4/3/2002	17	16.2	West St
5/2/2002	17	21.8	West St
6/6/2002	20	28.4	West St
7/2/2002	20.4	29.2	West St
8/7/2002	20.2	33.2	West St
9/4/2002	17	25.6	West St
10/3/2002	16.8	26.2	West St
11/6/2002	16.6	22	West St
12/2/2002	17	22.2	West St
1/15/2003	14.6	33	West St
2/5/2003	16.8	39.4	West St
3/13/2003	13.6	30.8	West St
4/3/2003	11.6	21	West St
5/8/2003	13.2	22	West St
6/6/2003	17	27.2	West St
7/11/2003	22.8	40.6	West St
8/7/2003	23.2	44	West St
9/4/2003	21	34.6	West St
10/2/2003	17.6	31.2	West St
11/6/2003	16.8	25.6	West St
12/2/2003	16.8	22.8	West St
1/7/2004	12.8	23	West St
2/5/2004	18.4	43.4	West St
3/4/2004	14	27.4	West St
4/8/2004	14.4	20.4	West St
5/6/2004	14	23.8	West St
6/2/2004	22	31.2	West St
7/8/2004	20	30.4	West St
8/5/2004	21.4	34.2	West St
10/8/2004	16.2	30.2	West St
11/3/2004	15.8	24.4	West St
Date	Raw Water Result (mg/L)	Finished Water Result (mg/L)	Location
12/1/2004	17	-	West St

1/6/2005	17.6	35	West St
2/3/2005	20	40.6	West St
3/3/2005	16.8	32.4	West St
4/7/2005	11.6	25.8	West St
5/5/2005	14.8	22.8	West St
5/17/2005	15.8	22	West St
6/2/2005	16.6	24.6	West St
7/7/2005	22	32.8	West St
8/4/2005	16.4	27.8	West St
9/8/2005	20.1	32.5	West St
10/6/2005	15.5	25.5	West St
11/3/2005	13.8	26.3	West St
12/8/2005	14.8	23.1	West St
1/4/2006	15.6	36.3	West St
2/1/2006	12.7	21.8	West St
3/2/2006	14.7	23.2	West St
4/6/2006	14.5	20.2	West St
5/3/2006	17.6	27.8	West St
6/8/2006	17	30.5	West St
7/6/2006	21.3	40.6	West St
8/2/2006	22	37.6	West St
9/6/2006	20.6	31.9	West St
10/5/2006	16	30.7	West St
11/1/2006	15	23.8	West St
1/3/2007	17.6	23.1	West St
2/7/2007	22.5	31.4	West St
3/8/2007	15.3	28.1	West St
4/4/2007	13.4	18	West St
5/2/2007	13.5	22.7	West St
6/6/2007	21.6	33.3	West St
7/5/2007	17.6	30.2	West St
8/3/2007	24.2	40.6	West St
9/6/2007	15.4	29.6	West St
10/4/2007	16.2	29.9	West St
11/7/2007	21.2	30.8	West St
12/6/2007	21.4	26.7	West St
2/6/2008	17.8	41.5	West St
3/5/2008	12.7	22.2	West St
Date	Raw Water Result (mg/L)	Finished Water Result (mg/L)	Location
4/3/2008	16.5	17	West St
5/7/2008	14.4	25	West St

6/5/2008	21.8	29.4	West St
7/17/2008	22.2	35.6	West St
8/6/2008	24.1	43.1	West St
9/3/2008	17.6	31.2	West St
10/2/2008	23	35.4	West St
11/5/2008	23.7	29.5	West St
12/4/2008	21	27.6	West St
1/8/2009	16.5	28.3	West St
2/5/2009	20.4	40.8	West St
3/5/2009	16.2	32.4	West St
4/2/2009	14.4	20.2	West St
5/7/2009	17.2	22.8	West St
6/4/2009	23.4	32	West St
7/9/2009	23.6	38	West St
8/6/2009	24.4	43.4	West St
9/2/2009	22.8	40.6	West St
10/13/2009	13.6	27	West St
11/4/2009	17.2	25.6	West St
12/2/2009	17.2	26.8	West St
2/3/2010	16.2	36.2	West St
3/3/2010	10.5	15	West St
4/1/2010	12	21.6	West St
May-10	NM	NM	West St
6/2/2010	25	33.5	West St
6/10/2010	3.6	20	West St
7/7/2010	10.2	16.4	West St
8/5/2010	11.4	20.2	West St

B.1.3 Manganese

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
1/5/2004	0.167	0.166	0.033	0.032
*1/8/2004	0.14	0.133	0.029	0.028
*1/12/2004	0.109	0.107	0.032	0.033
*1/15/2004	0.103	0.094	0.021	0.021
*1/20/2004	0.138	0.134	0.024	0.024
*1/26/2004	0.175	0.167	0.039	0.038
*1/30/2004	0.223	0.216	0.046	0.045
2/2/2004	0.261	0.251	0.025	0.024
2/5/2004	0.281	0.264	0.057	0.057
2/12/2004	0.364	0.351	0.083	0.082
2/17/2004	0.326	0.301	0.064	0.063
2/23/2004	0.208	0.189	0.017	0.017
2/26/2004	0.177	0.162	0.018	0.016
3/1/2004	0.145	0.131	0.018	0.015
3/5/2004	0.111	0.083	0.019	0.018
3/9/2004	0.057	0.055	0.012	0.014
3/12/2004	0.047	0.036	0.005	0.008
3/16/2004	0.038	0.024	0.012	0.012
3/22/2004	0.036	0.022	0.009	0.001
3/26/2004	0.027	0.012	0.022	0.018
4/1/2004	0.019	0.002	0.012	0.013
4/5/2004	0.072	0.054	0.03	0.03
4/8/2004	0.069	0.049	0.021	0.021
4/12/2004	0.06	0.042	0.031	0.032
4/30/2004	0.091	0.042	0.021	0.021
5/6/2004	0.082	0.012	0.003	0.005
5/10/2004	0.114	0.045	0.005	0
5/11/2004	0.115	0.047	0	0
5/14/2004	0.174	0.087	0.006	0.003
5/18/2004	0.231	0.151	0.01	0.01
5/21/2004	0.392	0.33	0.03	0.031
5/25/2004	0.288	0.246	0	0
5/28/2004	0.245	0.19	0.008	0.007
6/3/2004	0.29	0.152	0	0
6/9/2004	0.355	0.137	0.012	0.012
6/11/2004	0.314	0.147	0	0.002
6/17/2004	0.349	0.197	0	0
6/25/2004	0.442	0.318	0.023	0.022

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
6/29/2004	0.425	0.289	0.021	0.021
7/2/2004	0.602	0.449	0.024	0.024
7/6/2004	0.789	0.586	0.046	0.045
7/9/2004	1.008	0.79	0.052	0.055
7/12/2004	1.126	0.899	0.123	0.119
7/16/2004	0.701	0.581	0.103	0.1
7/20/2004	0.917	0.824	0.065	0.065
7/23/2004	1.046	0.836	0.16	0.156
7/26/2004	0.599	0.515	0.163	0.156
7/29/2004	0.629	0.56	0.115	0.117
8/3/2004	0.646	0.597	0.078	0.077
8/6/2004	0.455	0.373	0.078	0.077
8/10/2004	0.328	0.268	0.011	0.01
8/13/2004	0.317	0.25	0.027	0.027
8/17/2004	0.614	0.582	0.075	0.073
8/23/2004	0.652	0.562	0.015	0.014
8/26/2004	0.543	0.485	0.007	0.007
8/30/2004	0.293	0.234	0.005	0.008
9/2/2004	0.419	0.285	0.006	0.007
9/7/2004	0.42	0.337	0.01	0.012
9/10/2004	0.556	0.417	0.007	0.01
9/14/2004	0.227	0.103	0.012	0.014
9/17/2004	0.352	0.224	0.015	0.015
9/21/2004	0.215	0.13	0.002	0.002
9/24/2004	0.224	0.055	0.023	0.022
9/28/2004	0.186	0.056	0.023	0.023
10/4/2004	0.158	0.076	0.006	0.006
10/7/2004	0.088	0.028	0	0
10/14/2004	0.079	0.036	0	0
10/18/2004	0.066	0.02	0	0
10/22/2004	0.056	0.027	0	0
10/26/2004	0.044	0.013	0	0
11/1/2004	0.049	0.051	0	0
11/5/2004	0.047	0.016	0	0
11/9/2004	0.051	0.013	0	0
11/15/2004	0.042	0.028	0	0
11/24/2004	0.042	0.024	0	0
11/30/2004	0.062	0.044	0	0
12/7/2004	0.043	0.03	0	0
12/14/2004	0.067	0.057	0	0

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
12/17/2004	0.07	0.062	0	0
12/22/2004	0.068	0.059	0	0
12/28/2004	0.15	0.141	0	0
1/4/2005	0.183	0.176	0	0
1/7/2005	0.23	0.21	0	0
1/13/2005	0.33	0.316	0	0
1/20/2005	0.289	0.278	0	0
1/25/2005	0.331	0.325	0	0
1/28/2005	0.301	0.291	0	0
2/1/2005	0.0404	0.386	0.008	0.008
2/8/2005	0.579	0.571	0.002	0.003
2/10/2005	0.514	0.483	0	0
2/15/2005	0.472	0.472	0	0
2/25/2005	0.397	0.376	0	0.002
3/1/2005	0.324	0.318	0.102	0.1
3/4/2005	0.322	0.301	0.046	0.044
3/11/2005	0.281	0.265	0.051	0.051
3/15/2005	0.264	0.263	0.057	0.056
3/18/2005	0.32	0.308	0.05	0.049
3/22/2005	0.305	0.306	0.056	0.056
3/29/2005	0.275	0.262	0.025	0.025
3/31/2005	0.238	0.228	0.027	0.032
4/5/2005	0.197	0.192	0.029	0.032
4/12/2005	0.147	0.129	0.003	0.005
4/21/2005	0.055	0.012	0	0
4/26/2005	0.044	0.017	0	0
5/3/2005	0.081	0.045	0	0
5/10/2005	0.077	0.054	0.01	0.009
5/17/2005	0.036	0.006	0	0
5/24/2005	0.084	0.049	0	0
6/2/2005	0.057	0.009	0	0
6/7/2005	0.109	0.054	0	0
6/14/2005	0.866	0.651	0.069	0.061
6/21/2005	0.413	0.33	0.03	0.029
6/28/2005	0.392	0.295	0.032	0.033
7/1/2005	0.564	0.433	0.021	0.02
7/7/2005	0.467	0.371	0.073	0.07
7/19/2005	0.824	0.602	0.039	0.038
7/22/2005	1.01	0.741	0.102	0.017
7/25/2005	0.861	0.576	0.022	0.017

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
7/29/2005	0.693	0.5	0.029	0.022
8/1/2005	0.337	0.192	0	0
8/4/2005	0.587	0.353	0	0
8/8/2005	0.539	0.273	0	0
8/11/2005	0.651	0.32	0	0
8/15/2005	0.451	0.243	0.018	0.014
8/18/2005	0.768	0.549	0.036	0.028
8/22/2005	0.487	0.361	0	0
8/25/2005	0.601	0.508	0.04	0.039
8/29/2005	0.354	0.241	0	0
9/1/2005	0.487	0.356	0	0
9/9/2005	0.463	0.349	0.032	0.033
9/22/2005	0.325	0.338	-	-
10/13/2005	0.18	0.095	0	0
10/27/2005	0.192	0.159	0	0
11/4/2005	0.128	0.109	0.002	0
11/9/2005	0.146	0.128	0	0
11/15/2005	0.139	0.119	0.001	0
11/22/2005	0.097	0.071	0	0
12/2/2005	0.083	0.071	0	0
12/6/2005	0.136	0.119	0	0
12/9/2005	0.128	0.117	0	0
12/13/2005	0.206	0.186	0.002	0.013
12/20/2005	0.338	0.319	0.007	0.006
*12/27/2005	0.461	0.434	0	0
1/3/2006	0.425	0.394	0.013	0.011
1/6/2006	0.478	0.449	0.016	0.012
1/9/2006	0.384	0.362	0.022	0.021
1/12/2006	0.391	0.359	0.023	0.019
*1/17/2006	0.38	0.346	0.017	0.01
1/20/2006	0.198	0.179	0.013	0.013
1/23/2006	0.143	0.126	0.002	0
1/26/2006	0.139	0.121	0.004	0.004
1/30/2006	0.108	0.097	0.004	0
2/2/2006	0.101	0.096	0.001	0.001
2/6/2006	0.088	0.077	0.002	0.001
*2/13/2006	0.063	0.049	0.006	0.006
2/17/2006	0.062	0.05	0.001	0
2/24/2006	0.055	0.044	0	0
2/27/2006	0.061	0.053	0	0

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
*3/3/2006	0.042	0.028	0	0
*3/6/2006	0.043	0.026	0	0
3/9/2006	0.036	0.014	0.004	0.003
3/13/2006	0.032	0.007	0	0
3/16/2006	0.035	0.009	0.002	0.002
*3/20/2006	0.022	0	0.001	0
3/23/2006	0.024	0.002	0.008	0
3/27/2006	0.029	0.003	0	0
3/30/2006	0.023	0	0.001	0
4/3/2006	0.024	0	0.001	0.001
4/7/2006	0.037	0.002	0	0
4/10/2006	0.047	0.011	0	0
4/13/2006	0.058	0.013	0	0
4/20/2006	0.053	0	0	0
4/24/2006	0.07	0.006	0	0
4/27/2006	0.097	0.009	0.001	0.001
5/1/2006	0.074	0	0.002	0
5/5/2006	0.107	0.035	0.002	0.001
5/8/2006	0.09	0	0.001	0
5/11/2006	0.081	0.002	0	0
5/15/2006	0.276	0.197	0.001	0.001
5/18/2006	0.193	0.115	0.031	0
5/22/2006	0.186	0.088	0	0
5/25/2006	0.233	0.109	0	0
6/5/2006	0.487	0.307	0.017	0.015
6/8/2006	0.641	0.574	0.015	0.014
6/13/2006	0.481	0.432	0.026	0.025
6/15/2006	0.531	0.458	0.041	0.039
6/20/2006	0.717	0.572	0.066	0.065
6/23/2006	0.874	0.731	0.076	0.074
6/27/2006	0.858	0.737	0.077	0.074
6/29/2006	1.087	0.983	0.14	0.133
7/7/2006	1.561	1.477	1.268	1.231
7/10/2006	1.745	1.624	1.787	1.743
7/11/2006	1.71	1.548	1.919	1.865
7/13/2006	1.177	-	-	-
7/14/2006	1.69	1.609	-	-
7/17/2006	1.521	1.39	0.207	0.202
7/18/2006	1.606	1.321	0.162	0.154
7/21/2006	1.421	1.295	0.173	0.166

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
7/24/2006	1.387	1.233	-	-
7/25/2006	1.095	0.894	0.112	0.105
7/28/2006	0.871	0.702	0.055	0.051
7/31/2006	0.896	0.713	0.038	0.037
8/4/2006	0.88	0.63	0.038	0.035
8/7/2006	1.051	0.745	0.038	0.038
8/11/2006	0.738	0.633	0.03	0.025
8/15/2006	0.58	0.434	0.013	0.013
8/17/2006	0.529	0.387	0.008	0.008
8/21/2006	0.719	0.495	0.023	0.021
8/24/2006	0.575	0.419	0.029	0.029
8/28/2006	0.633	0.553	0.008	0.008
8/31/2006	0.432	0.325	0.008	0.008
9/5/2006	0.319	0.188	0.003	0.002
9/7/2006	0.262	0.105	0.002	0.002
9/11/2006	0.281	0.108	0.002	0.002
9/15/2006	0.266	0.22	0.003	0.002
9/18/2006	0.265	0.178	0.002	0.002
9/22/2006	0.222	0.076	0.002	0.001
9/25/2006	0.183	0.02	0.002	0.002
9/28/2006	0.171	0.051	0.002	0.001
10/3/2006	0.176	0.1	0.001	0.001
10/13/2006	0.11	0.056	0	0
10/17/2006	0.1	0.053	0.002	0
10/19/2006	0.099	0.052	0.001	0.001
10/24/2006	0.082	0.044	0	0
10/27/2006	0.06	0.024	0.001	0.001
10/30/2006	0.038	0.012	0	0
11/3/2006	0.046	0.018	0.001	0.001
11/6/2006	0.05	0.035	0.006	0.003
11/9/2006	0.058	0.04	0.004	0.004
11/13/2006	0.06	0.041	0	0
11/22/2006	0.183	0.154	0.001	0
11/27/2006	0.13	0.091	0.001	0.001
12/4/2006	0.081	0.048	0.002	0
12/8/2006*	0.043	0.016	0	0
12/12/2006	0.035	0.01	0.001	0.001
12/15/2006	0.037	0.01	0.002	0.003
12/18/2006	0.04	0.009	0.001	0.001
12/21/2006	0.038	0.008	0.001	0

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
12/29/2006	0.03	0	0.001	0
1/2/2007	0.025	0.005	0	0
1/8/2007	0.029	0.003	0.001	0.002
1/11/2007	0.025	0.003	0	0
1/16/2007	0.026	0.003	0.001	0.001
1/19/2007	0.03	0.012	0	0
1/22/2007	0.026	0.011	0	0
1/26/2007	0.03	0.015	0	0.001
1/29/2007	0.033	0.016	0	0
2/1/2007	0.035	0.021	0	0
2/5/2007	0.037	0.019	0	0
2/9/2007	0.069	0.008	0.001	0.001
2/12/2007	0.029	0.011	0	0
2/15/2007*	0.033	0.018	0	0
2/23/2007	0.116	0.076	0.002	0.002
2/27/2007	0.094	0.075	0.083	0.066
3/1/2007	0.092	0.081	0.003	0.003
3/5/2007	0.12	0.107	0.002	0
3/8/2007	0.135	0.119	0.003	0.003
3/12/2007	0.147	0.133	0.002	0.002
3/15/2007	0.141	0.122	0.002	0.002
3/19/2007	0.061	0.048	0	0
3/22/2007	0.056	0.046	0.002	0.002
3/26/2007	0.047	0.037	0.002	0.002
3/29/2007	0.046	0.039	0.006	0
4/2/2007	0.04	0.027	0.002	0.002
4/6/2007	0.029	0.02	0.004	0.004
4/9/2007	0.03	0.019	0.008	0.008
4/12/2007	0.02	0.009	0.008	0.008
4/17/2007	0.054	0.037	0.008	0.008
4/19/2007	0.054	0.033	0.006	0.006
4/23/2007	0.045	0.032	0.011	0.008
4/26/2007	0.043	0.014	0.01	0.009
5/4/2007	0.041	0.003	0.003	0.003
5/7/2007	0.07	0.013	0.008	0.007
5/10/2007	0.127	0.039	0.004	0.004
5/14/2007	0.11	0.036	0.008	0.008
5/17/2007	0.121	0.065	0.002	0
5/21/2007	0.21	0.169	0.019	0.017
5/25/2007	0.181	0.143	0.015	0.015

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
6/1/2007	0.333	0.259	0.024	0.024
6/4/2007	0.569	0.439	0.032	0.03
6/7/2007	0.528	0.39	0.033	0.033
6/11/2007	0.811	0.608	0.046	0.046
6/19/2007	0.611	0.364	0.036	0.036
6/26/2007	0.569	0.384	0.036	0.035
6/28/2007	0.598	0.406	0.043	0.043
7/2/2007	0.644	0.434	0.062	0.061
7/9/2007	1.059	0.721	0.062	0.06
7/12/2007	1.37	1.096	0.188	0.183
7/16/2007	1.336	1.061	0.124	0.123
7/23/2007	1.033	0.81	0.087	0.083
7/30/2007	0.954	0.816	0.077	0.072
8/6/2007	0.881	0.736	0.101	0.091
8/9/2007	0.821	0.652	0.044	0.042
8/13/2007	0.635	0.516	0.015	0.014
8/16/2007	0.765	0.602	0.013	0.012
8/20/2007	0.396	0.28	0.023	0.023
8/23/2007	0.346	0.226	0.014	0.012
8/27/2007	0.483	0.271	0.019	0.02
9/13/2007	0.318	0.276	0.007	0.003
9/17/2007	0.258	0.193	0.331	0.298
9/24/2007	0.185	0.089	0.008	0.007
9/27/2007	0.176	0.075	0.009	0.009
10/1/2007	0.177	0.081	0.006	0.004
10/9/2007	0.108	0.023	0.004	0.003
10/12/2007	0.11	0.04	0.002	0.002
10/15/2007	0.08	0.014	0.004	0.001
10/19/2007	0.085	0.013	0.006	0.006
10/23/2007	0.098	0.016	0.003	0.003
10/25/2007	0.094	0.014	0.004	0.004
10/29/2007	0.089	0.029	0.001	0
11/8/2007	0.054	0.022	0.001	0.001
11/15/2007	0.032	0.01	0.004	0.004
11/21/2007	0.039	0.021	0.006	0.005
11/29/2007	0.029	0.017	0.006	0.006
12/3/2007	0.035	0.023	0.004	0
12/10/2007	0.522	0.057	0.006	0.006
12/13/2007*	0.133	0.084	0.018	0.018
12/20/2007	0.225	0.203	0.073	0.073

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
12/28/2007*	0.782	0.753	0.125	0.123
1/4/2008	0.798	0.772	0.179	0.177
1/8/2008	0.871	0.85	0.233	0.227
1/10/2008	0.913	0.885	0.226	0.222
1/14/2008	0.8	0.781	0.237	0.236
1/17/2008	0.758	0.735	0.211	0.21
1/24/2008	0.434	0.418	0.165	0.157
1/28/2008*	0.424	0.411	0.339	0.336
1/31/2008*	0.387	0.372	0.114	0.11
2/4/2008	0.337	0.32	0.09	0.089
2/7/2008	0.303	0.294	0.098	0.091
2/12/2008	0.301	0.288	0.078	0.077
2/28/2008	0.128	0.121	0.04	0.038
3/3/2008*	0.093	0.082	0.025	0.023
3/6/2008	0.073	0.064	0.018	0.016
3/10/2008*	0.075	0.064	0.016	0.015
3/17/2008	0.122	0.085	0.017	0.017
3/20/2008	0.084	0.07	0.016	0.015
3/24/2008	0.072	0.047	0.01	0.009
3/27/2008	0.045	0.024	0.011	0.011
3/31/2008	0.04	0.02	0.005	0.005
4/7/2008	0.032	0.012	0.005	0.004
4/14/2008	0.024	0.008	0.005	0.005
4/28/2008	0.087	0.007	0.004	0.003
5/6/2008	0.146	0.096	0.015	0.014
5/12/2008	0.196	0.14	0.02	0.019
5/20/2008	0.135	0.073	0.011	0.011
5/30/2008	0.084	0.021	0.007	0.003
6/10/2008	0.385	0.158	0.025	0.025
6/16/2008	0.462	0.293	0.047	0.043
6/23/2008	0.733	0.453	0.054	0.051
7/2/2008	1.177	0.468	0.463	0.415
7/7/2008	0.841	0.495	0.795	0.737
7/8/2008	1.135	0.717	-	-
7/10/2008	1.261	0.618	0.8	0.783
7/14/2008	1.283	0.707	0.972	0.955
7/17/2008	1.152	0.53	0.772	0.756
7/21/2008	1.301	0.962	0.805	0.793
7/24/2008	0.685	0.497	0.711	0.598
7/28/2008	0.804	0.641	0.192	0.19

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
7/29/2008	0.798	0.626	-	-
7/30/2008	0.946	0.781	-	-
7/31/2008	1.095	0.889	0.104	0.103
8/1/2008	1.227	0.913	-	
8/7/2008	0.982	0.887	0.152	0.144
8/12/2008	0.912	0.76	0.083	0.08
8/15/2008	0.752	0.534	0.029	0.023
8/19/2008	0.868	0.62	0.013	0.01
8/20/2008	0.012	0.01	-	-
8/21/2008	0.048	0.048	-	-
8/22/2008	0.073		-	-
8/25/2008	0.618	0.393	0.136	0.128
8/28/2008	0.4	0.237	0.06	0.056
9/2/2008	0.43	0.149	0.131	0.124
9/8/2008	0.404	0.16	0.044	0.043
9/12/2008	0.51	0.368	0.055	0.052
9/15/2008	0.443	0.262	0.073	0.07
9/22/2008	0.355	0.152	0.024	0.022
9/26/2008	0.219	0.137	0.027	0.016
10/3/2008	0.429	0.29	0.018	0.017
10/6/2008	0.258	0.184	0.02	0.018
10/14/2008	0.256	0.229	0.045	0.016
10/20/2008	0.188	0.134	0.012	0.01
10/23/2008	0.107	0.072	0	0
10/28/2008	0.178	0.14	0	0
11/3/2008	0.082	0.045	0	0
11/12/2008	0.145	0.094	0	0
11/17/2008	0.191	0.135	0.011	0
11/20/2008	0.097	0.058	0	0
12/1/2008	0.073	0.048	0.003	0.002
12/11/2008	0.091	0.068	0.01	0.008
12/15/2008	0.098	0.083	0.002	0
12/18/2008	0.114	0.101	-	-
12/24/2008	0.103	0.095	0.004	0.003
12/31/2008	0.15	0.139	0.008	0.008
1/5/2009	0.137	0.128	0.006	0.005
1/12/2009	0.244	0.221	0.012	0.012
1/16/2009	0.253	0.24	0	0
1/22/2009	0.396	0.371	0.018	0.016
1/26/2009	0.543	0.506	0.019	0.017

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
1/29/2009	0.627	0.594	0.012	0.01
2/2/2009	0.641	0.62	0.053	0.047
2/9/2009	0.575	0.524	0.042	0.037
2/17/2009	0.435	0.409	0.046	0.043
2/20/2009	0.413	0.373	0.028	0.025
2/23/2009	0.376	0.342	0.08	0.076
3/3/2009	0.265	0.237	0.036	0.035
3/6/2009	0.197	0.175	0.04	0.02
3/9/2009	0.185	0.166	0.013	0.012
3/16/2009	0.127	0.104	0.002	0
3/23/2009	0.046	0.027	0	0
3/30/2009	0.022	0	0	0
4/6/2009	0.027	0.006	0	0
4/13/2009	0.047	0.028	0	0
4/21/2009	0.045	0.01	0	0
4/27/2009	0.065	0	0	0
5/4/2009	0.032	0	0	0
5/11/2009	0.191	0.098	0.008	0.008
5/18/2009	0.256	0.13	0	0
5/26/2009	0.295	0.11	0.009	0.008
6/1/2009	0.355	0.115	0.002	0
6/8/2009	0.45	0.194	0.019	0.016
6/15/2009	0.598	0.257	0.024	0.024
6/22/2009	0.35	0.215	0.031	0.031
6/30/2009	0.477	0.265	0.043	0.037
7/6/2009	0.641	0.458	0.107	0.102
7/10/2009	0.693	0.186		
7/13/2009	0.525	0.416	0.135	0.13
7/17/2009	0.589	0.289	0.095	0.096
7/23/2009	0.816	0.56	0.164	0.154
7/27/2009	0.559	0.366	0.058	0.052
7/31/2009	0.986	0.617	0.146	0.143
8/3/2009	1.435	1.125	0.568	0.53
8/4/2009	1.736	2.055	0.28	0.779
8/5/2009	1.76	1.312	0.669	0.618
8/6/2009	1.886	1.434	0.493	0.472
8/7/2009	1.926	1.451	-	-
8/8/2009	1.818	1.109	-	-
8/9/2009	2.476	0.715	-	-
8/10/2009	1.32	0.834	0.171	0.163

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
8/11/2009	0.954	0.86	-	-
8/12/2009	0.783	0.58	-	-
8/13/2009	1.272	1.094	-	-
8/14/2009	1.338	1.086	0.156	0.154
8/15/2009	0.147	0.128	-	-
8/16/2009	0.885	0.7	-	-
8/17/2009	1.452	1.133	0.114	0.106
8/18/2009	1.469	1.123	-	-
8/19/2009	1.713	1.448	-	-
8/20/2009	1.697	1.443	0.109	0.106
8/21/2009	1.73	1.504	-	-
8/22/2009	1.885	1.34	-	-
8/23/2009	1.47	1.152	-	-
8/24/2009	1.403	1.047	0.061	0.06
8/25/2009	1.821	1.247	-	-
8/26/2009	1.407	0.864	-	-
8/27/2009	1.367	0.775	0.043	0.042
8/28/2009	1.205	0.928	-	-
8/29/2009	0.83	0.625	-	-
8/30/2009	1.117	0.9	-	-
9/1/2009	1.2	0.55	0.015	0.003
9/3/2009	0.903	0.45	0.011	0.012
9/4/2009	0.786	0.424	-	-
9/5/2009	0.546	0.393	-	-
9/6/2009	0.601	0.501	-	-
9/7/2009	1.137	0.492	-	-
9/8/2009	0.583	0.336	0.033	0.021
9/10/2009	0.663	0.504	0.003	0
9/17/2009	0.43	0.211	0.012	0.011
9/22/2009	0.164	0.07	0.017	0.017
9/24/2009	0.281	0.13	0.014	0.012
9/29/2009	0.42	0.256	0.005	0.005
10/1/2009	0.237	0.179	0.001	0
10/5/2009	0.254	0.154	0	0
10/8/2009	0.183	0.114	0	0
10/13/2009	0.111	0.091	0	0
10/22/2009	0.079	0.057	0	0
10/27/2009	0.118	0.052	0	0
11/3/2009	0.071	0.034	0	0
11/9/2009	0.096	0.077	0	0

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
11/17/2009	0.06	0.045	0	0
11/23/2009	0.064	0.048	0	0
12/1/2009	0.04	0.024	0	0
12/8/2009	0.054	0.048	0	0
12/10/2009	0.047	0.035	-	-
12/15/2009	0.112	0.075	0	0
12/21/2009	0.045	0.035	0	0
12/28/2009	0.108	0.092	0	0
1/5/2010	0.123	0.108	0	0
1/12/2010	0.204	0.171	0	0
1/19/2010	0.305	0.281	0	0
1/27/2010	0.382	0.278	0	0
2/2/2010	0.321	0.28	0	0
2/8/2010	0.14	0.126	0	0
2/16/2010	0.085	0.075	0	0
2/23/2010*	0.006	0	0	0
3/2/2010*	0.006	0.006	0	0
3/8/2010*	0	0	0	0
3/16/2010*	0	0	0	0
3/22/2010*	0	0	0	0
3/29/2010	0	0	0	0
4/6/2010	0.112	0.086	0.001	0
4/12/2010	0.098	0.066	0	0
4/21/2010	0.08	0.024	0	0
4/26/2010	0.125	0	0	0
5/3/2010	0.103	0.045	0.01	0.004
5/10/2010	0.127	0.099	0	0
5/18/2010	0.047	0	0	0
5/24/2010	0.021	0	0	0
6/1/2010	0.548	0.115	0.006	0.006
6/7/2010	2.78	1.606	0.071	0.066
6/10/2010*	0.062	0.011	-	-
6/14/2010*	0.039	0	0	0
6/21/2010*	0.035	0	0	0
6/28/2010*	0.223	0.001	0.003	0.002
7/6/2010*	0.173	0.012	0	0
7/13/2010*	0.188	0.052	0.007	0.005
720/2010*	0.143	0.07	0.022	0.023
7/27/2010*	0.126	0.063	0.01	0.008
8/4/2010*	0.115	0.055	0.01	0.009

Date	Raw Intake Total	Raw Intake Dissolved	Finished Total	Finished Dissolved
8/9/2010*	0.083	0.047	0.008	0.008
8/16/2010	0.107	0.045	0.003	0.003

*Denotes water came from Manchester Reservoir

B.1.4 Sodium

Date	West Street Orr Finish Sodium (mg/L)	West Street Orr Raw Sodium (mg/L)
4/23/1998	33.8	-
6/23/1998	31.8	-
5/10/2000	41.0	-
3/14/2001	70.1	-
4/4/2001	83.9	-
11/14/2001	39.2	-
1/23/2002	62.8	-
4/23/2002	68.0	-
11/6/2002	44.7	-
5/4/2004	45.1	-
10/7/2004	44.3	-
2/7/2005	92.1	-
11/21/2005	66.7	-
1/24/2006	75.8	-
11/8/2006	49.4	-
2/6/2007	62.6	-
2/11/2008	81.2	-
4/16/2008	61.1	-
9/12/2008	48.6	-
11/5/2008	41.2	-
12/15/2008	41.2	-
1/8/2009	86.2	-
2/10/2009	140.0	-
2/18/2009	155.0	126.0
3/12/2009	114.0	99.7
4/9/2009	88.0	76.0
5/14/2009	58.0	-
6/11/2009	76.0	67.0
7/9/2009	54.0	42.8
8/13/2009	54.8	42.0
9/2/2009	59.2	42.1
10/1/2009	65.4	50.4
11/5/2009	49.0	37.6
12/3/2009	38.6	32.4
1/7/2010	66.3	53.2
2/4/2010	75.2	57.8
4/1/2010	50.4	43.2
5/5/2010	53.1	43.5
6/2/2010	54.5	40.7

B.1.5 Total Organic Carbon

Month	Raw TOC (mg/L)	Treated TOC (mg/L)
Jan-02	2.4	0.92
Feb-02	2.6	0.88
Mar-02	2.6	0.89
Apr-02	2.5	0.83
May-02	3.9	0.9
Jun-02	3.8	1.2
Jul-02	3.7	1.4
Aug-02	3.4	1.2
Sep-02	3.8	1.4
Oct-02	3.3	1.4
Nov-02	2.9	1.2
Dec-02	3.6	1.3
Jan-03	2.7	1.2
Feb-03	3.5	2.4
Mar-03	2.9	0.96
Apr-03	3.2	0.79
May-03	3.6	1.1
Jun-03	4.2	1.3
Jul-03	4.2	1.5
Aug-03	3.1	1.2
Sep-03	3.3	1.3
Oct-03	3.2	1.6
Nov-03	3.2	1.1
Dec-03	3	1.1
Jan-04	2.9	0.99
Feb-04	2.4	1.2
Mar-04	2.4	1.1
Apr-04	2.9	0.9
May-04	4	1.7
Jun-04	4.8	3
Jul-04	3.6	1.7
Aug-04	3.7	2.1
Sep-04	3.8	1.8
Oct-04	3.3	1.6
Nov-04	3.3	1.7
Dec-04	3.4	1.8
Jan-05	3	1.4
Feb-05	3	1.5
Apr-05	3	0.93

May-05	Lab Error	-
Jun-05	5.2	1.5
Jul-05	3.6	1.7
Aug-05	3.7	1.9
Sep-05	3.8	1.8
Oct-05	3.4	1.8
Nov-05	4.6	2
Dec-05	3.5	1.8
Jan-06	3	1.6
Feb-06	3	1.6
Mar-06	2.6	1.6
Apr-06	3.2	1.7
May-06	4.5	2.1
Jun-06	5.9	1.8
Jul-06	5.7	1.9
Aug-06	3.9	1.3
Sep-06	2.8	1.6
Oct-06	3.2	1.4
Nov-06	3.3	1.4
Dec-06	3.6	1.4
Jan-07	2.8	1.3
Feb-07	2.5	1.6
Mar-07	2.9	1.3
Apr-07	3.2	1
May-07	3.5	1.2
Jun-07	5.4	1.3
Jul-07	4.2	1.4
Aug-07	3.7	1.4
Sep-07	3.5	1.5
Oct-07	3.4	1.4
Nov-07	3.6	1.5
Dec-07	3.5	1.3
Jan-08	3.4	1.2
Feb-08	3.6	1.3
Mar-08	3	1.3
Apr-08	3.2	1.2
May-08	5.6	1.6
Jun-08	4.9	3
Jul-08	4.2	1.6
Aug-08	4.5	1.7
Sep-08	2.5	2.3
Nov-08	3.7	1.8
Dec-08	3.3	1.1
Jan-09	2.4	1.1

Feb-09	3	1.2
Mar-09	2.8	1.3
Apr-09	3.2	1.3
May-09	4.1	1.3
Jun-09	4.1	1.5
Jul-09	2.7	0.5
Aug-09	7	2.2
Sep-09	4.4	1.6
Oct-09	4.1	1.6
Nov-09	3.5	1.3
Dec-09	3.8	1.5
Jan-10	2.8	1.2
Feb-10	1.9	0.6
Mar-10	2.34	1.12
Apr-10	2.73	0.61
May-10	2.93	0.78
Jun-10	3.40	1.12
Jul-10	4.70	2.50
Aug-10	4.90	3.10

B.2 Graphical Representations of Historical Data

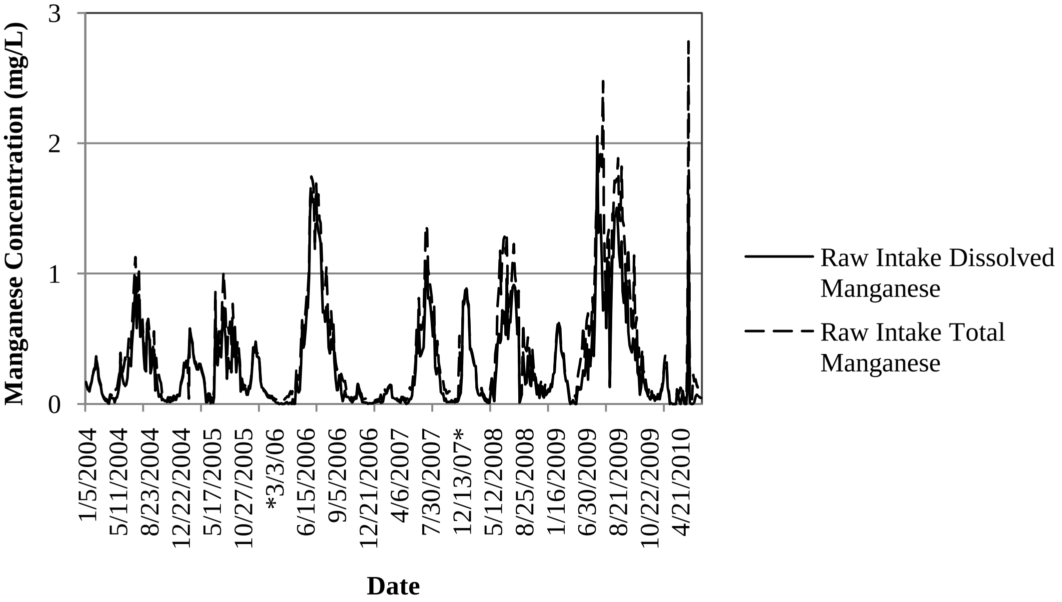


Figure B-1: Historical Dissolved and Total Manganese in Raw Water versus Time

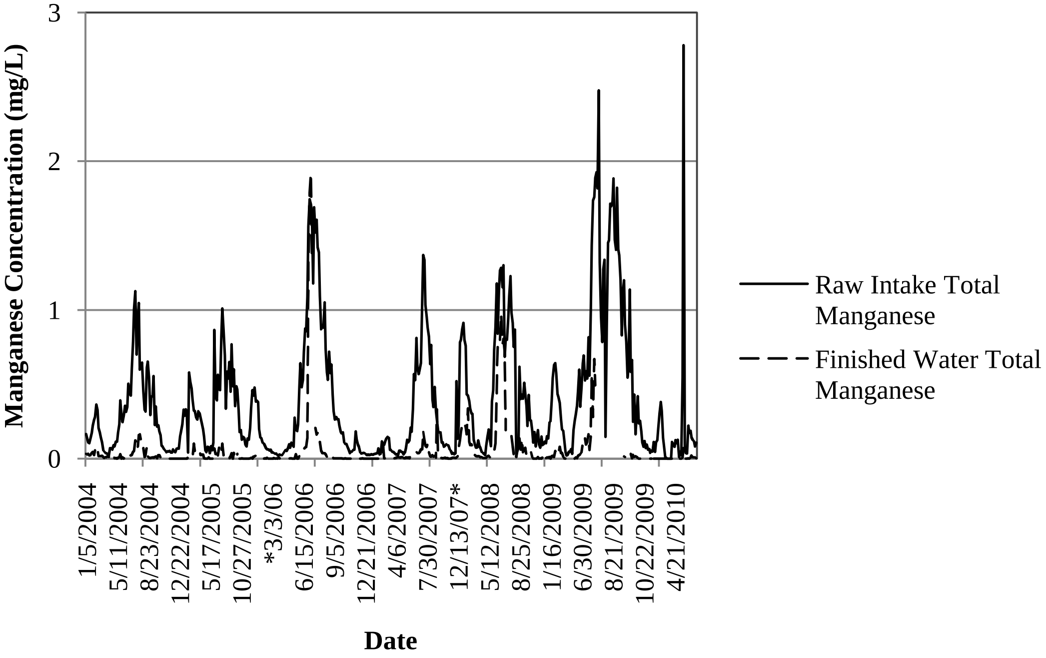


Figure B-2: Historical Total Manganese in Raw and Finished Water versus Time

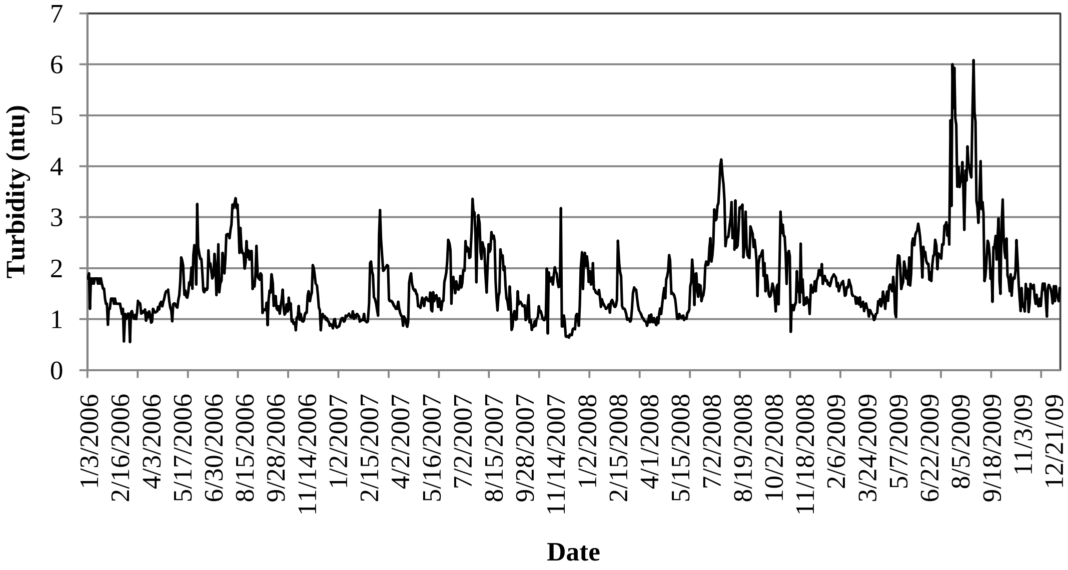


Figure B-3: Historical Turbidity versus Time

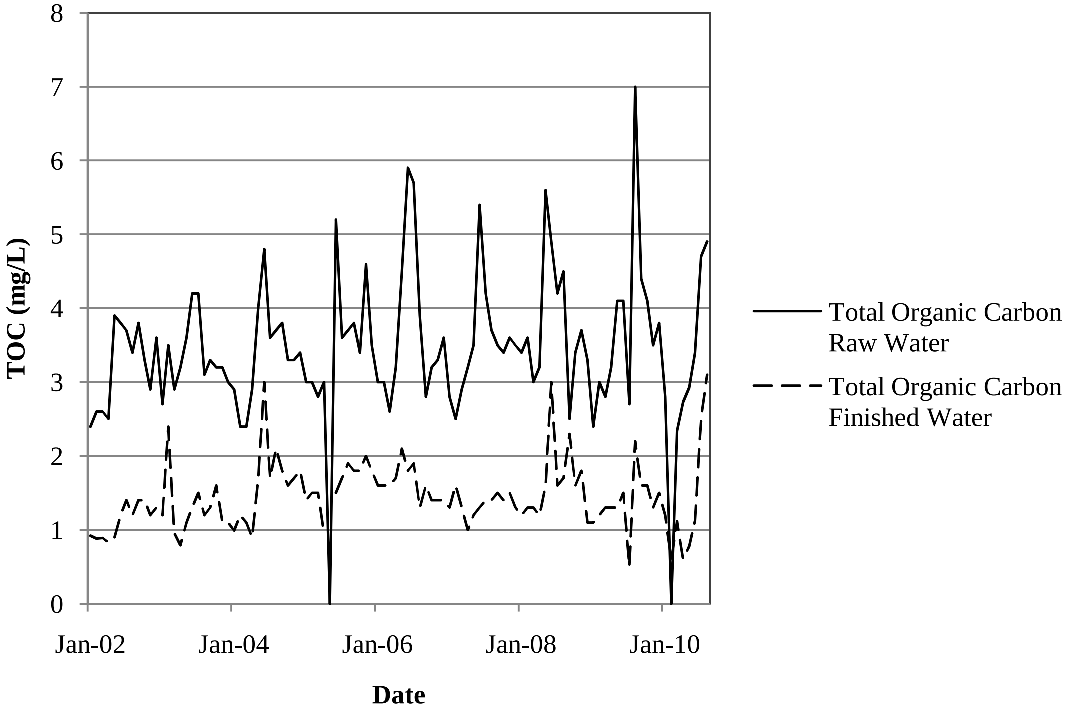


Figure B-4: Historical Total Organic Carbon versus Time

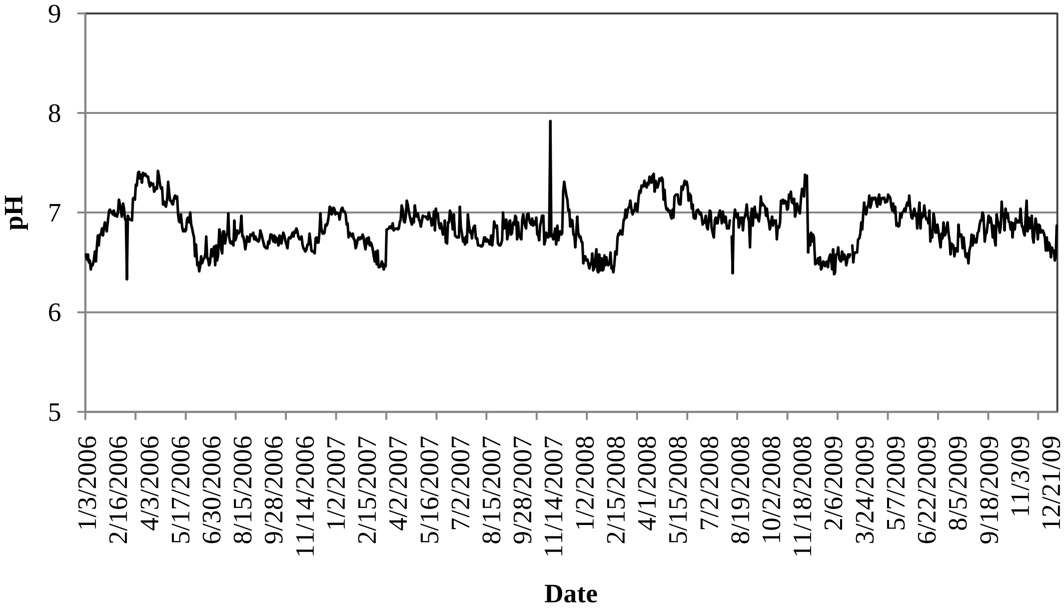


Figure B-5: Historical pH versus Time

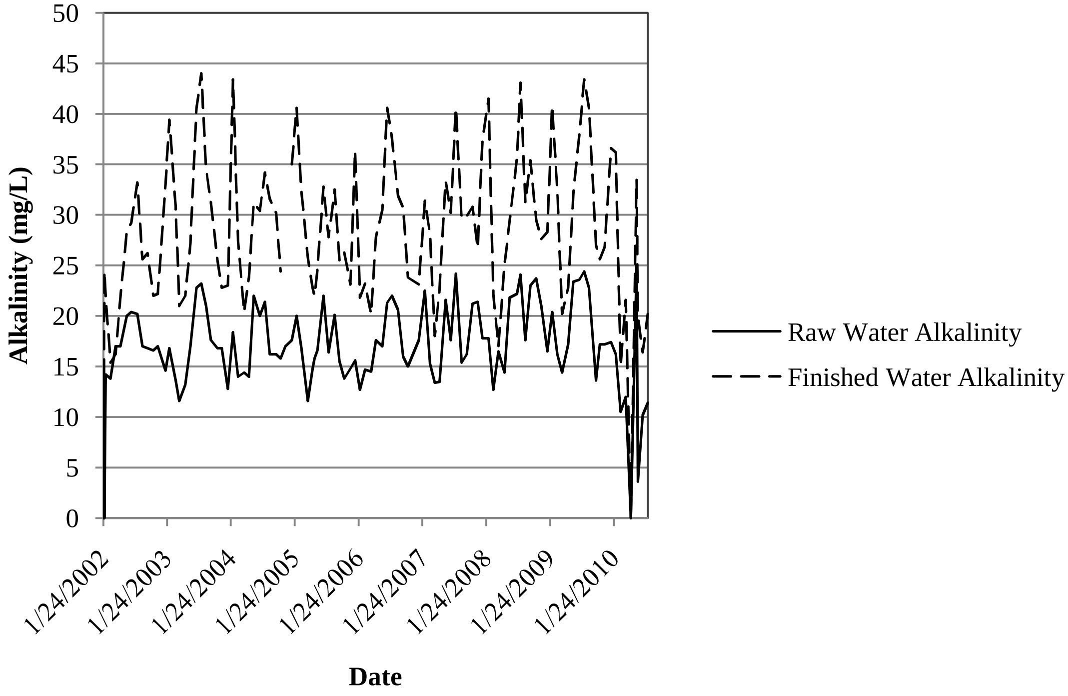


Figure B-6: Historical Alkalinity versus Time

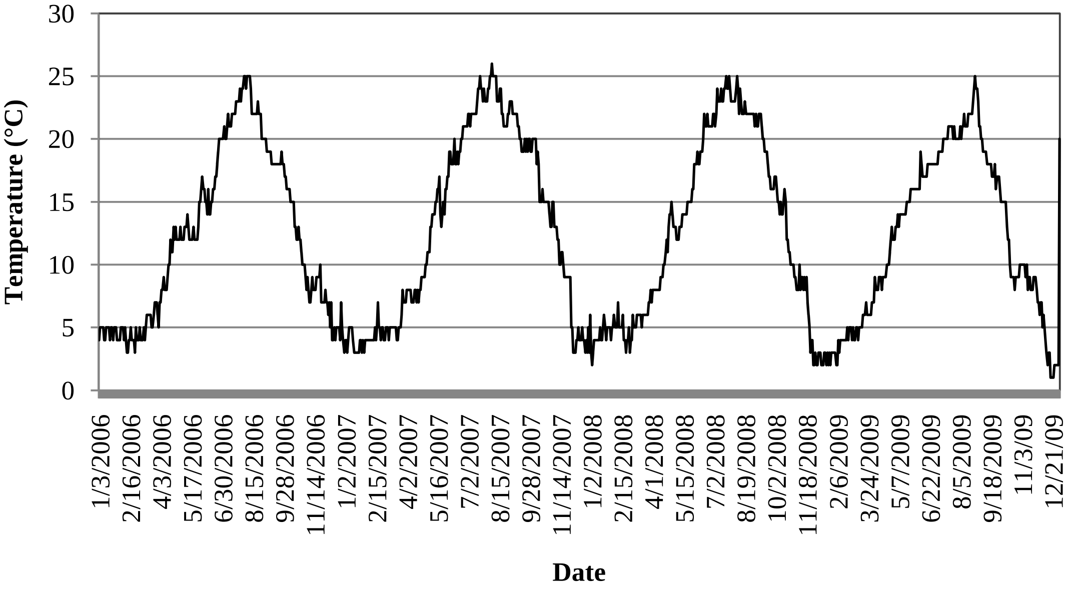


Figure B-7: Historical Temperature versus Time

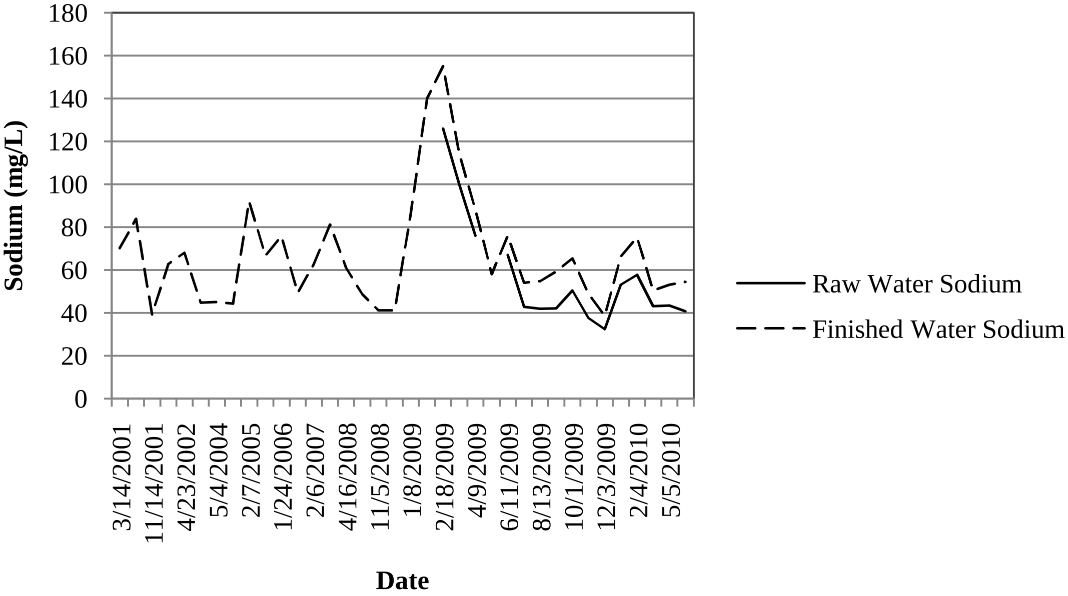


Figure B-8: Historical Sodium versus Time

Appendix C: 2010 Project Sampling Data

C.1 Tabular Representation of Project Sampling Data

Sample ID	Sample Date	Time	Sample Depth (ft)	Temperature (°C)	pH	Turbidity (ntu)	DO (mg/L)	Dissolved Fe (ppm)	Total Fe (ppm)	Dissolved Mn (ppm)	Total Mn (ppm)	Total Organic Carbon (mg/L)	Dissolved Organic Carbon (mg/L)
RW-1	8/3/10	AM	0	-	6.82	1.48	6.02	-	-	-	-	4.46	4.69
RW-2	8/17/10	PM	0	26.8	6.74	1.17	2.49	0.11	0.41	0.56	0.62	5.24	4.70
RW-3	8/17/10	PM	10	26.4	6.61	2.38	1.52	0.22	0.80	1.54	1.54	5.46	4.91
RW-4	8/17/10	PM	15	22.4	6.50	12.50	0.96	1.64	5.35	7.63	7.37	6.52	5.42
RW-5	8/17/10	PM	20	20.7	6.51	23.50	0.78	2.37	12.04	7.12	6.76	13.86	7.69
RW-6	8/17/10	PM	25	18.8	6.51	28.30	0.59	3.43	11.11	9.00	8.36	15.12	9.34
RW-7	8/30/10	AM	0	22.8	5.99	0.99	5.00	0.21	0.29	0.55	0.56	4.96	6.75
RW-8	8/30/10	AM	5	22.9	6.08	2.77	2.41	0.24	0.64	0.56	0.61	4.88	4.35
RW-9	8/30/10	AM	10	23.2	5.97	1.29	1.85	0.31	0.43	0.66	0.64	4.65	4.36
RW-10	8/30/10	AM	15	21.6	5.85	1.99	1.52	0.41	0.74	0.78	1.01	4.67	4.68
RW-11	8/30/10	AM	20	24.3	6.14	21.40	0.67	3.85	12.88	6.71	6.99	10.76	7.65
RW-12	8/30/10	AM	22.5	23.4	6.19	38.40	0.45	2.63	21.60	7.27	11.50	13.87	9.39
RW-13	9/9/10	PM	0	23.6	5.89	0.85	5.43	0.14	0.32	0.49	0.46	5.07	3.85
RW-15	9/9/10	PM	10	23.0	5.96	1.17	3.73	0.24	0.53	0.73	0.74	4.39	4.83
RW-16	9/9/10	PM	15	23.0	6.15	2.75	2.58	0.37	1.25	1.40	1.45	5.37	4.48
RW-17	9/9/10	PM	20	23.3	6.04	16.45	1.68	3.21	7.43	7.23	7.07	5.71	5.18
RW-18	9/9/10	PM	25	23.6	6.09	81.80	0.58	3.55	26.22	8.55	9.21	23.99	13.41
RW-19	9/23/10	PM	0	22.3	5.94	0.94	6.30	0.09	0.26	0.19	0.20	4.09	4.46
RW-20	9/23/10	PM	5	22.3	5.72	4.04	6.13	0.08	0.55	0.26	0.33	4.93	3.77
RW-21	9/23/10	PM	10	21.1	6.05	5.83	5.78	0.15	0.57	0.23	0.32	5.28	4.61
RW-22	9/23/10	PM	15	20.2	6.02	4.11	5.25	0.15	0.77	0.19	0.30	5.69	3.72
RW-23	9/23/10	PM	20	20.0	6.14	10.01	3.85	1.54	3.00	3.05	3.22	7.26	5.23
RW-24	9/23/10	PM	25	16.8	6.25	86.70	2.75	0.62	42.75	13.12	17.52	31.82	26.50
RW-25	10/7/10	PM	0	17.1	6.05	1.58	6.36	0.19	0.39	0.28	0.29	4.6	4.962
RW-26	10/7/10	PM	5	17.4	5.98	9.11	7.38	0.18	0.51	0.37	0.37	5.139	3.788
RW-27	10/7/10	PM	10	17.0	5.97	4.25	7.14	0.20	0.73	0.30	0.31	3.456	3.33
RW-29	10/7/10	PM	20	17.2	6.05	5.64	6.78	0.55	1.38	0.55	0.59	3.829	3.735
RW-30	10/7/10	PM	25	17.1	5.98	12.45	6.71	0.93	2.05	0.86	0.84	4.38	4.84
RW-31	10/19/10	PM	0	13.9	7.32	2.15	7.40	0.17	0.38	0.18	0.19	3.794	5.67
RW-32	10/19/10	PM	10	14.0	6.97	3.45	8.00	0.16	0.26	0.24	0.24	5.076	3.959
RW-33	10/19/10	PM	15	13.6	6.58	5.89	7.90	0.13	0.75	0.19	0.23	4.431	3.519

Sample ID	Sample Date	Time	Sample Depth (ft)	Temperature (°C)	pH	Turbidity (ntu)	DO (mg/L)	Dissolved Fe (ppm)	Total Fe (ppm)	Dissolved Mn (ppm)	Total Mn (ppm)	Total Organic Carbon (mg/L)	Dissolved Organic Carbon (mg/L)
RW-35	10/19/10	PM	25	14.0	6.74	11.40	7.70	0.25	4.04	0.14	0.40	6.955	3.346
IP-36	10/19/10	PM	Intake	14.0	6.48	2.20	7.00	0.18	0.48	0.18	0.20	3.163	3.357
RW-37	11/1/10	PM	0	8.2	7.13	1.45	12.50	0.10	0.24	0.21	0.21	3.614	3.358
RW-38	11/1/10	PM	5	8.8	7.05	8.63	12.60	0.10	0.59	0.29	0.30	3.532	3.362
RW-39	11/1/10	PM	10	8.5	7.42	6.51	12.10	0.11	0.55	0.24	0.25	3.623	3.379
RW-40	11/1/10	PM	15	8.9	7.21	5.18	11.60	0.08	0.44	0.21	0.22	9.911	4.041
RW-42	11/1/10	PM	25	8.9	7.33	12.95	11.80	0.14	2.60	0.23	0.35	4.514	3.271
RW-44	12/3/10	PM	0	6.4	6.31	0.954	10.23	0.026	0.097	0.092	0.122	3.255	3.074
RW-45	12/3/10	PM	5	6.4	6.3	10.1	11.7	0.03	0.997	0.158	0.213	3.464	3.222
RW-46	12/3/10	PM	10	5.4	6.3	3.27	11.61	0.033	0.317	0.102	0.143	3.263	3.027
RW-47	12/3/10	PM	15	5.0	6.21	3.9	12.15	0.038	0.348	0.107	0.14	-	-
RW-48	12/3/10	PM	20	4.9	6.14	5.74	12.31	0.052	0.407	0.106	0.152	3.087	3.029
RW-49	12/3/10	PM	25	5.4	6.25	22.65	11.99	0.133	2.299	0.14	0.289	3.444	3.241
IP-50	12/3/10	PM	Intake	6.0	6.34	9.76	10.93	0.06	0.993	0.106	0.163	4.232	3.036

C.2 Graphical Representations of Project Sampling

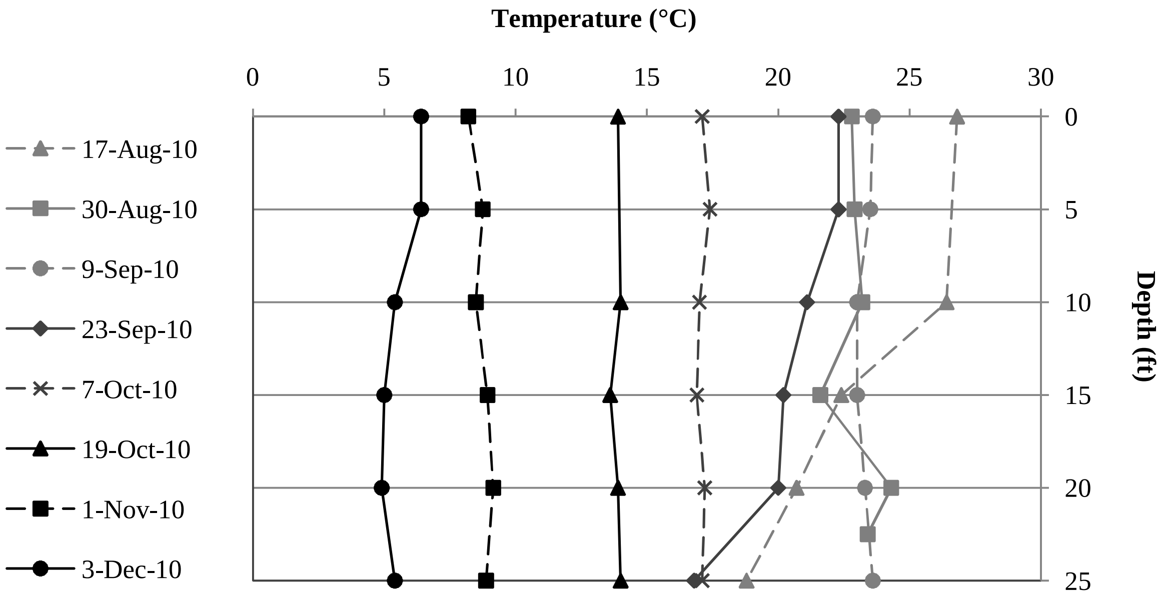


Figure C-1: Temperature versus Depth

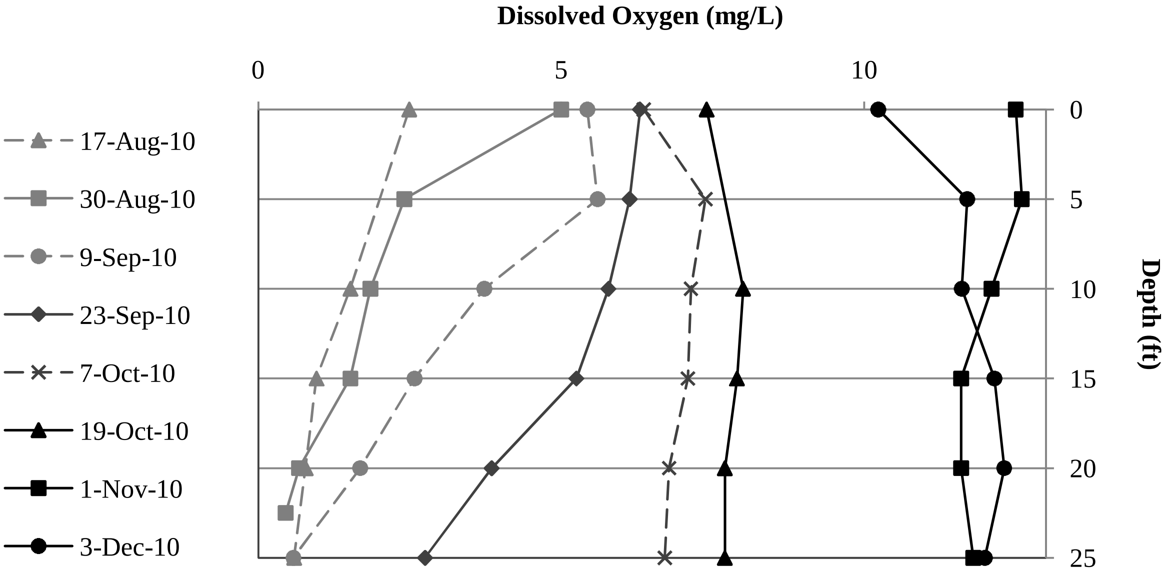


Figure C-2: Dissolved Oxygen versus Depth

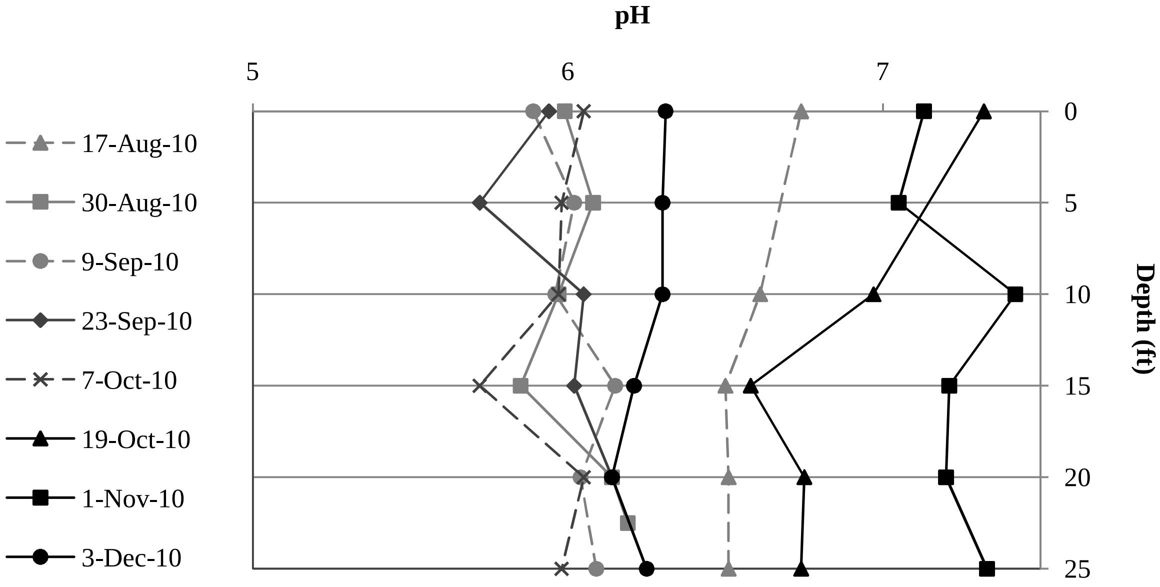


Figure C-3: pH versus Depth

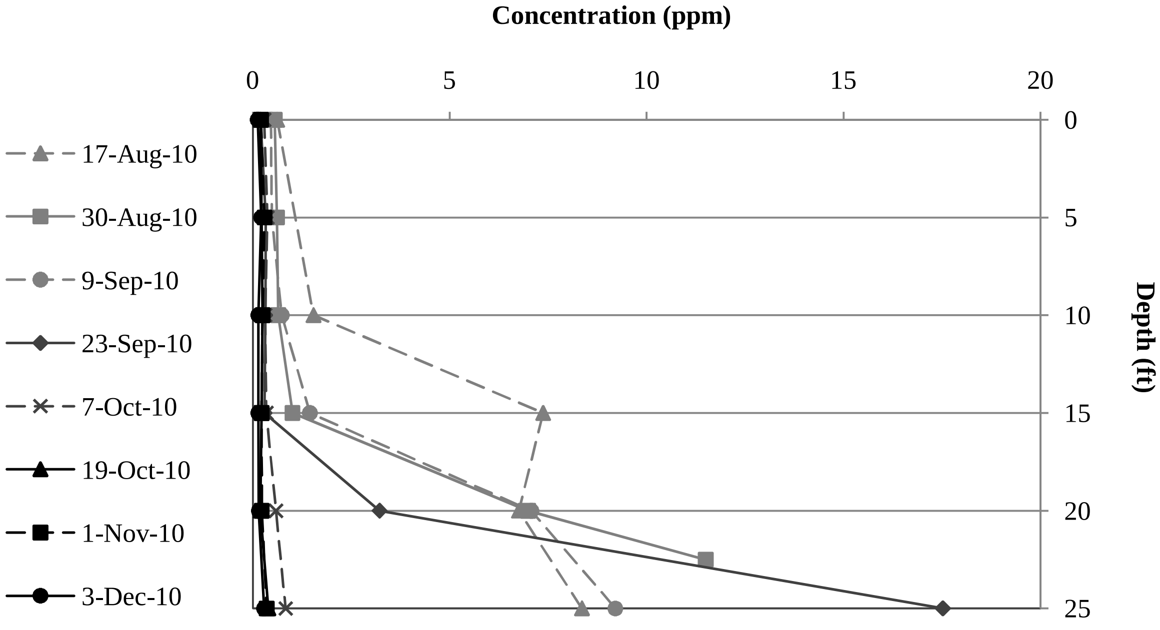


Figure C-4: Total Manganese versus Depth

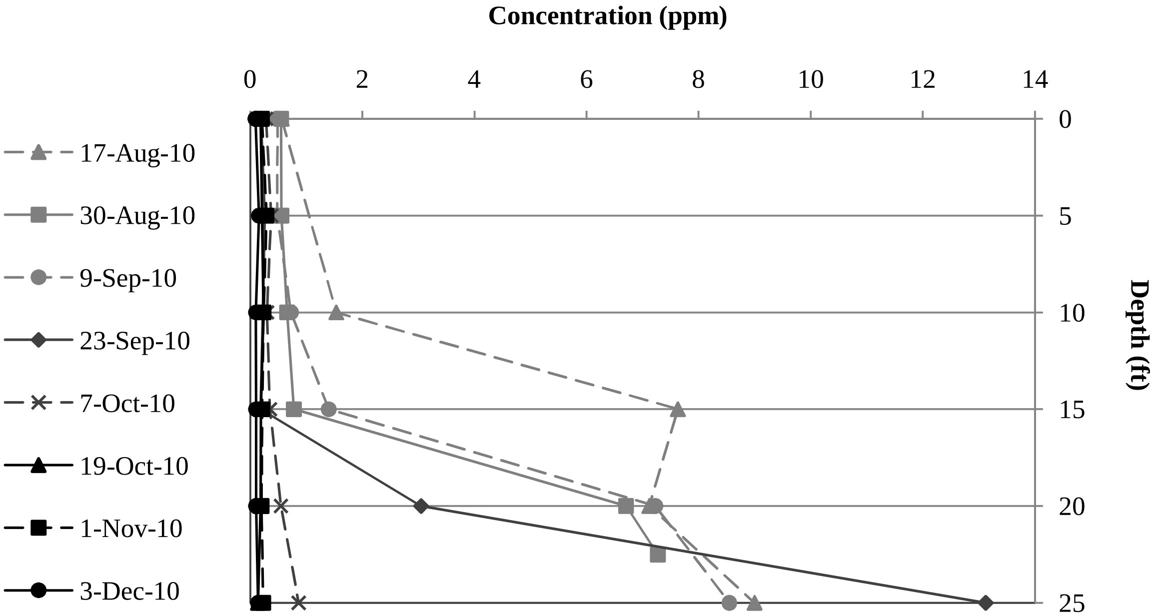


Figure C-5: Dissolved Manganese versus Depth

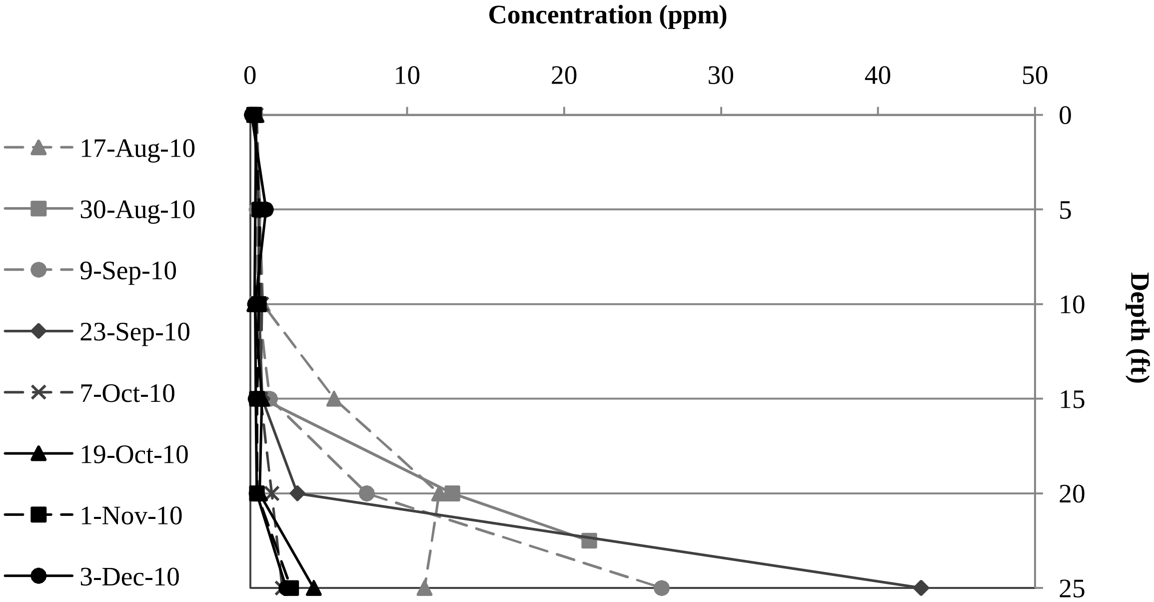


Figure C-6: Total Iron versus Depth

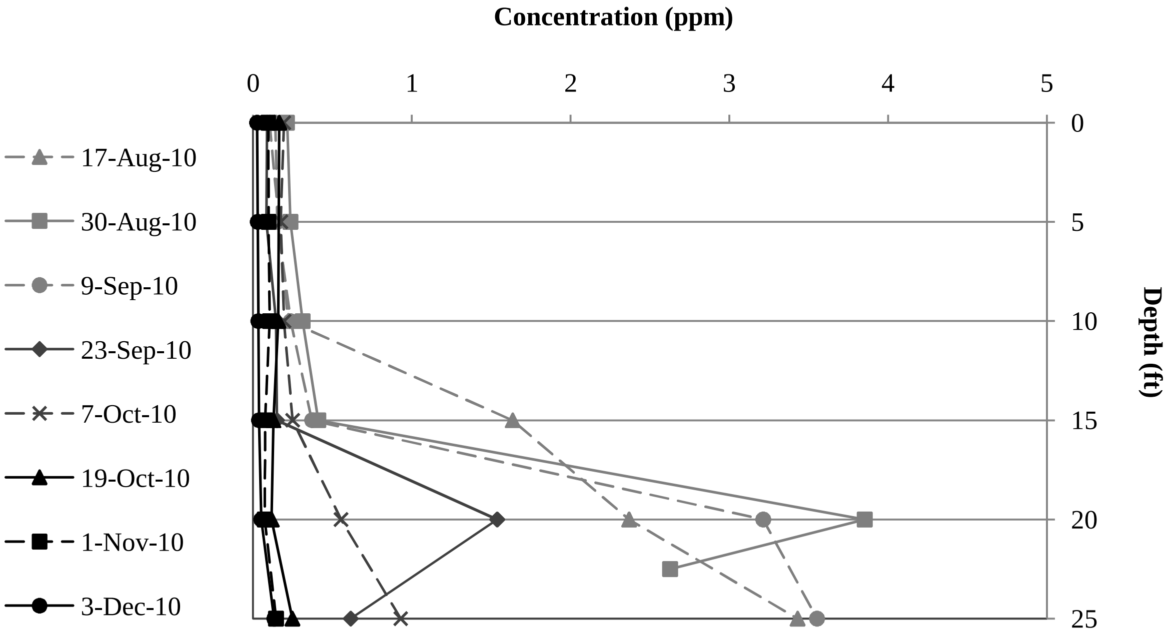


Figure C-7: Dissolved Iron versus Depth

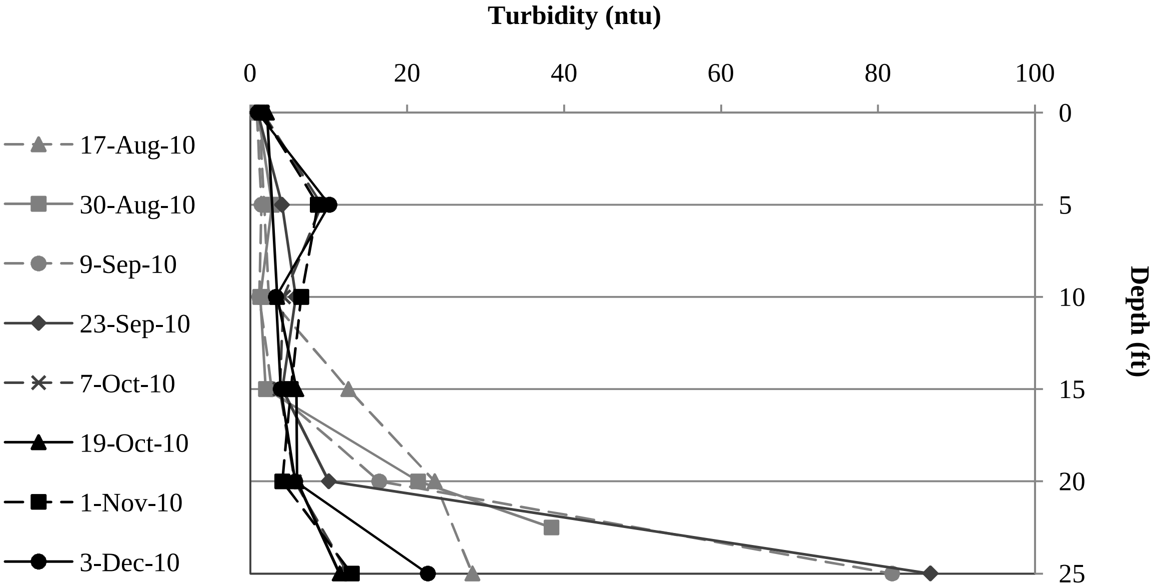


Figure C-8: Turbidity versus Depth

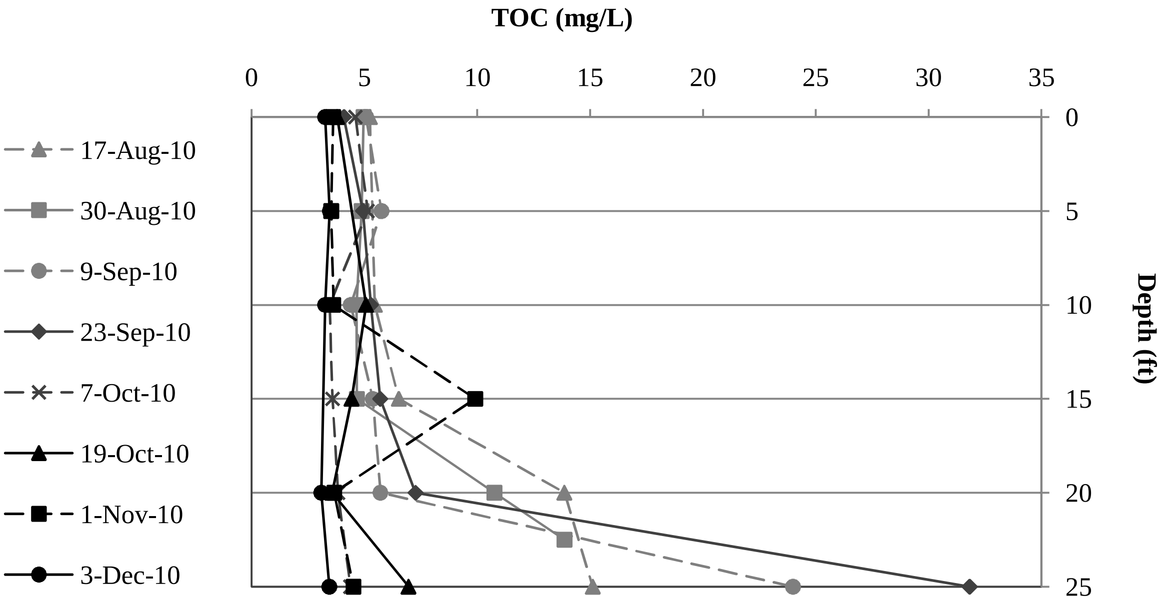


Figure C-9: Total Organic Carbon versus Depth

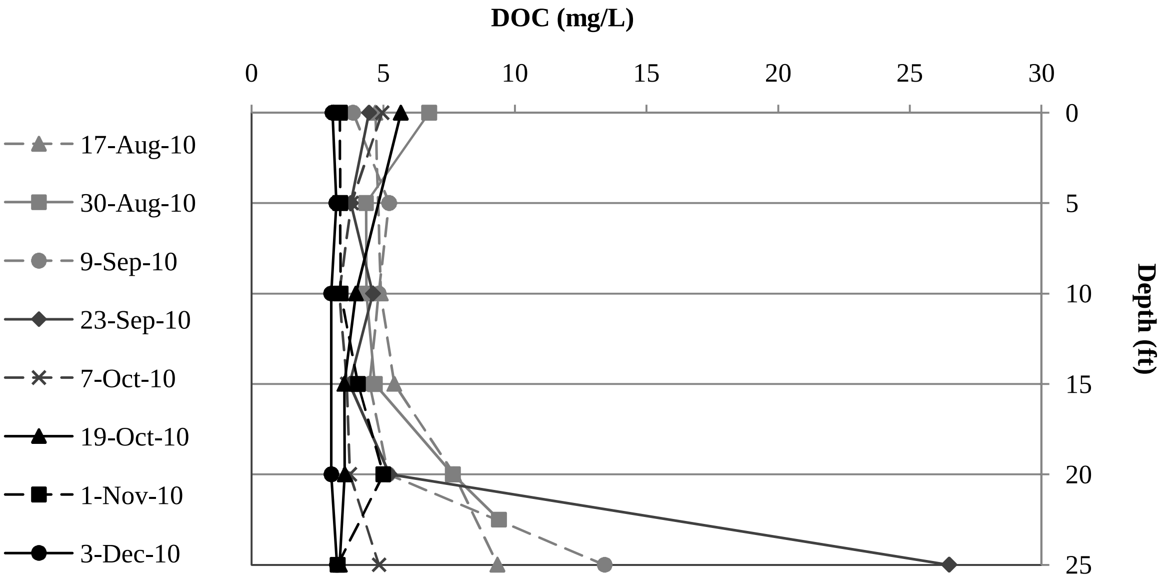
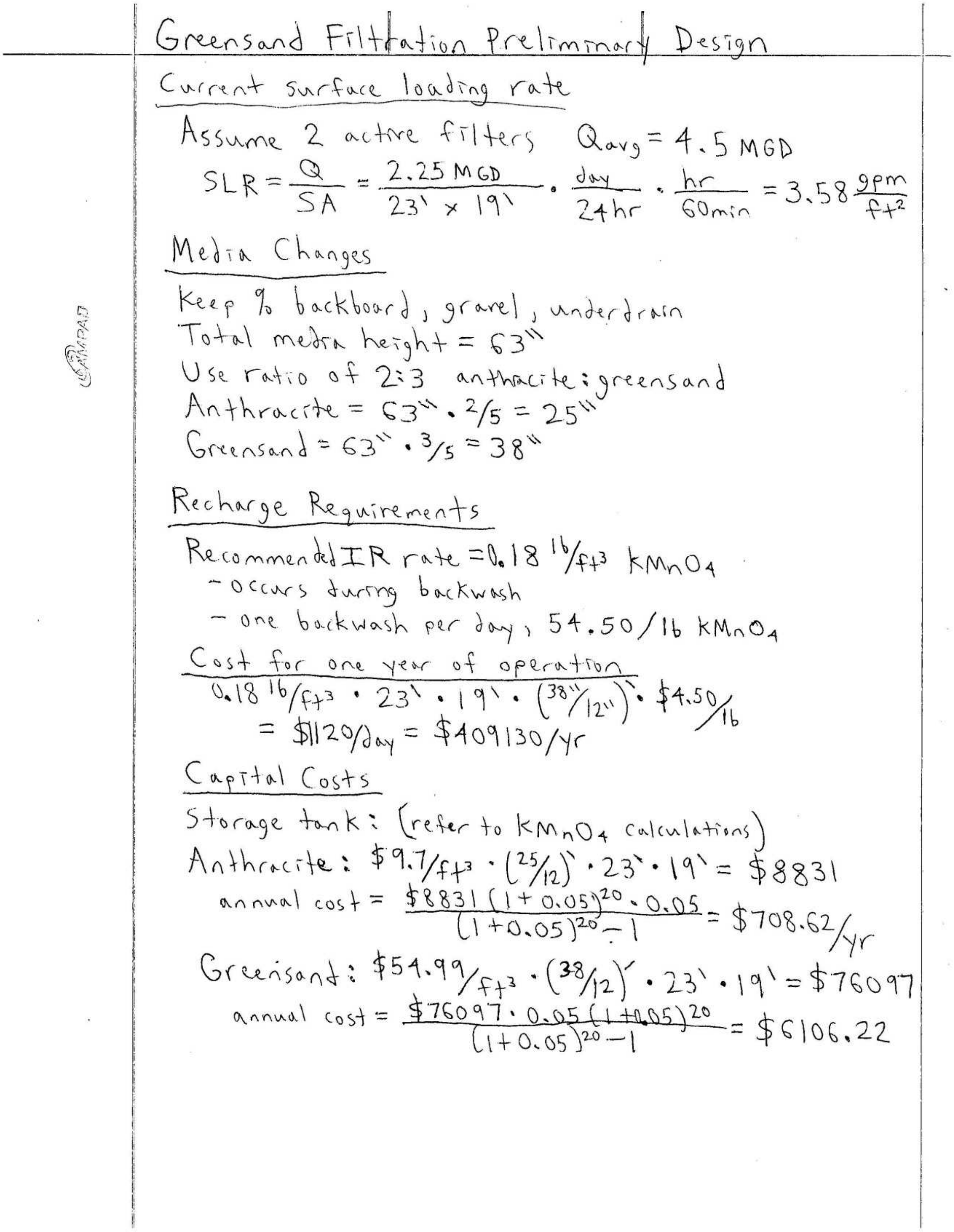


Figure C-10: Dissolved Organic Carbon versus Depth

Appendix D: Design Calculations

D.1 Greensand Filtration Preliminary Design



Greensand Filtration Preliminary Design

Current surface loading rate

Assume 2 active filters $Q_{avg} = 4.5$ MGD

$$SLR = \frac{Q}{SA} = \frac{2.25\text{ MGD}}{23' \times 19'} \cdot \frac{\text{day}}{24\text{hr}} \cdot \frac{\text{hr}}{60\text{min}} = 3.58 \frac{\text{gpm}}{\text{ft}^2}$$

Media Changes

Keep % backboard, gravel, underdrain
Total media height = 63"
Use ratio of 2:3 anthracite:greensand
Anthracite = 63" · 2/5 = 25"
Greensand = 63" · 3/5 = 38"

Recharge Requirements

Recommended IR rate = 0.18 lb/ft³ $KMnO_4$
- occurs during backwash
- one backwash per day, 54.50/lb $KMnO_4$

Cost for one year of operation

$$0.18\ \text{lb/ft}^3 \cdot 23' \cdot 19' \cdot \left(\frac{38''}{12''}\right) \cdot \$4.50/\text{lb}$$
$$= \$1120/\text{day} = \$409130/\text{yr}$$

Capital Costs

Storage tank: (refer to $KMnO_4$ calculations)

Anthracite: $\$9.7/\text{ft}^3 \cdot \left(\frac{25}{12}\right)' \cdot 23' \cdot 19' = \$8831$

$$\text{annual cost} = \frac{\$8831\,(1+0.05)^{20} \cdot 0.05}{(1+0.05)^{20}-1} = \$708.62/\text{yr}$$

Greensand: $\$54.99/\text{ft}^3 \cdot \left(\frac{38}{12}\right)' \cdot 23' \cdot 19' = \$76097$

$$\text{annual cost} = \frac{\$76097 \cdot 0.05\,(1+0.05)^{20}}{(1+0.05)^{20}-1} = \$6106.22$$

D.2 Oxidation with Potassium Permanganate Detailed Design

Oxidation with $KMnO_4$ Design

Chemical dosing

Theoretical dosing: $\frac{1.92\ mg/L\ KMnO_4}{mg/L\ Mn}$, $\frac{0.94\ mg/L\ KMnO_4}{mg/L\ Fe}$

- Use highest historical Mn value (2.78 mg/L)
- Use highest observed dissolved Fe value (3.85 mg/L)

$$\text{Peak dose} = 2.78\ mg/L\ Mn \left(\frac{1.92\ mg/L\ KMnO_4}{mg/L\ Mn}\right) + 3.85\ mg/L\ Fe \left(\frac{0.94\ mg/L\ KMnO_4}{mg/L\ Fe}\right) = 8.96\ mg/L\ KMnO_4$$

$$\text{Low Dose} = 0.01\ mg/L\ Mn \left(\frac{1.92\ mg/L\ KMnO_4}{mg/L\ Mn}\right) + 0.03\ mg/L\ Fe \left(\frac{0.94\ mg/L\ KMnO_4}{mg/L\ Fe}\right) = 0.05\ mg/L\ KMnO_4$$

$$\text{Median dose} = 0.21\ mg/L\ Mn \left(\frac{1.92\ mg/L\ KMnO_4}{mg/L\ Mn}\right) + 0.19\ mg/L\ Fe \left(\frac{0.94\ mg/L\ KMnO_4}{mg/L\ Fe}\right) = 0.58\ mg/L\ KMnO_4$$

Reaction time

Required: 5–10 min

Add $KMnO_4$ at raw water intake

Available volume for water to travel:

- Raw water before Venturi = 16206 gal
- Raw water after Venturi = 10041 gal
- Split at pretreatment = 2114 gal
- Rapid mix = 24681 gal

53042 gal

Use Q_{avg} of 4.5 MGD

$$t_D = V/Q = \frac{53042\ gal}{4.5 \cdot 10^6\ \cancel{MGD}\ \frac{gal}{day}} \cdot \frac{24\ hr}{day} \cdot \frac{60\ min}{hr} = 17.0\ min > 10$$

adequate detention time without additional storage

Oxidation with $KMnO_4$ Design

Alkalinity Consumption

Rate for oxidizing Mn = 1.21 mg/L as $CaCO_3$ per mg/L Mn

Rate for oxidizing Fe = 1.49 mg/L as $CaCO_3$ per mg/L Fe

Peak consumption = 2.78 mg/L · 1.21 + 3.85 mg/L · 1.49
= 9.10 mg/L

Low ~~dose~~ consumption = 0.01 mg/L · 1.21 + 0.03 mg/L · 1.49 = 0.06 mg/L

Median ~~dose~~ consumption = 0.21 mg/L · 1.21 + 0.19 mg/L · 1.49
= 0.54 mg/L

Sizing Storage Tank

Use peak dose and 31 day month (monthly refills)

V = 8.95 mg/L · 4.5 MGD · 8.34 · 31 days = 10424 lbs
= 770 gal

2000 gal tank allows for bimonthly refills and margin of error.

Fixed Cost

$27000 for storage tank and accessories

$$\rho = \frac{P_o r(1+r)^n}{(1+r)^n - 1} \quad P_o = \$27,000 \quad r = 5\% \quad n = 20\,yr$$

$$\rho = \frac{(\$27000)(0.05)(1+0.05)^{20}}{(1+0.05)^{20} - 1} = \$2166.55$$

Operating Cost

Assumptions:

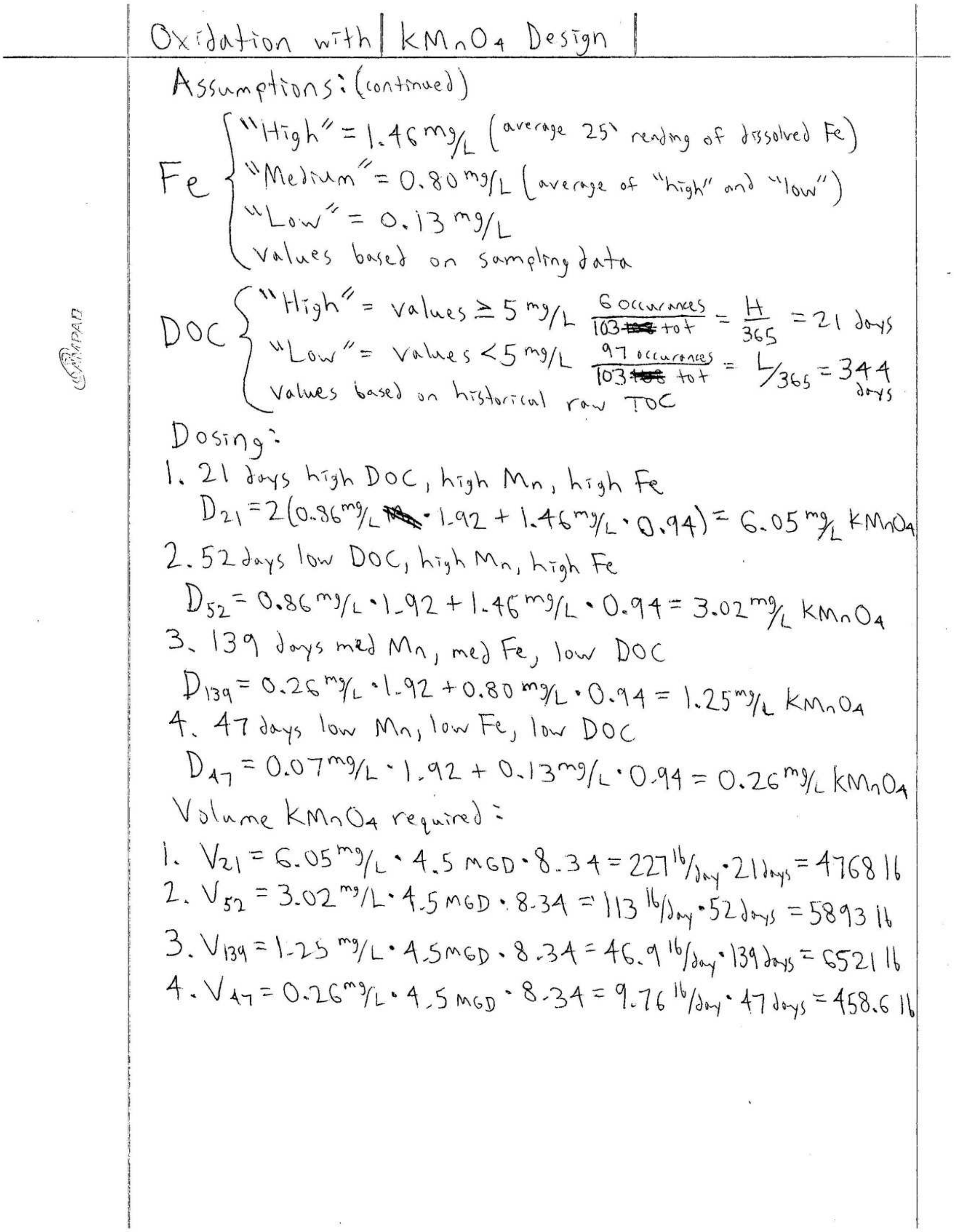
Mn (based on historical averages)

"High" values ≥ 0.5 mg/L $\frac{106\ \text{occurances}}{532\ \text{tot}} = \frac{H}{365}$ H = 73 days
C = 0.86 mg/L

"Medium" = 0.5 mg/L < values < 0.1 mg/L
202 occurances / 532 tot = M/365 M = 139 days
C = 0.26 mg/L

"Low" = 0.05 mg/L < values ≤ 0.1 mg/L L = 47 days
69 occurances / 532 tot = L/365 C = 0.07 mg/L

No operation ~ 106 days of year



Oxidation with KMnO₄ Design

Assumptions: (continued)

Fe {
"High" = 1.46 mg/L (average 25' reading of dissolved Fe)
"Medium" = 0.80 mg/L (average of "high" and "low")
"Low" = 0.13 mg/L
Values based on sampling data

DOC {
"High" = values ≥ 5 mg/L $\frac{6 \text{ occurances}}{103 \text{ ~~100~~ tot}} = \frac{H}{365} = 21$ days
"Low" = values < 5 mg/L $\frac{97 \text{ occurances}}{103 \text{ ~~100~~ tot}} = L/365 = 344$ days
Values based on historical raw TOC

Dosing:

1. 21 days high DOC, high Mn, high Fe
   $D_{21} = 2(0.86 \text{ mg/L} \cdot 1.92 + 1.46 \text{ mg/L} \cdot 0.94) = 6.05 \text{ mg/L KMnO}_4$
2. 52 days low DOC, high Mn, high Fe
   $D_{52} = 0.86 \text{ mg/L} \cdot 1.92 + 1.46 \text{ mg/L} \cdot 0.94 = 3.02 \text{ mg/L KMnO}_4$
3. 139 days med Mn, med Fe, low DOC
   $D_{139} = 0.26 \text{ mg/L} \cdot 1.92 + 0.80 \text{ mg/L} \cdot 0.94 = 1.25 \text{ mg/L KMnO}_4$
4. 47 days low Mn, low Fe, low DOC
   $D_{47} = 0.07 \text{ mg/L} \cdot 1.92 + 0.13 \text{ mg/L} \cdot 0.94 = 0.26 \text{ mg/L KMnO}_4$

Volume KMnO₄ required:

1. $V_{21} = 6.05 \text{ mg/L} \cdot 4.5 \text{ MGD} \cdot 8.34 = 227 \text{ lb/day} \cdot 21 \text{ days} = 4768 \text{ lb}$
2. $V_{52} = 3.02 \text{ mg/L} \cdot 4.5 \text{ MGD} \cdot 8.34 = 113 \text{ lb/day} \cdot 52 \text{ days} = 5893 \text{ lb}$
3. $V_{139} = 1.25 \text{ mg/L} \cdot 4.5 \text{ MGD} \cdot 8.34 = 46.9 \text{ lb/day} \cdot 139 \text{ days} = 6521 \text{ lb}$
4. $V_{47} = 0.26 \text{ mg/L} \cdot 4.5 \text{ MGD} \cdot 8.34 = 9.76 \text{ lb/day} \cdot 47 \text{ days} = 458.6 \text{ lb}$

Oxidation with $KMnO_4$ Design

Cost:

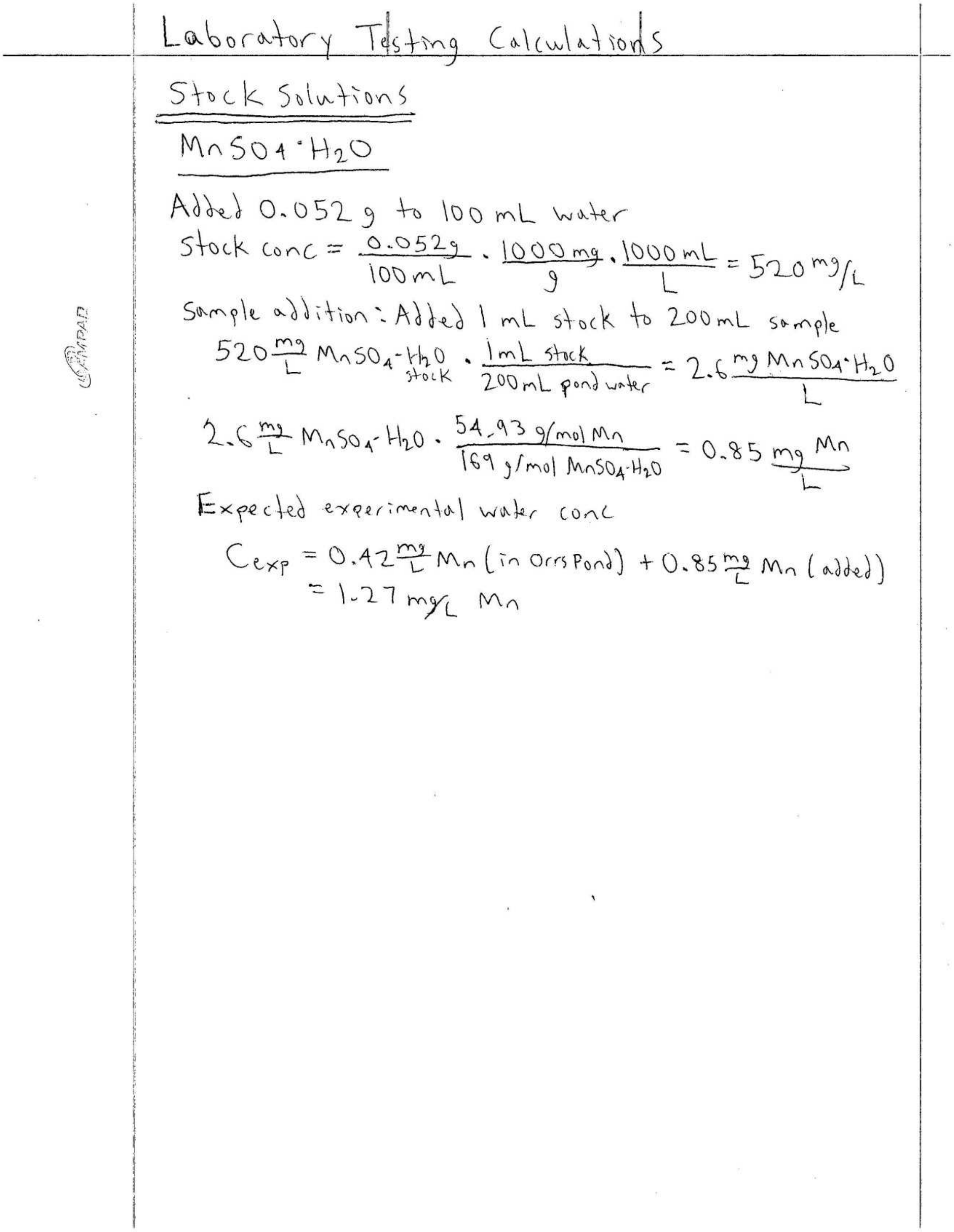
1. $C = \$4.50/\text{lb} \cdot 4768\ \text{lb} = \$21456$
2. $C = \$4.5/\text{lb} \cdot 5893\ \text{lb} = \$26{,}519$
3. $C = \$4.5/\text{lb} \cdot 6521\ \text{lb} = \$29345$
4. $C = \$4.5/\text{lb} \cdot 458.6\ \text{lb} = \$2064$

Total annual $KMnO_4$ cost $= \$79384$

Total annual cost $= \$81549.25$

Appendix E: Oxidation with Potassium Permanganate Laboratory Testing

E.1 Stock Solution Calculations



Laboratory Testing Calculations

Stock Solutions

$MnSO_4 \cdot H_2O$

Added 0.052 g to 100 mL water

$$\text{Stock conc} = \frac{0.052\,g}{100\,mL} \cdot \frac{1000\,mg}{g} \cdot \frac{1000\,mL}{L} = 520\,mg/L$$

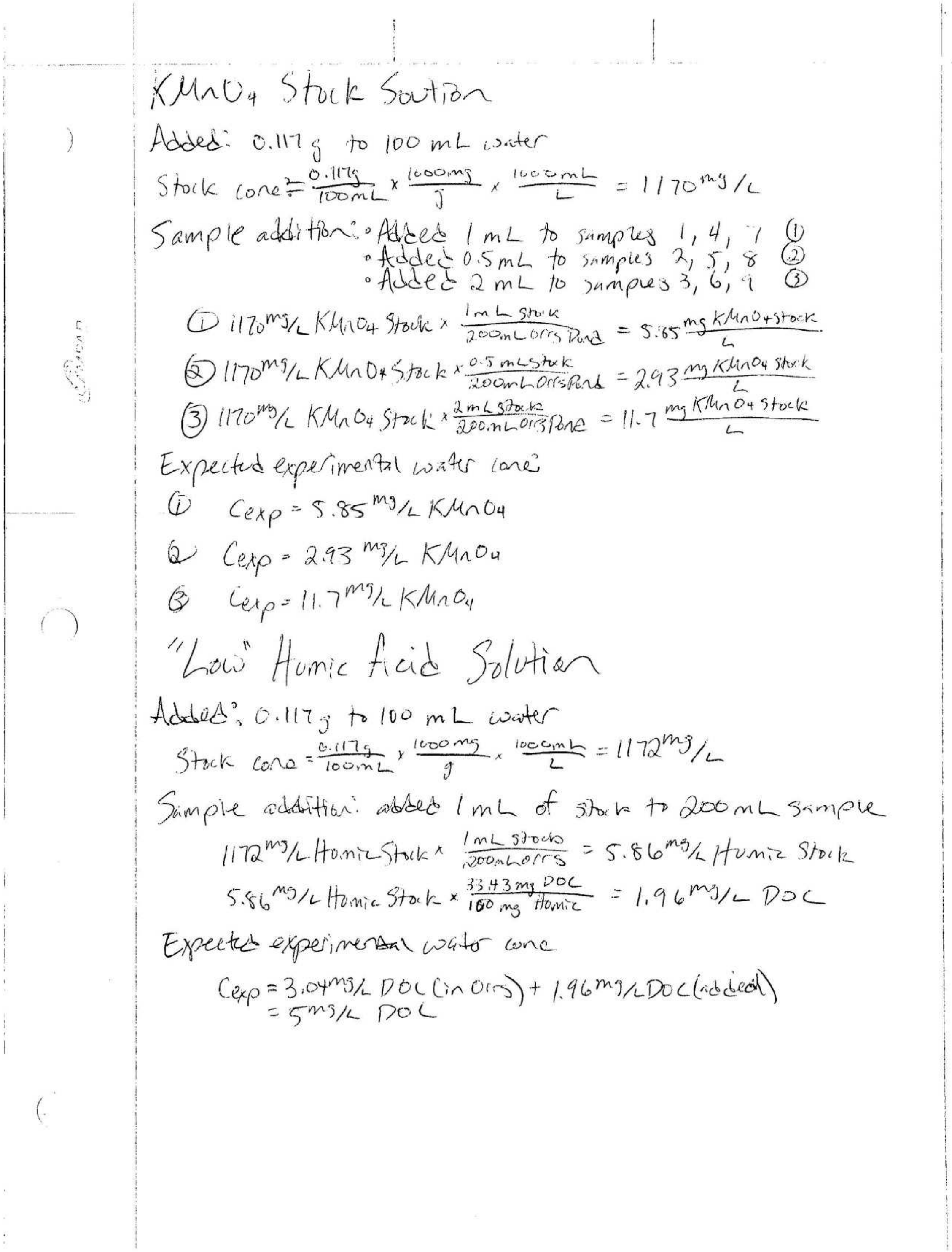
Sample addition: Added 1 mL stock to 200 mL sample

$$520 \frac{mg}{L} \underset{stock}{MnSO_4\text{-}H_2O} \cdot \frac{1\,mL\ stock}{200\,mL\ pond\ water} = 2.6 \frac{mg\ MnSO_4 \cdot H_2O}{L}$$

$$2.6 \frac{mg}{L} MnSO_4\text{-}H_2O \cdot \frac{54.93\,g/mol\ Mn}{169\,g/mol\ MnSO_4 \cdot H_2O} = 0.85 \frac{mg\ Mn}{L}$$

Expected experimental water conc

$$C_{exp} = 0.42 \frac{mg}{L} Mn\ (\text{in Orrs Pond}) + 0.85 \frac{mg}{L} Mn\ (\text{added})$$
$$= 1.27\,mg/L\ Mn$$



KMnO4 Stock Soution

Added: 0.117 g to 100 mL water

Stock conc = $\frac{0.117g}{100mL} \times \frac{1000mg}{g} \times \frac{1000mL}{L} = 1170 \, mg/L$

Sample addition: ◦ Added 1 mL to samples 1, 4, 7 ①
◦ Added 0.5 mL to samples 2, 5, 8 ②
◦ Added 2 mL to samples 3, 6, 9 ③

① $1170 \, mg/L$ KMnO4 Stock × $\frac{1 \, mL \, stock}{200 \, mL \, Orrs \, Pond} = 5.85 \frac{mg \, KMnO_4 \, stock}{L}$

② $1170 \, mg/L$ KMnO4 Stock × $\frac{0.5 \, mL \, stock}{200 \, mL \, Orrs \, Pond} = 2.93 \frac{mg \, KMnO_4 \, stock}{L}$

③ $1170 \, mg/L$ KMnO4 Stock × $\frac{2 \, mL \, stock}{200 \, mL \, Orrs \, Pond} = 11.7 \frac{mg \, KMnO_4 \, stock}{L}$

Expected experimental water conc:

① $C_{exp} = 5.85 \, mg/L \, KMnO_4$

② $C_{exp} = 2.93 \, mg/L \, KMnO_4$

③ $C_{exp} = 11.7 \, mg/L \, KMnO_4$

"Low" Humic Acid Solution

Added: 0.117 g to 100 mL water

Stock conc = $\frac{0.117g}{100mL} \times \frac{1000mg}{g} \times \frac{1000mL}{L} = 1172 \, mg/L$

Sample addition: added 1 mL of stock to 200 mL sample

$1172 \, mg/L$ Humic Stock × $\frac{1 \, mL \, stock}{200 \, mL \, Orrs} = 5.86 \, mg/L$ Humic Stock

$5.86 \, mg/L$ Humic Stock × $\frac{33.43 \, mg \, DOC}{100 \, mg \, Humic} = 1.96 \, mg/L$ DOC

Expected experimental water conc

$C_{exp} = 3.04 \, mg/L$ DOC (in Orrs) + $1.96 \, mg/L$ DOC (added)
$= 5 \, mg/L$ DOC

"High" Humic Acid Solution

Added: 0.237 g to 100 mL

$\text{Stock conc} = \frac{0.237\text{ g}}{100\text{ mL}} \times \frac{1000\text{ mg}}{\text{g}} \times \frac{1000\text{ mL}}{\text{L}} = 2370\text{ mg/L}$

Sample addition: added 1 mL of stock to 200 mL sample

$2370\text{ mg/L Humic Stock} \times \frac{1\text{ mL Stock}}{200\text{ mL ORRS}} = 11.85\text{ mg/L Humic Stock}$

$11.85\text{ mg/L Humic Stock} \times \frac{33.43\text{ mg DOC}}{100\text{ mg Humic}} = 3.96\text{ mg/L DOC}$

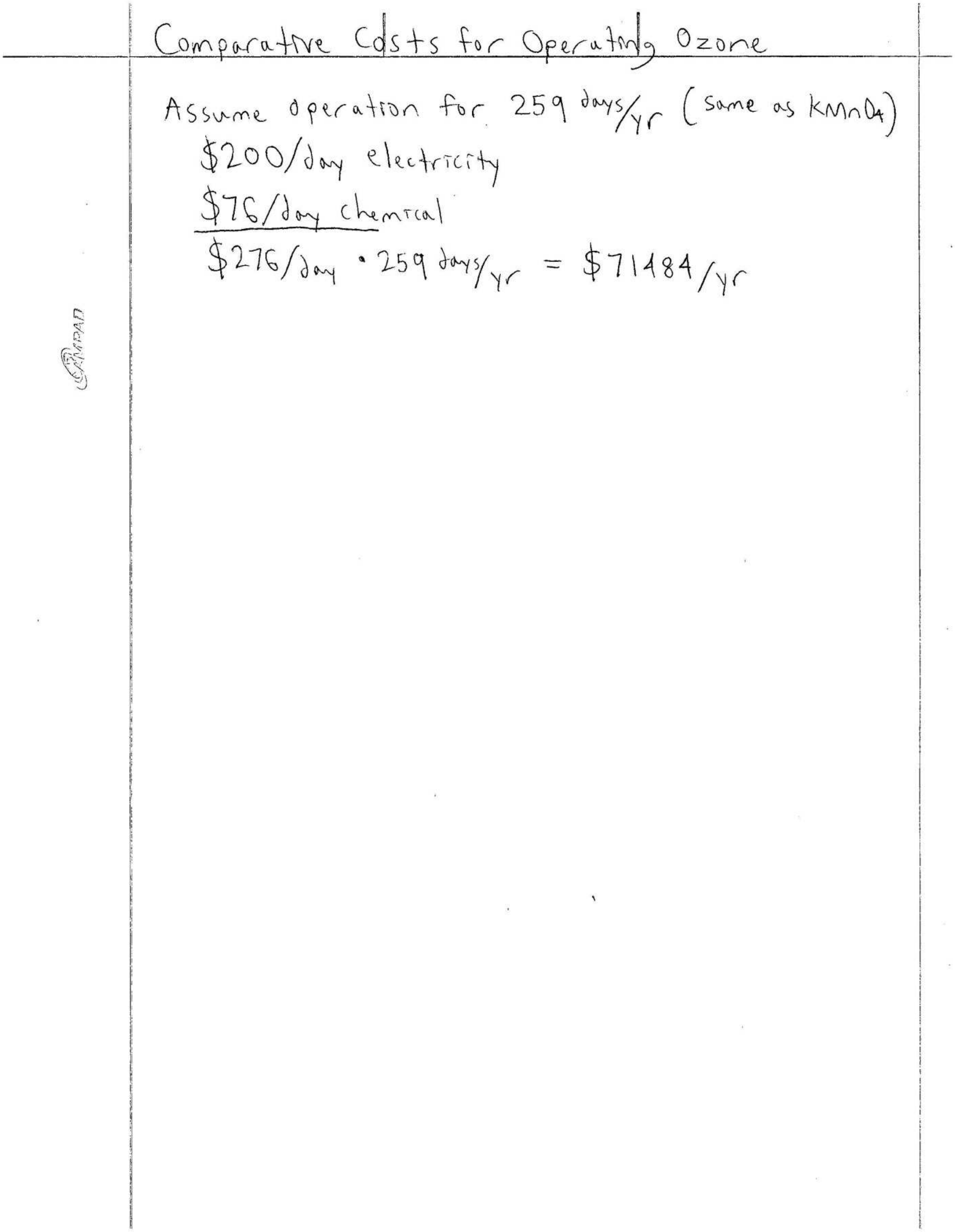
Expected experimental water conc

$C_{exp} = 3.04\text{ mg/L DOC (in ORRS)} + 3.96\text{ mg/L DOC (added)}$
$= 7\text{ mg/L DOC}$

E.2 Water Quality Testing Results

Sample ID	$KMnO_4$ Dose (mg/L)	Dissolved Mn (mg/L)	% Mn Oxidized	Dissolved Fe (mg/L)	% Fe Oxidized	DOC (mg/L)	% OC Oxidized	Unfiltered Water Color
T1	5.83	0.02	98.6	0.01	93.7	2.70	25.39	light pink/orange
T2	2.92	0.16	89.6	0.03	83.5	4.13	26.37	light pink/orange
T3	11.67	0.31	79.5	0.04	80.6	6.10	-2.62	light-med pink/orange
T4	5.83	0.08	94.6	0.03	83.5	4.12	26.53	light-med pink/orange
T5	2.92	2.31	-53.5	0.24	-16.7	5.99	-0.81	light pink/light yellow
T6	11.67	0.01	99.2	0.04	79.1	2.60	27.93	light-med pink/orange
T7	5.83	1.34	10.9	0.14	32.4	5.85	1.58	light pink/light yellow
T8	2.92	0.02	98.9	0.04	80.6	2.70	25.14	light pink/light yellow
T9	11.67	0.05	96.7	0.04	80.1	5.21	7.05	light pink/orange
T10	None	1.45	--	0.16	--	3.61	--	clear
T11	None	1.49	--	0.21	--	5.60	--	clear
T12	None	1.58	--	0.25	--	5.94	--	clear

Appendix F: Comparative Estimated Ozone Treatment Costs



Comparative Costs for Operating Ozone

Assume operation for 259 days/yr (same as $KMnO_4$)

$200/day electricity

$76/day chemical

$276/day • 259 days/yr = $71484/yr