EFFECT OF STORAGE TANK MIXING ON WATER QUALITY

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The Regional Water System Research Consortium (RWSRC) was formed to support research and development projects to develop management and operational tools to sustain the development and service life of regional rural water systems. RWSRC is supported by funds contributed by South Dakota regional rural water systems, the South Dakota Association of Rural Water Systems, and several water development districts in South Dakota. Administrative support and project management are provided through the Water and Environmental Engineering Research Center in the College of Engineering at South Dakota State University.

ABOUT this report.

This report is the second of two reports examining water quality in water storage facilities installed in South Dakota's regional rural water systems. The first report, authored by Christopher Olson and Delvin DeBoer, examined the effects of tank operation and design characteristics on water quality in distribution system storage tanks. This report focuses on the impacts of mixing on water quality in storage tanks. The reports were completed in two consecutive years of field studies of storage tank water quality. This report also served to meet the Master of Science thesis requirements for Andy Lemke, graduate research assistant in the Civil and Environmental Engineering Department at South Dakota State University.

ACKNOWLEDGEMENTS:

The assistance of personnel from the following systems is gratefully acknowledged: Randall Community Water District, Aurora Brule Rural Water Supply System, Clay Rural Water System, Brookings-Deuel Water System, Bon Homme-Yankton Rural Water System, and Lincoln Pipestone Water System.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

H:D Ratio	Height to diameter ratio
^{0}C	Degrees Celsius
ft/s	Feet per second
gpm	Gallons per minute
ft.	Feet
ft/s^2	Feet per second squared
slug/ft^3	Slug per cubic foot
ft^3/s	Cubic feet per second
BTU	British thermal unit
lb/ft^3	Pounds per cubic foot
ft-s/lb	Feet-second per pound
lb-ft/s	Foot pounds per second
lb-s/ft^2	Pound-second per square foot
sec	Second
s^{-1}	Per second
CFD	Computational fluid dynamics
TTHM	Total trihalomethanes
HAA5	Haloaecetic acid
NDMA	*N*-Nitrosodimethylamine
ng/L	Nanograms per liter
EPA	Environmental Protection Agency
SCADA	Tank system control and data acquisition
mg/L	Milligrams per liter
mg/L as N	Milligrams per liter expressed as nitrogen
MCL	Maximum contaminant level
DBP	Disinfection byproduct
AOB	Ammonia oxidizing bacteria
NOB	Nitrite oxidizing bacteria
NOM	Natural organic matter
Mgal	Million gallons
WEERC	Water and Environmental Engineering Research Center
SDSU	South Dakota State University

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

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2012

Storage tanks are used by water systems to maintain pressure in the distribution system and to meet the varying water demands of the system. The design and operation of the storage tanks affect their mixing characteristics which affect the water quality. Poor mixing can lead to stratification in the tanks, which can lead to low chlorine residual causing microbial growth and nitrification.

This thesis presents the results of the study of seven storage tanks used in South Dakota's rural water systems. The tanks were chosen to represent varying height to diameter ratios, varying types of disinfectant, and to study passive mixing systems. The study used temperature data from all of the tanks and water quality data from five of the tanks. Temperature and water sampling apparatus were installed into each of the five tanks to examine the tanks' behavior at varying heights.

Hydraulic parameters including volumetric exchange, densimetric Froude number, and the dimensionless mixing parameter (Roberts et al. 2006) were examined to determine if they could predict the tanks' mixing capabilities by comparing the actual values with theoretical values required for mixing the tank. Chlorine decay modeling was completed using the CompTank program. The model results were compared with actual data obtained during the study to determine the models capability to predict chlorine decay.

The data showed that thermal stratification occurred in a few of the tanks resulting in water quality stratification and depleted chlorine residual in the upper zone of the tanks. High height-to-diameter storage tanks were more susceptible to stratification. To remediate stratification in one tank, the water system drained a large portion of the tank volume into its distribution system and refilled the tank with fresh water. A second system with a stratified tank chose to overflow the storage tank. Both methods were successful in restoring the chlorine residual.

Passive mixing systems were installed in two tanks to prevent stratification. As a result of the passive mixing systems, both tanks were properly mixed, indicating that passive mixing systems can be effective in mixing storage tanks.

Chorine residual measurements in two tanks throughout the study were used to develop chlorine decay coefficients used for the CompTank model. When the resulting decay coefficients were inserted into the model, the model substantially fit the chlorine decay that occurred in the upper zone of the stratified tanks.

CHAPTER 1: INTRODUCTION

1.1 Background

South Dakota rural water systems use water storage tanks throughout their systems to meet the varying demands of the customers. Storage tanks can be categorized into elevated towers, standpipes, ground storage tanks, and below grade storage tanks. Fill and draw cycles in the storage tanks are controlled by pump controls and system demands. Water systems keep storage tanks nearly full to be able to supply peak demands in the system.

Design of storage tanks effects mixing in the tanks. Many storage tanks were designed without consideration of mixing. Storage tanks have been designed with high height to diameter ratio, single inlet/outlet, or other characteristics that promote poor mixing. Mixing in storage tanks depends on water movement during the filling cycle, unless the tank has artificial mixing. Poor mixing in storage tanks can lead to stagnant water, which can lead to declining disinfectant residuals. Low disinfectant residuals could permit nitrification in chloraminated systems.

Water quality issues, such as low chlorine residuals and nitrification events, have caused water system operators and managers to question the mixing characteristics of their storage tanks and to seek advice in how operational changes could help promote mixing in the storage tanks.

1.2 Objective and Scope

The hypothesis of the study was that the mixing characteristics of a storage tank can affect the quality of water stored in the tank. The objective of the study was to determine the effects of mixing characteristics of a storage tank on the quality of the water in storage tanks, and to model chlorine decay in a storage tank. The scope of the study included a literature review, collection of water quality and temperature data from tanks, collection of operational data from tanks, evaluation of water quality data based on hydraulics and operations, and modeling chlorine decay in a storage tank.

A literature review was performed to summarize previous work from others who studied tank mixing and water quality in water reservoirs. The literature review provided data to compare with the experimental data from the study and provide a basis for interpreting the results.

Tanks chosen for the study represented a wide range of tanks used in regional rural water systems. Five tanks were selected for long term study, while two tanks were chosen for short term study. Water quality and temperature data were collected for the long term tank study whereas only temperature data were collected for the short term tank study. The collected data was correlated with operational data and design characteristics gathered from the water systems.

Tank hydraulic parameters were calculated and compared to storage tank water quality data. Also, chlorine decay was modeled and compared to storage tank water quality data collected from thermally stratified tanks. If the hydraulic parameters and the chlorine decay model were effective in predicting mixing and water quality, then the information could be used by water systems to optimize their tank operation.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

A literature review was completed to provide background information for the project. Effects of distribution storage on water age and water quality are introduced. Methods of predicting mixing and modeling chlorine decay are summarized.

2.2 Factors Affecting Mixing in Storage Tanks

High water age can be a problem in storage tanks. Poor mixing and location in low demand areas can lead to high water age in storage tanks. If a tank is poorly mixed, dead zones may be formed where water remains for substantial time leading to high water age. High water age can also be created by dead zones created from temperature differences between the filling water and the temperature of the water volume in the tank. Design and operation of storage tanks can factor into high water age. High height to diameter ratio, inlet location and orientation, and location within the system are some design parameters that can affect water age. Daily operations of the tank such as daily turnover and volume added during the filling cycle also affect water age.

2.2.1 Thermal Stratification

Causes of thermal stratification in storage tanks are introduced in the following sections. Also, hydraulic parameters to model the impact of ambient temperature on temperatures of the water in the storage tank are introduced.

2.2.1.1 Causes of Stratification

Stratification in storage tanks occurs when the density of the water in the tank is different than the density of the filling water. Density of water is a function of temperature. Therefore, stratification can occur when the water in the storage tank is different than the temperature of the filling water. Other factors that can affect stratification are a tank's inlet orientation, momentum of the filling water, and the type of buoyancy.

Unless a storage tank has an artificial mixing device, the water movement from the filling water is the only means of mixing in the tank. When the filling water enters the inlet, the water forms a jet. Even if the momentum of the jet is able to mix the tank, temperature or density differences in the filling water and the water in the tank can cause stratification in the storage tank (Grayman et al., 2004).

Figure 2.1 illustrates two different alternatives of how stratification can occur within a storage tank. A negatively buoyant jet is created when the filling water is colder than the water in the tank, which causes the new water to remain at the bottom of the tank leaving aging water in the upper zone. A positively buoyant jet is created when the filling water is warmer than the water in the tank. The new water rises to the top of the tank (Grayman et al, 2004).

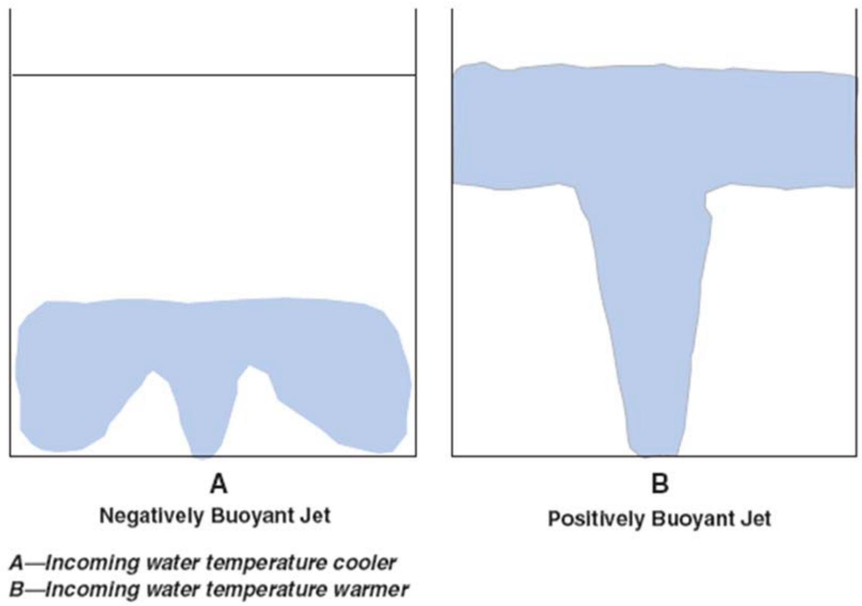


Figure 2.1: Dead zones created from negatively and positively buoyant jets (Adapted from Grayman et al., 2004).

Mahmood et al. (2005) used computational fluid dynamic software to model a comparison of negatively buoyant jets and isothermal conditions. Figure 2.2 is the result of a computational fluid dynamics (CFD) model of a standpipe with a vertical inlet. On the left image, the filling water is 1 ˚C colder than the water in the tank. When the filling water was colder, the water jet mixed less than a third of the tank. The right picture illustrates isothermal conditions when the inflow water and the water in the tank have the same temperature. Under isothermal conditions, the water jet was able to reach the top of the tank and mix the tank. A small change in temperature between the filling water and the water in the tank impacts mixing.

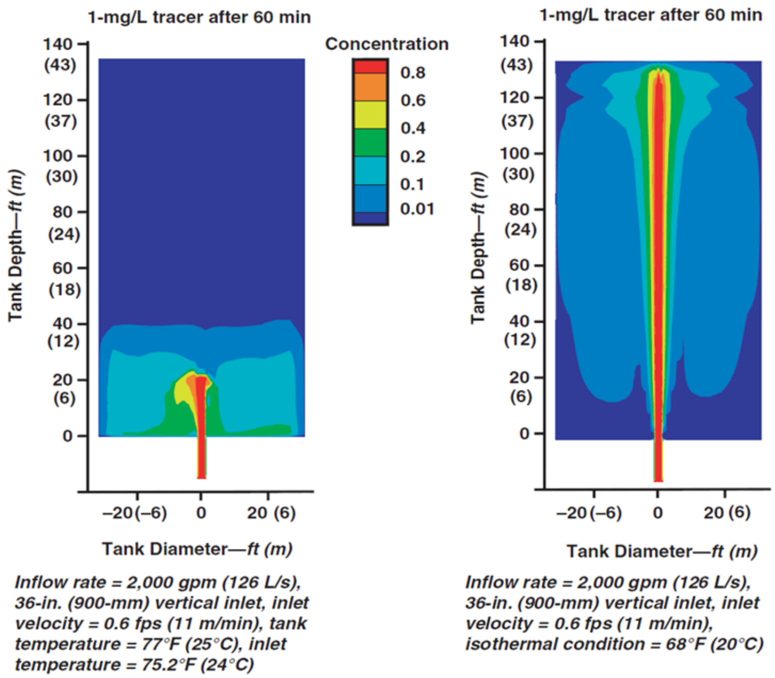


Figure 2.2: Effects of negatively buoyant jet on tank mixing (Mahmood et al., 2005)

2.2.1.2 Predicting Stratification in Storage Tanks

This section introduces hydraulic parameters that can be used to predict tank mixing. The densimetric Froude number can be calculated and compared to a theoretical value developed by Rossman and Grayman (1999) to determine if the tank should mix. A dimensionless mixing parameter developed by Roberts et al. (2006) can also be used to predict tank mixing.

The densimetric Froude number is the inflow's inertial force divided by the buoyant force (Rossman and Grayman, 1999). The buoyant force is created as the filling water and the water in the tank have different temperatures therefore different densities. Fischer et al. (1979) predicted stratification in unconfined bodies of water for negatively buoyant conditions, while Lee and Jirka (1981) examined positively buoyant conditions. Both studies concluded that the occurrence of stratification is related to the densimetric Froude number. Rossman and Grayman (1999) expanded on the work of Fischer et al. (1979) and Lee and Jirka (1981) to study stratification in storage tanks by performing a series of scale tracer studies. Equation 1 was defined by Rossman and Grayman (1999) for the densimetric Froude number:

$$F_d = \frac{u}{\sqrt{g'd}} \qquad (1)$$

where F_d = densimetric Froude number; u = the vertical inflow velocity, ft/s; d = pipe diameter, ft.; and $g' = g(\rho_f - \rho_a)/\rho_a$ where g = acceleration of gravity, ft/s^2; ρ_f=density of inflow, slug/ft^3; ρ_a=density of the ambient water, slug/ft^3. The density of the water can be found using standard tables or approximated using equation 2, which was used by White (2008) to obtain the density +/- 0.2%.

$$\rho \approx \frac{1}{515.379}(1000 - 0.0178|T - 4|^{1.7}) \qquad (2)$$

In Equation 2, ρ = density (slug/ft^3); and T = temperature (˚C).

The experiment completed by Rossman and Grayman (1999) consisted of filling the scale storage tanks with deionized water. Conductivity meters were suspended at varying depths in the tank. After the meters readings stabilized, tap water was pumped into the tank. Inflow characteristics and conductivity were monitored during the experiment. The resulting densimetric Froude number was plotted against the water height/inlet diameter. A line was created that separated the mixed and stratified tanks and the slope of the line (C) was determined. Table 2.1 lists the resulting C values (Rossman and Grayman, 1999).

Table 2.1. Slopes of densimetric Froude number as a function of water height/inlet diameter determined by Rossman and Grayman (1999).

Inlet Orientation	**Inflow Buoyancy**	**C**
Vertical	Negative	0.8
Vertical	Positive	1.5
Horizontal	Negative	1.5
Horizontal	Positive	0.8

Rossman and Grayman (1999) determined an equation that could be compared to the actual densimetric Froude number to predict whether the tank would be mixed. Equation 3 shows the comparison. If the densimetric Froude number (Equation 1) is greater than the right side of Equation 3, then the tank should be mixed:

$$F_d > C\frac{H}{d} \qquad (3)$$

where F_d= densimetric Froude number; C = slope from Table 2.1; H = water height, ft.; d = diameter of inlet, ft.

Roberts et al. (2006) studied jet induced mixing in storage tanks. They derived a dimensionless mixing parameter that was a function of inflow momentum, buoyancy force, and water depth. The dimensionless mixing parameter was related to the occurrence of stratification in tanks. A 3-dimensional laser induced fluorescent tracer system was used to test the relationship. A simple criterion to tell whether water with negative buoyancy should mix in a tank was created by Roberts et al. (2006) and is presented in Equation 4:

$$\frac{M^{0.5}}{B^{\frac{1}{3}} * H^{\frac{2}{3}}} > 0.85 - 0.05n \quad (4)$$

where M = inflow momentum, ft^4/s^2; B = Buoyant Force, ft^4/s^3; H = water depth, ft.; and n = number of inlets. The buoyant force can be found using Equation 5 from Roberts et al. (2006):

$$B = g\left(\frac{\rho_a - \rho_f}{\rho_a}\right)Q \quad (5)$$

where g = 32.2 ft/s^2; ρ_a = density of the water in the tank volume; ρ_f = density of the filling water; and Q = flow rate (cfs). The density of the water can be found using standard tables or approximated using equation 2. If the left side of Equation 4 is greater than the right side, the tank should be mixed.

Roberts et al. (2006) conducted other tracer tests to examine the effects of inlet orientation, negative buoyancy, and positive buoyancy. Olson (2011) summarized the data from Roberts et al. (2006) as shown in Table 2.2.

Table 2.2: Summary of tracer study with single inlet and buouancy effects from Roberts et al. (2006)(Olson, 2011).

Tank Geometry	**Buoyancy Type**	**Inlet Configuration**	**Result of Study**
H:D Ratio ≤ 1.0	Positive	Vertical, single inlet	No scale model tanks became mixed as a result of new water rising to the surface and forming a layer on top of the initial volume
H:D Ratio ≤ 1.0	Positive	Horizontal, single inlet	Tanks whose value of $M^{1/2}/(B^{1/3}H^{2/3})$ >1.3 became mixed
0.25<H:D<2.5	Negative	Horizontal, single inlet	No scale model tanks became mixed as a result of new water hitting the sidewall, losing momentum, and forming a layer at the bottom of the tank

Roberts et al. (2006) results support the findings of Rossman and Grayman (1999). The characteristics of the tanks that did not mix in Roberts et al. (2006) corresponded with similar characteristics of the tanks that received the highest C-value in Rossman and Grayman (1999), which supports the conclusion that these tanks are more susceptible to stratification. Rossman and Grayman (1999) found stratification occurred more readily in tanks with positive buoyancy and vertical single inlet (C=1.5). Roberts et al. (2006) was unable to mix a tank with these conditions, supporting the results of Rossman and Grayman (1999). Tanks with a horizontal inlet were more susceptible to stratification with negative buoyancy (C=1.5) (Rossman and Grayman, 1999), which was again supported by Roberts et al. (2006) when they were unable to mix a tank under these conditions.

2.2.1.3 Heat Transfer in Storage Tanks

Heat transfer can occur through both convection and conduction. Moran et al. (2003) describes both. Convection has two different types - forced convection occurs when an outside factor forces water movement, whereas free convection occurs when there is a difference in density between a portion of water and the surrounding water. Both of these types of convection occur in water storage tanks. An example of free convection is when the water near the outside of the tank is heated and the warmer water rises to the top of the storage tank. Forced convection would occur if a mechanical mixer was installed into the tank forcing movement of water in the tank.

According to Moran et al. (2003) conduction occurs between two points of different temperatures. The warmer point will heat the other. Conduction occurs in a water tank when water in the tank is heated through the tank wall by warmer temperature outside the tank.

Mills (1995) describes a third type of heat transfer, solar radiation. Solar radiation is described as electromagnetic waves produced from the sun, which travel to Earth. Many factors affect the strength of the radiation on a storage tank on Earth, including time of year, time of day, weather, cover from the sun, and location on Earth. Some of the radiation will be reflected from the storage tank instead of being absorbed. Factors affecting absorbance include the material used in constructing the storage tank and the color of the storage tank. Darker colors absorb more than lighter colors. Equation 6 describes the rate of heat transfer (Moran et al., 2003):

$$q_x = UA(T_1 - T_2) \tag{6}$$

in which q_x = heat transfer rate, BTU/hr; U = overall heat transfer coefficient, BTU/(ft^2×˚F×hr); A = surface area of the wall, ft^2; T_1 = warmer temperature, ˚F; and T_2 = cooler temperature, ˚F. Moran et al. (2003) determined Equation 7 to find U:

$$U = \frac{1}{[(1/h_1)+(L/K)+(1/h_2)+(1/h_{rad})]} \tag{7}$$

where U = overall heat transfer coefficient, BTU/(ft^2×˚F×hr); h_1 = convective heat transfer coefficient outside of the tank, BTU/(ft^2×˚F×hr); h_2 = convective heat transfer coefficient inside of the tank, BTU/(ft^2×˚F×hr); L = thickness of the tank wall, in; K = thermal conductivity of the tank wall, BTU×in/(ft^2×˚F×hr); and h_{rad} = radiation heat transfer coefficient. $h_1$and h_2 are affected by the movement of water inside the tank and air outside of the tank. The tank's shape also affects these coefficients. K is affected by the type of material used to construct the storage tank.

2.2.2 Effects of Tank Design on Mixing

The design of a storage tank has an impact on mixing in the tank. Design characteristics such as the height to diameter ratio (H:D) and the inlet characteristics affect mixing in a storage tank. Water systems can install artificial mixing into a storage tank to promote mixing.

2.2.2.1 Effect of Inlet Characteristics on Mixing

Two inlet characteristics that affect mixing include the orientation of the inlet and the inlet's diameter. A storage tank's ability to mix depends on the characteristics of the jet of water formed by the inlet during the filling cycle. The jet's momentum affects the mixing of the storage tank, and the momentum is related to the inlet diameter and the flow rate. The proper tank mixing time is a function of the inflow momentum, geometry, and the volume of water.

The inlet configuration affects mixing in storage '. Grayman et al. (2004) states that a jet is formed when water enters the storage tank through the inlet. Ideally, a vertical inlet will create a jet that has enough momentum to reach the water surface and circulate mixing the tank. A horizontal inlet will ideally have enough momentum to reach the opposite tank wall and circulate to mix the tank. Figure 2.3 illustrates ideal mixing in a storage tank with both a vertical and horizontal inlet orientation.

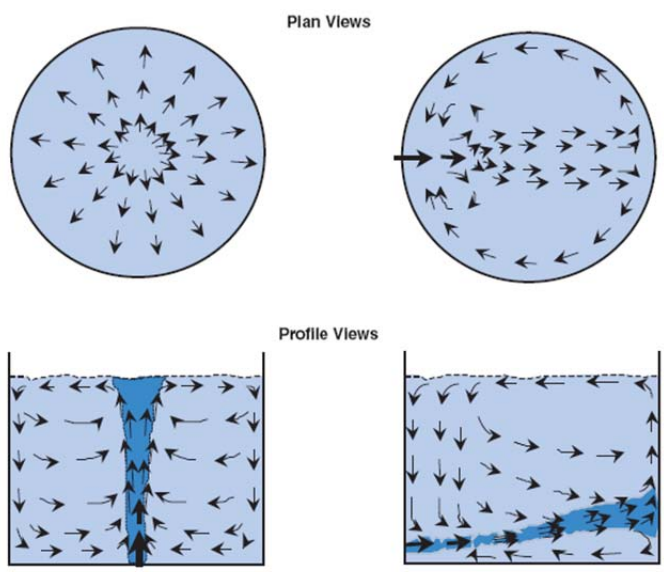


Figure 2.3: Ideal mixing for vertical and horizontal inlet orientations adapted from Okita and Oyama (1963) (Grayman et al. 2004).

The tank's mixing time effects mixing in storage tanks. Rossman and Grayman (1999) determined a tank's mixing time using a scale study. The tank's mixing time was the time needed to obtain 95% uniformity in the conductivity probe readings. Several empirical equations were developed in the chemical engineering profession to determine the tank's mixing time; however, these equations were for tanks that used recirculation pumps and the tank volume remains constant. Rossman and Grayman (1999) modified some of the equations to better describe a storage tank and the fluctuating volume. Using the results of the tracer study and dimensional analysis Rossman and Grayman (1999) derived an equation for the mixing time required to mix a storage tank, which is presented as Equation 8:

$$t_m = \tau_m \frac{V^{2/3}}{M^{1/2}} \quad (8)$$

where t_m = time to completely mix the tank, seconds; τ_m = dimensionless mixing time = 10.2; V=tank volume, ft^3; and M= momentum, ft^4/s^2. The temperature of the filling water and the water in the tank volume are assumed to be equal.

Rossman and Grayman (1999) performed a tracer study in full a scale storage tank to validate Equation 8. The experimental t_m was 4.7 hours, while the calculated t_m was 4.3 hours. The result of the study verifies that Equation 8 can be used for full scale systems.

The work done by Rossman and Grayman (1999) was used by Roberts et al. (2006) to include standpipes. A 3-dimensional laser induced fluorescence system was used to analyze tank mixing in the tracer studies performed by Roberts et al. (2006). More accurate description of water movement was determined from the laser system than the submerged probes used in the tracer study completed by Rossman and Grayman (1999). Roberts et al (2006) used Equation 8; however, the dimensionless mixing time was modified to be a function of the H:D ratio. Equation 9 shows the modifications to the dimensionless mixing time:

$$\tau_m = 10.0 \; for \; \frac{H}{D} \leq 1.0 \quad (9)$$

$$\tau_m = 10.0 + 3.5\left(\frac{H}{D} - 1\right) \; for \; \frac{H}{D} > 1.0$$

where τ_m= dimensionless mixing time; H = tank height, ft; and D = tank diameter, ft.

Roberts et al. (2006) performed multiple tracer studies to determine the dimensionless mixing time of storage tanks with different inlet orientation, different inlet location, and different number of inlets. The data from the tracer studies was presented by Roberts et al. (2006). Olson (2011) summarized the data by finding the average dimensionless mixing time for each inlet scenario. Table 2.3 lists the results of the tracer studies.

The inflow momentum of the filling water is an important factor in mixing a storage tank. Increasing the inflow momentum can be accomplished by increasing the flow into the tank or decreasing the inlet diameter. Equation 8 describes the relationship between inflow momentum and the time required for mixing. An increase in momentum will lead to a smaller mixing time (Rossman and Grayman, 1999).

Table 2.3. Dimensionless mixing times to mix tank in standpipes from Roberts et al. (2006) summarized by Olson (2011).

Inlet Configuration		**Average Dimensionless Mixing Time**
	One port, bottom, side, horizontal	18.4
	One port, bottom, side vertical	15.4
	One port, bottom, center, horizontal	15.4
	Two ports, horizontal	10.6
	Seven ports, horizontal	13
	One port, center, vertical, with draft tube	Did not mix under isothermal condition

Mahmood et al. (2005) completed experiments that analyzed the effect of the inflow momentum on mixing in standpipes. One experiment showed the effect of inlet diameter. A standpipe's characteristics were 24 inch diameter horizontal inlet and flow of about 2000 gpm. The tank had a filling time of 3 hours, but the tank did not mix due to low inflow momentum. The inlet was changed to 12 inches in diameter and vertical orientation, which would increase the momentum. The tank was mixed well after only an hour of fill time. Mahmood et al. (2005) recommended an inflow momentum between 20-30 ft^4/s^2 for standpipes to mix properly and that vertical inlets were better for mixing.

Grayman et al. (2004) concluded that the inlet's orientation affects mixing in a storage tank. Due to the water height in standpipes, standpipes are more susceptible to being poorly mixed; therefore, more susceptible to stratification. Figure 2.4 illustrates inlet configurations that Grayman et al. (2004) found to prevent mixing.

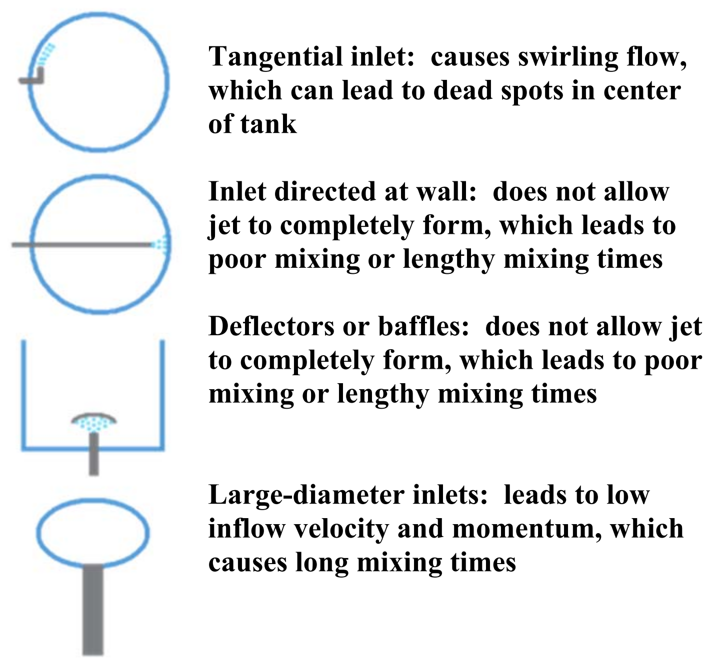


Figure 2.4. Inlet configurations that do not promote mixing (Adapted from Grayman et al. 2004).

The inflow velocity and momentum are also factors in the densimetric Froude number and the dimensionless mixing parameter from Roberts et al. (2006). Both of these parameters are also impacted by buoyancy forces created by density differences in the filling water and the water inside the tank. Increased buoyancy forces cause an increase in difficulty for mixing the tank. Increased buoyancy forces will lead to greater inflow momentum and inflow velocities to be needed in order to mix a storage tank as shown in Equation 1 and Equation 4. Increasing the velocity and the momentum of the inflow can be accomplished by decreasing the inlet diameter or by increasing the flow into the tank.

2.2.2.2 Effects of Tank Geometry on Mixing

Kennedy et al. (1993) used full-scale tracer studies to describe the effect of tank geometry on mixing. Standpipes were found to be the most susceptible to stratification. Due to the high height to diameter ratios, inflow water cannot reach the upper zone (dead zone) of the tank causing poor mixing and stagnant water in the upper zone (Kennedy et al. 1993).

The required densimetric Froude number (Equation 3), dimensionless mixing parameter from Roberts et al. (2006) (Equation 4), and the required mixing time (Equation 8) are all affected by the H:D ratio. An increase in H:D ratio causes an increase in the required densimetric Froude number, a decrease in the dimensionless mixing parameter (Roberts et al. 2006), and a longer filling time. Therefore, taller standpipes are more susceptible to poor mixing and stratification.

2.2.2.3 Effects of Artificial Mixers on Mixing

Mechanical mixing in a storage tank is similar to mixing tanks of water in water treatment plants. The velocity gradient (G) is the measurement of the amount of agitation in a mixing tank (Qasim et al. 2000) and Equation 10 is a method for calculating the velocity gradient:

$$G = \sqrt{\frac{P}{(V\mu)}} \tag{10}$$

where G = velocity gradient, 1/s; P = power imparted to the water, lb×ft/s; V = volume, $ft^{3;}$ μ = absolute viscosity, $lb\times s/ft^2$.

The effect of mechanical mixing on storage tanks was studied by Giguere and Fiske (2010). According to Giguere and Fiske (2010) a simple way to observe the effect of active mixing in a storage tank is to install a mechanical mixer in a storage tank that is thermally stratified and observe the time for the tank volume to become a uniform temperature. Two tanks were studied by installing submersible temperature sensors at varying depths within the tank. The mechanical mixer was turned on and the temperatures were monitored to determine the amount of time to create uniform temperature throughout the tank volume. A 500,000 gallon storage tank that was thermally stratified by 5 ˚C between the top and bottom of the storage tank was studied by Giguere and Fiske (2010). After turning on the mechanical mixer, 4 hours elapsed before the tank volume's temperature was uniform at 15 ˚C. The power needed to mix the tank was 223 Watts. Using Equation 10 the velocity gradient for the tank was approximately 10.1 s^{-1}. The other tank studied was a 2.75 million gallon square storage tank with a 10 ˚C difference between water in the bottom of the tank and the top of the tank. After 5 hours of turning on the mechanical mixer, the temperature in the tank volume became uniform at about 23 ˚C. The power required for the tank was not provided in the study; therefore, the velocity gradient cannot be calculated.

2.2.3 Effects of Tank Operation on Mixing

How a water system operates a storage tank affects mixing in the tank. Rossman and Grayman (1999) determined that the volumetric exchange in a storage tank affects mixing in the tank. Equation 8, required mixing time to mix a tank, was extended by Rossman and Grayman (1999) to derive an equation for the required volumetric exchange during the fill and draw cycle to mix a storage tank. Equation 11 is a comparison of the actual volumetric exchange and the required volumetric exchange. If the left side of the equation is greater than the right, than the storage tank should be mixed.

$$\frac{\Delta V}{V} = \frac{9d_i}{V^{1/3}} \tag{11}$$

In Equation 11, ΔV= volume added to the tank during a fill cycle, ft^3; V=minimum tank volume, ft^3; d_i=inlet diameter, ft. The temperature of the filling water and the tank volume are assumed to be the same for the volumetric exchange parameter. Mahmood et al. (2009) completed full-scale temperature studies of storage tanks that were also analyzed using Equation 11. The results confirmed Equation 11 as storage tanks that stratified did not meet the required volumetric exchange.

Rossman and Grayman (1999) derived Equation 11 from Equation 8 to relate the volumetric exchange required during a fill cycle to mix the tank. Olson (2011) showed a generalized derivation of Equation 8. Equation 12 is the generalized derivation of Equation 8 for the required volumetric exchange.

$$\frac{\Delta V}{V} > \frac{(\pi)^{1/2}\tau_m d_i}{2V^{1/3}} \tag{12}$$

In Equation 12, ΔV = volume of water added during fill, ft^3; V= minimum tank volume, ft^3; τ_m = constant; and d_i = inlet diameter, ft. Equation 12 also assumes no difference in temperature between the filling water and the water in the tank.

Kennedy et al. (1993) studied the effect of volumetric exchange on storage tanks. A full scale study was completed with two storage tanks. One 12-hour fill cycle was analyzed. One tank exchanged 10% of the tank's volume, while the other tank exchanged 64% of the tank's volume. The tank that exchanged 10% of the tank's volume lost 50% of the tank's chlorine residual, while the other tank only lost 30% of the tank's chlorine residual. Kennedy et al. (1993) concluded that water systems should try and meet the required volumetric exchange for mixing to prevent poor water quality.

2.3 Modeling of Mixing in Storage Tanks

Mixing in a storage tank and disinfectant residuals can be modeled by using systematic models, computation fluid dynamics, or scale models. Each of these methods should be calibrated using field data to ensure proper modeling technique.

2.3.1 Systematic Modeling

Systematic models are simplified models used to describe physical situations. Grayman et al. (2000) states that systematic models are based on statistics and empirical equations. Systematic modeling creates a model that depicts a physical process in a highly conceptual manner. Systematic models divide a tank into zones, in which each zone is completely mixed and flow between each zone occurs (Grayman et al. 2000). Mau et al. (1995) performed a study to describe different systematic models. In the study, several parameters were assumed including constant inflow and outflow rates, similar flow rates between zones, and uni-directional flow. Clark et al. (1996) expanded on the work of Mau et al. (1995) by studying time-varying flow rates using polynomials. Olson (2011) summarized the different systematic models from the previous studies. Table 2.4 lists and describes the systematic models.

Table 2.4 Systematic Models for Mixing in Storage Tanks (Olson 2011).

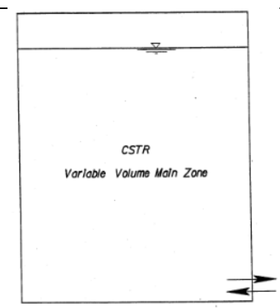
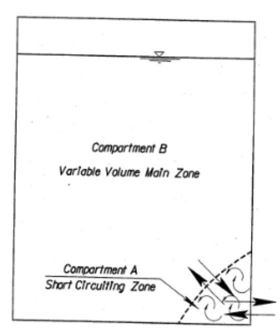
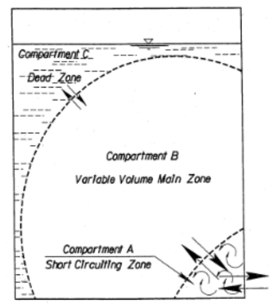
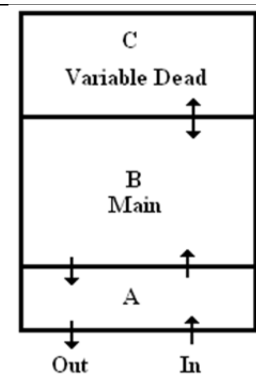
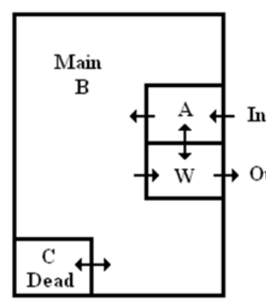
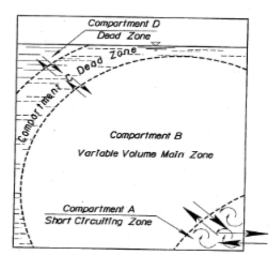
Name of Model	Description of Model	Figure	Reference
Plug flow model	A Plug flow reactor (PFR) is also known as a first in-first out (or last in last out). In an ideal plug flow case, no mixing occurs within the tank, and each fluid particle remains independent of surrounding fluid particles. Plug flow reactors are most commonly found in treatment plants, rather than storage facilities in the distribution system.		
Mixed Flow Model	A mixed flow model assumes that the tank is constantly mixed at all times. It can be described as a continuously stirred tank reactor (CSTR).		Mau et al. (1995)
Two-compartment model	In a two-compartment model, the tank is divided into two regions, compartments A and B. Both of these compartments are modeled as individual CSTRs. The volume of compartment A is fixed, while B is variable. The inflow to the tank enters compartment A, while compartment B either increases in volume, receiving flow from A, or transfers water to A depending on the flow conditions.		Mau et al. (1995)

Table 2.4 (Continued) Systematic Models for Mixing in Storage Tanks (Olson 2011).

Three-compartment model	In a three-compartment model, a third region (compartment C) is added to the two-compartment model to represent a dead storage zone in the tank. The volume of compartments A and C are assumed to be constant, while B is variable. The addition of the third compartment adds a fixed flow between B and C to the model.		Mau et al. (1995)
Stratified three-compartment model	An additional three-compartment model was developed to better represent a study with stratified reservoirs. The only difference between this and the original three-compartment model is the variable zone is changed from compartment B to compartment C.		Mau et al. (1995)
Three-and-one half-compartment model	The three- and-one-half model was developed to represent a continuous inflow/outflow condition. The name for this model was created to prevent confusion with a four-compartment model developed by Mau et al. (1995). Compartment B is considered the variable zone, while all others are fixed, with the following image showing all the flows between compartments. Compartment C is set as the dead zone.		Grayman et al. (2000)
Four-compartment model	The four-compartment model was developed to provide a representation for tanks containing extreme dead storage. This is represented by adding an additional compartment as a buffer zone between the main compartment and the dead storage area.		Mau et al. (1995)

A software package for modeling storage tanks called CompTank was included with Grayman et al. (2000). CompTank can model 9 different mixing models for a storage tank. The 9 mixing models are:

- Fill and Draw – Complete Mix
- Fill and Draw – Plug Flow
- Fill and Draw – Last in/First out (LIFO)
- Fill and Draw – 3 Compartment
- Fill and Draw – Stratified, 3 Compartment
- Continuous Flow – Complete Mix
- Continuous Flow – Plug Flow
- Continuous Flow – Last in/First out (LIFO), and
- Continuous Flow – 3 ½ Compartment

The simplification of these models creates a greater need for calibration according to Grayman et al. (2000). Calibration is best conducted by comparing field data collected to the model results. If no field data are available, the effectiveness of the model is dependent on the user's knowledge.

2.3.2 Computational Fluid Dynamic Modeling

Computational Fluid Dynamic (CFD) modeling is used to describe the movement of gases and liquids (Grayman et al., 2000). According to Grayman et al. (2000), three different processes for representing a physical product occur in CFD modeling. The three processes are the mathematical representation, the numerical representation of the mathematical model, and the computational method for solving the numerical representation. The equations for the conservation of energy, mass, and momentum are used to describe the movement of fluid in CFD modeling (Grayman et al., 2000). CFD modeling can be an asset in the design and the operation of a storage tank. In design, a CFD model can illustrate the effects of different inlet configurations on the storage tank to find the best possible orientation and diameter of the inlet to promote mixing. In operations, CFD models can show the effect of increasing the inflow rate on mixing in the storage tank. CFD models create more accurate representation of mixing in a storage tank than a systematic model because of the computer models ability to calculate complex mathematical equations (Grayman et al., 2000).

Determining whether to use CFD modeling comes down to a few factors - the cost of the software, the computer resources, and the training required to use the program. Grayman et al. (2000) describes two different types of software. FIRE is a commercial program that can be used to model compressible or incompressible fluids in different situations. HydroTank is a program that is designed to examine common water storage tank geometries with one inlet and outlet. Although HydroTank is not as comprehensive as FIRE, HydroTank is more affordable and does not require as much training as FIRE requires (Grayman et al., 2000). Similar to systematic modeling, calibration should be done to any CFD model created.

2.3.3 Scale Modeling

Scale modeling uses a smaller physical model that behaves similarly to an actual storage tank or a prototype of a storage tank. According to Grayman et al. (2000), scale models have been used for centuries in the hydraulic structure field. Rossman and Grayman (1999) used a scale model study to determine the mixing time to predict mixing in a storage tank (Equation 8) that was previously discussed in section 2.2.2.1. Roberts et al. (2006) also used scale models to determine the dimensionless mixing times in various storage tanks as discussed in section 2.2.2.1.

2.3.4 Testing Models

A systematic, CFD, or scale model can be tested by gathering field data from a full scale system. The most common types of tests are water quality, temperature, and tracer tests. Although sampling can occur at the inlet, outlet, or inside of the tank; the most effective sampling method is to sample all of the locations. These types of studies are useful in identifying mixing and water quality issues.

Interior sampling is an effective method to determine a storage tank's mixing characteristics and water quality characteristics. Interior sampling can be accomplished in a few ways. Grayman et al. (2000) described two different methods. Sampling taps could be installed at varying depths of the storage tank, or a sampling apparatus could be constructed and lowered into the storage tank with sampling locations at varying depths of the tank. The data obtained from interior sampling studies can illustrate problem areas in a storage tank. Mahmood et al. (2005) used an interior temperature apparatus in full-scale tanks to confirm the CFD models created in the study. Figure 2.5 is an illustration of the temperature apparatus used by Mahmood et al. (2005). The apparatus consisted of temperature sensors attached to a chain at varying depths of the tank. The apparatus was weighted to be sure the chain remained straight throughout the study. A data logger was used to store the temperature data obtained by connecting the temperature sensors to the data logger.

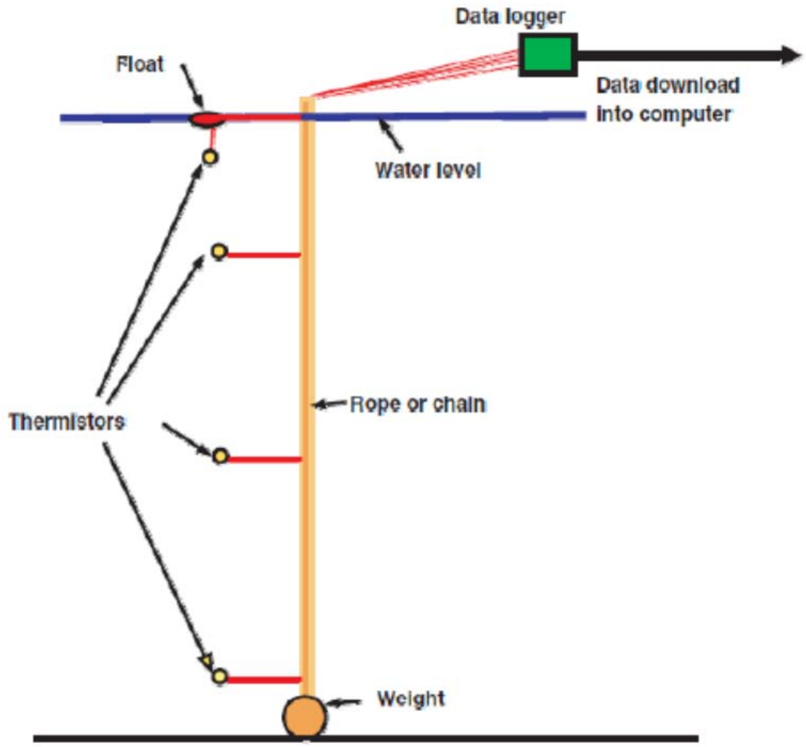


Figure 2.5: Temperature collection apparatus used by Mahmood et al. (2005)

Exterior sampling is not as affective in determining problem areas in storage tanks as interior sampling. Monitoring the inflow and the outflow does not accurately portray the storage tank's mixing characteristics. Issues such as stratification and short circuiting could cause a difference in water quality between the bottom of the tank and the upper zone of the tank. Collecting samples from the outlet will not show the water quality issues in the upper zone.

2.4 Effects of Mixing on Water Quality

The ability for a storage tank to mix can affect the water quality in the storage tank. If a storage tank does not mix properly, disinfectant decay can occur in portions of the storage tank. Disinfectant decay occurs when the chemicals used for disinfection react with other substances. A loss in disinfectant residual can lead to microorganism growth, nitrification, and formation of disinfection by-products. Disinfection, disinfectant decay, nitrification, microbial growth, and drinking water regulations are discussed in this section.

2.4.1 Disinfection

Drinking water needs to be disinfected to prevent harmful organisms from being transferred to the customers. Disinfection at a water treatment plant serves two purposes.

Primary disinfectants kill the harmful organisms in the water, while secondary disinfectants maintain a proper chlorine residual throughout the distribution system.

2.4.1.1 Free Chlorine

Free chlorine is an ideal disinfectant because chlorine is soluble in water, easily measured, and compared to other disinfectants chlorine is less expensive (Qasim et al., 2000). Qasim et al. (2000) explains use of chlorine gas and hypochlorite salts for disinfection. The disadvantages to free chlorine are that compared to combined chlorine the residual decays quickly and the reaction with organic material can lead to disinfectant by-products.

2.4.1.2 Combined Chlorine

The combined chlorine residual is created when chlorine reacts with ammonia to form chloramines. In the chloramine form, chlorine is a weak disinfectant; however, chloramine provides a stable residual in the distribution system. Chloramine also does not produce trihalomethanes (Qasim et al., 2000). Chloramines exist in three different forms in the distribution system: monochloramine (NH_2Cl), dichloramine ($NHCl_2$), and trichloramine (NCl_3). Qasim et al. (2000) lists the three forms and the chemical reactions required to produce each.

$$NH_3 + HOCl \leftrightarrow NH_2Cl + H_2O$$
$$NH_2Cl + HOCl \leftrightarrow NHCl_2 + H_2O$$
$$NHCl_2 + HOCl \leftrightarrow NCl_3 + H_2O$$

To form chloramine, ammonia is added to chlorinated water. According to Qasim et al. (2000), the appropriate chlorine-to-ammonia weight ratio is 3:1 to 4:1 and breakpoint chlorination occurs at 5:1.

2.4.2 Disinfectant Decay

Disinfectant decay occurs when the disinfectant reacts with organic material, organisms, and surfaces in the distribution system such as pipe walls. These reactions cause a decrease in disinfectant residual. If the disinfectant residual becomes too low; microbial growth can occur and nitrification can occur in chloraminated systems.

2.4.2.1 Free Chlorine Decay

Free chlorine decays when chlorine reacts with organic material in the water and when chlorine reacts with the pipe walls. When chlorine reacts with organic matter, disinfectant by-products such as TTHMs and HAA5s can be formed. The health risks of TTHMs and HAA5s were studied by Boorman et al. (1999). The study found that the main concern with TTHMs and HAA5s is cancer.

Boulos et al. (1996) states that free chlorine decay can be described as a first order equation. The first order equation used is shown in Equation 13:

$$C_t = C_0 e^{-kt} \quad (13)$$

where C_t = the concentration at time "t", mg/L; C_0 = the concentration at time "0", mg/L; k = decay coefficient, d^{-1}; and t = time, days. Equation 13 can be solved for the decay coefficient:

$$k = -\frac{\ln(\frac{C}{C_o})}{t} \quad (14)$$

where k = decay coefficient, d^{-1}; C = final chlorine concentration, mg/L; C_o= initial chlorine concentration, mg/L; and t = time, days. The decay coefficient is dependent on temperature. At higher temperatures, the decay coefficient is greater. An equation to adjust the decay coefficient was stated by Gowda (1978):

$$k_2 = k_1 * \theta^{T_2 - T_1} \quad (15)$$

where k_1 = decay coefficient at T_1, d^{-1}; k_2 = decay coefficient at T_2, d^{-1}; T_1= initial temperature, ˚C; T_2 = correcting temperature, ˚C; and θ is a constant. Gowda (1978) performed calculations to find the θ value at varying temperatures and pH. The range of θ calculated was 1.025 to 1.031. Gowda (1978) used θ = 1.03.

2.4.2.2 Chloramine Decay

Chloramine reactions with materials in the distribution system will lower the combined chlorine residual. During these reactions, ammonia is released into the system, which can lead to nitrification. Regan et al. (2007) lists four reactions in which chloramines release ammonia into the water system. Table 2.5 lists the four reaction that produce ammonia.

Table 2.5 Chloramine decay reactions that release ammonia (Regan et al. 2007)

Reaction	Stoichiometry
Chloramine auto-decomposition	$3NH_2Cl \rightarrow N_2 + NH_4^+ + 3Cl^- + 2H^+$
Oxiditation of organic matter by chloramine	$0.1C_5H_7O_2N + NH_2Cl + 0.9H_2O \rightarrow 0.4CO_2 + 0.1HCO_3^- + 1.1NH_4^+ + Cl^-$
Reaction of chloramine with corrosion products at pipe walls	$0.5NH_2Cl + H^+ + Fe^{2+} \rightarrow Fe^{+3} + 0.5NH_4^+ + 0.5Cl^-$
Oxidation of nitrite by chloramine	$NH_2Cl + NO_2^- + H_2O \rightarrow NH_3 + NO_3^- + HCl$

Chloramine decay has been modeled using a first order equation similar to the free chlorine decay equation (Equation 13). Gyürék and Finch (1998) used the first order equation to model the decay of chloramines. However, Valentine et al. (1998) developed a second order equation to model the decay of chloramine. Equation 16 is the second order equation developed by Valentine et al. (1998):

$$\frac{1}{[NH_2Cl]} - \frac{1}{[NH_2Cl]_0} = k_{OBS}t \qquad (16)$$

where $[NH_2Cl]$ = monochloramine concentration at t, moles/L; $[NH_2Cl]_0$ = monochloramine concentration at t = 0, moles/L; t = reaction time, hr; and k_{OBS} = second order rate constant. k_{OBS} is the slope of $\frac{1}{[NH_2Cl]}$ versus t if plotted.

Valentine et al. (1998) performed a full-scale study of a water system to compare the field data with the second order model. The results of the second order model and the full scale study fit well, illustrating that the second order equation could be used for modeling purposes. Valentine et al. (1998) ignored the presence of natural organic material when creating the second order equation. When samples included natural organic material, the model was not as successful in predicting the chloramine decay.

Regulated disinfectant by-product concentrations (TTHMs and HAA5s) decrease when chloramines are used as disinfectant. However, *N*-Nitrosodimethylamines (NDMAs) can form. Wilczac et al. (2003) states that NDMAs formation is increased when water systems over dose polymer or recycle the filter backwash water because a source of residual cationic polymer is provided. Wilczac et al. (2003) found NDMA to be carcinogenic. NDMA formation can be reduced by allowing free chlorine contact time of 1 to 4 hours before the ammonia addition (Wilczac et al., 2003). Even with the studies showing the danger of NDMA, no maximum contaminant level (MCL) has been set by the federal government (Crittenden et al., 2005).

2.4.3 Nitrification

In a chloraminated system, nitrification can occur when the chlorine residual is lost. Wilczac et al. (1996) describes nitrification as the oxidation of ammonia to nitrite and then the oxidation of nitrite to nitrate. The bacteria responsible for these reactions are ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB). Wilczac et al (1996) performed experiments that showed the ability for AOB to survive in water with chloramine residuals of 1.2 mg/l to 8 mg/l. Nitrification produces nitrite and nitrate. Both nitrite and nitrate are regulated in drinking water.

2.4.4 Microbial Growth

The loss of disinfectant residual can lead to microbial growth in a water system. Water contaminated with microorganisms can be a risk to the consumers' health. Microbial growth can be monitored by testing for heterotrophic organisms or coliforms, which can be analyzed by heterotrophic plate count and total coliform tests, respectively.

2.4.4.1 Heterotrophic Plate Count

Heterotrophic Plate Count (HPC) is a method used to estimate the number of heterotrophic organisms in a water sample (WHO et al., 2003). HPC testing does not distinguish the type of heterotrophic organisms present in the water sample. Heterotrophic organisms are organisms that use organic carbon as an energy source for cell synthesis (Qasim et al. 2000). Standardized methods for HPC analyses are available; however, no universal method is accepted throughout the water treatment field. HPC testing can be completed with many variations including different media, plating techniques, incubation temperature, and incubation duration (WHO et al., 2003). With multiple variations in methodology, a wide range of results are obtained. To find the number of colony forming units (CFUs), the colonies formed during the incubation are simply counted (APHA et al., 1998).

Prevost et al. (1998) stated that HPC numbers can range from less than 1 CFU/ml to 10,000 CFU/ml in water distribution systems, which shows that contamination or microbial growth occurs in some distribution systems. Contamination can occur during contact with part of the distribution system such as pumps, storage tanks, and piping. Internal microbial growth can occur due to biofilms within the distribution system (Van der Wende et al., 1989). Microorganisms that pass through the treatment process without being removed can cause growth within the distribution system (Momba et al., 2000).

The growth of heterotrophic organisms can be affected by many different factors. Studies by LeChevallier et al. (1991), McCoy and Olson (1986), Neden et al. (1992), Skadsen (1993), and Niquette et al. (2001) have determined some key factors in heterotrophic organism growth. The factors include temperature, detention time in distribution system, source water, pipe material, the disinfectant residual, and the organics in the water. These factors can influence the heterotrophic organisms' growth.

HPC analyses are not used by regulatory agencies to determine the quality of water. However, a water system could use the HPC analyses to observe the microbial characteristics in a distribution system. According to the EPA, HPC results are successful in describing the bacteriological quality of drinking water (USEPA, 1975).

2.4.4.2 Total Coliform

Total coliform analysis became the method used to determine the safety of the drinking water after E. Coli was found to be more resistant to disinfectants than other organisms (Percival et al., 2000). The Total Coliform Rule (TCR) was adopted to regulate fecal contamination by testing for total coliforms since total coliforms are an indicator of fecal contamination. A water systems population served determines the amount of sampling required to comply with the TCR. 95% of the samples tested for total coliforms are required to be negative for coliform growth to comply with the TCR. If a sample tests positive for coliforms, another sample from the same location should be obtained and analyzed. If the new sample also tests positive for coliforms, the sample should be tested for E. Coli. A violation needs to be reported if the E. Coli test is positive (USEPA, 1989).

Geldreich et al. (1972) performed a study that showed high HPC can interfere with the total coliform results. Coliform formation and counting was less efficient when the HPC was 500 CFU/ml or greater. Geldreich et al. (1978) confirmed the previous findings, concluding that high HPC will interfere with coliform testing. LeChevallier and McFeters (1985) performed an experiment with water that was spiked with coliform bacteria and concluded that congestion and interactions with heterotrophic organisms factored into the interference of coliform tests.

2.4. Water Quality Regulations

Drinking water is regulated to maintain a safe standard in water quality. Loss of disinfectant residual throughout a water distribution system can lead to disinfectant by-product formation and nitrification. Water systems are regulated to maintain certain water quality by the Stage 1 and Stage 2 Disinfectant and Disinfection By-Product Rule.

2.4.5.1. Safe Drinking Water Act

The federal government created the Safe Drinking Water Act to regulate certain drinking water standards. A chloraminated water system needs to prevent nitrification because the primary drinking water standards regulate the amount of nitrite and nitrate in the water. Nitrite's standard is 1 mg/l as N, while nitrate's standard is 10 mg/l as N.

2.4.5.2 Disinfectants and Disinfection By-Product Rule

Disinfectant by-products (DBPs) are formed when disinfectants react with materials in the system. Chlorinated systems can form trihalomethanes (TTHMs) and haloaecetic acids (HAA5s). As discussed in section 2.4.2.1, TTHMs and HAA5s have a risk of causing cancer. The risk caused the EPA to adopt the Stage 1 Disinfectant and Disinfection By-Product Rule (D/DBP Rule) (USEPA, 1998). The D/DBP Rule set MCL for TTHMs at 0.08 mg/l and HAA5s at 0.06 mg/l. The D/DBP Rule also set the maximum disinfectant residual levels (MDRLs). Free chlorine system's MDRL is 4 mg/l measured as free chlorine. Chloraminated system's MDRL is 4 mg/l measured as total chlorine. The Stage 2 D/DBP Rule was adopted by the EPA because certain areas in distribution systems did not meet the MCLs, but passed the Stage 1 D/DBP Rule because the bases of the MCLs were system wide running annual averages. Compliance for TTHM and HAA5 for the Stage 2 D/DBP Rule is based on locational annual running averages rather than a system wide average. (USEPA, 2009).

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

Data were collected from water tanks that were chosen based on the past study done and the South Dakota rural water survey completed by Olson (2011). The tanks were selected based on characteristics of the tanks that made them unique from each other such as the size of tank and type of disinfectant used.

This section will introduce the equipment used to obtain temperature data and water quality data from each tank. The method of sampling, preservation, and testing of the samples for water quality are also introduced. The thermal stratification data analyses and the data analyses for showing proper tank mixing are reviewed. This section also introduces the chlorine decay modeling process and the microbial testing processes.

3.2 Tank Selection for Study

The scope of this project required tank selection for long term temperature data collection and multiple samplings for water quality data and microbial tests. There were many factors contributing to selecting which tanks to use in the long term study.

One of the key factors was the tank's geometry. The height to diameter ratio was used to group the tanks into five different groups (0-0.5, 0.5-1, 1-2, 2-4, and >4). Olson's study included a tank that theoretically should have fallen into the 1-2 H:D category, however; the operational water levels in the tank caused the H:D ratio fall into the 0.5-1 H:D ratio (Olson, 2011). To provide data for the 1-2 H:D range, two of the tanks that were chosen during this study were from tanks in the 1-2 H:D range (Tank F and G).

Another factor that was considered was the type of disinfectant. The two tanks that were chosen in the 1-2 H:D range (Tank F and G) also used free chlorine instead of chloramines for disinfection. The other three tanks were from chloramine disinfection systems.

Three of the long term tanks were the same used in Olson's study. These tanks showed stratification during the cooling down period of the year (Olson, 2011). The effect of the warming period on stratification was one of the goals of this project. Two of these tanks also have a mechanical mixers installed (Tank D and E) with the main purpose to prevent freezing during the cold months. Table 3.1 shows the characteristics of the selected long term tanks.

Table 3.1: Tanks Selected for Long Term Study

H:D Category	Tank Name	Capacity (gal)	Height (ft)	Dia. (ft)	H:D Ratio	Common Inlet/Outlet	SCADA for Water Level	Artificial Mixer Installed
1-2	C	65000	28	20	1.41	Y	Y	N
2-4	D	175,000	75	20	3.75	Y	Y	Y
>4	E	140,000	86	14	6.14	Y	Y	Y
1-2	F	55,000	34	17	2.00	N	Y	N
1-2	G	140,000	44	24	1.83	N	Y	N

Two additional tanks with passive mixing systems were chosen for a short term study. The passive mixing system consisted of piping the influent water up to a certain height in the tank. One of these tanks was also studied previously (Short term tank 4) before the passive mixing system was installed, which would enable comparison of data to see the effectiveness of the passive mixing system.

3.2.1 Long Term Tank C

Tank C's H:D ratio was 1.41. The tank height was 28 ft. and the tank diameter was 20 ft. The capacity of the tank was 65,000 gallons. At a height of 28 feet, the tank was the shortest of the five selected tanks. The common inlet and outlet pipe at the base of the tank was 6 inches in diameter. Equipment used for the tank consisted of a string of thermocouples and sampling tubes at 1.5, 6.5, 11.5, 16.5, 21.5, and 26.5 feet from the bottom of the cable. Figure 3.1 is a picture of long term tank C.

Figure 3.1: Long Term Tank C

3.2.2 Long Term Tank D

Tank D's capacity was 175,000 gallons. The height of the tank was 75 feet and the diameter was 20 feet, therefore the H:D ratio was 3.75. The common inlet/outlet at the base of the tank was 6 inches in diameter. A mechanical mixer was installed in the tank to prevent the water from freezing during the winter months. The water system agreed to operate the mixer to benefit the study. The equipment for the tank consisted of a string of thermocouples and sampling tubes spaced at 7 foot increments that covered 75 feet of depth. The thermocouple data and water quality data points were at 1.5, 8.5, 15.5, 29.5, 43.5, 57.5, 64.5, and 71.5 feet from the base of the cable. A picture of long term tank D is shown in Figure 3.2.

Figure 3.2: Long Term Tank D

3.2.3 Long Term Tank E

Tank E's capacity was 140,000 gallons. The height was 86 feet and the diameter was 14 feet, therefore the H:D ratio was 6.14. A single inlet/outlet at the base of the tank was 6 inches in diameter. An artificial mixer was used in this tank to prevent freezing during the cold months. The system agreed to run the mixer during the study. Equipment for this tank consisted of a string of thermocouples and sampling tubes at 7 foot intervals covering 85 feet of depth. Thermocouple data and water quality samples were collected from 1.5, 8.5, 22.5, 29.5, 43.5, 50.5, 64.5, and 71.5 feet from the bottom of the cable. Figure 3.3 shows a picture of long term tank E.

Figure 3.3: Long Term Tank E

3.2.4 Long Term Tank F

Tank F was 34 feet tall and 17 feet in diameter. Tank F's capacity was 55,000 gallons and the H:D ratio was 2. The tank does not have a common inlet and outlet. The inlet was 4 inches in diameter and was located to the side of the tank's floor, while the outlet was 4 inches in diameter and was located in the center of the bottom of the tank. Adjacent trees caused the tank to be in the shade for part of the day. Equipment used consisted of a string of thermocouples and sampling tubes spaced at 7 foot increments covering 40 feet of depth. The resulting thermocouple points and sampling points were 1.75, 5.25, 8.75, 15.75, 22.75, and 29.75 feet from the bottom of the cable. A picture of long term tank F is shown in Figure 3.4.

Figure 3.4: Long Term Tank F

3.2.5 Long Term Tank G

Tank G's dimensions were 44 feet tall and 24 feet in diameter. Tank G's capacity was 140,000 gallons and the H:D ratio was 1.83. The inlet was on the north side of the tank floor and was 8 inches in diameter, while the outlet was on the east side of the tank bottom and had a diameter of 8 inches. The tank was painted a light blue color. Equipment in the tank consisted of a string of thermocouples and sampling tubes spaced at 6 feet intervals over 45 feet of depth. Figure 3.5 shows a picture of long term tank G.

Figure 3.5: Long Term Tank G

3.2.6 Short Term Tank 4

Tank 4's capacity was 100,000 gallons. The height was 120 feet and the diameter was 12 feet, therefore the H:D ratio was 10. A passive mixing system was installed in the tank by the water system, which consisted of a 6 inch riser pipe from the floor to 80 feet level, where the pipe diameter was reduced to 2.5 inches. An additional 2 foot length of 2.5 inch pipe created a jet to force the water upward. Thus the influent water enters the tank at 82 feet above the floor. A check valve at the base of the riser pipe enables water to leave the tank. Equipment used included temperature sensors and pressure sensors. Sensors were placed at 16.5, 25, 42, 59, 75, 104 feet above tank bottom, and one on a float to stay with the water level as it changes. Pressure sensors were at 104 feet and in the open space at the top of the tank. A picture of short term tank 4 is shown in figure 3.6.

Figure 3.6: Short Term Tank 4

3.2.7 Short Term Tank 9

Tank 9 was 75 feet tall and 25 feet in diameter. The H:D ratio was 3 and the capacity was 240,000 gallons. A passive mixing system was installed by the water system, which consisted of piping the influent water up 15 feet in an 8 inch pipe and then

5 more feet in a 3 inch pipe. The influent water entered the tank 20 feet above the floor of the tank. Water was released from the tank through a check valve at the base of the riser pipe. Temperature sensors and pressure sensors were used to gather data from the tank. The temperature sensors were placed 1.5, 10, 20, 30, 40, 50 feet above the tank bottom, and one on a float to stay at the highest water level as it changed. Pressure sensors were at 20 ft. and in the empty space at the top of the tank. A picture is shown of short term tank 9 in figure 3.7.

Figure 3.7: Short Term Tank 9

3.3 Equipment to Measure Temperature and Water Quality

The temperature was measured at various depths in the tanks. Measuring temperature was a simple and cost effective method to show the nature of mixing in the tank. Tanks in systems using surface water sources were included in the tank inventory to examine effects of seasonal temperatures of the surface water on the stratification of tanks. Water quality samples were also collected and analyzed from the various depths in the tank.

3.3.1 Long Term Study Equipment

The study required equipment for measuring the temperature of the water and for obtaining samples from the tanks at varying depths. For the temperature data collection, type T thermocouples were used. Thermocouples were spaced evenly down a length of steel cable and then covered with a vinyl covering. For sample gathering, a ¼-inch polyethylene tubing was used. The open end tube was positioned at its respective thermocouple to obtain a sample from each location. The tubes exited the top of the storage tank in accordance to the water system's preference and were attached to the ladder to reach ground level. A thermocouple lead wire was also bundled with the tubing as it exited the tank and was attached to the ladder. At ground level, the lead wire was attached to an OCTTEMP data logger, which recorded the temperature data obtained from the thermocouples. A temperature sensor in the OCTTEMP data logger collected the ambient temperature data. The OCTTEMP data logger would store the information until the data was downloaded to a computer. Figure 3.8 shows the sampling and data logging system. Figure 3.9 shows a picture of the OCTTEMP data logger.

Every ten minutes a temperature reading was recorded by the data logger. The temperature data was downloaded to a computer every time SDSU personnel arrived on the site. A schematic showing how the data logger is connected to a computer is shown in Figure 3.10.

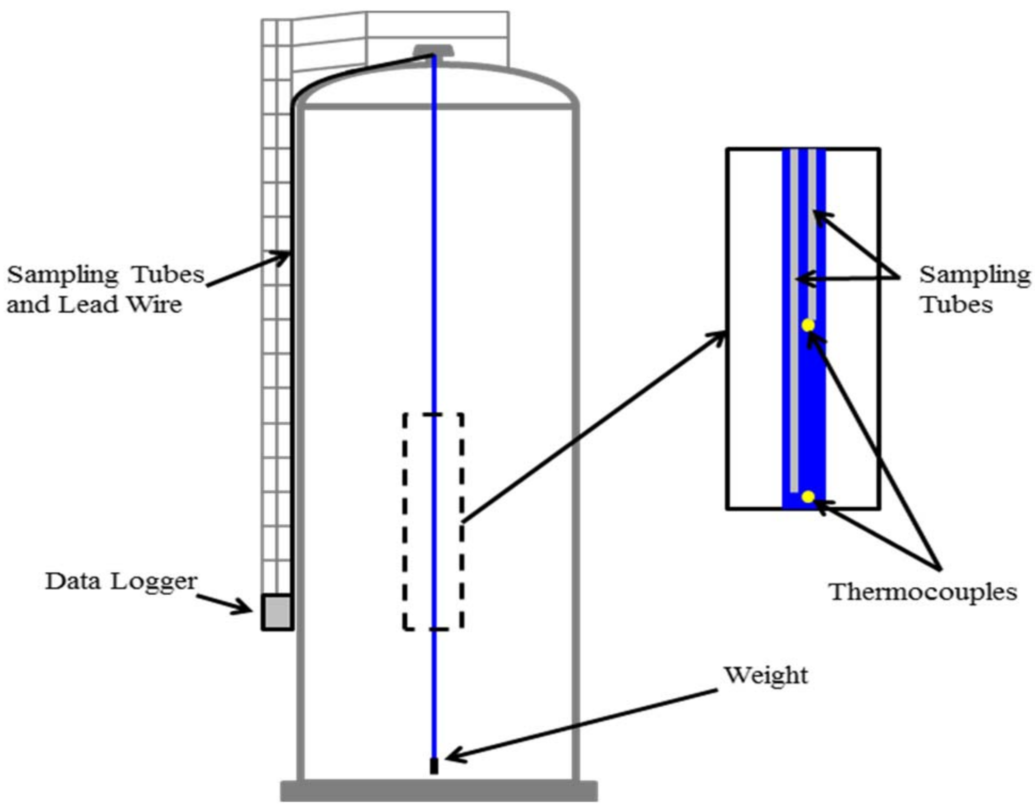


Figure 3.8: Visual representation of the data logging and sampling system. (Olson,2011)

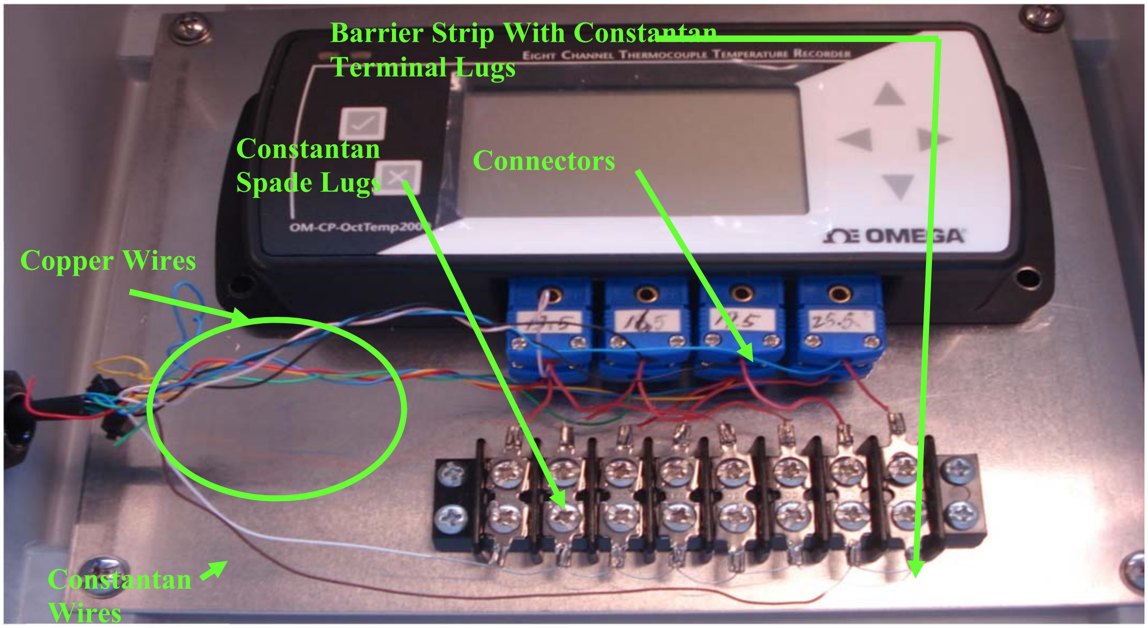


Figure 3.9: Photograph of the OCTTEMP data logger (Olson, 2011)

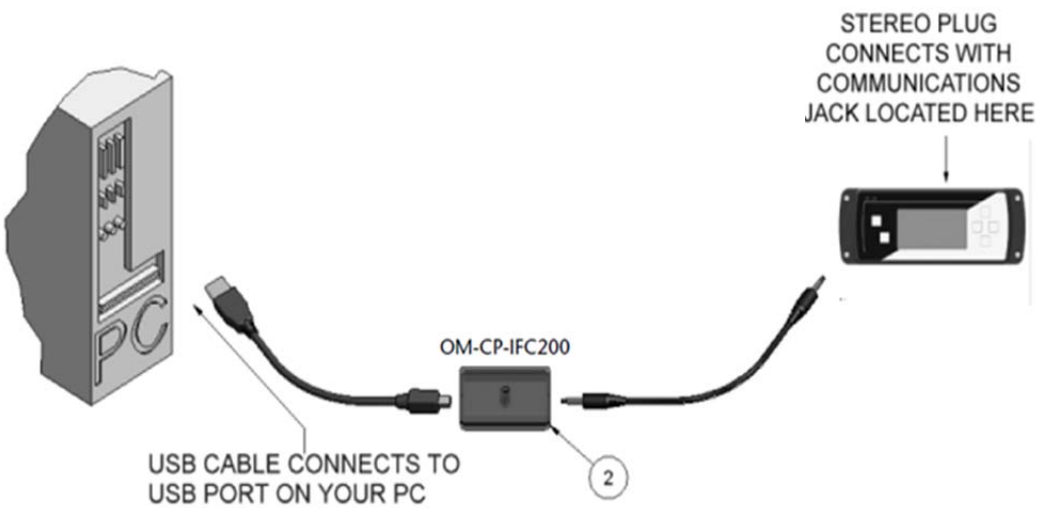


Figure 3.10: Computer Interface Connecction (www.omega.com)

3.3.2 Short Term Tank Equipment

The short term tank study required temperature data at varying depths in the tanks. Sensors that only measured temperature were used along with two sensors that measured both temperature and pressure. The pressure was measured to obtain the water elevation in the tank. Each sensor stored the information in the sensor itself. Seven sensors were used for each tank with one being the pressure sensor. One sensor was attached to a float in order to measure the temperature at the top of the water as the water level fluctuated. One additional pressure sensor was attached in the headspace of the tower to find water elevation in each tank. The sensors were zip tied to loops made in the

1/16-inch stainless steel cable. Each loop was made so the sensor was at the desired height in the tank. A weight was attached to the end of the wire to make the wire sink to the bottom. The equipment used in the short term tank study is shown in Figure 3.11.

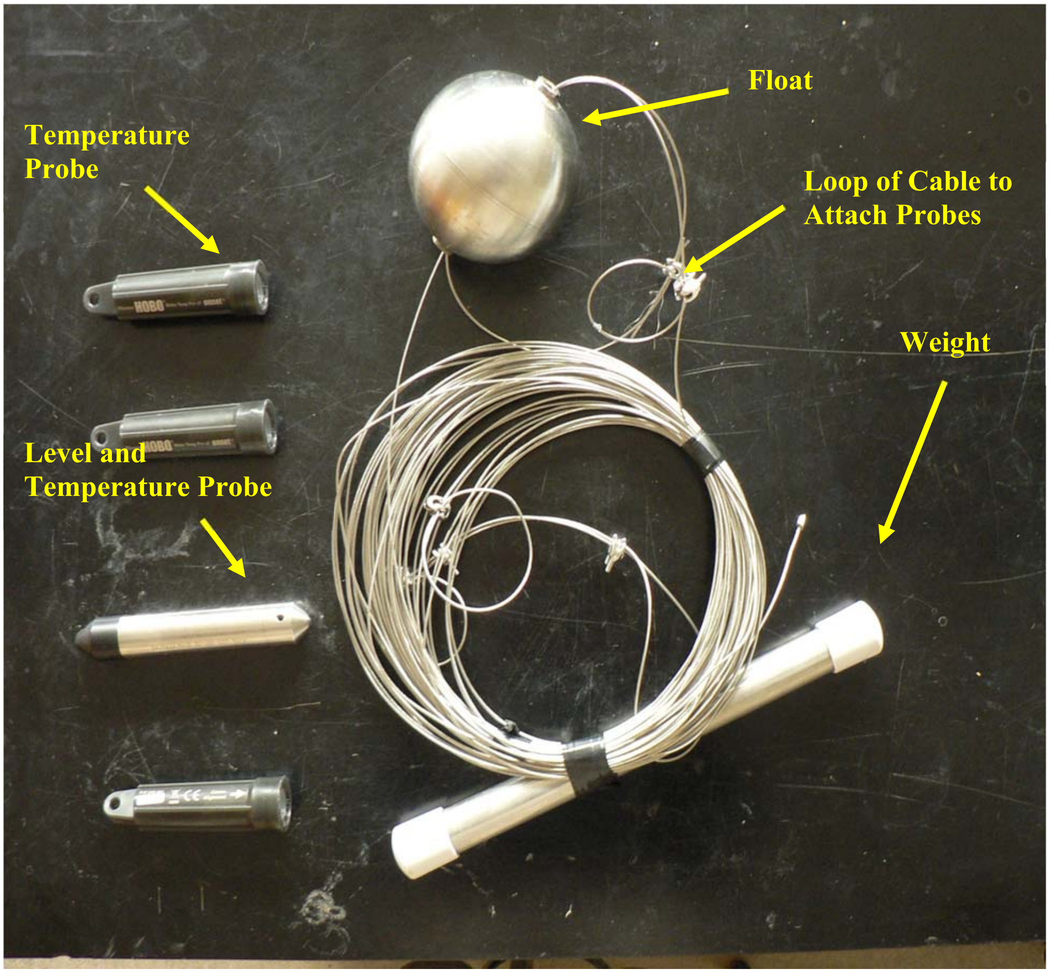


Figure 3.11: Short Term Tank Equipment (Olson, 2011)

The cable would exit the tank through a vent or hatch in the roof. Then the cable would be attached to the top of the roof by looping the wire around a part of the tank on the roof. Wire clamps were used to attach the wire to the tank. Figure 3.12 shows a picture of how the equipment was attached to the top of the short term tanks.

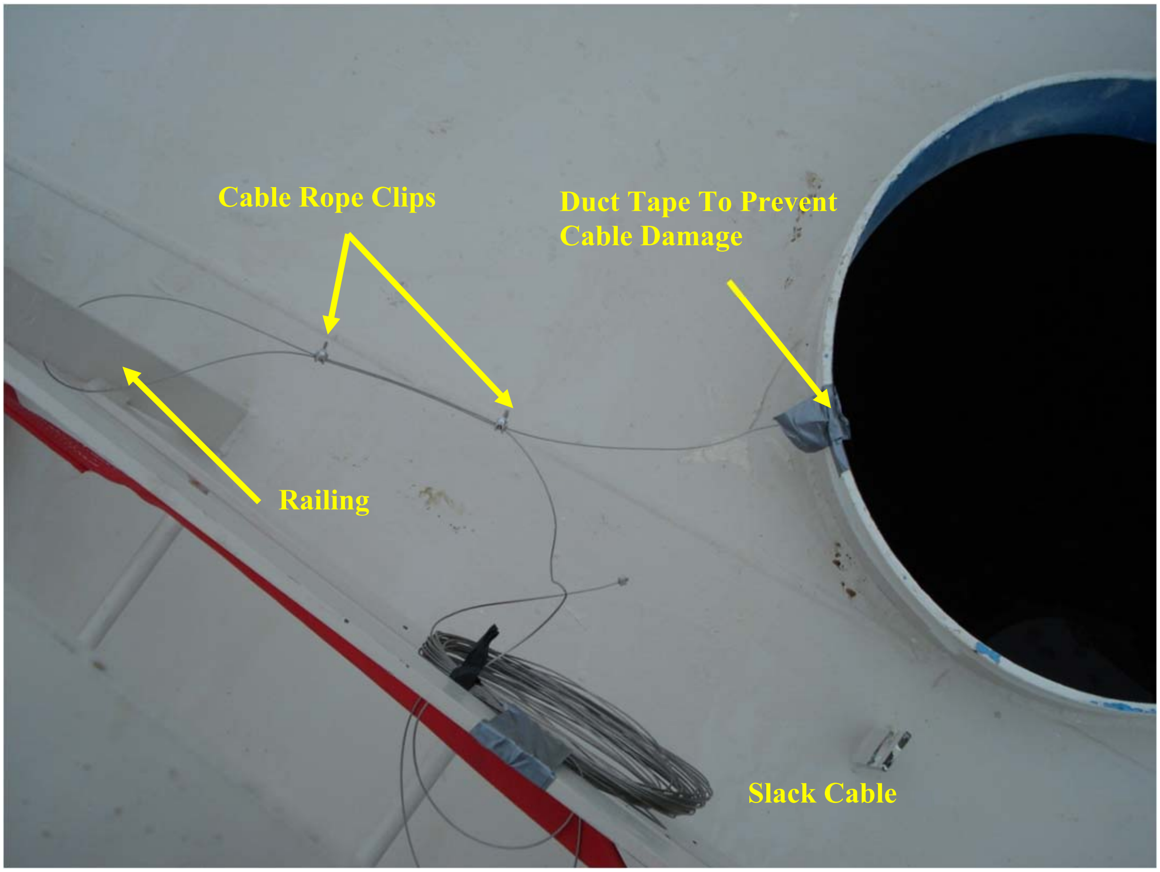


Figure 3.12: Photograph of how cable was attached to tank. (Olson, 2011)

At the end of the study, the equipment was removed from the tank. Then the sensors were removed from the wire, and the data from the sensors was downloaded onto a computer. The separate sensors and the method of attaching them to the wire lends itself well for multiple tank study since the equipment can easily be redone to fit another tank.

3.4 Sample Collection and Preservation

In order to obtain samples, a siphon was created using a peristaltic pump, which was powered by a car battery through a power inverter. Water was allowed to drain from the sampling tubes for at least 15 minutes to make sure the sample was representative of the tank at each elevation sampled. Equipment used to start the siphon in order to collect samples is shown in Figure 3.13.

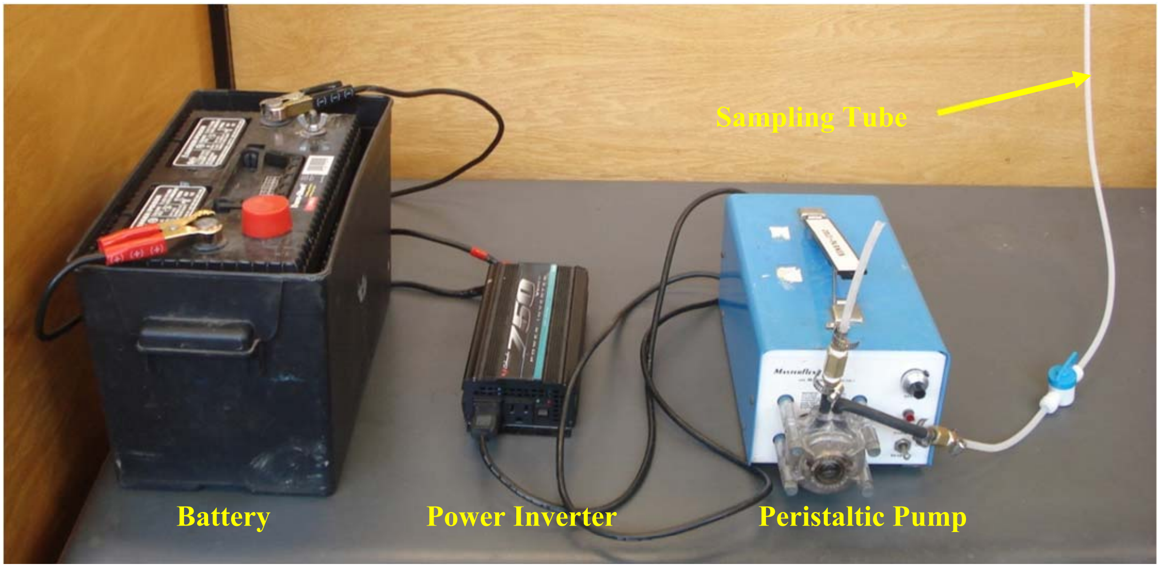


Figure 3.13: Picture of equipment used to obtain samples. (Olson, 2011)

For the chloraminated systems, the samples were tested on-site for total chlorine, monochloramine, free ammonia, and nitrite. A sample was also collected in a 250 mL plastic bottle for each sampling point in the tank for later analysis for nitrate at the Water and Environmental Engineering Research Center (WEERC) laboratory at SDSU. For the free chlorine systems, samples were tested on-site for total and free chlorine.

For all long term tanks, samples from varying depths were collected in sterile bottles containing sodium thiosulfate to dechlorinate the water. The samples were labeled, transported back to WEERC laboratory, and analyzed for total coliform and HPCs. A picture of the sampling bottles used is found in Figure 3.14.

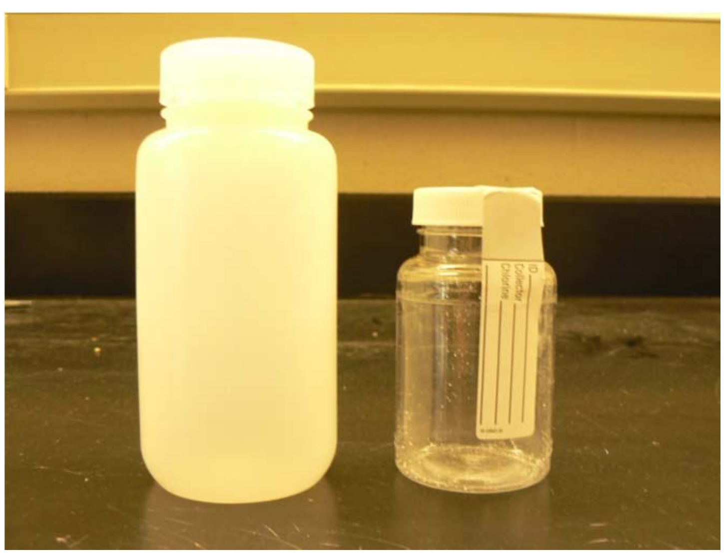


Figure 3.14: 250 mL sample bottle and a sterile sampling bottle with sodium thiosulfate

After the on-site analyses were complete and the samples collected, the sampling tubes were purged by pressing a nozzle of an air tank to the end of the sampling tube and blowing compressed air into the sampling tube. The end of the sampling tubes were then crimped and tied with a zip tie to ensure that the siphons did not restart.

3.5 Water Quality Measurements

Water quality samples were analyzed for several parameters. The parameters tested depended on the type of disinfectant used in the water system.

3.5.1 Temperature Measurements

The temperature was collected using the equipment described in section 3.3.1 for long term tanks and section 3.3.2 for short term tanks. The data logger or the sensors recorded the temperature data every ten minutes. The data would later be downloaded to the computer. Figure 3.15 shows a sample of the raw data that was collected from the long term tanks.

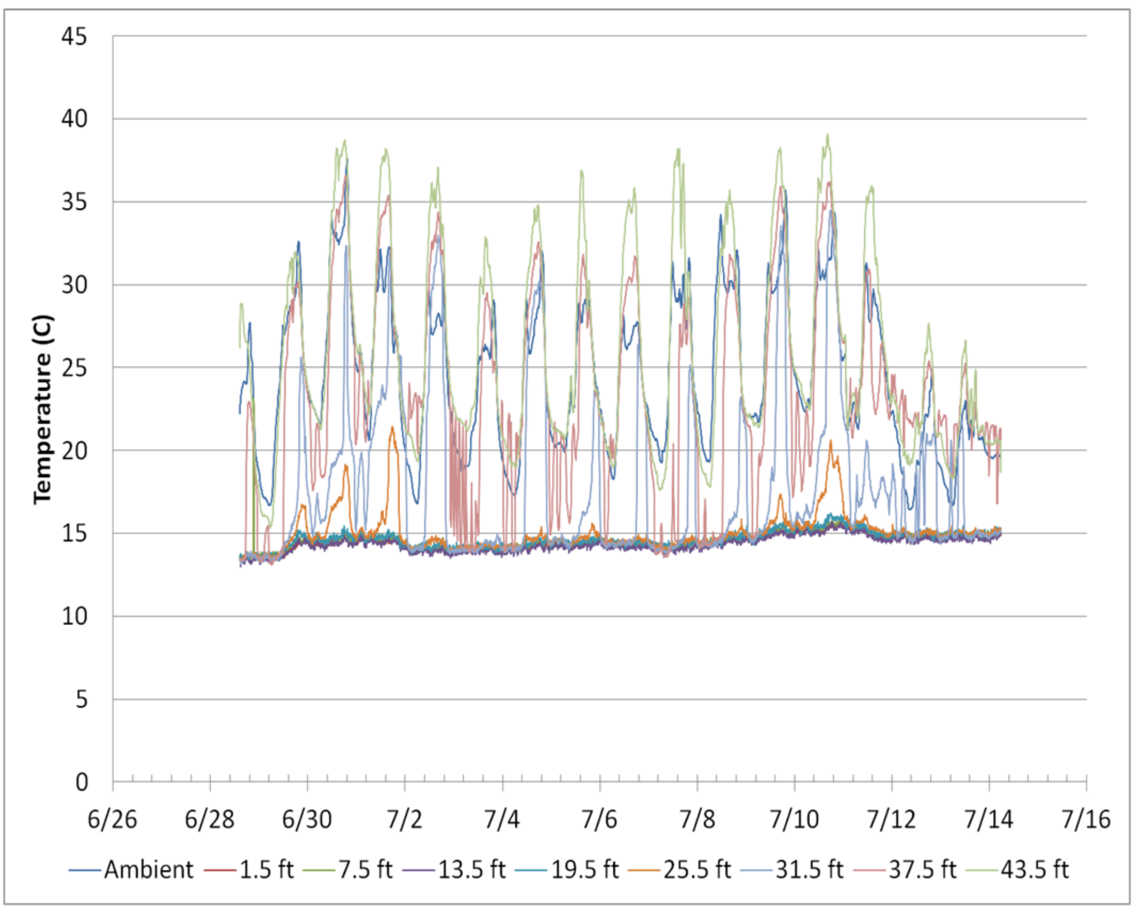


Figure 3.15: Raw temperature data

Due to the fluctuating water level in the tank, some of the top thermocouples were not always in the water. Spikes in the temperature data appeared that do not represent the actual temperature of the water in the tank. These spikes in data can be removed by reviewing the water elevation data and removing the temperature data of the thermocouples when they are out of the water. Removal of these temperature spikes makes the data a better representative of the tank temperature and it makes the data less confusing and easier to understand. Figure 3.16 shows the same tank during the same time span with the thermocouple data removed when they were out of water.

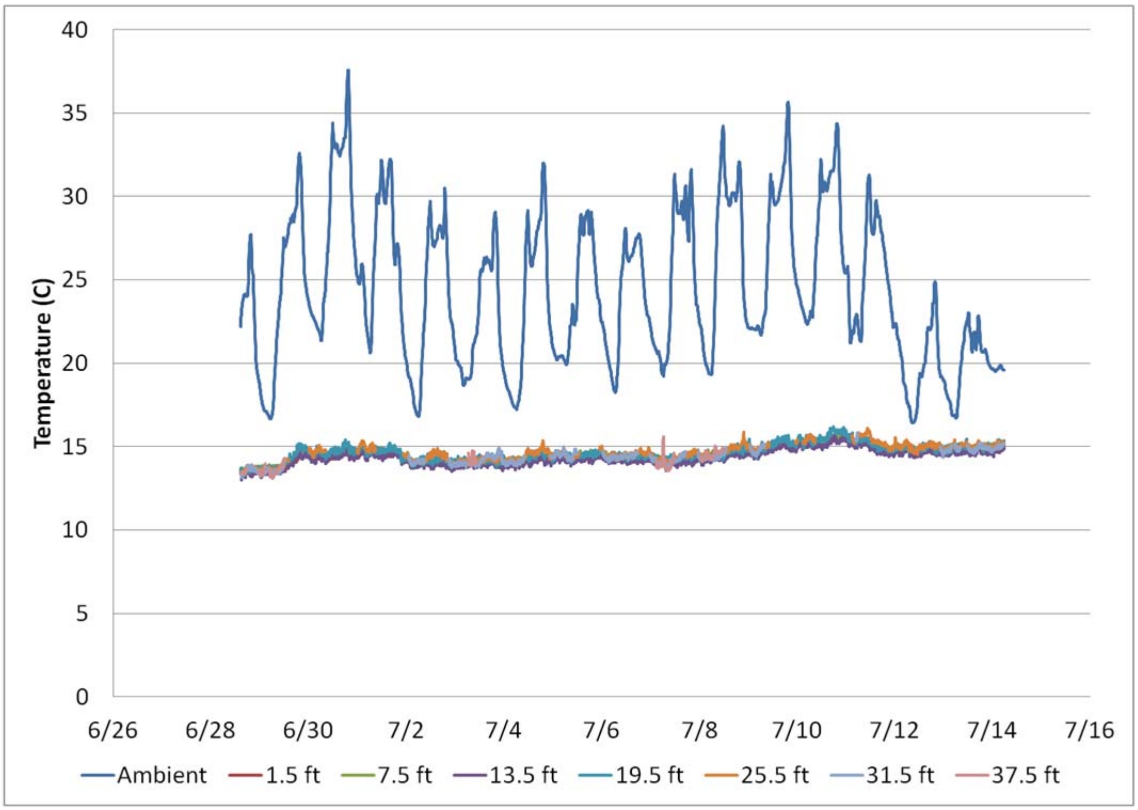


Figure 3.16: Filtered temperature data

3.5.2 On-site Measurements

The parameters that were measured in the field were determined by the type of disinfectant the water system used. Total chlorine and free chlorine were analyzed for tanks that used free chlorine as the disinfectant. Tanks that used chloramine as their disinfectant were tested for monochloramine, free ammonia, and nitrite. Long term tank C, D, and E used chloramine for disinfectant while tanks F and G used free chlorine.

All of the on-site tests were conducted with a HACH DR/890 colorimeter. Figure 3.17 shows the HACH DR/890 colorimeter and Table 3.2 shows the HACH method and reagent used for each test.

Figure 3.17: HACH DR/890 colorimeter (Olson, 2011)

Table 3.2 Methods and reagents used for on-site water quality testing

Constituent	**HACH Method Number**	**Reagents Used**	**Range (mg/L)**
Total Chlorine	8167	DPD – Total Chlorine Reagent (10 mL sample)	0.0-2.0
Free Chlorine	8021	DPD – Free Chlorine Reagent (10 mL sample)	0.0-2.0
Monochloramine	10020	Monochlor F Reagent	0.0-4.5
Free Ammonia	10020	Monochlor F reagent + hypochlorite solution	0.0-0.5
Nitrite	8507	Nitriver 3 Reagent	0-0.35

3.5.3 Analysis Performed in WEERC Laboratory

Samples from each tank were transported back to the WEERC laboratory at SDSU for additional tests as described below.

3.5.3.1 Nitrate

The samples were analyzed for nitrate by following the EPA method 300.0 (Determination of Inorganic Anions by Ion Chromatography).

3.5.3.2 Total Coliform

Samples from long term tanks were analyzed for total coliform. The total coliform test was performed following Standard Method 9222 B. Standard Total Coliform Membrane Filter Procedure using m-endo broth (APHA et al., 1998). First, the mEndo broth was prepared and 2 milileters of broth were dispensed on a sterile pad in each Petri dish. Using sterilized forceps, the filter was placed on the filtering apparatus. The 100 mL sample was filtered and the filter was placed in a Petri dish with sterilized forceps. The Petri dishes were incubated in a water bath at 35˚C for 24 hours. Between each sample the filtering apparatus was rinsed with a bleach solution to kill any bacteria left over and then rinsed with distilled water to remove the bleach solution. The shiny gold colonies were counted to find the CFU/100 mL. Figure 3.18 shows the materials needed and the apparatus used to run the total coliform test.

3.5.3.3 Heterotrophic Plate Count (HPC)

Every long term tank was analyzed for HPC. The samples were collected from 6 sample points in a sterile bottle with sodium thiosulfate. The samples were transported back to the WEERC laboratory for analysis. The HPC test was completed using IDEXX SimPlate for HPC method (IDEXX, 2009). First, the media was hydrated by adding 100 mL of sterile water to the media vessel. Then 1 mL of sample and 9 mL of media was

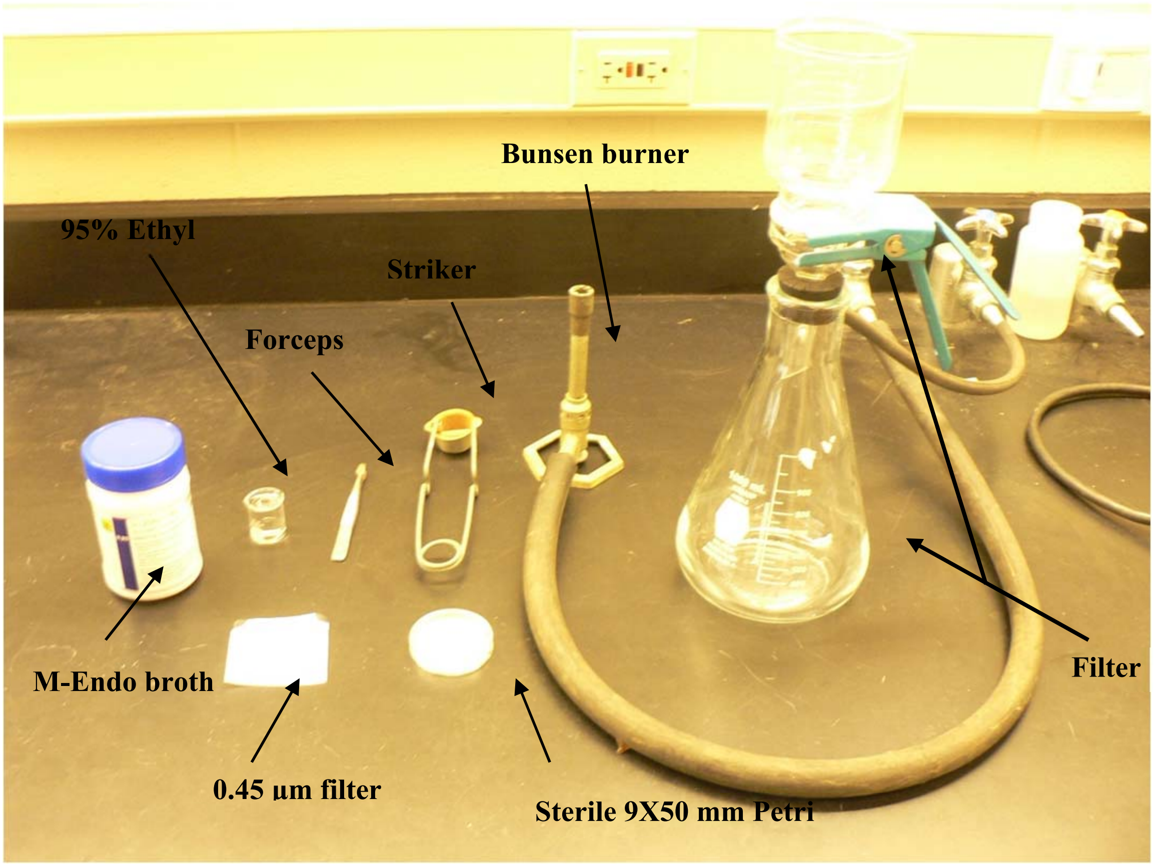


Figure 3.18: Total coliform materials and setup

added to the plate. The plate was covered and swirled to distribute the sample and media around the plate. Next, the plates were inverted and incubated in a water bath at 35˚C for 48 hours. Counting the plates consisted of using a 6-watt, 365nm, UV light about 5 inches above the plates. Count the fluorescent wells and refer to the MPN tables provided with the Simplates. The pipettes used were rinsed with bleach solution to kill bacteria and then rinsed with sterile water to remove the bleach between each sample. The materials needed to run the SimPlate test for HPC are shown in Figure 3.19.

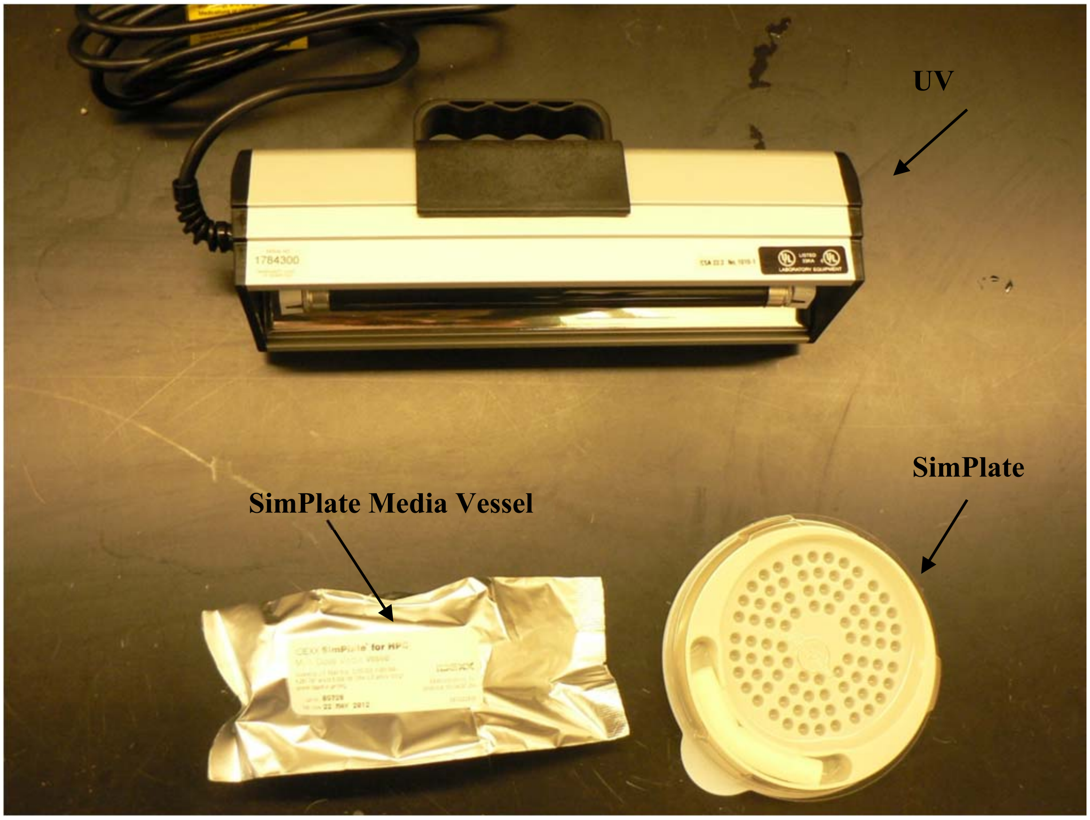


Figure 3.19: Materials for SimPlate test for HPC

3.6 Analysis of Mixing Characteristics

There are several parameters that were calculated that affect the mixing in the tanks from the data collected throughout this study. Examples of all calculations are found in Appendix A.

3.6.1 Determining the Fill and Draw Cycles

The fill and draw cycles were needed to calculate the hydraulic parameters. For the long term tanks, water elevation in the tanks was obtained from the water systems. For short term tanks, the pressure sensor in the tank was used to find the water elevations during the time in the tank. Elevation data was analyzed, and the fill and draw cycles were found by finding the lowest and highest elevations in each cycle. The water elevation change was not the only significant piece of data found. The time interval for each fill and draw cycle was important. Temperatures at the start and stop of each cycle were also needed. The temperatures used were the temperature at the bottom of the tank and the temperature of the upper most thermocouple that was submerged in the water.

3.6.2 Height to Diameter Ratio

The actual H:D ratio was found for each cycle. Change in the water level in the tank, causes the H:D ratio to change. The average ratio was found during the time that each tank was studied.

3.6.3 Flow Rate During Fill Cycle

The flow rate during each fill cycle was determined for each tank and was used in the calculations. The flow rate was calculated using the inlet diameter, water level, and the amount of time for the fill cycle to be completed.

3.6.4 Velocity of Inflow during Fill Cycle

The velocity of the inflow was calculated for each fill cycle in each tank. The velocity was found using the inlet pipe area and incoming water flow rate. The calculation was done so the value could be used in later calculations.

3.6.5 Volumetric Exchange

The volume of water needed to be exchanged in order for the tank to be considered well mixed was determined along with the actual volumetric exchange that the tank achieved. A comparison of these numbers could show if a tank was mixed and what could be done in the operation of the tank to help promote mixing. As discussed in the literature review, if Equation 12 was true, the tank should be mixed (Rossman and Grayman, 1999). The temperature of the influent and the temperature of the water in the tank were assumed to be the same in this calculation:

$$\frac{\Delta V}{V} > \frac{(\pi)^{1/2}\tau_m d_i}{2V^{1/3}} \qquad (12)$$

where: ΔV = volume of water added during fill (ft^3); V=tank volume (cubic feet); τ_m = constant; and d_i = inlet diameter.

3.6.6 Densimetric Froude Number

The densimetric Froude number was calculated for every cycle in each tank by using Equation 1 (Rossman and Grayman, 1999):

$$F_d = \frac{u}{\sqrt{g'd}} \qquad (1)$$

in which u = the vertical inflow velocity; d = pipe diameter; and $g' = g(\rho_f - \rho_a)/\rho_a$ where g = acceleration of gravity; ρ_f=density of inflow; ρ_a=density of the ambient water.

The densimetric Froude number was compared to a calculated value based on tank geometry. If the in-tank densimetric Froude number was greater than the value given by Equation 3, then the tank should not stratify (Rossman and Grayman, 1999). Equation 3 shows the comparison:

$$F_d > C\frac{H}{d} \tag{3}$$

where F_d= densimetric Froude number; C = slope of plot; H = water height; d = diameter of inlet.

3.6.7 Dimensionless Mixing Parameter

The dimensionless parameter shows the required momentum to overcome stratification in the tank. The calculation was made for each cycle in each tank. Equation 4 shows the comparison made to determine if the momentum is enough to overcome stratification (Roberts et al., 2006):

$$\frac{M^{0.5}}{B^{\frac{1}{3}} * H^{\frac{2}{3}}} > 0.85 - 0.05n \tag{4}$$

where M = inflow momentum; B = Buoyant Force; H = water depth; and n = number of inlets.

3.7 Chlorine Decay Modeling

The chlorine decay was modeled in the tanks that stratified. The model relied on the concentration of chlorine in the influent water, the data for the fill and draw cycles, and the decay coefficient (k).

3.7.1 Decay Coefficient (k)

The decay coefficient was found by comparing the chlorine concentration of one visit (initial concentration) with the chlorine concentration of the next visit. The chlorine concentrations used were the average concentrations in the upper zone of the stratified tank. Equation 14 shows the formula used (Boulos et al., 1996):

$$k = -\frac{\ln(\frac{C}{C_o})}{t} \tag{14}$$

where k = decay coefficient; C = final chlorine concentration; C_o= initial chlorine concentration; and t = elapsed time between samples.

The decay coefficient was also corrected for temperature using Equation 15 (Gowda, 1978):

$$k_2 = k_1 * \theta^{T_2 - T_1} \tag{15}$$

where k_1 = decay coefficient at T_1; T_1= Initial temperature; T_2 = Correcting temperature

3.7.2 Modeling of Tanks

The tanks were modeled using a computer program called CompTank. The influent chlorine concentration was used along with the inflow velocities throughout a time period. An average decay coefficient was calculated during the study and was used in the program. The data used for the chlorine decay coefficient are in Appendix C and a sample calculation is in Appendix A. Long term tanks D and E where the focus of the modeling since both where stratified. The stratification allowed for the decay coefficient to be calculated. Each tank was modeled as a stratified 3 compartment tank since the data showed stratification in these tanks. The computer read outs were then compared to the data that was obtained throughout the study to see if this type of model was effective.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The study focused on the effects of distribution systems' water storage facilities mixing characteristics on water quality. Storage facilities were studied in regional water systems in South Dakota. Tanks were selected based on the survey of water systems and the previous study performed by Olson (2011). The tanks that were chosen included tanks that varied in size to show the effect of tank geometry on mixing and water quality. The effect of passive mixing systems was studied in two tanks in which the water systems installed passive mixing systems.

Long term tanks were analyzed for temperature at varying depths throughout the tank. Water quality samples were collected from the same points as were temperature readings to analyze for certain water quality parameters. The parameters tested were based on the type of disinfectant the water system used. In chloraminated systems, parameters were measured to show whether nitrification had occurred. All of the samples were analyzed for total coliform and heterotrophic plate count.

Short term tanks had temperature collecting sensors at varying depths in the tank. Water quality data were not collected in short term tanks. A passive mixing system was installed by the water system in each tank. One of the tanks studied was also studied during Olson's research; however, the water system installed the passive mixing system after Olson's research (Olson, 2011). Both sets of data were compared to show the effect of the passive mixing system on water quality.

All of the tanks were analyzed for hydraulic parameters that are used to characterize mixing in the tanks. The hydraulic parameters included the densimetric Froude number, the volumetric exchange, and the dimensionless mixing parameter. A comparison between the hydraulic parameters and the actual behavior in the tanks was done in order to show whether the hydraulic parameters correctly predicted the mixing behavior.

4.2 Long Term Tank Study

Long terms tanks were analyzed for both temperature and water quality parameters at varying depths in the tanks. The temperature was recorded once every 10 minutes. The water quality parameters that were tested for each tank depended on the type of disinfectant used by the water system. Each tank was also tested for total coliform and heterotrophic plate count at varying depths of the tank. Hydraulic parameters for each tank were calculated to show whether the tank should mix properly.

4.2.1 Long Term Tank C

The temperature profile for long term tank C is shown in Figure 4.1. Around the sampling event on June 8, the operation of the tank changed when the pump that filled the tank stopped working. After the pump failed, the tank was filled by using water from a storage tank next to tank C. The data in Figure 4.1 indicate thermal stratification occurred throughout the study, exhibiting as much as 10 degree Celsius difference between the bottom of the tank and the top of the tank.

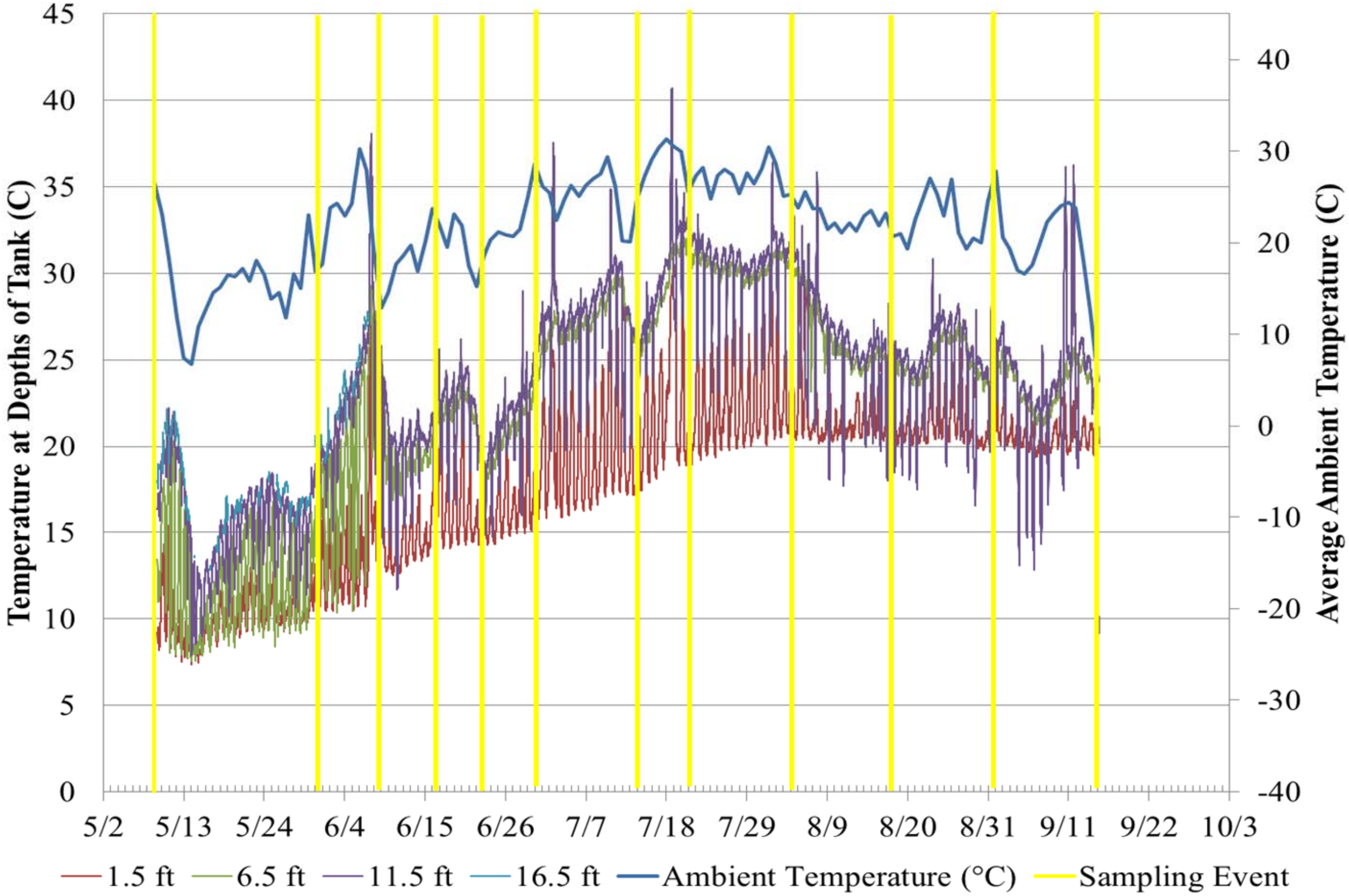


Figure 4.1: Long term tank C temperature and sampling times.

Water quality was tested before and after the change in the tank's operation. Figure 4.2 shows the water quality data on May 31 and Figure 4.3 shows the water quality data on June 16. On May 31, the total chlorine residual remains around 2.5 mg/L throughout the tank. On June 16, the total chlorine residual was 2.24 mg/L at the lower portion of the tank and 2.16 mg/L in the upper portion of the tank. Throughout the study the water quality parameters did not show stratification.

In Figure 4.4, the temperatures in the tank are shown along with the water depth, which shows the fill and draw cycles. Comparing the fill and draw cycles to the temperature indicates whether or not the temperatures are influenced by the filling water temperature. Figure 4.4 shows that the lower thermocouples are influenced by the influent water. During the fill cycle, the temperature at 1.5 ft. decreases and then increases during the draw cycle as warm water lowers due to the draw. Before the pump quit working, the temperatures at 1.5 ft., 6.5 ft., and 11.5 ft. were influenced by the filling water. The temperatures indicate stratification was occurring; however, the mixing occurring during the fill and draw cycles was sufficient to maintain a consistent disinfectant residual throughout the tank.

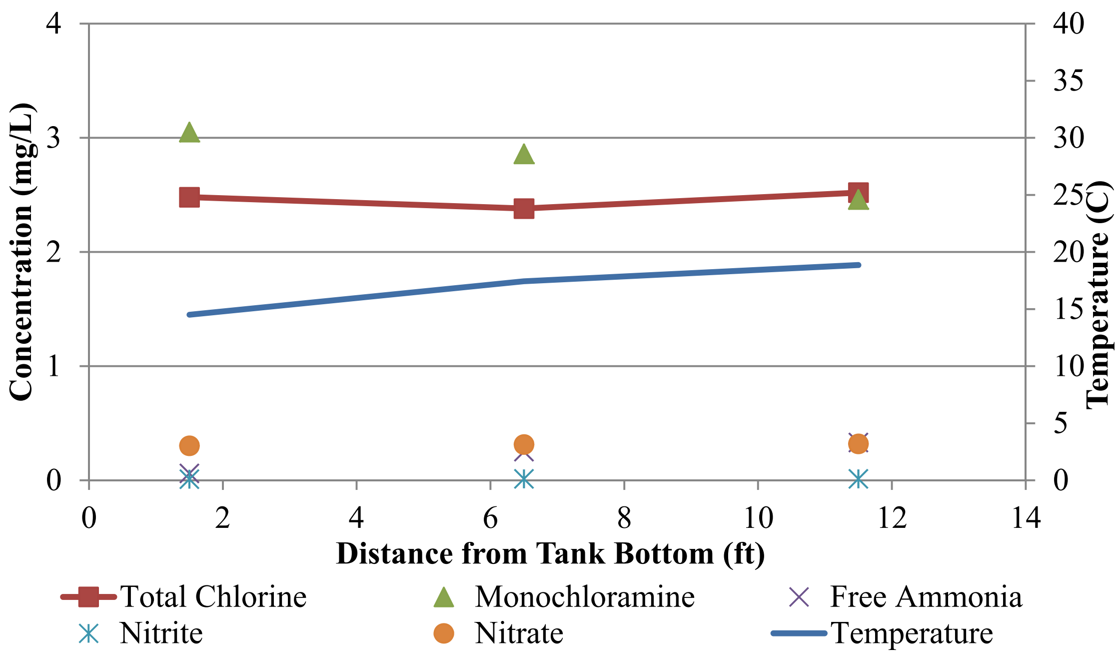


Figure 4.2: Water quality data for long term tank C on May 31.

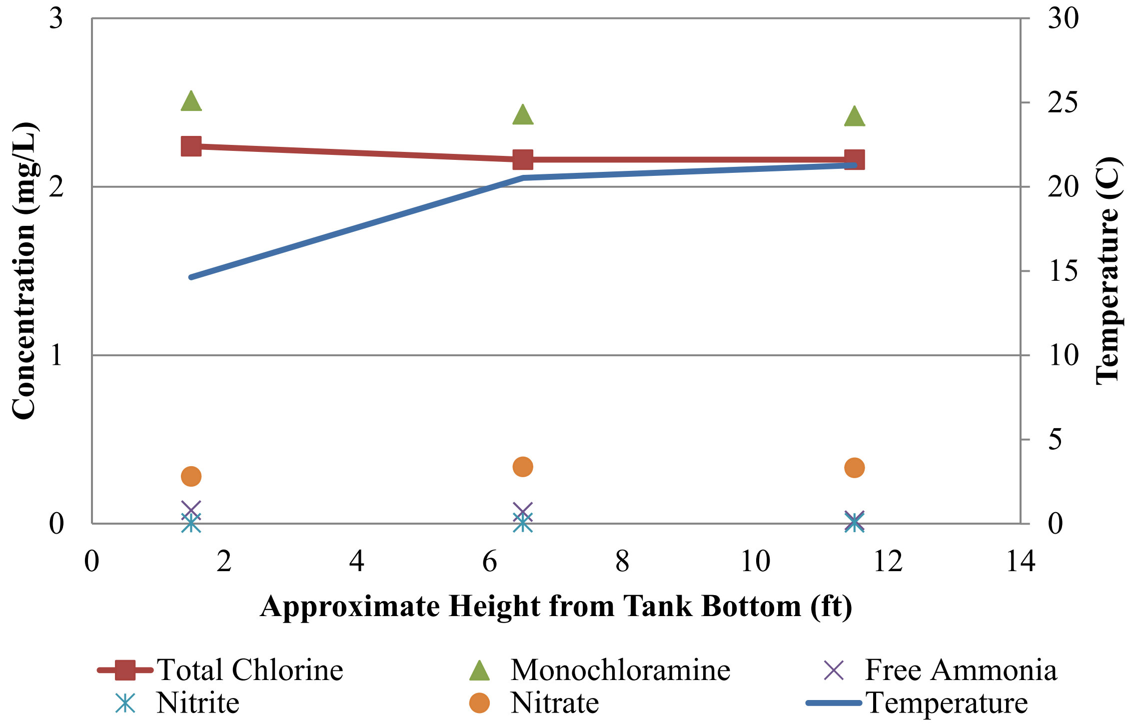


Figure 4.3: Water quality data for long term tank C on June 16.

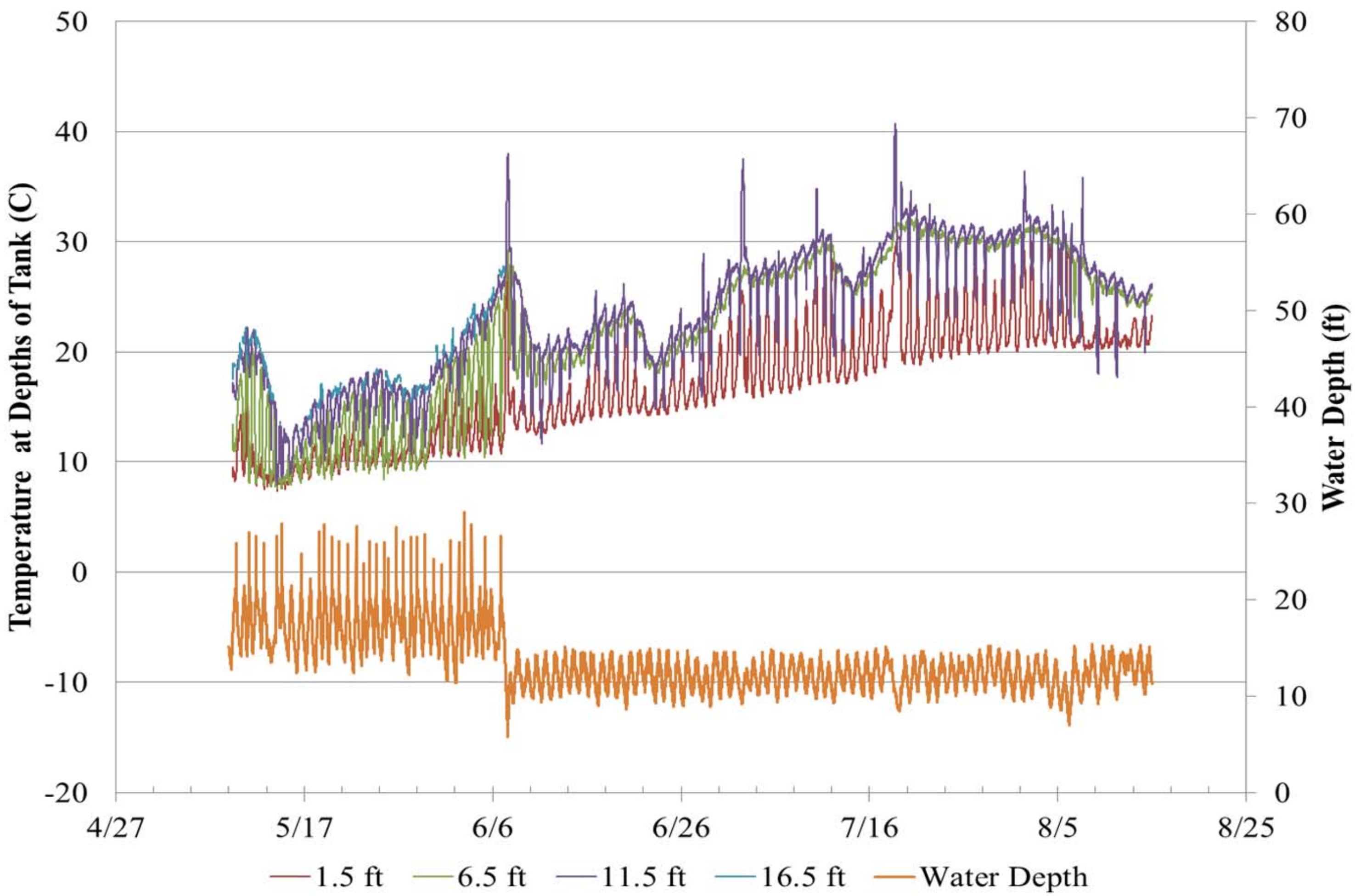


Figure 4.4: Long term tank C tank temperatures and water depth.

Hydraulic parameters were calculated and compared to required values to show whether the tank should mix properly or not. Figure 4.5, Figure 4.6, and Figure 4.7 show the densimetric Froude number, volumetric exchange, and dimensionless mixing parameter respectively. Calculations used in finding the hydraulic parameters are presented the Appendix A.

Both the densimetric Froude number and the dimensionless mixing parameter show that the tank operation does not obtain the required value for the tank to be properly mixed; however, the volumetric exchange in the tank was greater than that required for mixing, indicating the tank should be mixed. The proper volumetric exchange could be the reason that the tank did not stratify in terms of water quality. The disinfectant residual remained at an appropriate level (greater than 2 mg/L) throughout the tank even though the temperature data showed stratification.

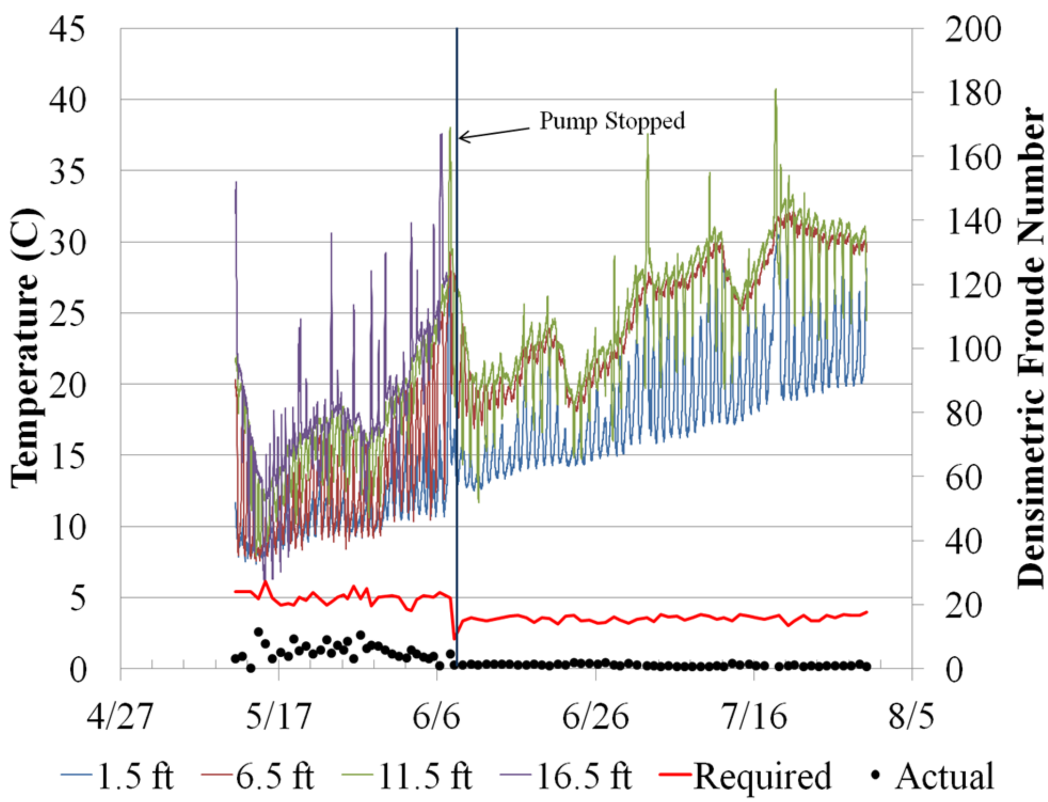


Figure 4.5: Long term tank C densimetric Froude number

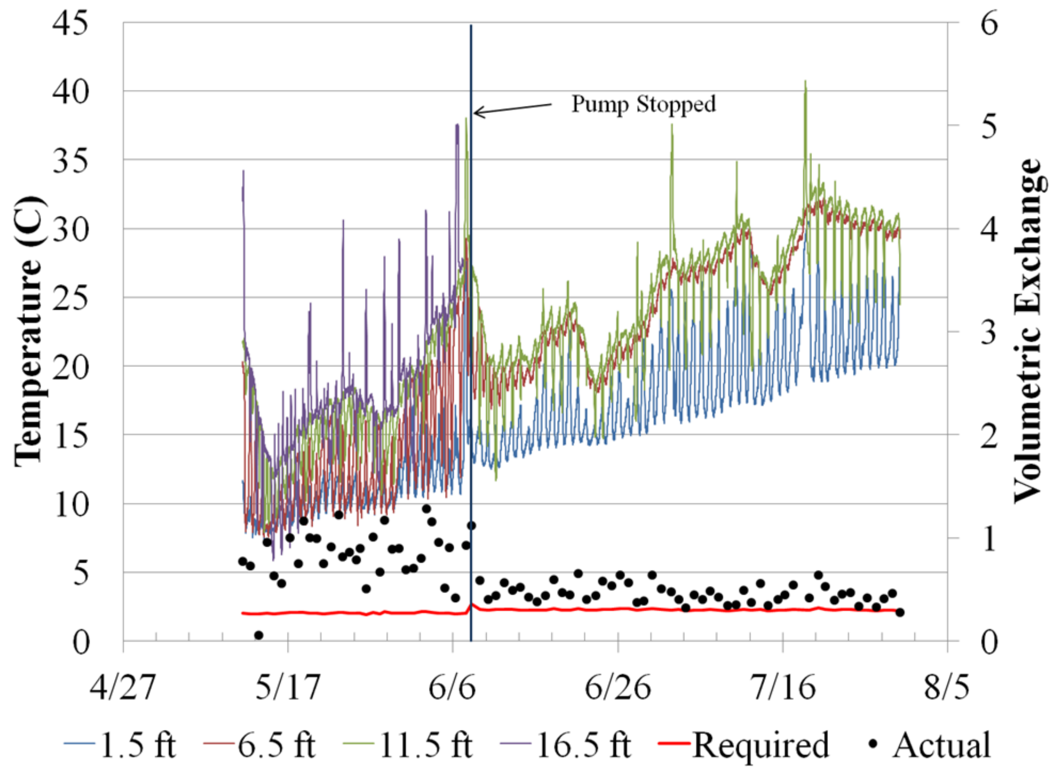


Figure 4.6: Long term tank C volumetric exchange

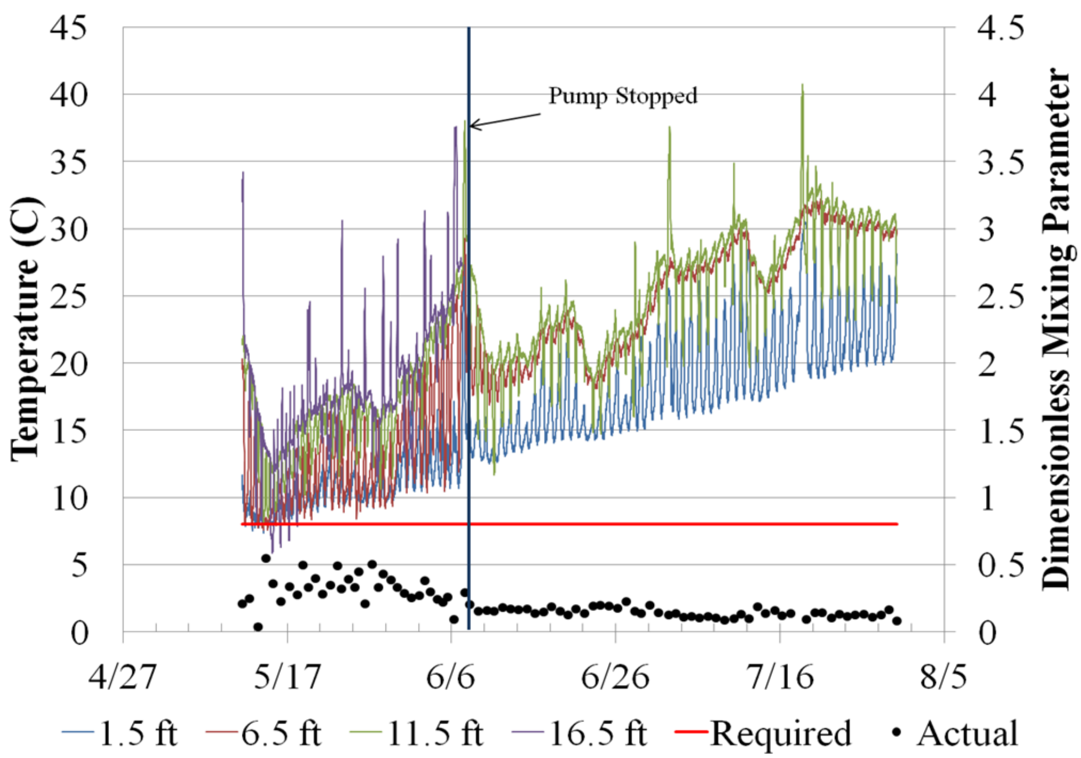


Figure 4.7: Long term tank C dimensionless mixing parameter

4.2.2 Long Term Tank D

Figure 4.8 shows the temperature profile of long term tank D throughout the study. Also, sampling events and the period the tank was drained are noted in Figure 4.8. Tank D was thermally stratified throughout the study. During the cooler temperatures at the beginning of monitoring, the stratification between the lower and upper zone were not as significant as the stratification that occurred between the zones when the temperature became warmer. At the warmest temperatures, the temperature difference between the upper and lower zone was approximately 10 degrees Celsius. The thermocline appeared to be between the depths of 1.5 feet and 8.5 feet. The impact of the thermal stratification on water quality was observed by analyzing water samples from the varying depths of the tank. An example of the water quality data is shown in Figure 4.9.

Figure 4.9 shows a substantial drop in total chlorine residual between 1.5 feet (1.75 mg/L) and 8.5 feet (0.57 mg/L) above the tank bottom. The total chlorine residual were usually low in the warmer upper zone of the tank. Tank D showed stratification in both temperature and water quality. The chlorine residuals that were measured on September 1 were low, which lead to concern from the water system. To restore the chlorine residual to the upper portion of the tank, the water system chose to drain the tank lower than during normal operation and then refill the tank.

Figure 4.10 shows the water quality parameters above the thermocline throughout the study. Draining the tank did achieve the goal of restoring the chlorine residual to an appropriate level. Before the tank was drained, the water system was concerned about nitrification arising as a result of low chlorine residual. Figure 4.10 shows no sign that nitrification had occurred in the upper zone before the water system drained the tank.

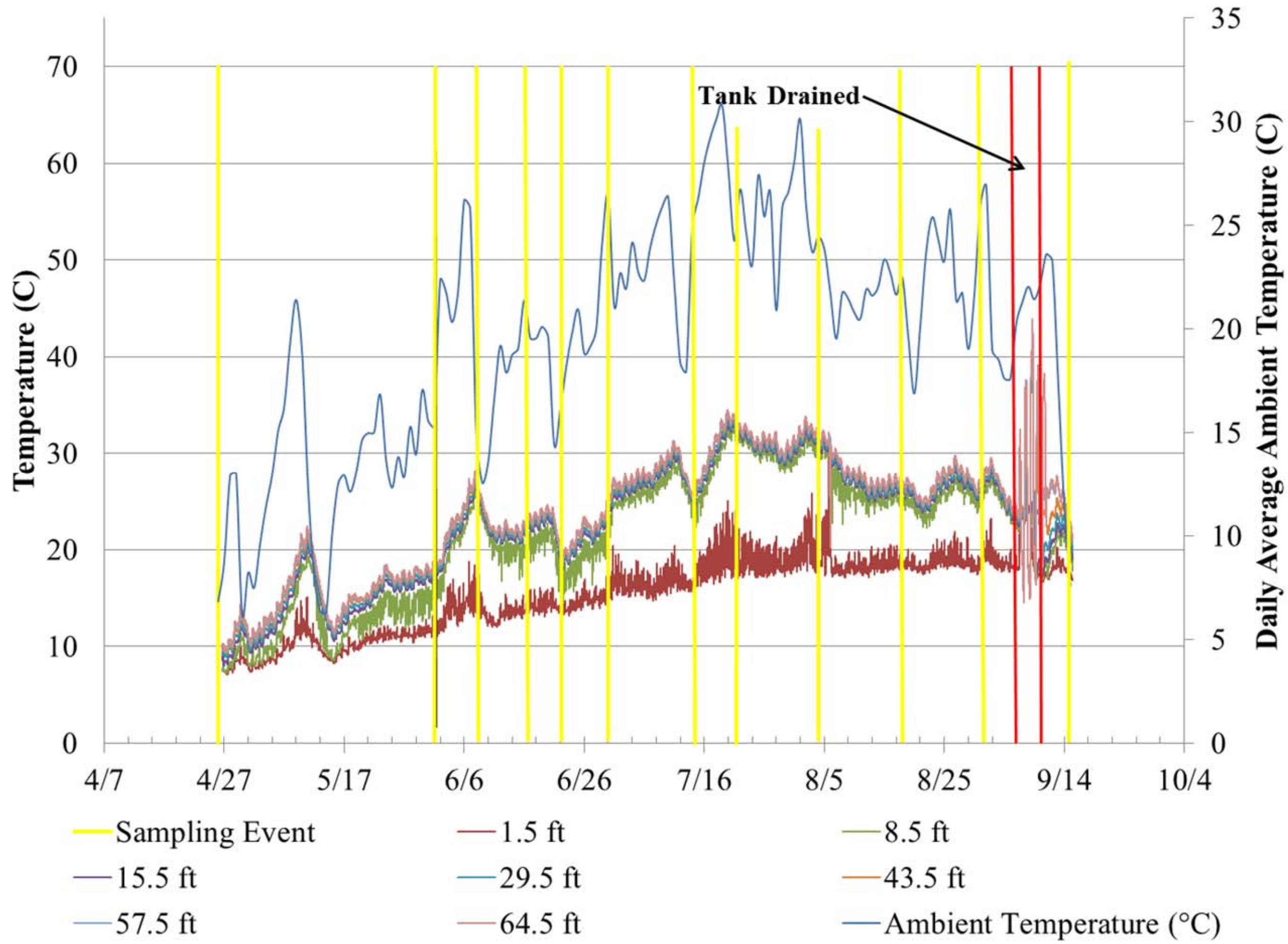


Figure 4.8: Long term tank D (H-D 2-4) temperature profile along with sampling dates and period when tank was drained.

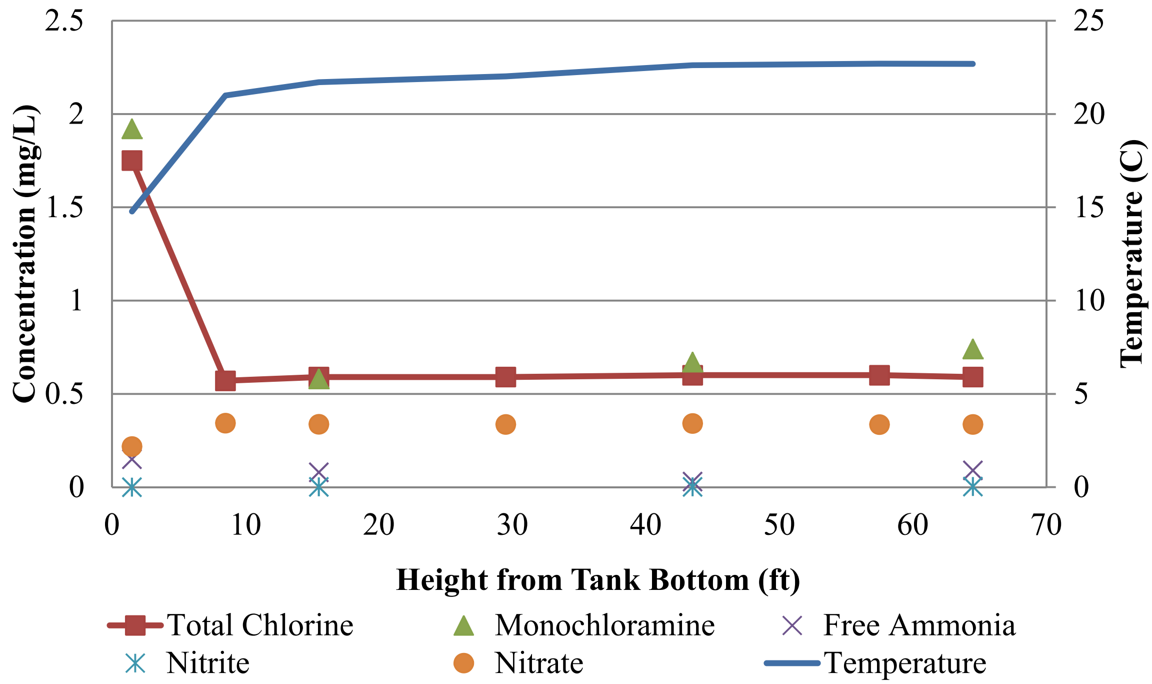


Figure 4.9: Long term tank D water quality data on June 16.

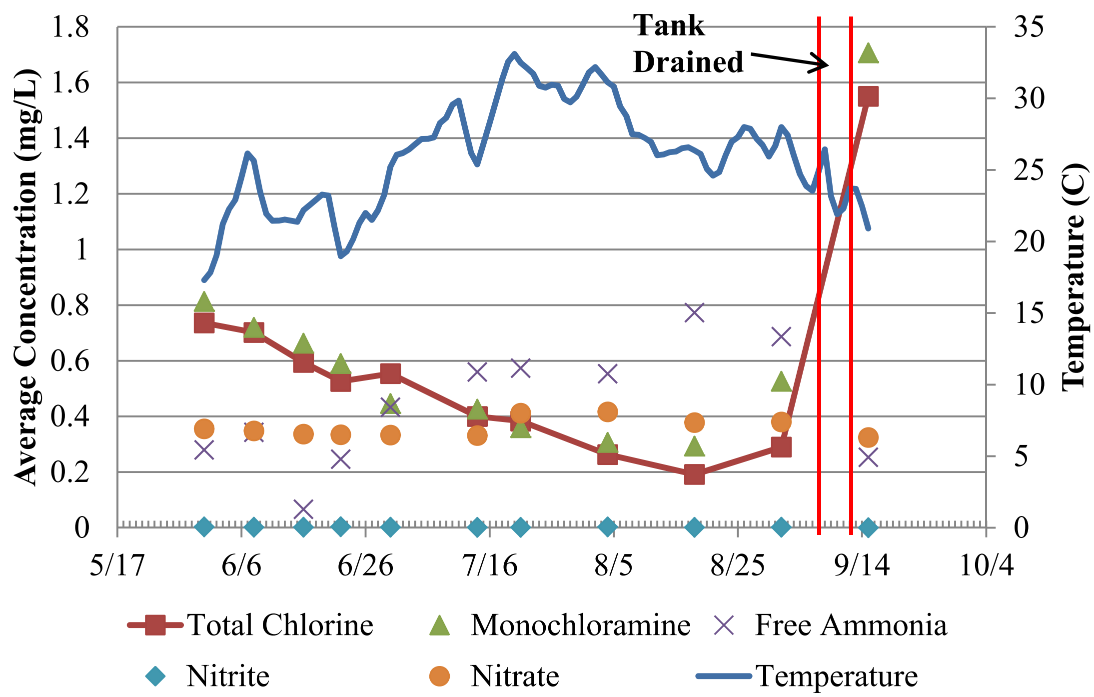


Figure 4.10: Long term tank D water quality parameters throughout study

Figure 4.11 portrays the water quality parameters on the first sampling event after the water system drained the tank. The chlorine residual returned to a proper level. However, the data indicated the tank was stratified. A drop in chlorine residual occurred between the 8.5 foot sampling point (1.92 mg/L) and the 15.5 foot sampling point (1.46 mg/L).

Figure 4.12 shows the temperature profile after the tank was drained. After draining, the temperatures were similar but the temperatures started to re-stratify as time passed with warmer ambient temperatures. However, the ambient temperature dropped and the temperatures started to unstratify.

Figure 4.13, Figure 4.14, and Figure 4.15 show the densimetric Froude number, volumetric exchange, and dimensionless mixing parameter calculated for tank D respectively. The densimetric Froude number, the volumetric exchange, and the dimensionless mixing parameter all show that the tank should not be mixed, which agrees with the temperature data and the water quality data. Hydraulic parameter calculations are presented in the Appendix A.

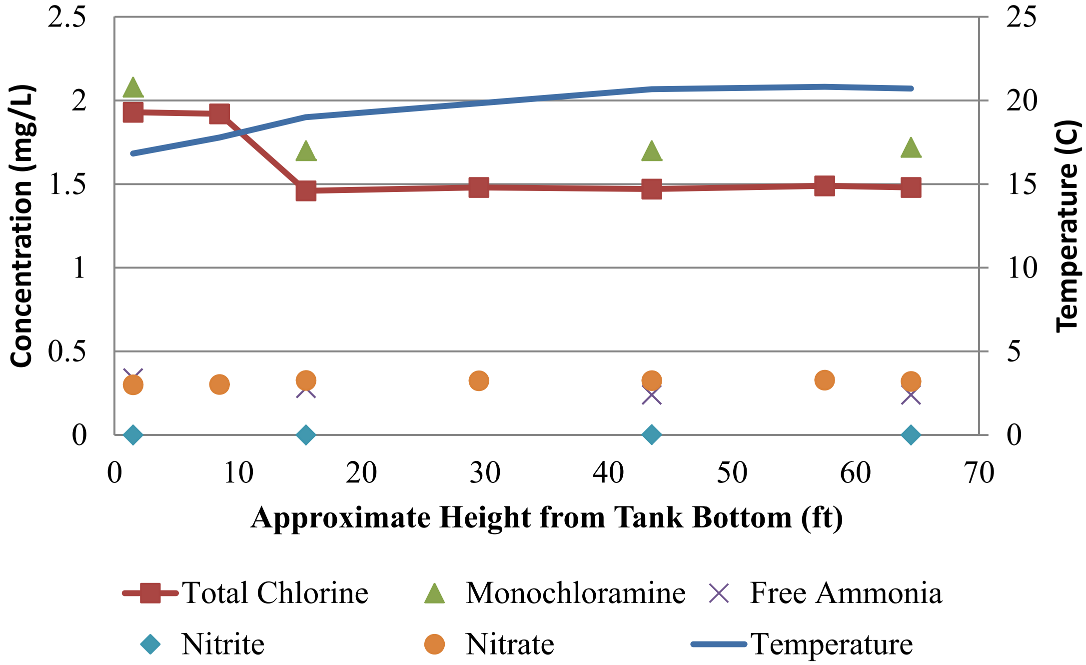


Figure 4.11:Long term tank D water quality sampling event after tank was drained

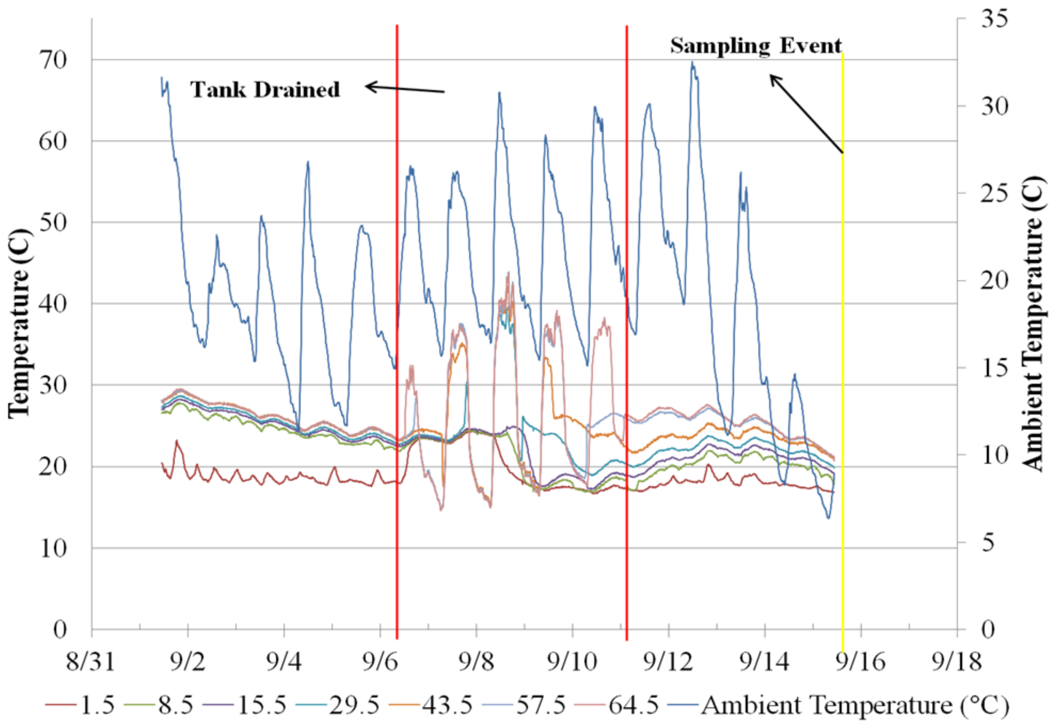


Figure 4.12: Long term tank D temperature profile after tank was drained.

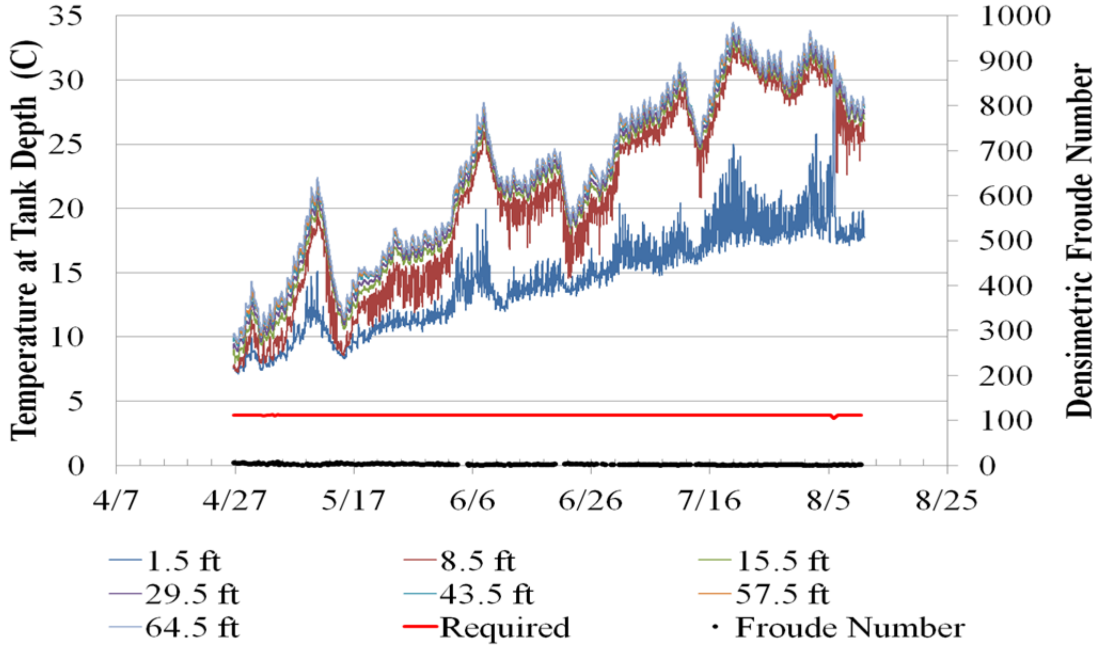


Figure 4.13: Long term tank D densimetric Froude number.

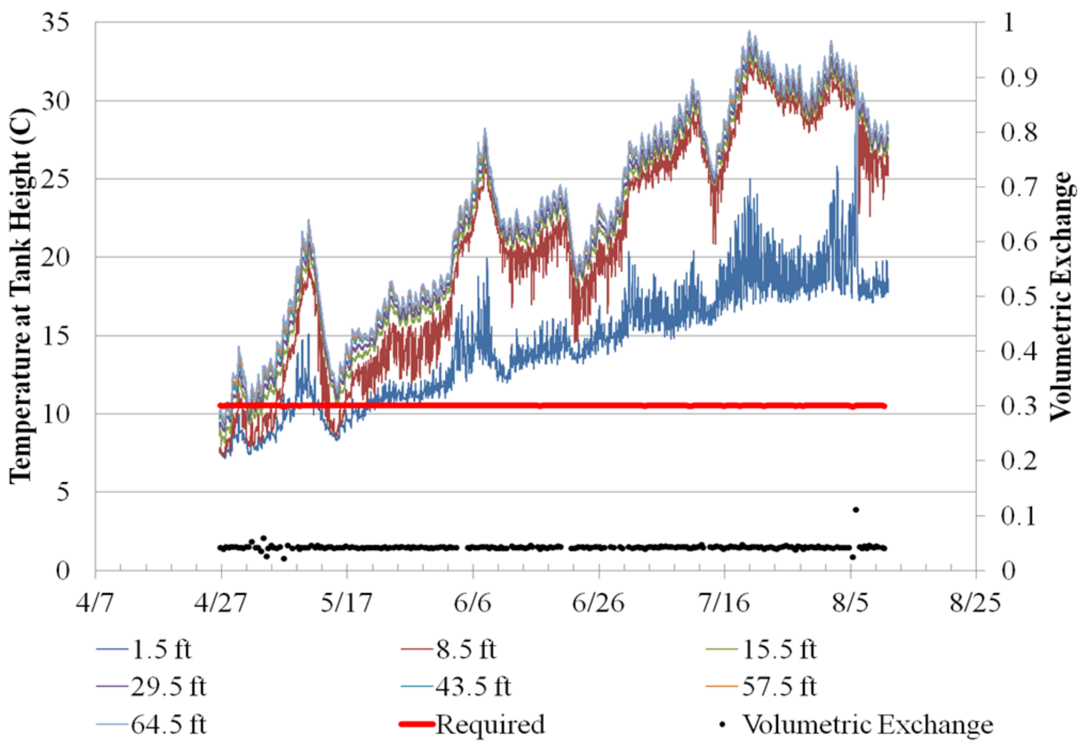


Figure 4.14: Long term tank D volumetric exchange.

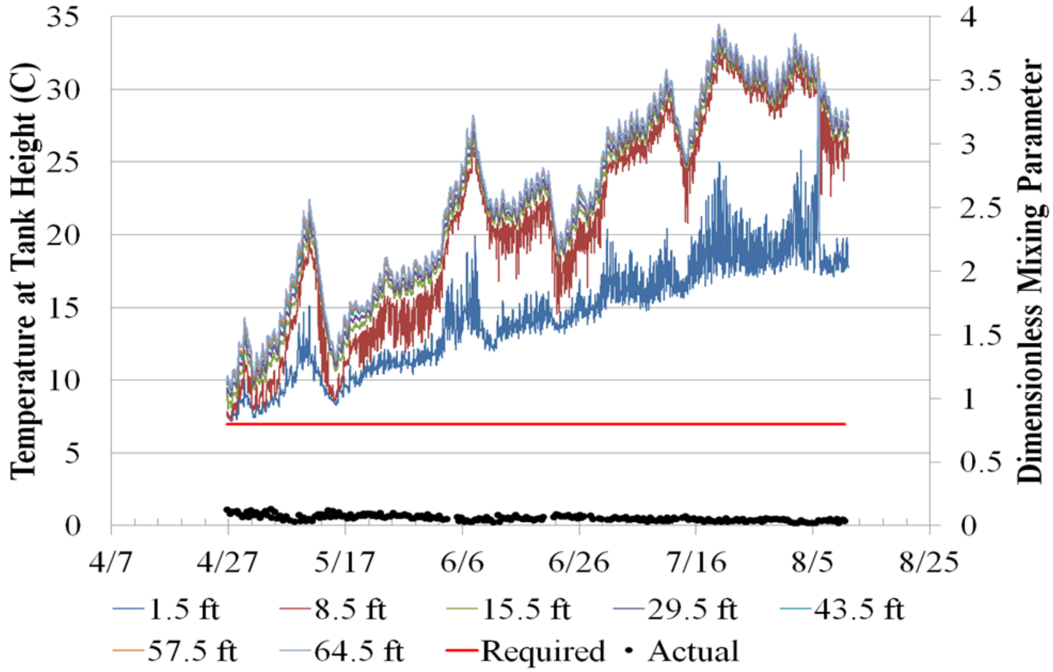


Figure 4.15: Long term tank D dimensionless mixing parameter.

4.2.3 Long Term Tank E

The temperature profile for tank E is shown in Figure 4.16. Sampling events and the period that the tank was overflowed are indicated in Figure 4.16. During the early part of the study the temperature cool and the tank showed little stratification. As the temperature increased stratification became more apparent. Between 8.5 feet and 22.5 feet above the tank bottom, a temperature difference of around 8 degrees Celsius was observed at times. The effect of stratification on water quality was observed by collecting samples from varying depths of the tank and analyzing the samples for water quality parameters. Figure 4.17 shows an example of the water quality parameters analyzed.

The chlorine residual dropped considerably between 8.5 feet and 22.5 feet above the tank bottom. At 8.5 feet, the chlorine residual was 1.58 mg/L, while the chlorine

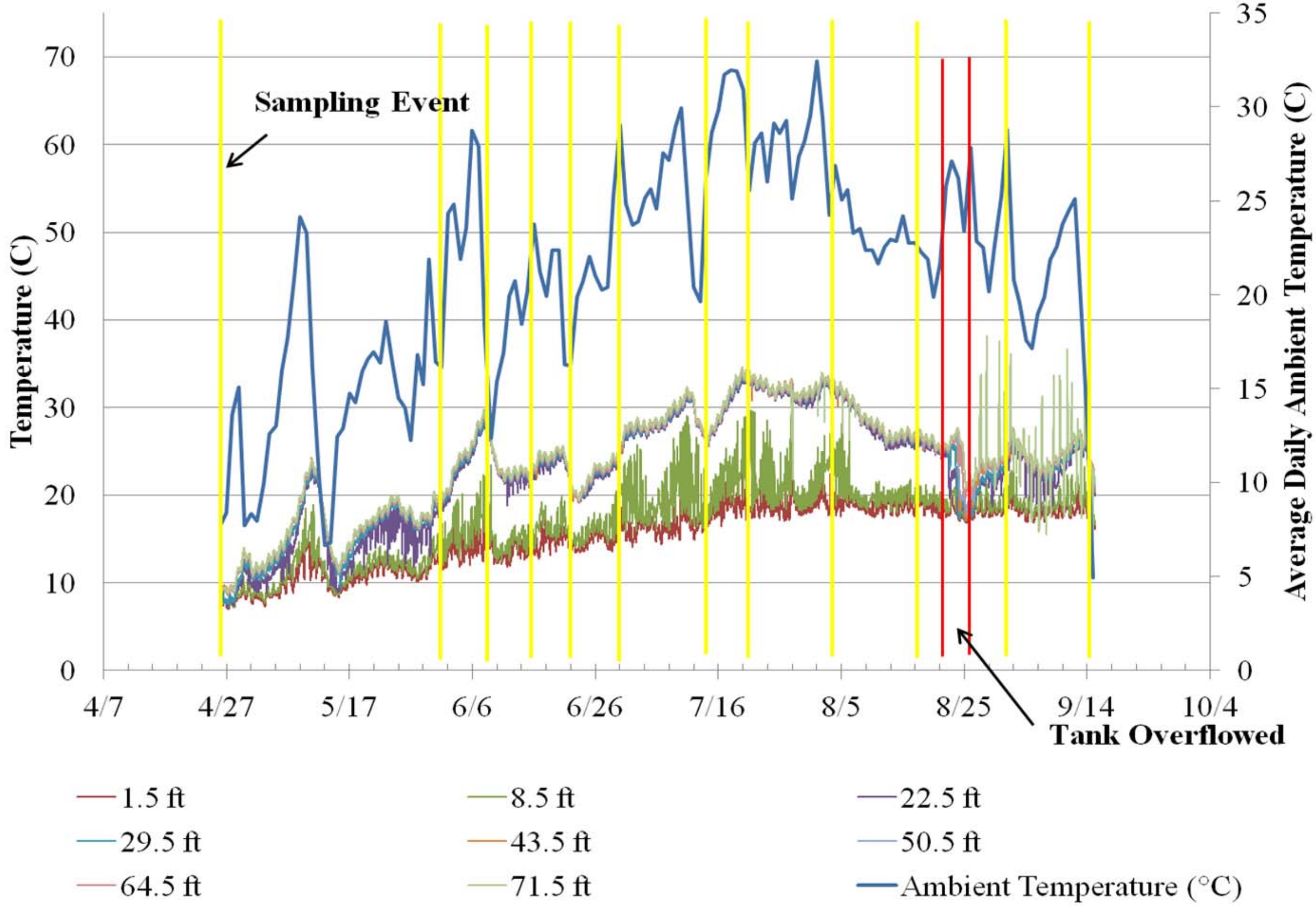


Figure 4.16: Long term tank E temperature profile with sampling events and period of tank overflow shown.

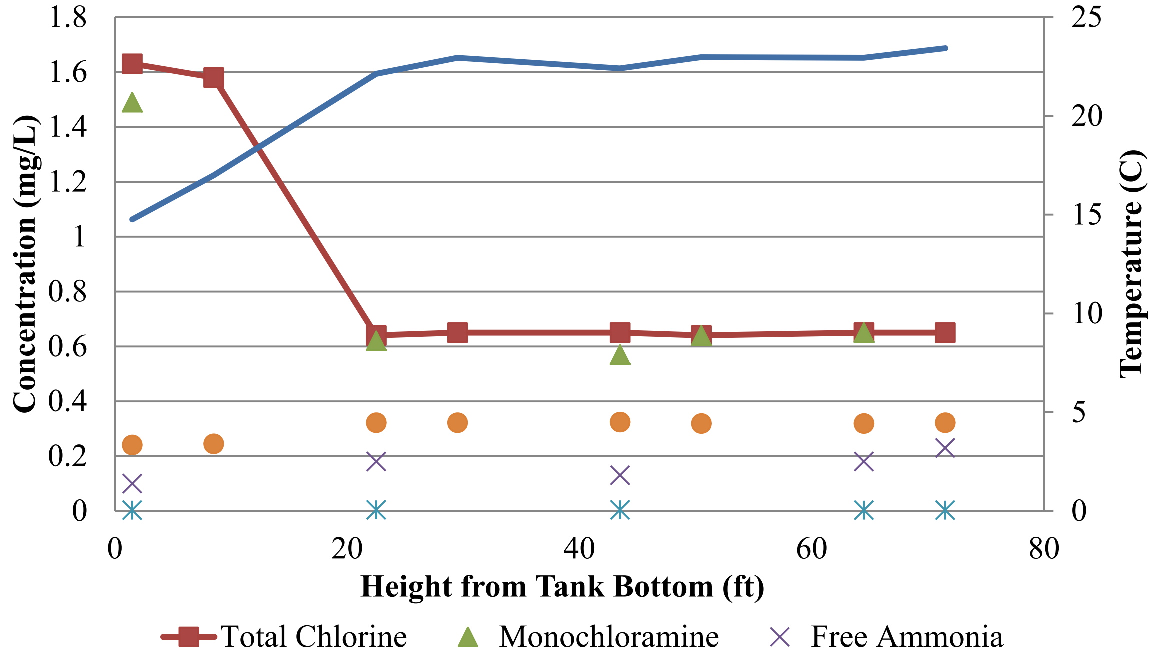


Figure 4.17: Long term tank E water quality parameters on June 16.

residual dropped to 0.64 mg/L at 22.5 feet. The temperature in the upper zone was about 6 degrees Celsius greater than the bottom zone. Stratification occurred in both temperature and water quality.

Figure 4.18 shows the water quality parameters throughout the study above the thermocline. On August 18, the low chlorine residuals measured in the upper portion of the tank caused the water system to overflow the tank in order to establish proper chlorine residuals.

Overflowing the tank restored a greater chlorine residual in the upper portion of the tank. The water system was worried about nitrification with the low chlorine residual before overflowing the tank. Figure 4.18 does show signs of nitrification in the tank before the tank was overflowed. The free ammonia was oxidized into nitrite between the sample events of August 4 and August 18. Nitrite increased from 0.009 mg/L as N to 0.38 mg/L as N. Oxidation to nitrate did not occur before the tank was overflowed and the chlorine residual was restored by the overflow event.

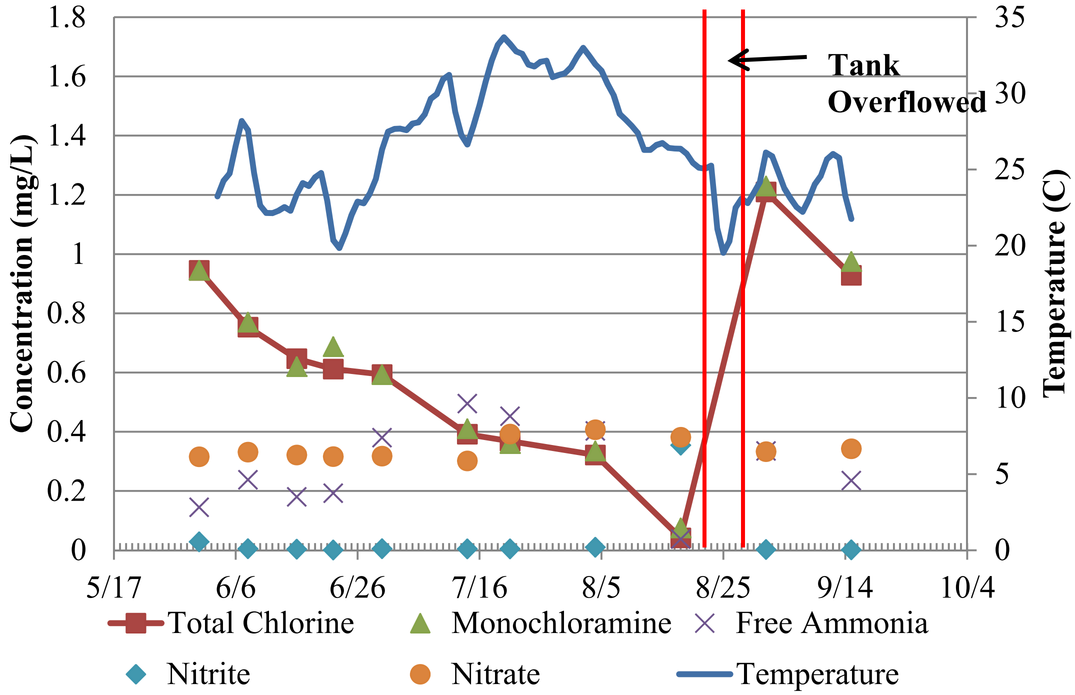


Figure 4.18: Long term tank E water quality parameters throughout study.

Figure 4.19 shows the water quality data on the first sampling event after the water system overflowed the tank. The chlorine residual was restored to a proper level; however, the tank indicated stratification. A difference in chlorine residual occurred between the 8.5 foot sampling point (1.72 mg/L) and the 15.5 foot sampling point (1.2 mg/L). The nitrite concentration went from an average of 0.38 mg/L as N before the tank was overflowed to an average of 0.002 mg/L as N.

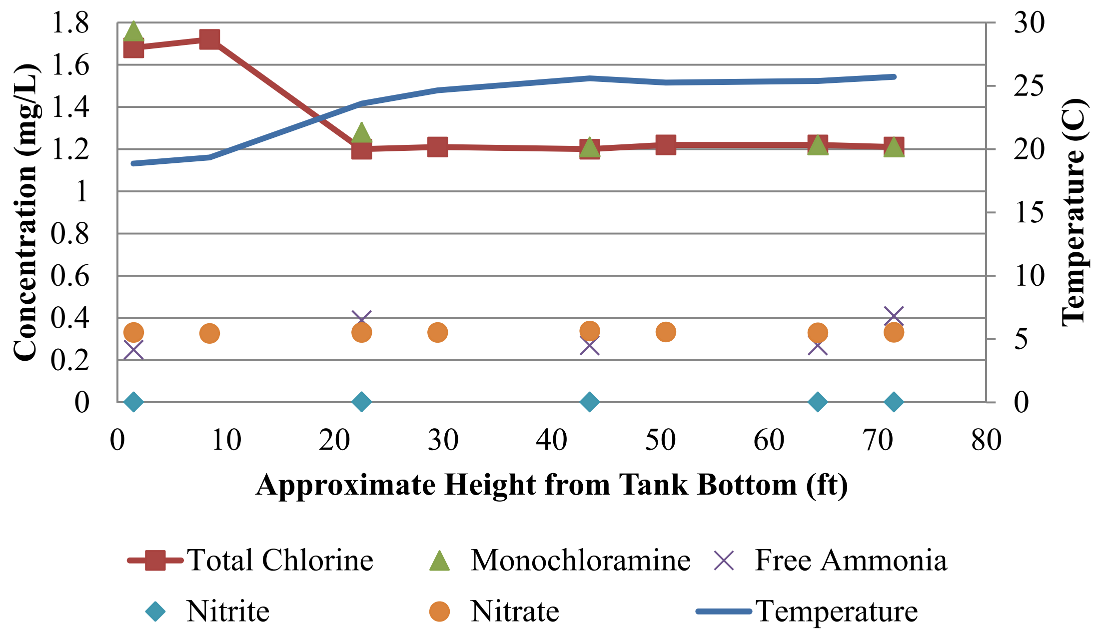


Figure 4.19: Long term tank E water quality data on sampling event after tank was overflowed.

The temperature profile after the tank was overflowed is shown in Figure 4.20. Overflowing the tank caused the warmer water in the upper portion to be released from the tank and replaced with the cooler water that was filling the tank. During the overflow, the temperatures were not stratified. However, after the overflow was done the temperatures started to stratify again.

Figure 4.21 shows the temperature profile along with the water depth in the tank. At the beginning of the temperature profile, the temperature at 22.5 feet showed that the fill and draw cycles influenced the temperature. As the temperature increased, the 22.5 foot temperature was less influenced; however, the temperature at 8.5 feet became more influenced by the fill and draw cycles. The temperature would increase during the draw cycle as warm water lowered in the tank and then the temperature would decrease during the fill cycle when the colder influent water entered the tank.

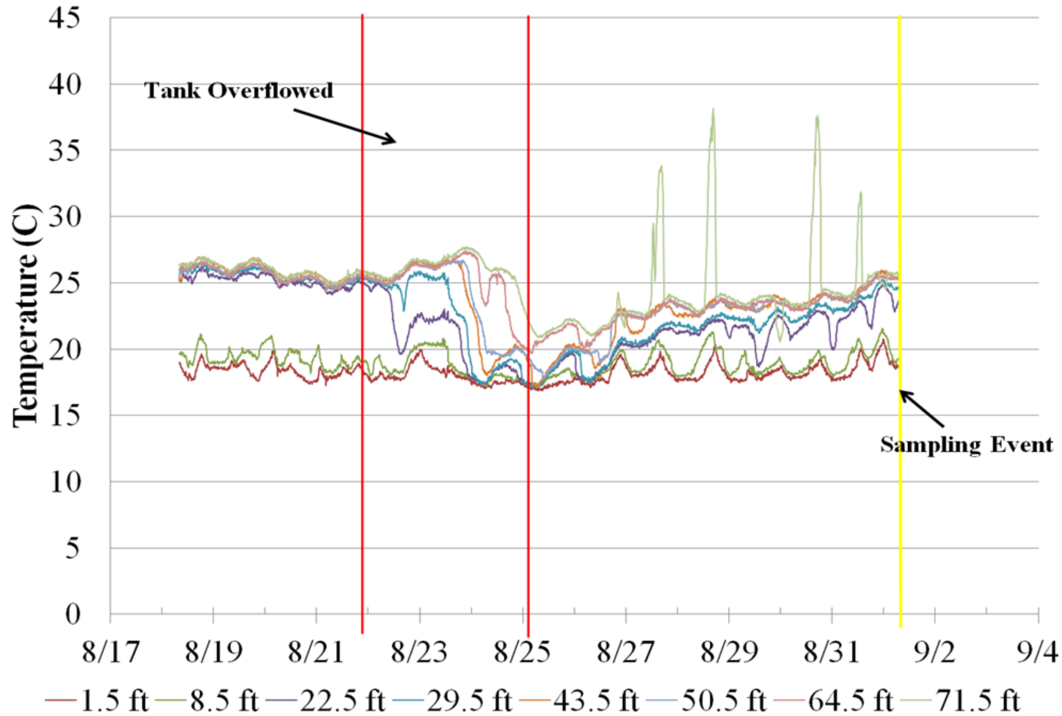


Figure 4.20: Long term tank E temperature profile after tank was overflowed.

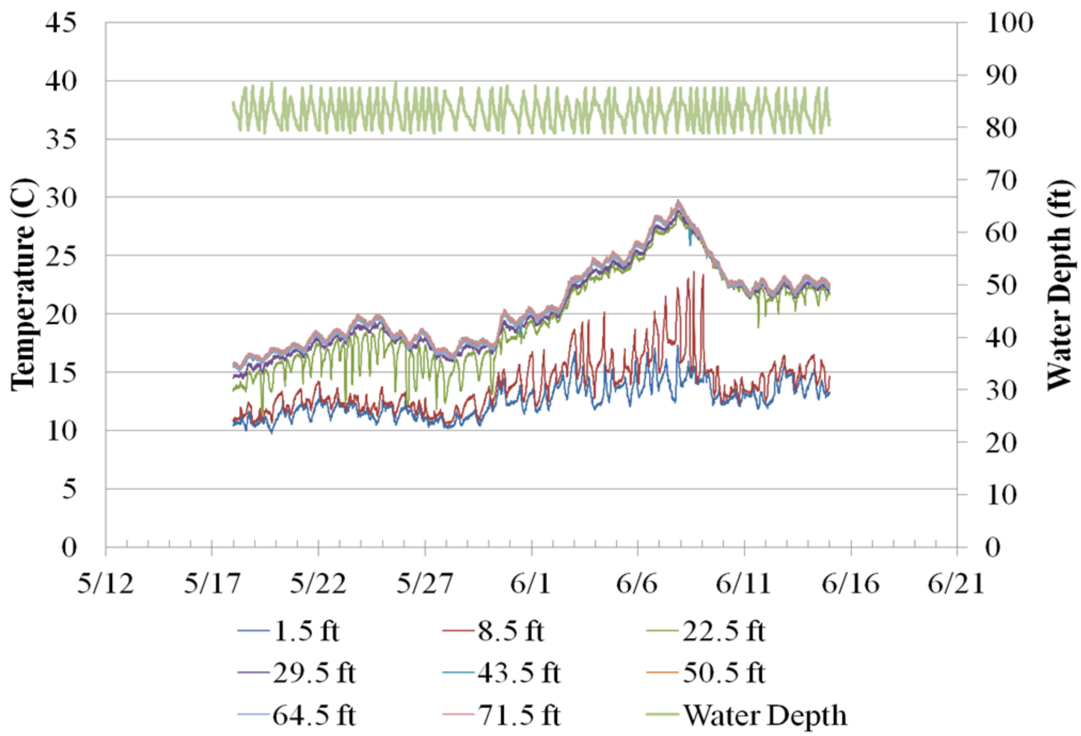


Figure 4.21: Long term tank E temperature profile with water depth.

The densimetric Froude number, volumetric exchange, and dimensionless mixing parameter were calculated and are shown in Figure 4.22, Figure 4.23, and Figure 4.24 respectively. Each of the three hydraulic parameters shows that the tank should not be mixed. Therefore, the hydraulic parameters agree with how the temperature and water quality behaved within the tank.

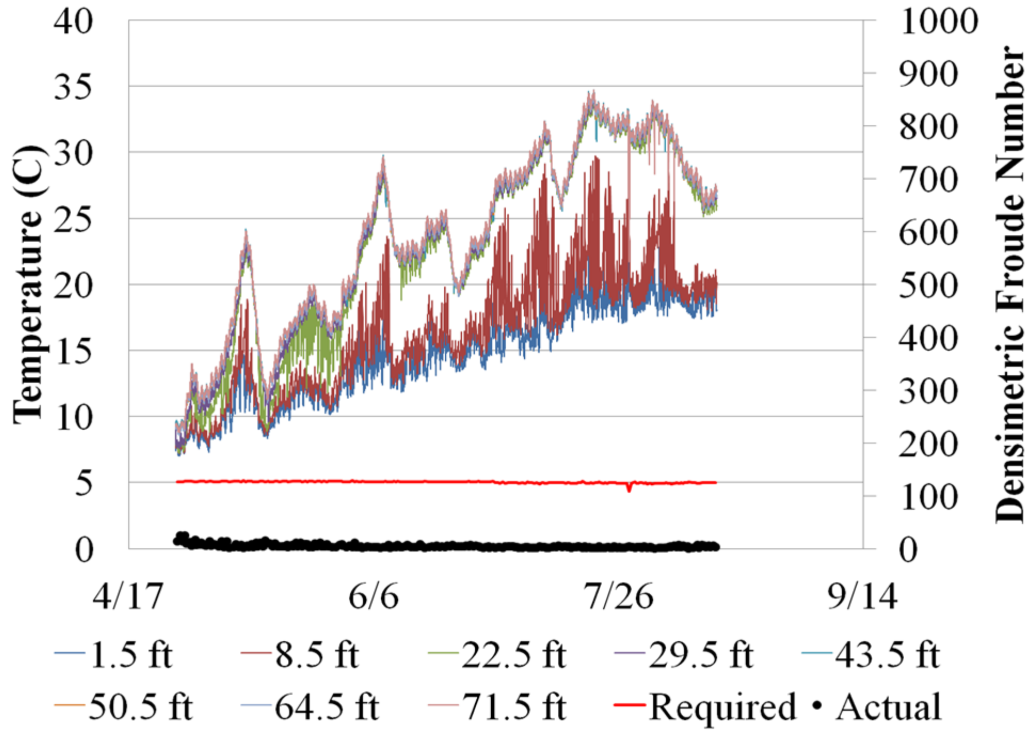


Figure 4.22: Long term tank E densimetric Froude number.

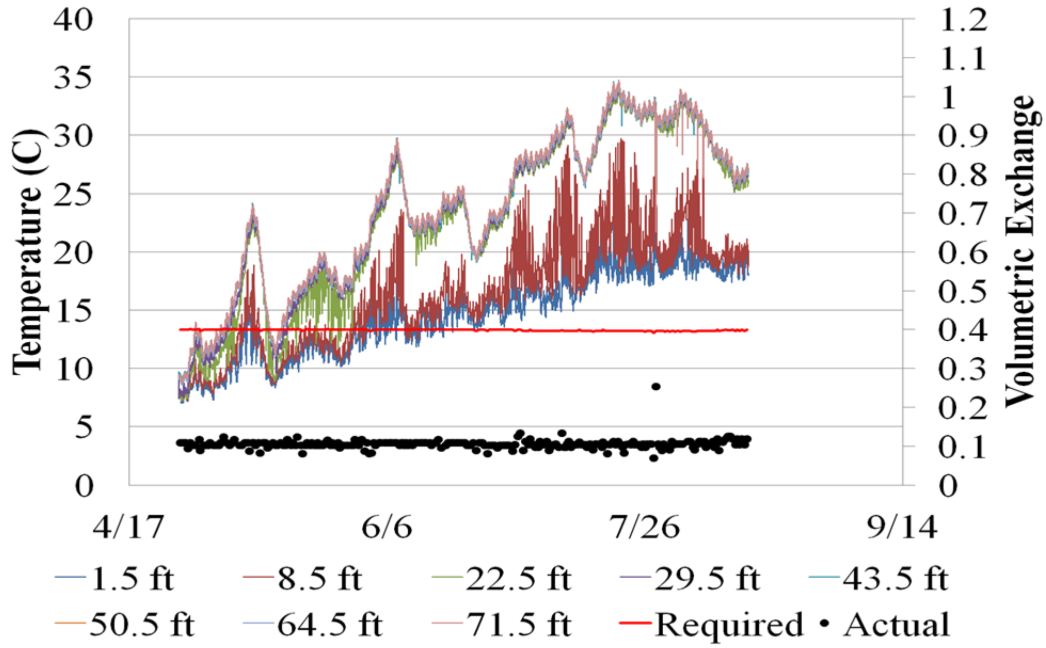


Figure 4.23: Long term tank E volumetric exchange.

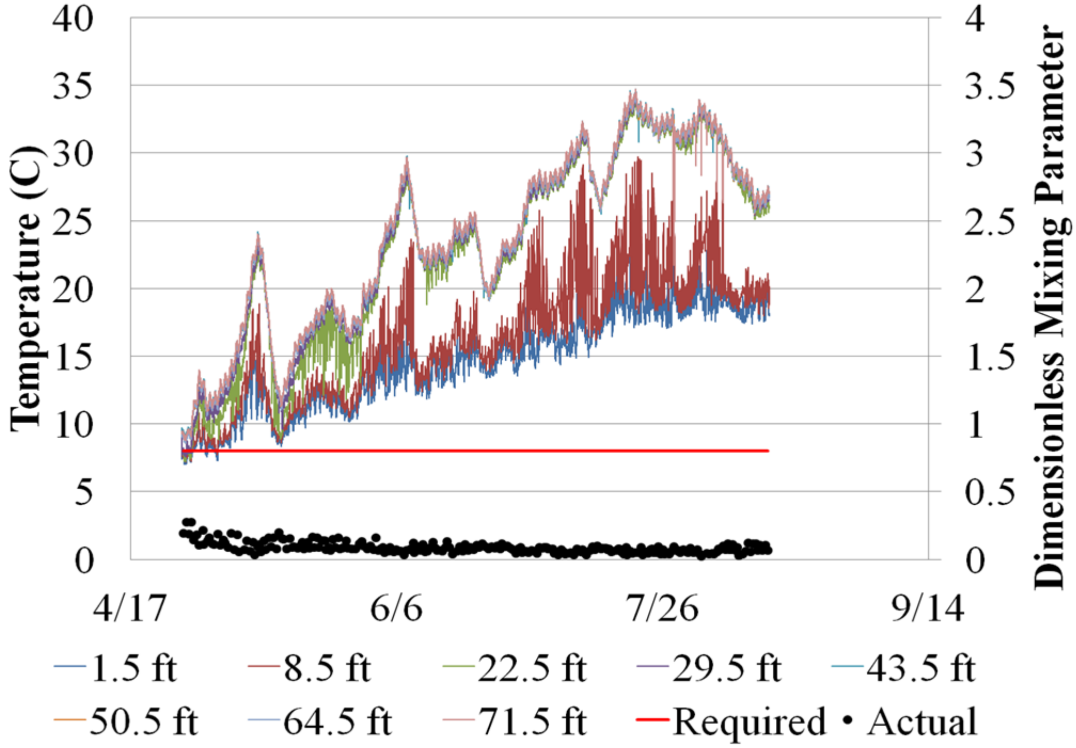


Figure 4.24: Long term tank E dimensionless mixing parameter.

4.2.4 Long Term Tank F

Figure 4.25 shows a temperature profile along with the sampling events of long term tank F. The temperature profile shows that the tank was stratified between 15.75 feet and 22.75 feet above the tank bottom. However, the temperature at 22.75 feet was influenced by the fill and draw cycles at times. Figure 4.26 shows the relationship between the temperature and the fill and draw cycle. Filling the tank caused the upper temperature to decrease in temperature, while the temperature increased during the draw cycle.

Stratification in the temperature had an effect on the water quality in the tank. An example of the water quality data is shown in Figure 4.27. A drop in the chlorine residual occurred between the lower zone of the tank and the upper zone of the tank. In the lower zone, the chlorine residual was around 1.8 mg/L, while the upper zone's chlorine residual was around 0.7 mg/L. The temperature difference was close to 10 degrees Celsius. Both the temperature and the water quality showed stratification during the tank visit.

At times during the study, the temperature at 22.75 feet was influenced by the fill and draw cycles. Figure 4.28 shows that the water quality was affected during the periods of influence. The chlorine residual was constant throughout the tank at around 1.9 mg/L, while the temperature also remained constant around 16 degrees Celsius. Figure 4.25 shows that the periods that the temperature at 22.75 ft. was influenced by the fill and draw cycles, coinciding with ambient temperatures around 20 degrees Celsius or lower.

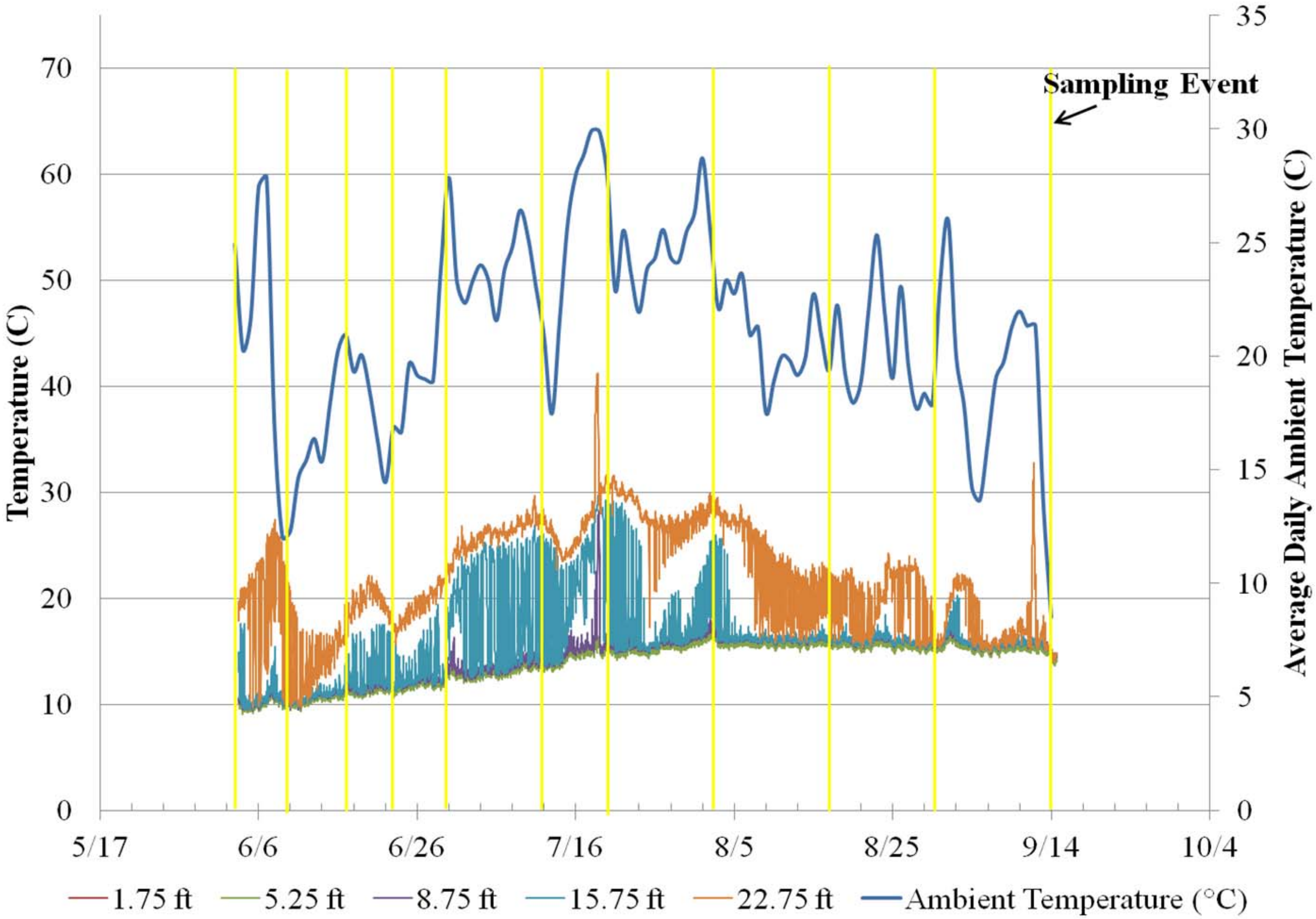


Figure 4.25: Long term tank F temperature profile.

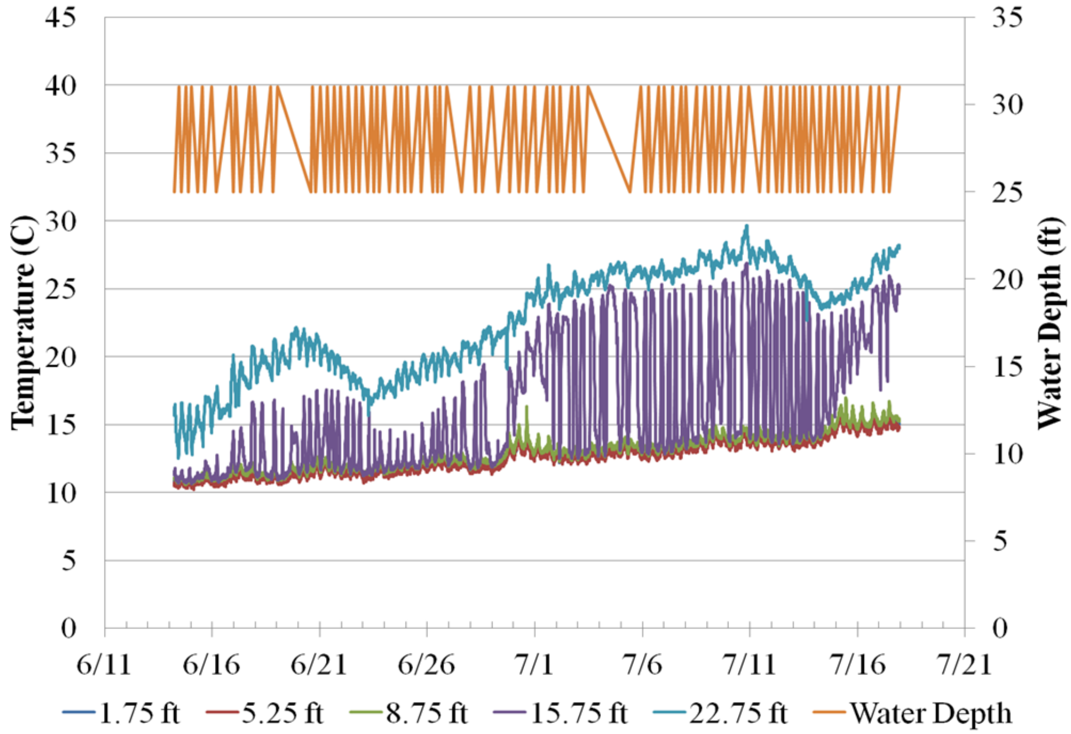


Figure 4.26: Long term tank F temperature profile and water depth.

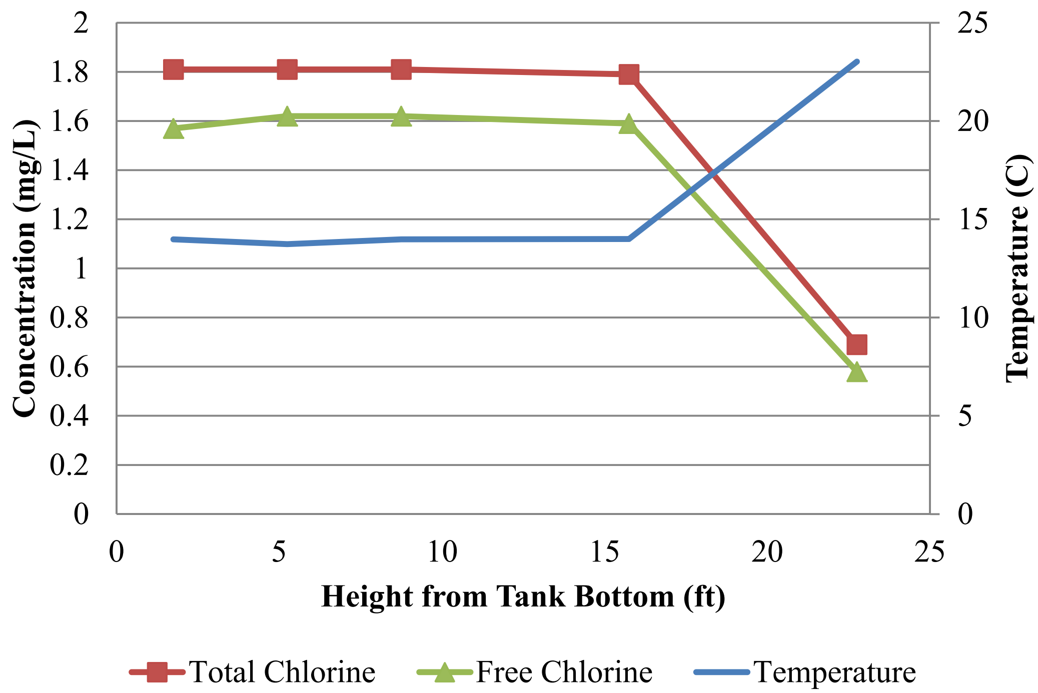


Figure 4.27: Long term tank F water quality data on July 13.

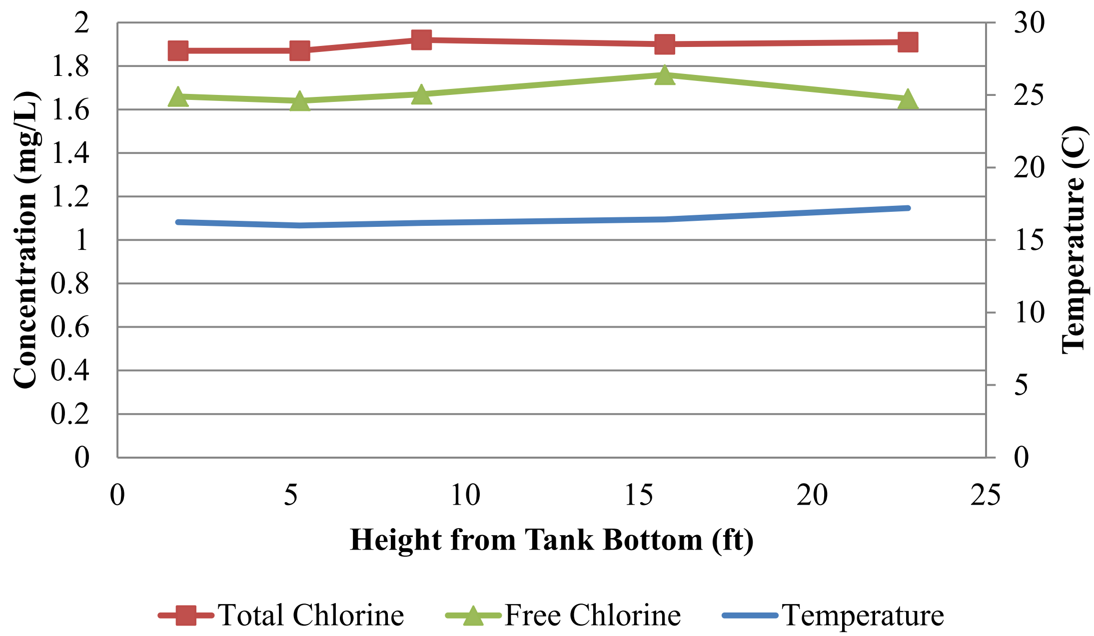


Figure 4.28: Long term tank F water quality data on August 31.

Three hydraulic parameters were calculated to show the tank's expected behavior. Figure 4.29, Figure 4.30, and Figure 4.31 show the densimetric Froude number, volumetric exchange, and dimensionless mixing parameter calculated respectively. The densimetric Froude number and the dimensionless mixing parameter show that the tank should not be mixed, which agrees with the temperature profile during the same period. The actual volumetric exchanges calculated in Figure 4.30 did not vary because the fill and draw cycles do not change. According to the volumetric exchange calculations, the tank should be mixed; however, the temperature profile does not agree during the period analyzed. The calculations used to calculate the hydraulic parameters are presented in Appendix A.

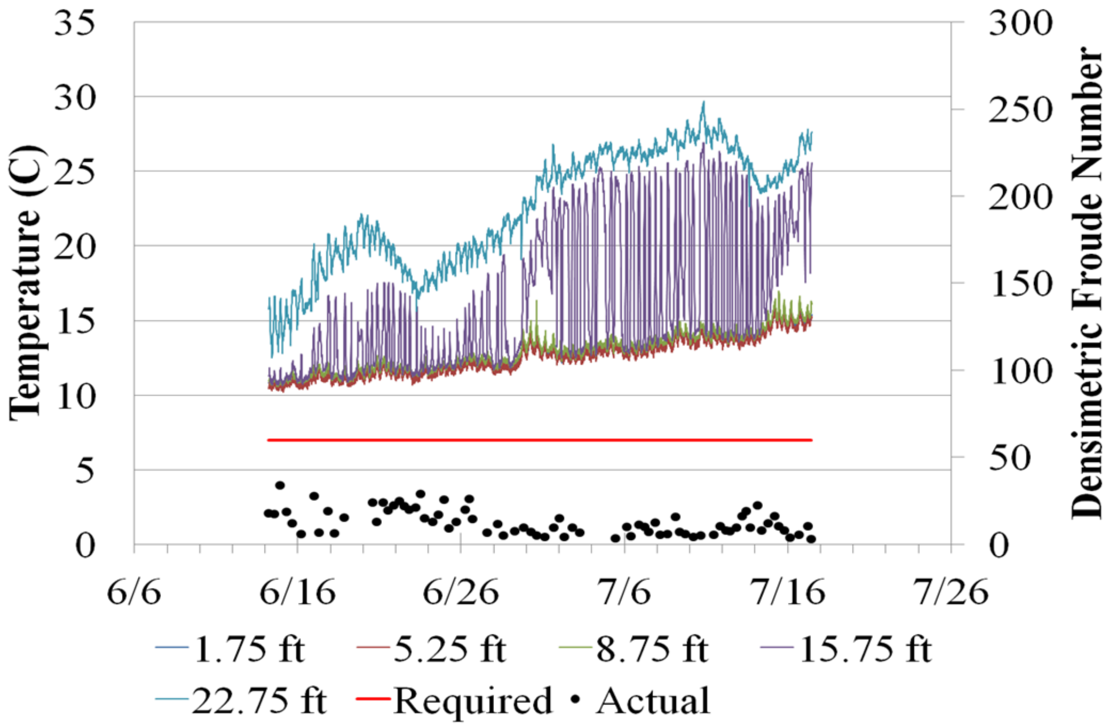


Figure 4.29: Long term tank F densimetric Froude number.

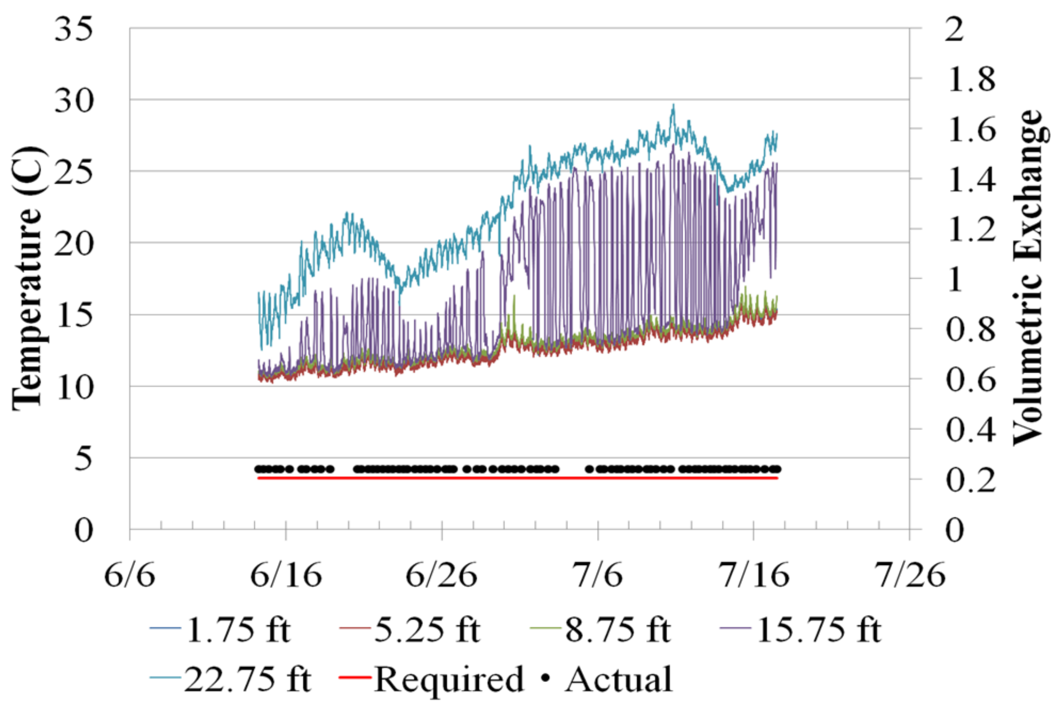


Figure 4.30: Long term tank F volumetric exchange.

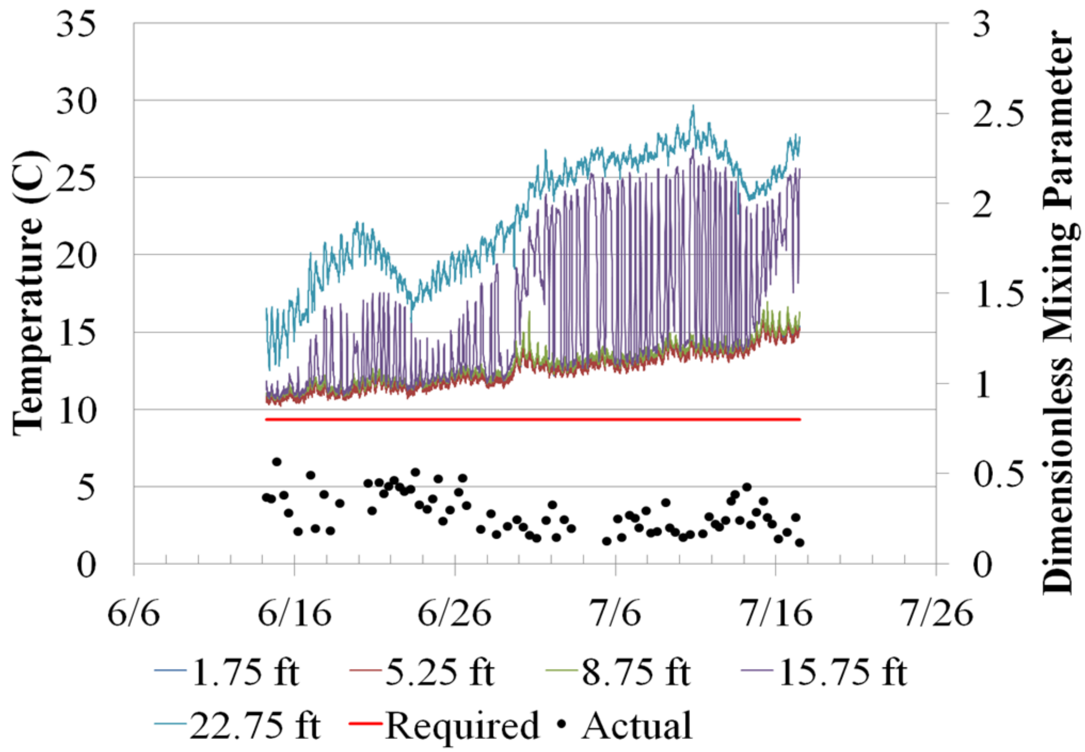


Figure 4.31: Long term tank F dimensionless mixing parameter.

4.2.5 Long Term Tank G

Figure 4.32 shows the temperature profile along with the time of the sampling events for long term Tank G. Throughout the study, tank G did not stratify in terms of temperature as shown in Figure 4.32. The temperatures throughout the tank remained steady around 15 degrees Celsius even with the changing ambient temperature, which shows that the temperature of the tank volume does not significantly depend on the ambient temperature outside of the tank.

Samples were collected and analyzed for total and free chlorine. Figure 4.33 shows an example of the data from the tests performed on July 14. Total chlorine residuals along with the free chlorine residuals were steady throughout the tank depth. At the bottom of the tank the total chlorine residual was 0.96 mg/L and the free chlorine residual was 0.86 mg/L. In the top of the tank, the total chlorine residual was 0.93 mg/L and the free chlorine residual was 0.90 mg/L. Both the temperature data and the water quality data show that tank G did not stratify.

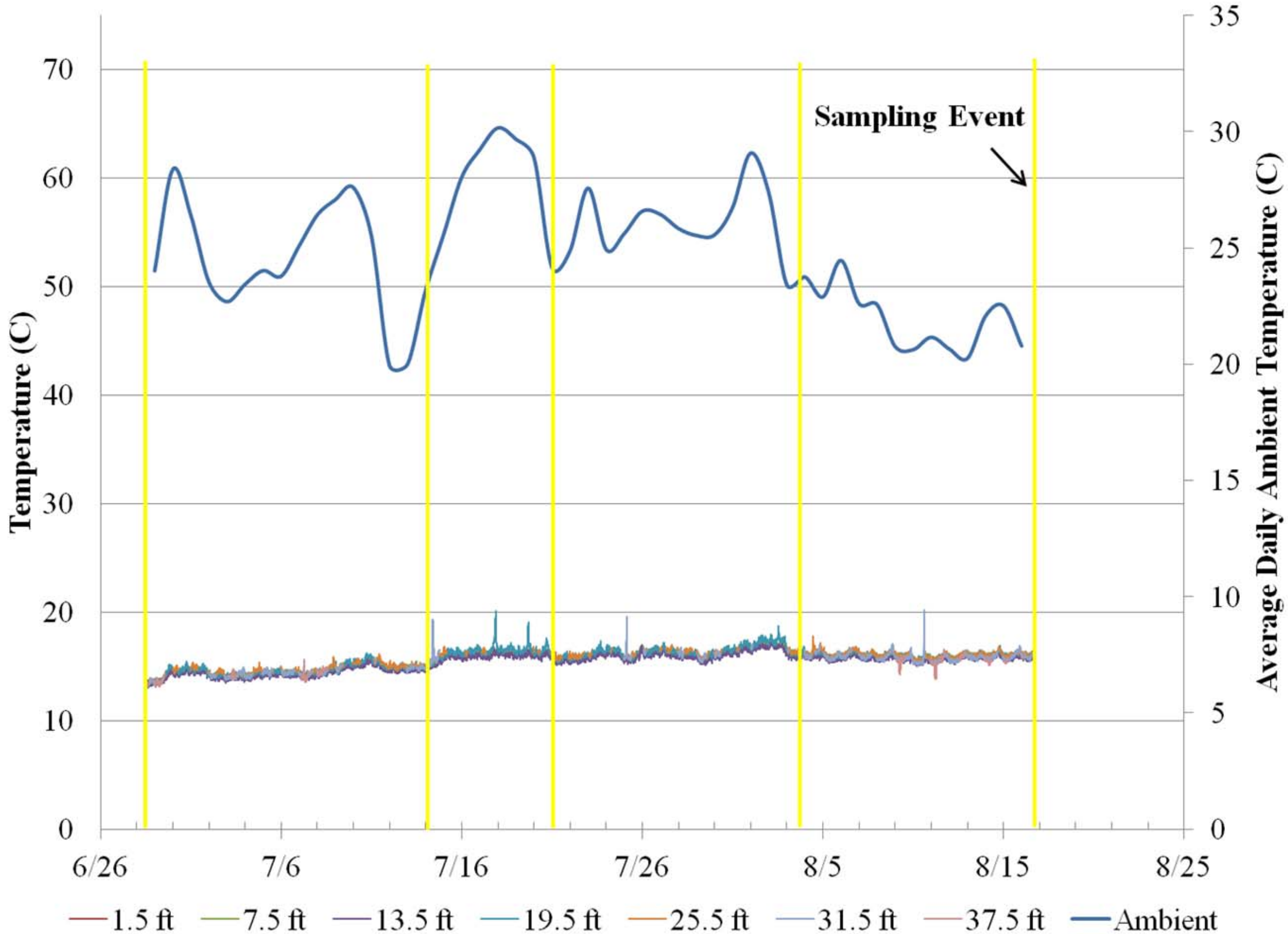


Figure 4.32: Long term tank G temperature profile and sampling events.

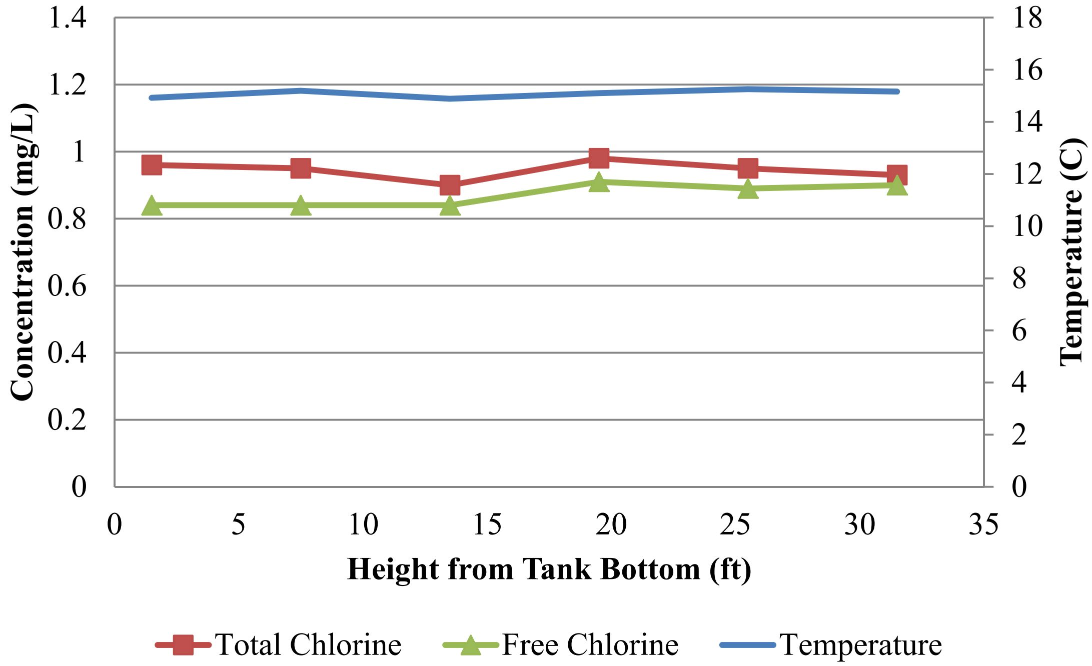


Figure 4.33: Long term tank G water quality parameters on July 14.

Hydraulic parameters were calculated to show the expected behavior of the tank. The densimetric Froude number, the volumetric exchange, and the dimensionless mixing parameter that were calculated are shown in Figure 4.34, Figure 4.35, and Figure 4.36 respectively. Both the densimetric Froude number and the dimensionless mixing parameter show that the tank operation did not meet the required values except in a few occasions, which does not agree with the temperature data and the water quality data. The volumetric exchanged shows mixed results as well; however, the volumetric exchange meets the required value more often than the other two parameters.

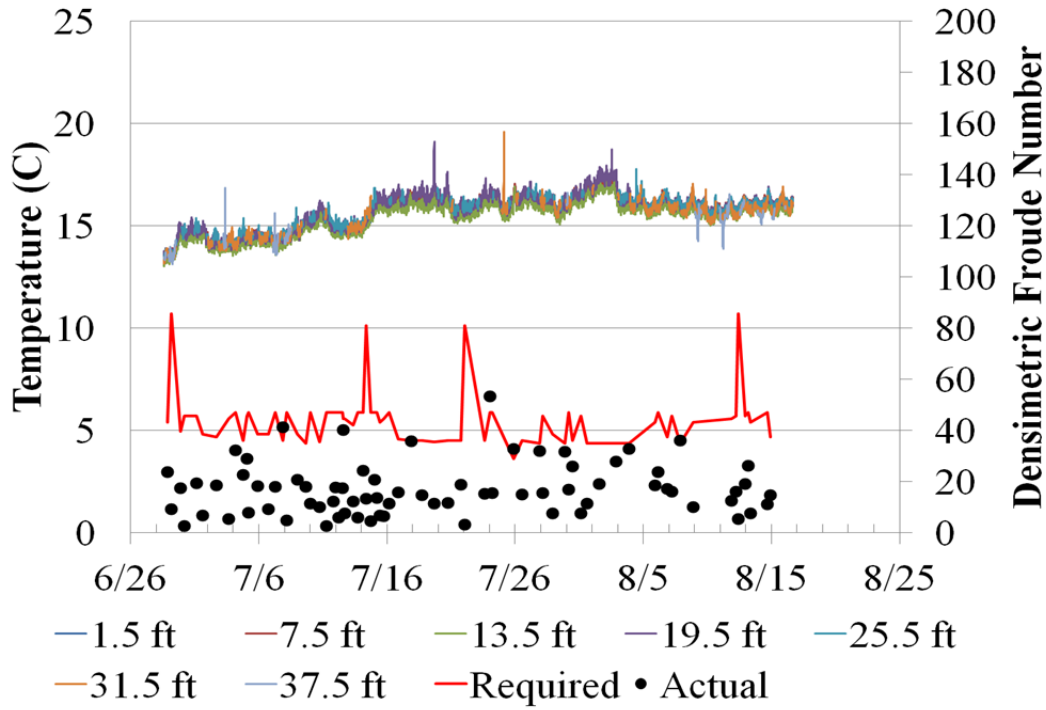


Figure 4.34: Long term tank G densimetric Froude number.

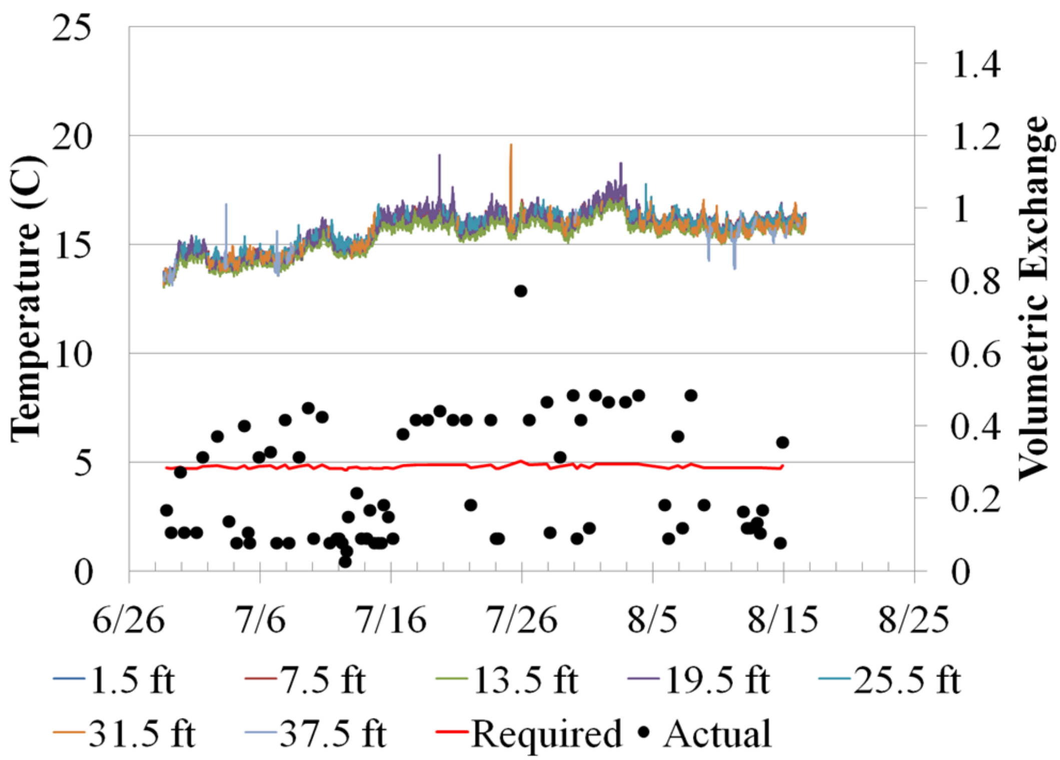


Figure 4.35: Long term tank G volumetric exchange.

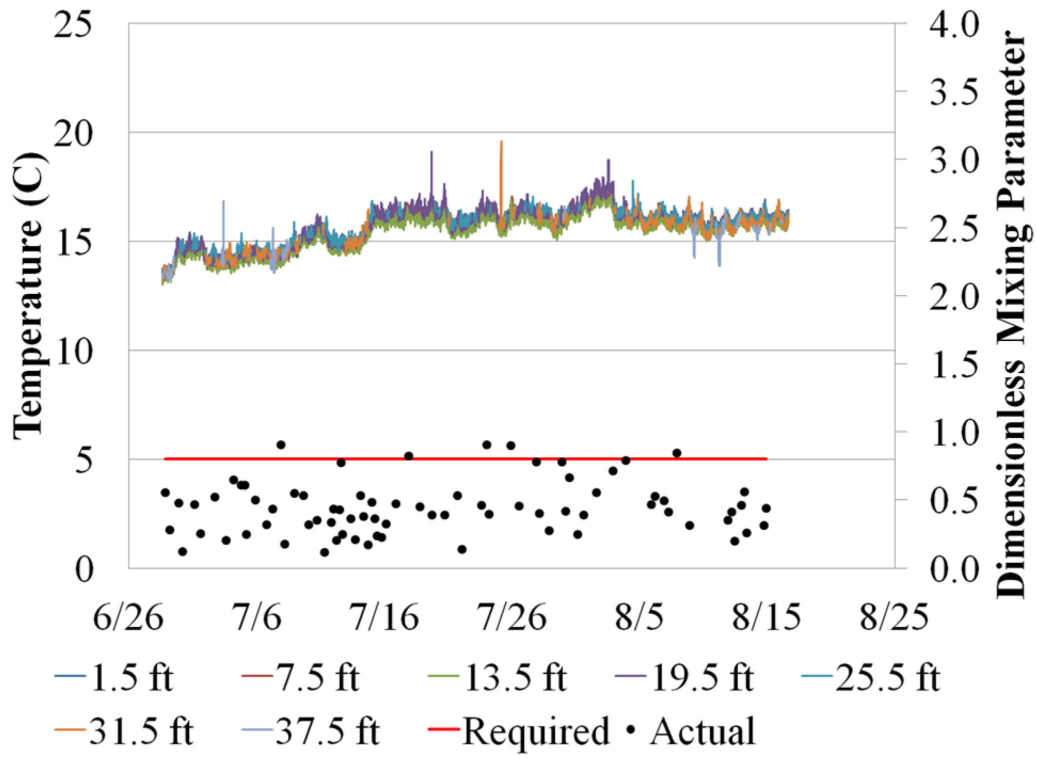


Figure 4.36: Long term tank G dimensionless mixing parameter.

4.2.6 Total Coliform

Samples were collected throughout the study on the long term tanks to perform the test for total coliform. Drinking water is regulated by the Total Coliform Rule, which states that 95% of the samples should contain 0 cfu/ml. Throughout the study, the results of the total coliform test were that there were no coliforms present. Therefore, the tanks followed the total coliform rule.

4.2.7 Heterotrophic Plate Count (HPC)

The samples that were collected for the total coliform test were also analyzed for heterotrophic plate count. Table 4.1 and Table 4.2 show the results of the HPC tests during the study. Results from long term tank C, D, and E are shown in Table 4.1. Tank D and E both have a HPC test that resulted in values significantly greater than the other tests. Both tests were conducted on June 16, which could have been caused by contamination of the medium used during the test. Tanks F and G also have a similar error as shown in Table 4.2. The tests were performed on consecutive days and used the same media, so contamination could explain the higher results. The rest of the samples showed low HPC results, which indicates low heterotrophic microbial growth.

Table 4.1: Heterotrophic plate count results for long term tanks C, D, and E.

Heterotrophic Plate Count (MPN/ml) for Tanks F and G																
	6/3	6/9	6/17	6/23	6/28	6/29	7/13	7/14	7/20	7/21	8/3	8/4	8/16	8/17	8/31	9/14
Long Term Tank F	2	2.8	4.2	0	--	272	22.2	--	0.4	--	0	--	--	0	0.7	1.3
Long Term Tank G	--	--	--	--	276	--	--	15	--	1.7	--	0	1	--	--	--

Table 4.2: Heterotrophic plate count results for long term tanks F and G.

Heterotrophic Plate Count (MPN/ml) for Tanks C , D, and E											
	5/31	6/8	6/16	6/22	6/30	7/14	7/21	8/4	8/18	9/1	9/15
Long Term Tank C:	1.3	0	1.3	0	12.5	13.5	3.3	0	0	0	0
Long Term Tank D: Below Thermocline	0	0	161	4	6	10	0	0	2	0	0
Long Term Tank D: Above Thermocline	1.2	0.4	91	0	2	15.8	4	1.6	2.4	1.6	0.8
Long Term Tank E: Below Thermocline	1	2	124	0	6	0	0	0	0	0	0
Long Term Tank E: Above Thermocline	2	1.6	92.4	0	2	3.6	4	1.2	2.4	0	0.4

Long term tank E indicated the occurrence of nitrification; therefore, the water in the tank contained nitrifying organisms.

4.3 Short Term Tank Study

Short term tanks were analyzed for temperatures at varying depths throughout the tank. Temperature data was collected for a shorter period of time compared to the long term tanks, and the temperature data was gathered using separate temperature sensors at each depth of the tank. A pressure sensor was used to calculate the water depth in the tank during the study, which was used to calculate the hydraulic parameters. Both short term tanks had a passive mixing system installed.

4.3.1 Short Term Tank 4

Figure 4.37 shows the temperature profile of short term tank 4. Stratification did not occur throughout the study period. Temperatures throughout the tank remained relatively constant. The effect of the ambient temperature on the temperature of the water in the tank is also shown in Figure 4.37. Change in the ambient temperature correlates with the change in the temperature of the water in the tank. Occasionally, the upper two temperature sensors would show little separation from the other temperature sensors. Figure 4.38 shows the temperature profile compared with the water elevation in the tank. The fill and draw cycles do not affect the temperatures in the tank. The change in temperature observed on Figure 4.38 is due to daily cycle of ambient temperature. The temperature increases during the day and then decreases during the night.

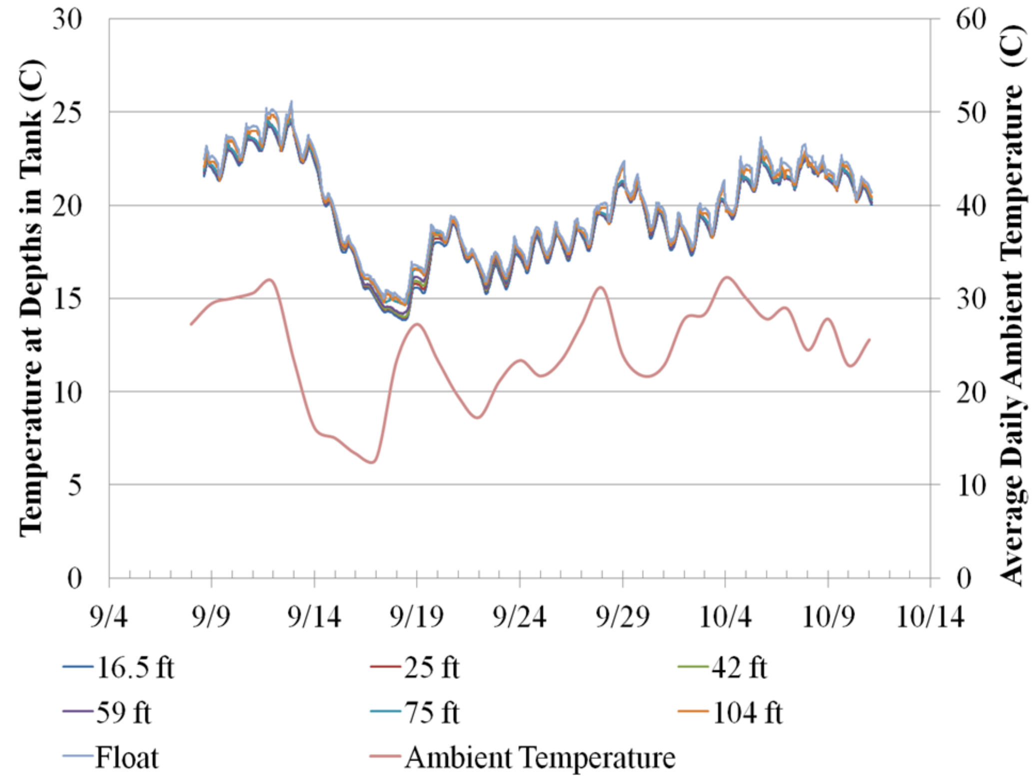


Figure 4.37: Short term tank 4 temperature profile.

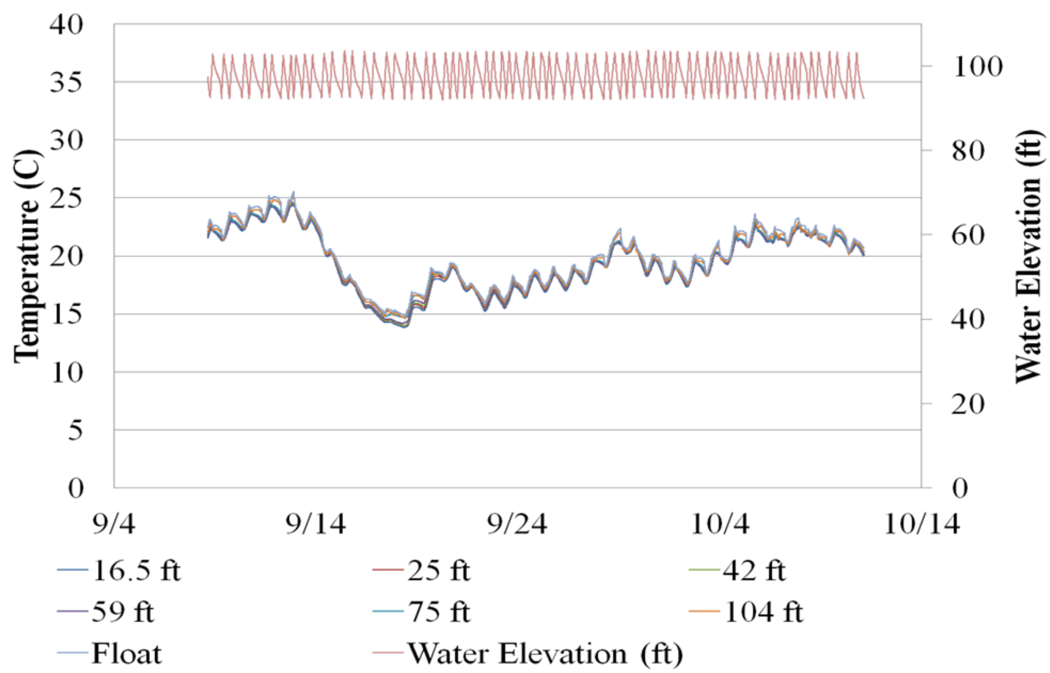


Figure 4.38: Short term tank 4 temperature profile and water elevations.

Short term tank 4 was also studied in a previous study in which the passive mixing system was not installed (Olson, 2011). Comparing the data from the two studies can illustrate the impact of the passive mixing system. Figure 4.39 shows the temperature profile from the study performed by Olson. Figure 4.40 shows a portion of the temperature profile from the current study that shows similar temperatures in the tank (15-20 degrees Celsius). Stratification occurred when there was not a passive mixing system with a temperature difference up to around 8 degrees Celsius, while there was no stratification when the passive mixing system was installed. A passive mixing system helped in preventing stratification throughout the tank.

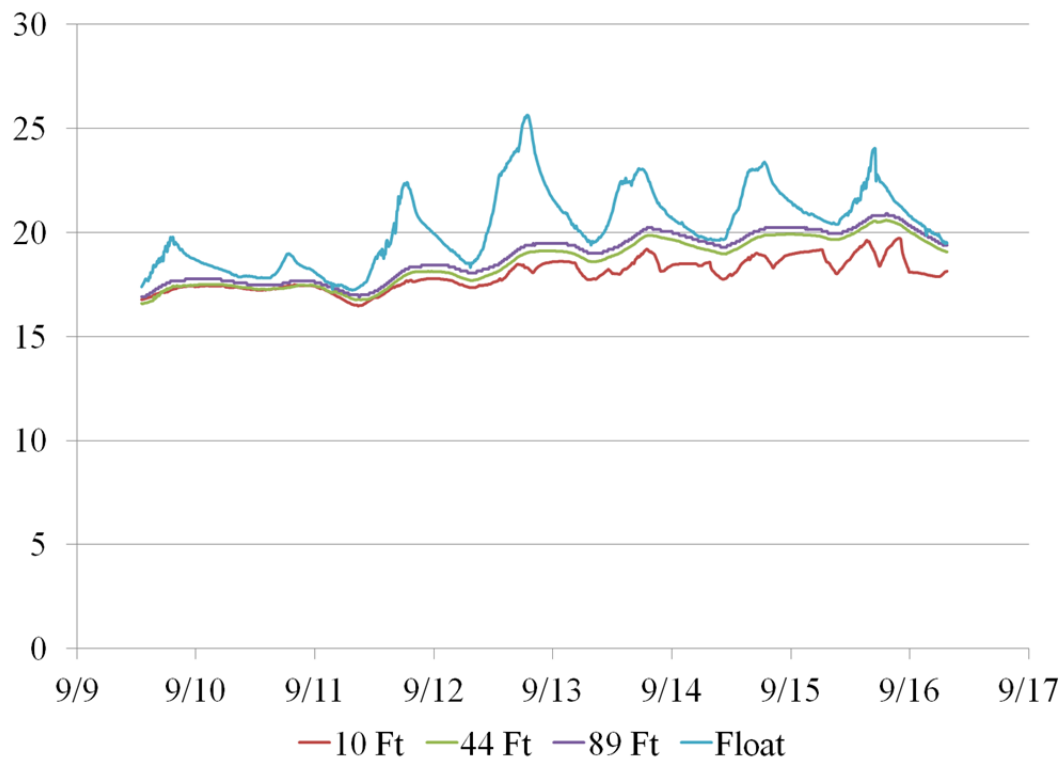


Figure 4.39: Short term tank 4 temperature profile without passive mixing system.

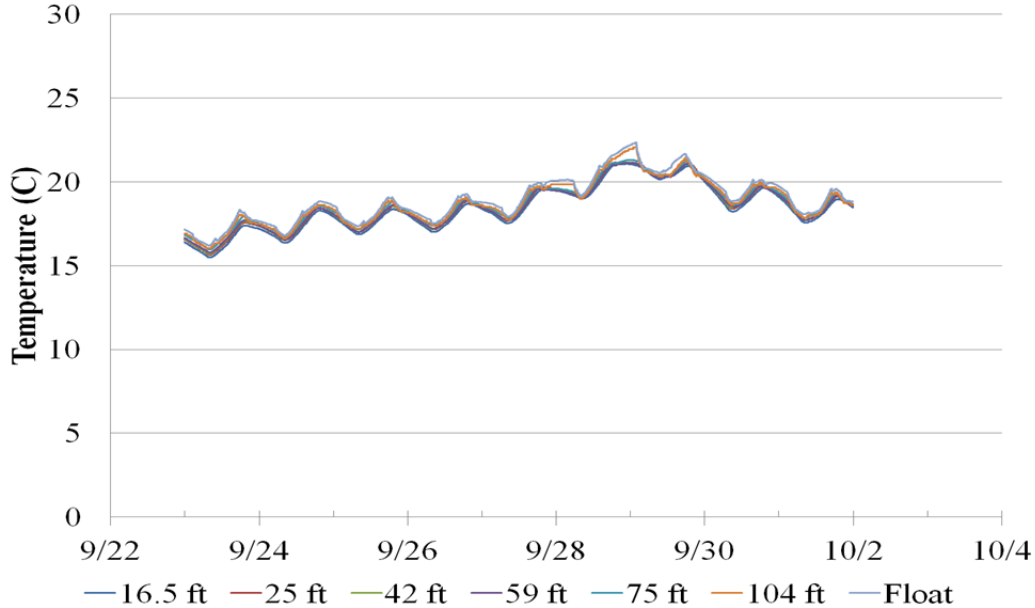


Figure 4.40: Short term tank 4 temperature profile with passive mixing system installed.

Hydraulic parameters were calculated using the height of the tank as the distance from the top of the inlet pipe to the top of the water elevation (38 ft.) since that is the height of water that required mixing (based on hydraulic considerations). The densimetric Froude number, the volumetric exchange, and the dimensionless mixing parameter calculated are shown in Figure 4.41, Figure 4.42, and Figure 4.43 respectivly. Both the densimetric Froude number and the dimensionless mixing parameter comparisons indicate the actual values obtained do not always meet the required value to promote mixing. The volumetric exchange shows that the required value usually doubles the required value, which may explain why the tank is not stratified during the times that the other hydraulic parameters show that the tank should be improperly mixed.

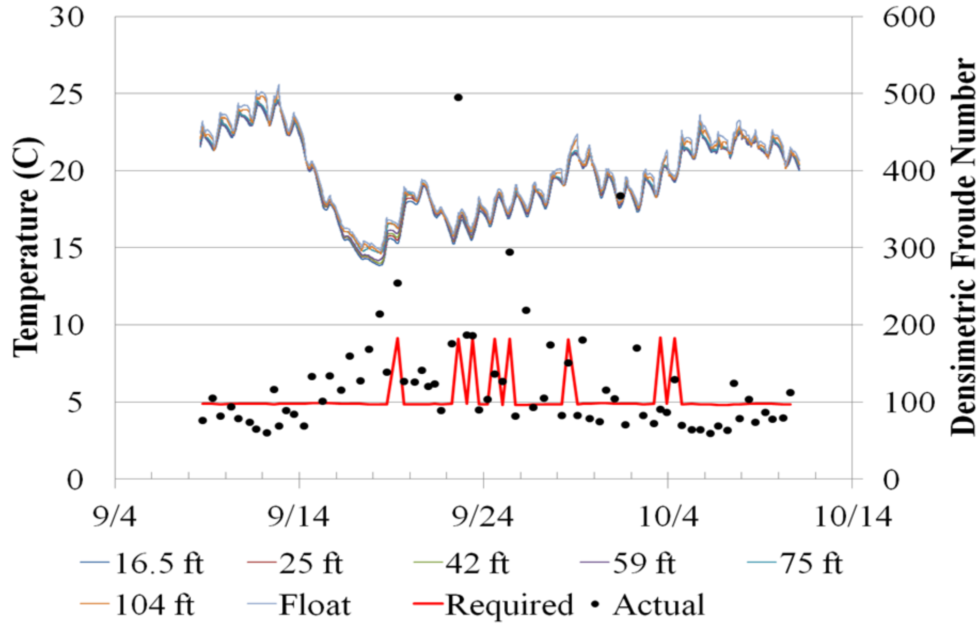


Figure 4.41: Short term tank 4 densimetric Froude number.

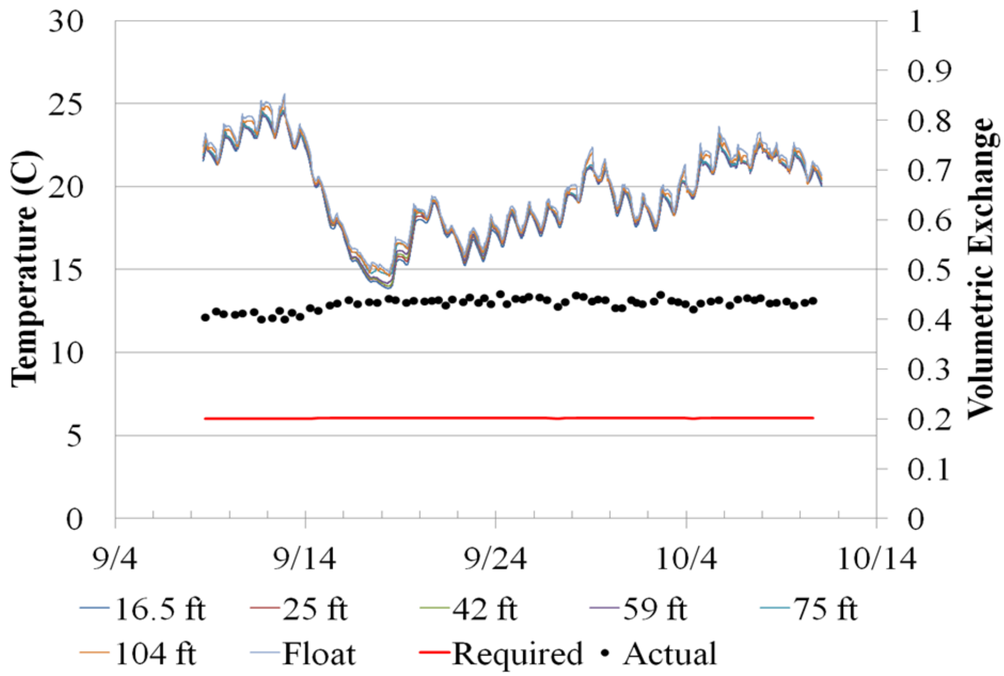


Figure 4.42: Short term tank 4 volumetric exchange.

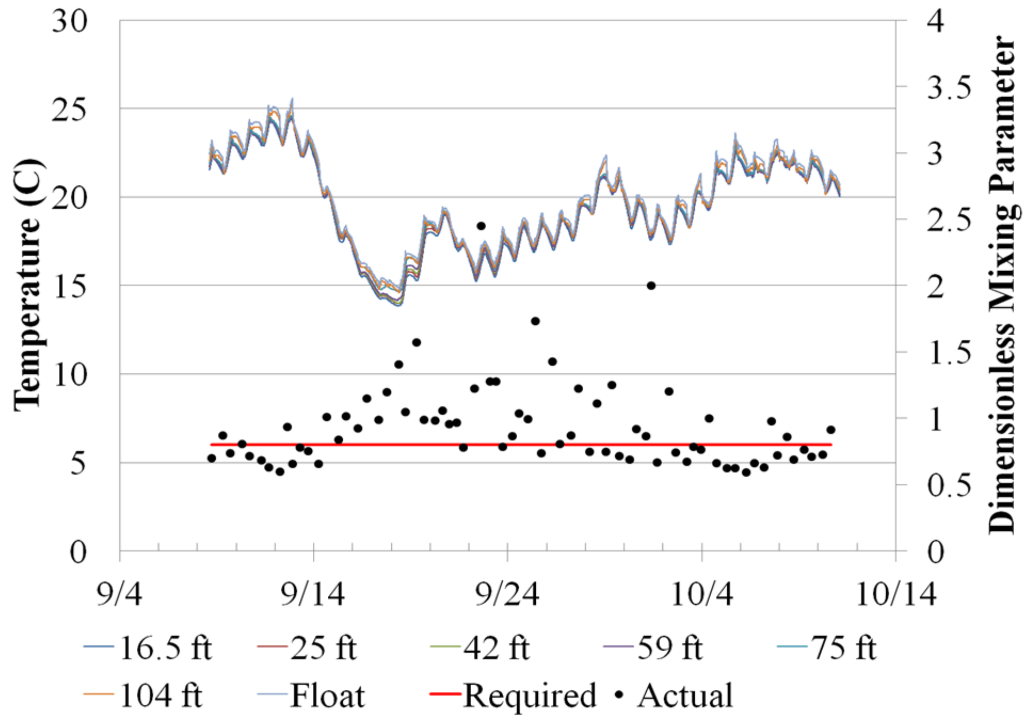


Figure 4.43: Short term tank 4 dimensionless mixing parameter.

4.3.2 Short Term Tank 9

Figure 4.44 shows the temperature profile for short term tank 9 during the study. In the first part of the study, stratification occurred; however, as the ambient temperature decreased, stratification no longer occurred throughout the tank. Figure 4.45 shows how the fill and draw cycle affected the temperature in the tank. During the period of stratification, the upper portion of the tank's temperature was affected by the fill and draw cycle. The temperature increased during the draw cycle as the warmer water lowered through the tank and then decreased during the fill cycle due to the cooler temperature of the influent water.

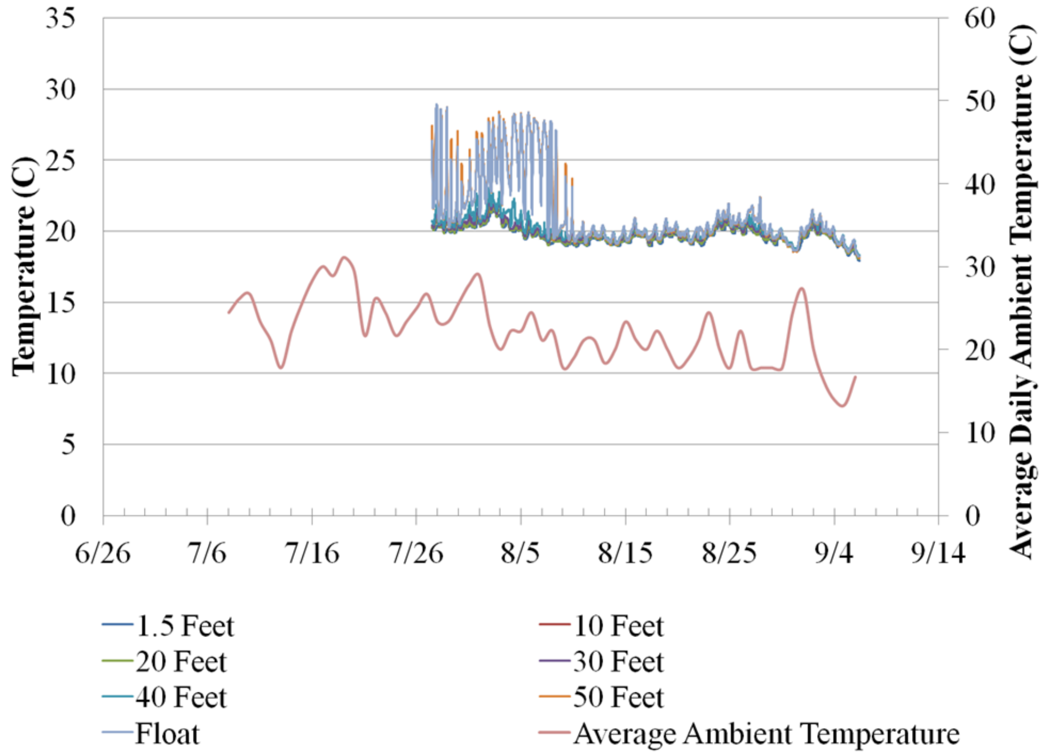


Figure 4.44: Short term tank 9 temperature profile.

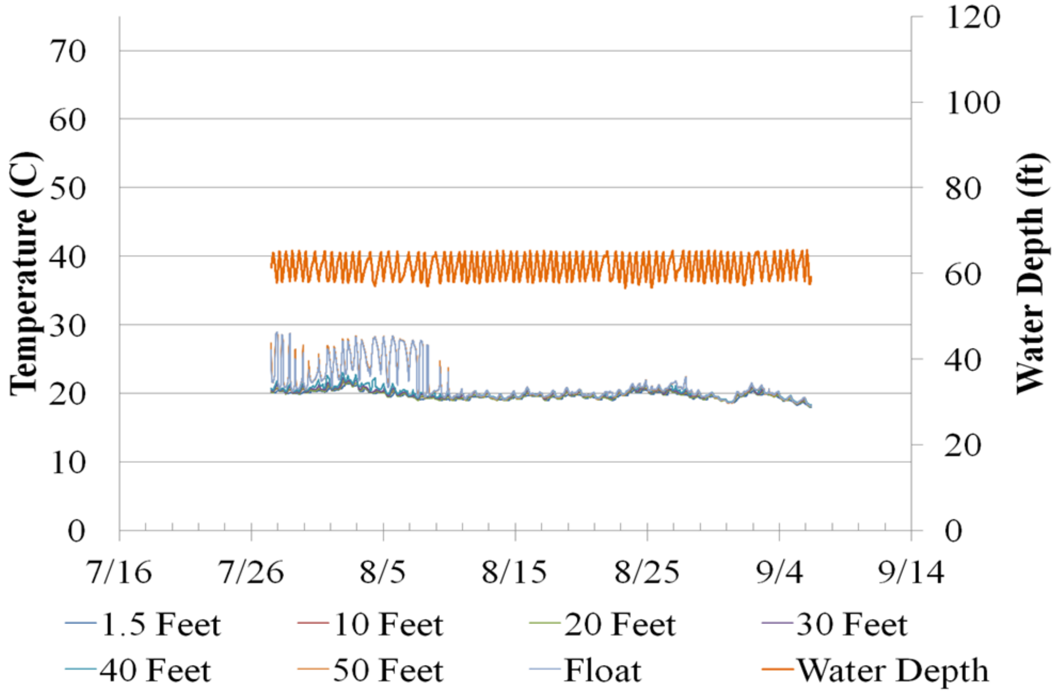


Figure 4.45: Short term tank 9 temperature profile and water elevation data.

The densimetric Froude number, volumetric exchange, and dimensionless mixing parameter were calculated for tank 9. Figure 4.46, Figure 4.47, and Figure 4.48 show the three hydraulic parameters respectively. Both the actual densimetric Froude number and the actual dimensionless mixing parameter surpassed the required value in only a few instances, while the actual volumetric exchange surpassed the required value consistently throughout the study. The volumetric exchange was a factor in influencing the temperatures during stratification and preventing stratification when the tank was not stratified.

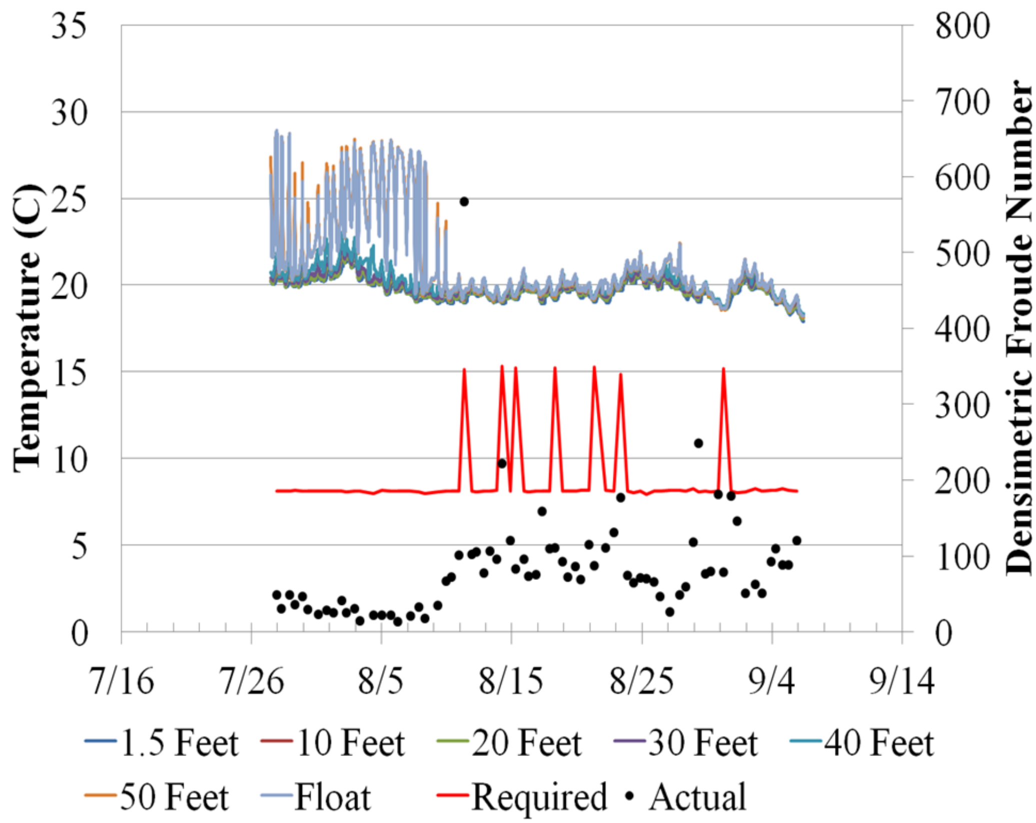


Figure 4.46: Short term tank 9 densimetric Froude number.

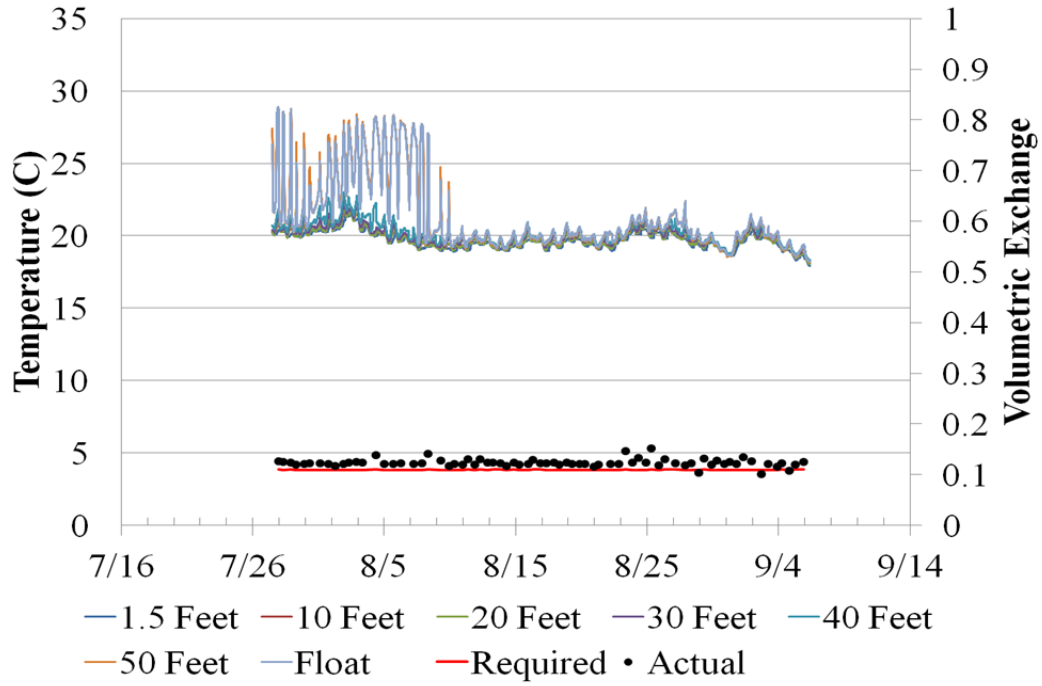


Figure 4.47: Short term tank 9 volumetric exchange.

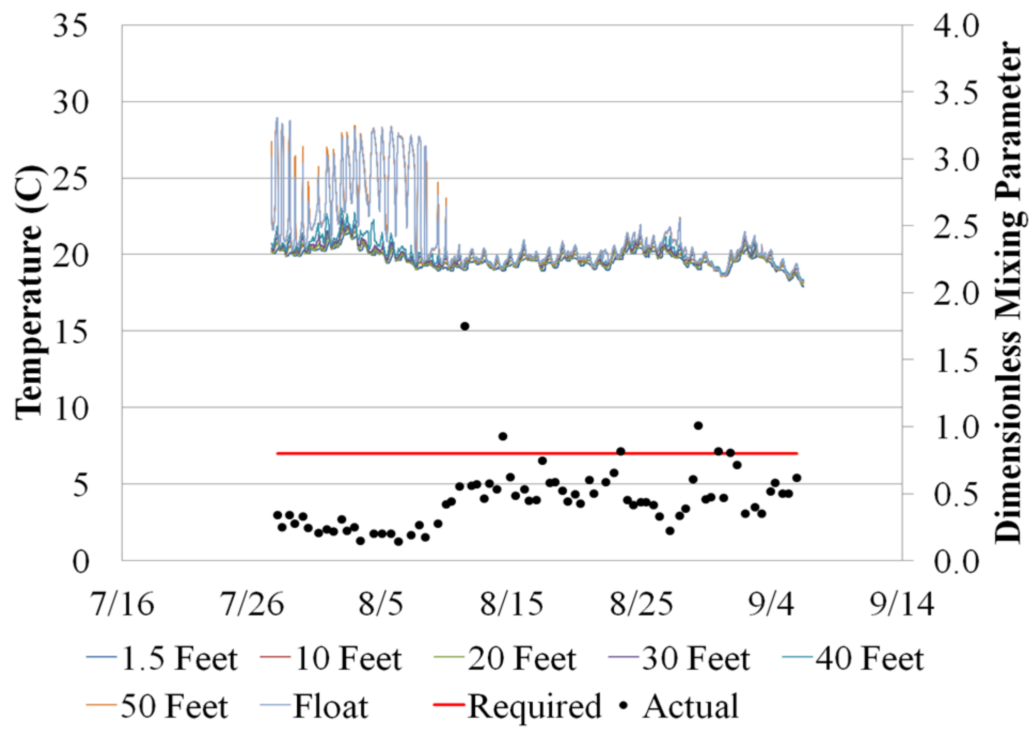


Figure 4.48: Short term tank 9 dimensionless mixing parameter.

4.4 Disenfectant Decay Modeling for Long Term Tanks D and E

A disinfectant decay model was created using the computer program CompTank. Parameters used were initial chlorine concentration, flow in and out of the tank, and the disinfectant decay coefficient. The model created was compared to data obtained from the sampling events in order to show whether the model represented the field conditions.

4.4.1 Disinfectant Decay Coefficient

A disinfectant decay coefficient was calculated between each sampling event using a simple first order equation. The calculated values were corrected to 20 degrees Celsius for comparison of values. An average decay coefficient was found and corrected for the average temperature of the dead zone in the tank during the study to use in the CompTank program. The data used for these calculations are in Appendix C.

4.4.2 Long Term Tank D

Long term tank D was modeled using a stratified 3-compartment model. The model was created for the time period of 4/26 to 8/10. Table 4.3 shows the inputs used for the CompTank program. The initial total chlorine concentrations are from the data obtained on the first site visit (4/26), while the inflow chlorine concentration was an average of the total chlorine concentrations at the bottom of the tank during the period. Inflow and outflow rates were calculated using the water elevation data from the water system. The volumes used for each zone were calculated based on the temperature profiles. The inlet zone was the volume below the 8.5 foot sampling point and the main zone was the volume between the 8.5 foot and 15.5 foot sampling point. The dead zone was the remaining volume in the tank.

Table 4.3: Inputs for the stratified long term tank D model.

Model Input	**Inlet Zone**	**Main Zone**	**Dead Zone**
Volume	0.02 Mgal	0.02 Mgal	0.12 Mgal
Initial total chlorine concentration	1.67 mg/L	1.44 mg/L	1.44 mg/L
Decay coefficient	0.018 d^{-1}	0.018 d^{-1}	0.018 d^{-1}
Average inflow rate	28.3 gpm		
Average outflow rate	27.6 gpm		
Inflow concentration	1.65 mg/L		
Flow rate between main and dead zone	0 gpm		
Flow rate between inlet and main zone	0 gpm		

The modeling results are shown in Figure 4.49 along with actual data measured throughout the time period. The modeled concentration in the dead zone declined throughout the time period. The actual data shows a decline as well. At certain points, the actual concentrations are greater than the predicted value. The largest difference was about 0.1 mg/L. Mixing between the inlet zone and the dead zone could explain this difference. The temperature profile of long term tank D (Figure 4.8) shows that the temperatures of the upper zone and inlet zone neared each other around June 30. Also, if the zones mixed the inlet concentration would decrease as the dead zone concentration increases, which is supported by the data obtained on June 30.

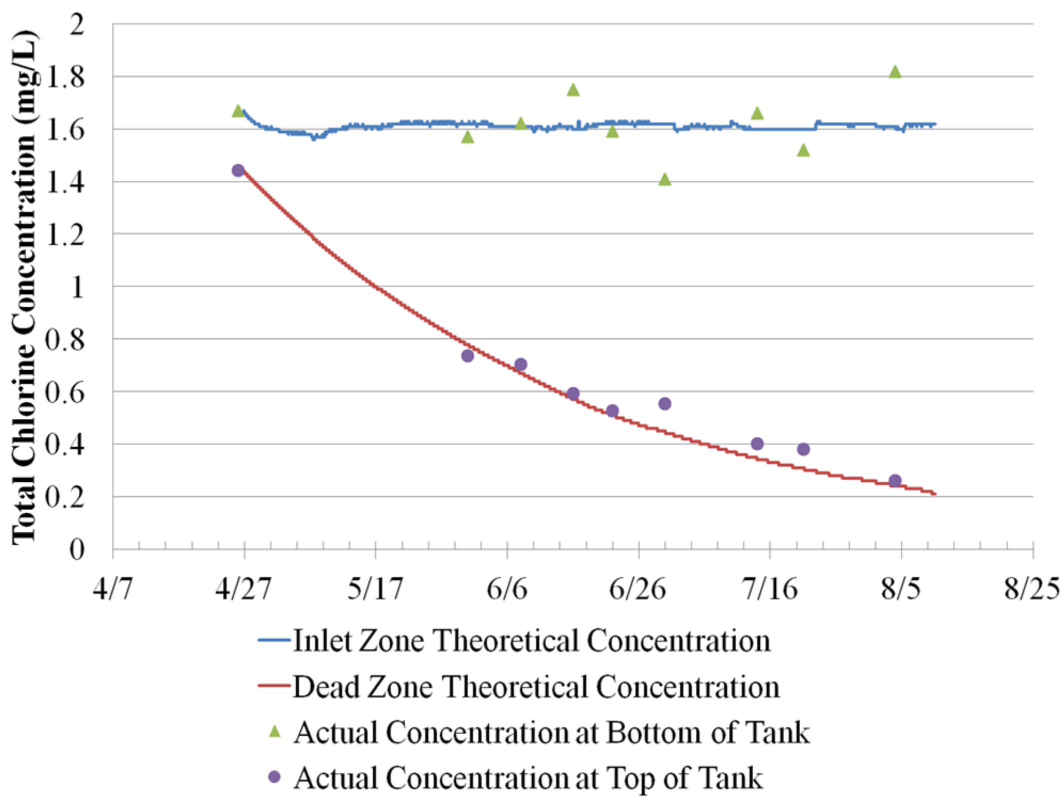


Figure 4.49: Long term tank D modeling results with actual concentration data.

The theoretical concentration in the inlet zone remained constant around 1.65 mg/L, which was the concentration of the influent water. Differences between the theoretical concentration and the actual concentrations occurred. The concentration of the influent water does not remain constant during operation, which explains some of the differences between the actual total chlorine concentration and the theoretical concentration. Mixing between the zones can also lead to differences as illustrated by the June 30 data.

4.4.3 Long Term Tank E

Long term tank E was modeled using the stratified 3-compartment model from 4/26 to 8/15. Table 4.4 shows the input data used for the CompTank model. The initial concentrations are from the data obtained on the first site visit (4/26). Inflow concentration was an average of influent concentrations obtained from the water system. Inflow and outflow rates were calculated using the water elevation data obtained from the water system. The volumes used for each zone were calculated based on the temperature profiles. The inlet zone was the volume below the 8.5 foot sampling point and the main zone was the volume between the 8.5 foot and 22.5 foot sampling point. The dead zone was the remaining volume in the tank.

Table 4.4 Inputs for the stratified long term tank E model.

Model Input	**Inlet Zone**	**Main Zone**	**Dead Zone**
Volume	0.01 Mgal	0.02 Mgal	0.11 Mgal
Initial total chlorine concentration	1.75 mg/L	1.53 mg/L	1.53 mg/L
Decay coefficient	0.011 d^{-1}	0.011 d^{-1}	0.011 d^{-1}
Average inflow rate	59.0 gpm		
Average outflow rate	50.7 gpm		
Inflow concentration	1.66 mg/L		
Flow rate between main and dead zone	0 gpm		
Flow rate between inlet and main zone	0 gpm		

The modeling results are shown in Figure 4.50 along with actual total chlorine concentrations obtained during the time period. A steady decline is shown in the modeled total chlorine concentration in the dead zone. The actual total chlorine concentration shows a similar trend in decline; however, the concentrations are lower than the predicted values from the model. At certain points, the difference between the theoretical total chlorine concentration and the actual total chlorine concentration was 0.2 mg/L. A couple of factors could lead to the higher predicted values. First, the decay coefficent use was for the average temperature (23.6 degrees Celsius), while temperatures were higher at certain times. The decay coefficient is greater in warmer temperatures.

The theoretical total chlorine concentration in the inlet zone remained around 1.66 mg/L, which was the concentration used for the influent water. Differences in the theoretical concentration and the actual concentration occurred. During operation, the influent concentration does not remain constant, which could lead to the differences. Mixing in the tank could also cause the concentrations to differ.

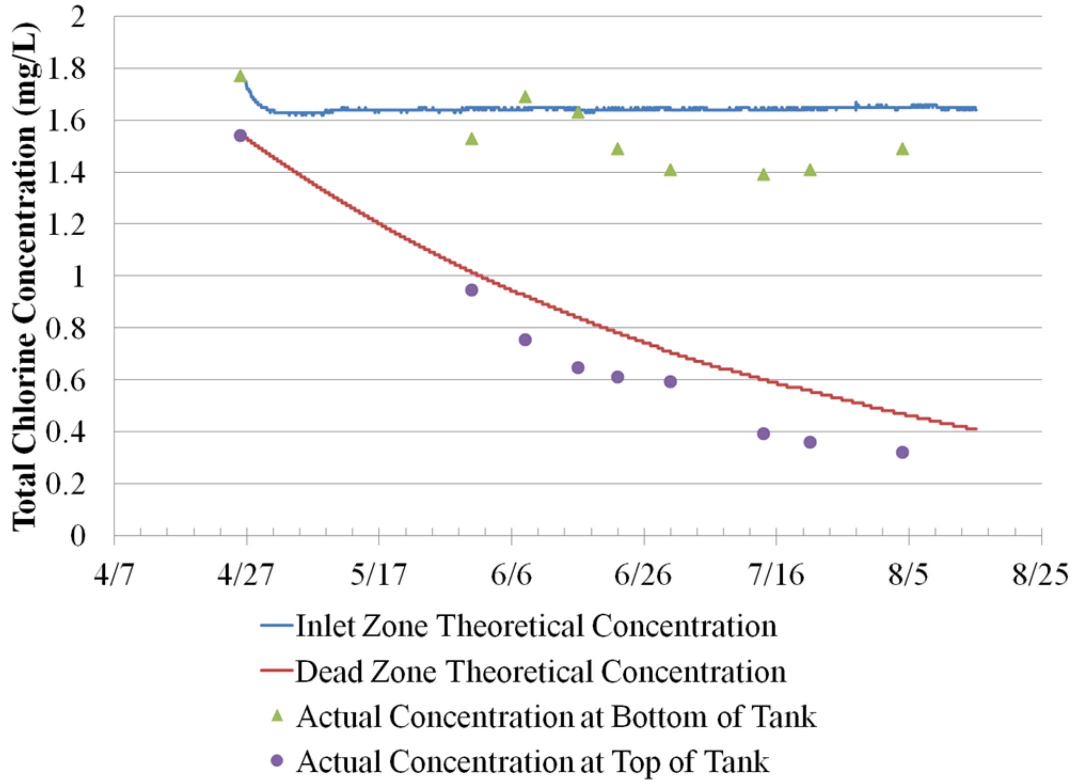


Figure 4.50: Long term tank E modeling results with actual concentration data.

4.5 Hydraulic Parameters Excel Program

An Excel sheet was created to allow water systems to optimize their design or operation to reach the required hydraulic parameters. The affect of a riser pipe in a tank can also be calculated. The inputs for the program are the tank's diameter, the inlet diameter, the low and high water level, the height of a riser pipe, flow into the tank, and the temperature of the water in the tank and the filling water. Using the inputs, the Excel program calculates the required value and actual value for volmetric exchange, densimetric Froude number, and the dimensionless mixing parameter. A water system can change the inputs to optimize their operation. Also, the water system could use the program to guide decisions for new designs. Table 4.5 shows the Excel spreadsheet created.

In the hydraulic parameter Excel program, the black values represent inputs that may be changed by the user, while the red values are calculated values. For the volumetric exchange, the tank's diameter, the water levels, the inlet's diameter, and the height of a riser pipe may be varied. The program will calculate the required and the actual volumetric exchange along with the percent of the required volumetric exchange achieved.

The densimetric Froude number calculator uses inputs from the volumetric exchange calculator and new inputs (flow into the tank and the temperature of the filling water and the water in the tank). The required densimetric Froude number, the actual densimetric Froude number, and the percent of the required densimteric Froude number can be calculated from these inputs. With the inputs from the volumetric exchange and the densimetric Froude number calulator; the required dimensionless mixing parameter, the actual dimensionless mixing parameter, and the percent achieved of the required dimensionless mixing parameter can be calculated.

Table 4.5: Hydraulic parameter Excel program (continued to following page)

Volumetric Exchange		
Tank Diameter	20	ft
Inlet Diameter	3	in
Low Water Level	75	ft
High Water Level	80	ft
Riser Pipe Height	60	ft
Corrected Low Water Level	15	ft
Corrected High Water Level	20	ft
Operational Zone	5	ft
Aspect Ratio	0.875	
Dimensionless Mixing Time	10.00	
Required Volumetric Exchange	13%	
Actual Volumetric Exchange	33%	
% Required Exchange Achieved	252%	
Densimetric Froude Number		
Inlet Orientation (Vertical/Horizontal)	Vertical	
Flow of Filling Water	60000	gpd
Flow of Filling Water	0.093	ft^3/s
Velocity of Filling Water	1.89	ft/s
Temperature of Filling Water	5.3	˚C
Temperature of Water in Tank	8.9	˚C
Density of Filling Water	1.940	$slug/ft^3$
Density of Water in Tank	1.940	$slug/ft^3$

g'	0.0076	ft/s^2
Bouyancy	Negative	
C	0.8	
Required Densimetric Froude Number	48	
Actual Densimetric Froude Number	43.25	
% Required Froude Number	90.10%	
Dimensionless Mixing Parameter		
Inlet Momentum	0.1756	ft^4/s^2
Bouyant Force	0.0007	ft^4/s^3
Required Dimensionless Mixing Parameter	0.8	
Actual Dimensionless Mixing Parameter	0.7722	
% Required Dimensionless Mixing Parameter	96.5%	

Figure 4.51 illustrates the effect of installing a riser pipe on the volumetric turnover in a standpipe. The standpipe used was assumed to be 20 ft. in diameter, with an 80 ft. high water level, and 75 ft. low water level. As the height of the riser pipe increased, the percentage of the volumetric turnover achieved increased. In this example with a 6 in diameter inlet, the volumetric turnover required was achieved when the riser pipe was about 55 ft. tall.

Figure 4.52 illustrates the effect of changing the low water level, increasing the operational zone, on the volumetric exchange. The same standpipe was used as the previous example except the inlet diameter is 6 inches. Increasing the operational zone leads to an increase in the percentage of the volumetric exchange achieved. At about 18 ft. operational zone, the tank's volumetric turnover achieved was the same as the volumetric turnover requried.

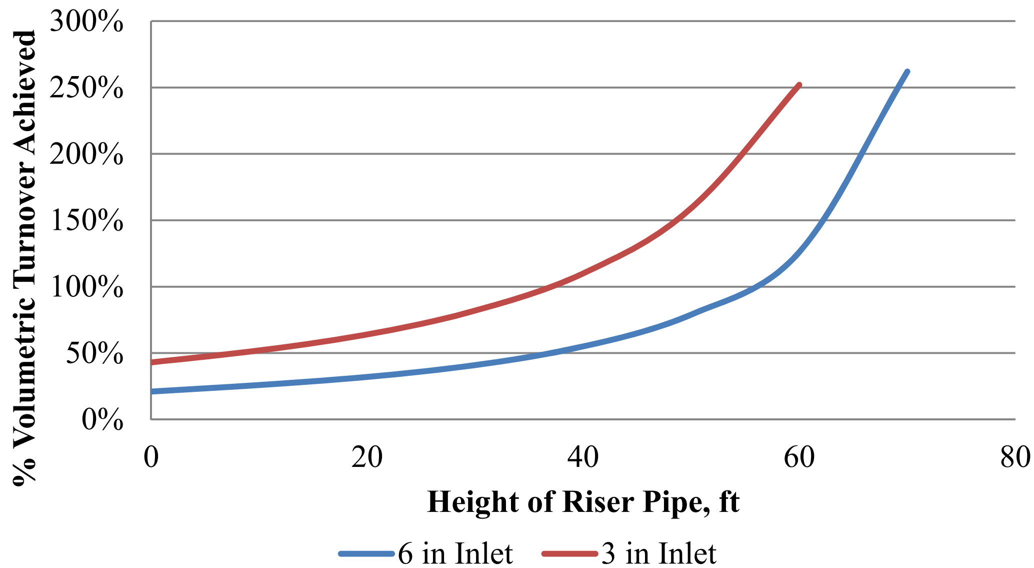


Figure 4.51: The effect of riser pipes on the volumetric exchange

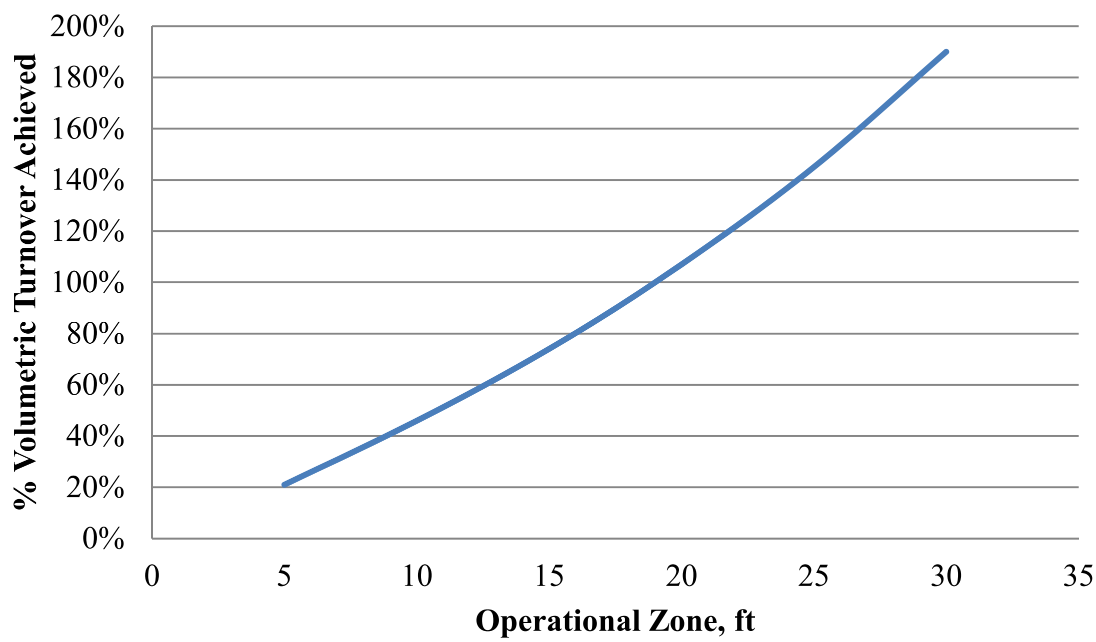


Figure 4.52: The effect of operational zone on volumetric exchange

CHAPTER 5: SUMMARY AND CONCLUSION

5.1 Summary of Work

Storage facilities were evaluated to observe the impacts of storage tank mixing characteristics on water quality. Tanks were chosen for long term tank study using the water system survey and data from the previous study (Olson, 2011). Two short term tanks were also chosen because each tank included a passive mixing system. For the long term tank study, an apparatus was constructed to measure temperature and collect samples for water quality analysis from varying depths in the tank. For the short term tanks, an apparatus was constructed to measure temperature. Elevation data was obtained from the water systems for long term tanks and by a pressure sensor for short term tanks. Temperature profiles and water parameter profiles were created for the tanks.

Several parameters were calculated to provide information on the tank's mixing ability. The parameters include the densimetric Froude number, the volumetric exchange, and the dimensionless mixing parameter (Roberts et al, 2006). A disinfectant decay model was created for stratified tanks using CompTank to estimate the chlorine residual. The model was compared to actual values obtained during the study.

5.2 Conclusions

After evaluating the results from the study, the following conclusions could be made.

1. Affects of tank geometry on mixing

Long term tank C obtained an average operational H:D of 0.98 at the beginning of the study. After the filling pump failed, the average operational H:D was 0.60. Throughout the study, thermal stratification occurred in the tank with a maximum difference in temperature between the top and bottom of the tank being around 10 ^{o}C. Although the tank was thermally stratified, the chlorine concentrations did not stratify in the tank due to the tank operation maintaining sufficient volumetric exchange. The total chlorine concentration ranged from 1.77 mg/L to 2.62 mg/L. Therefore, a tank can show thermal stratification and still maintain an adequate chlorine concentration.

Long term tank D and E both have an average operational H:D above 3.5. Both of the tanks showed stratification in temperature and water quality. Tank D showed a temperature difference of around 10 ^{o}C between the top and the bottom of the tank, while tank E showed a difference of 15 ^{o}C. Before the water system drained tank D, the chlorine concentration in the upper zone was 0.30 mg/L compared to 1.66 mg/L in the lower zone. In tank E, the concentration in the upper zone was 0.05 mg/L compared to

1.25 mg/L in the lower zone before the water system overflowed the tank. The stratification, both thermal and in water quality, of tanks D and E indicate that storage tanks with a H:D greater than 3.5 are at risk of poor mixing and water quality.

Long term tanks F and G both fall in the H:D range of 1-2 with H:D of 1.65 and 1.60 respectively. Tank F showed thermal stratification with a maximum difference between the upper and lower zones of the tank of around 12 ^{o}C. The total chlorine concentrations at times showed stratification. On June 23, the upper zone's concentration was 0.99 mg/L while the lower zone had a concentration of 1.70 mg/L. Although the upper zone concentration was lower, the amount of chlorine was adequate. At other times, the chlorine concentration did not show stratification. The operation of the tank surpassed the required volumetric exchange, which allowed for the tank to maintain adequate chlorine concentrations when thermal stratification occurred. Tank G showed no stratification in temperature or water quality throughout the tank. The chlorine concentration in the tank ranged from 0.92 mg/L to 1.34 mg/L. Tanks F and G indicate that tanks in the 1-2 H:D category may have thermal stratification, but if operated correctly the tanks can maintain adequate mixing to prevent poor water quality.

The temperature and data profiles created in the study show that shorter and wider tanks promote good mixing. Although the tank geometry is important, the operation of the tank needs to be optimized to prevent stratification and poor water quality.

2. Impact of ambient temperature on water quality in tall standpipes

In taller standpipes (H:D >3.5) ambient temperature affects the temperature in the tank and therefore the water quality. The tanks tended to start stratifying when the ambient temperature rose above 15 ^{o}C. As the ambient temperature increased, the temperatures in the upper zone of the tank increased. Increased temperature cause an increase in chlorine decay, which can lead to poor water quality.

3. Total coliform and heterotrophic plate count

Throughout the study, the total coliform tests showed zero coliforms in the storage tanks. The heterotrophic plate counts were also low throughout the study ranging from 0 MPN/ml to 22.5 MPN/ml. Long term tanks C, F, and G maintained proper chlorine concentrations due to proper mixing. Long term tanks D and E showed low chlorine concentrations above the thermocline; however, the water systems either drained or overflowed their tank to replenish the chlorine concentration in the upper zone before microbiological activity could thrive. Water systems need to maintain a proper chlorine concentration in their storage facilities to prevent microbiological growth from occurring.

4. Impact of passive mixing systems

Two short term tanks were studied with passive mixing systems. The temperature profile (Figure 4.37) of short term tank 4 showed the tank did not stratify. Tank 4 was studied by Olson (2011) and stratification occurred in the tank when no passive mixing system was installed. The temperature profile for short term tank 9 (Figure 4.44) showed stratification at the beginning of the study with the upper zone being highly influenced by the influent water. As the temperature cooled, the tank became unstratified. Both tanks show signs of proper mixing as the volumetric exchange for both tanks met the required value. Therefore, passive mixing systems could be used to obtain proper mixing in a storage tank.

5. Volumetric exchange affects mixing

The tanks that met the required value for volumetric exchange showed signs of proper mixing. Long term tank C achieved an average of 213% of the required volumetric exchange. Although tank C showed thermal stratification, the chlorine concentration did not stratify. Long term tank F achieved an average of 118% of the required volumetric exchange. Tank F maintained a proper chlorine concentration even though thermal stratification occurred. Both of the short term tanks met the required volumetric exchange and both showed proper mixing.

Tanks that did not meet the required volumetric exchange consistently showed stratification. Both long term tank D and E did not meet the required volumetric exchange and both tanks were stratified. Meeting the required volumetric exchange in the taller standpipes can be difficult. The water level would need to be drawn down to a lower level, which could cause pressure issues and insufficient storage for the demand in the system.

6. Densimetric Froude number

Long term tank G and short term tank 4 did not always meet the required densimetric Froude number; however, both tanks did not show signs of stratification. All of the other tanks did not meet the required densimetric Froude number and each showed some sign of stratification. Operating the tanks to meet the required densimetric Froude number should promote mixing in the tank.

7. Dimensionless mixing parameter

The dimensionless mixing parameter ($M^{1/2}/(B^{1/3}H^{2/3})$) presented in Roberts et al. (2006) was only consistently met in short term tank 4, which did not show stratification. Short term tank 4 required a dimensionless mixing parameter of 0.8 and achieved an average dimensionless mixing parameter of 0.93. All of the other tanks did not meet the required value and each tank showed signs of stratification except for long term tank G. A tank that is designed and operated to maintain the required dimensionless mixing parameter should cause the tank to be well mixed.

Water systems can optimize tank design and operation to increase the dimensionless mixing parameter. One method would be to increase the inlet momentum, which can be done by increasing flow rates, increasing velocity, or both. Velocity can be increased by decreasing the size of the inlet. Another method would be to decrease the initial water level before the fill cycle.

8. Disinfectant decay modeling

CompTank software was used to create a model of chlorine decay in long term tanks D and E, which both showed stratification. The actual chlorine concentrations measured throughout the study followed the predicted chlorine concentrations in the dead zone. Long term tank D showed a 0.1 mg/L maximum difference. The predicted chlorine concentrations were lower than the actual concentrations. Long term tank E showed a maximum difference of 0.2 mg/L. The predicted chlorine concentration was higher than the actual concentration. Overall, the model demonstrated the chlorine decay trend with some error due to occasional mixing between the inlet and dead zones and the decay coefficient changing due to temperature. Both models show that if the input parameters are accurate, then chlorine concentration decay can be modeled.

9. Hydraulic parameter Excel program

The hydraulic parameter Excel program created can be used for design of a storage tank or the operation of a storage tank. Designers can use the program to find the appropriate design for a tank to promote mixing based on the hydraulic parameters. Water systems can use the program to optimize a tank by tank design and operation characteristics to obtain the required hydraulic parameters for the tank. The effects of a riser pipe on mixing in a tank can also be calculated.

CHAPTER 6: RECOMMENDATIONS

6.1 Recommendations

The following recommendations are based on the analyses of the data collected throughout the study.

6.1.1 Recommendations for design and operation of storage tanks

1. Higher H:D ratio standpipes (taller tanks) are more likely to exhibit mixing problems, which leads to stratification in the tank. In designing a new tank, taller standpipes should be avoided.

2. If a tank experiences water quality issues due to stratification, the water systems could drain the water in the tank into the distribution system before the chlorine concentration drops below the acceptable level. The tank would then be filled with water with a higher chlorine concentration to replenish the chlorine concentration in the tank.

3. Hydraulic parameters such as the volumetric exchange, densimetric Froude number, and the dimensionless mixing parameter from Roberts et al (2006) could be used by the water systems and tank designers to optimize their storage tanks' mixing characteristics.

4. Water systems need to sample from the upper levels in the tank for chlorine residual to understand the water quality in the tank. Water samples collected from the bottom of the storage tank are not always representative of the whole tank.

5. Adding a riser pipe (passive mixing system) to a storage tank is an effective way of promoting mixing in the tank.

6. Mechanical mixing equipment is available for installation into storage tanks. This study did not focus on the mechanical mixing options.

6.1.2 Recommendations for further study

1. The effectiveness of mechanical mixers should be studied to see if they mix standpipes effectively.

2. This study focused on vertical mixing. Mixing in the horizontal direction should be studied since stagnant water in the horizontal direction could occur, which could lead to poor water quality.

3. Chlorine decay modeling could be improved by collecting samples from the inflow pipes to obtain an average inflow chlorine concentration to be used in the modeling program.

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APPENDIX A

CALCULATIONS

Table A.1 contains data used for some upcoming calculations.

Table A.1: Data points used in sample calculations for mixing parameters.

	Time	**Water Level**
Start of fill	T_{SF} = 5/11/11 12:25	L_{SF} = 15 ft.
End of fill	T_{EF} = 5/11/2011 21:40	L_{EF} = 26.6 ft.
End of draw	T_{ED} = 5/12/2011 10:20	L_{ED} = 15 ft.

Temperature at top of tank: 21^{O} C

Temperature at bottom of tank: 8.15^{O} C

Tank diameter = 20 ft.

Inlet diameter = 6 inches

Aspect ratio

$$Aspect\ ratio = \frac{(L_{SF} + 0.5(L_{EF} - L_{SF})}{(D_T)}$$

$$Aspect\ ratio = \frac{(15\ ft + 0.5(26.6\ ft - 15\ ft)}{(20\ ft)}$$

$$Aspect\ ratio = 1.04$$

Flow Rate

$$Q_{fill} = \frac{(L_{EF} - L_{SF}) * \frac{\pi D_T^2}{4}}{(T_{EF} - T_{SF}) * 86{,}400}$$

$$Q_{fill} = \frac{(26.6\,ft - 15\,ft) * \frac{\pi 20^2}{4}}{(5/11/2011\ 21{:}40 - 5/11/11\ 12{:}25) * 86{,}400}$$

$$Q_{fill} = 0.109\,cfs$$

Inflow Velocity

$$v = \frac{Q_{fill}}{\left(\frac{\pi d_i^2}{4}\right)}$$

$$v = \frac{0.109\,cfs}{\frac{\pi\left(\frac{6\,in}{12}\right)^2}{4}}$$

$$v = 0.56 ft/s$$

Volumetric Exchange Required to Achieve a 90% Mixed Tank

For a tank to be mixed the actual volumetric exchange must be greater than the required volumetric exchange as shown in the following equation.

$$\frac{\Delta V}{V} > \frac{(\pi)^{1/2} \tau_m d_i}{2V^{1/3}}$$

Since H:D > 1:

$$\tau_m = 10.0 + 3.5\left(\frac{H}{D} - 1\right)$$

$$\tau_m = 10.0 + 3.5(1.04 - 1)$$

$$\tau_m = 10.14$$

$$\frac{\Delta V}{V} > \frac{(\pi)^{1/2}(10.14)0.5\,ft}{2\left(15 * \frac{\pi}{4} * 20^2\right)^{1/3}}$$

$$\frac{\Delta V}{V} > 0.27$$

Compared to the actual volumetric exchange ratio:

$$\frac{\Delta V}{V} = \frac{(26.6\,ft - 15\,ft)\frac{\pi 20^2}{4}}{(15\,ft)\frac{\pi 20^2}{4}} = 0.77$$

Densimetric Froude number

$$F_d = \frac{v}{\sqrt{g'd}}$$

$$g' = g\frac{\rho_f - \rho_a}{\rho_a}$$

$$\rho = \frac{1}{515.379}(1000 - 0.0178(T-4)^{1.7})$$

$$\rho_f = \frac{1}{515.379}(1000 - 0.0178(8.15-4)^{1.7}) = 1.940\frac{slug}{CF}$$

$$\rho_a = \frac{1}{515.379}(1000 - 0.0178(21-4)^{1.7}) = 1.936\ \frac{slug}{CF}$$

$$g' = 32.2\frac{ft}{s^2}\left(\frac{1.940 - 1.936}{1.936}\right) = 0.067\frac{ft}{s^2}$$

The densimetric Froude number becomes:

$$F_d = \frac{0.56\frac{ft}{s}}{\sqrt{\left(0.067\frac{ft}{s^2}\right)(0.5\ ft)}} = 3.06$$

The required densimetric Froude number is:

$$F_d > C\frac{H}{D}$$

Because the inlet is vertical and under negatively buoyant conditions, C = 0.8

$$F_d > C\frac{H}{D}$$

$$F_d > 0.8\left(\frac{15\ ft}{0.5\ ft}\right)$$

$$F_d > 24$$

Dimensionless Mixing Parameter from Roberts et al (2006)

The criterion for a tank to be mixed under vertically oriented, negatively buoyant jets is:

$$\frac{\sqrt{Msin\theta}}{(B)^{1/3}H^{2/3}} > 0.85 - 0.05n$$

$$M = 0.0113\frac{ft^4}{s^2}$$

$$\theta = 90^0$$

$$B = g'Q = \left(0.067\frac{ft}{s^2}\right)(0.109\ cfs) = 0.0073\frac{ft^4}{s^3}$$

$$H = 15\ ft$$

$$\frac{\sqrt{\left(0.0113\frac{ft^4}{s^2}\right)\sin(90^0)}}{\left(0.0073\frac{ft^4}{s^3}\right)^{1/3}(15\ ft)^{2/3}} = 0.212$$

To mix the tank:

$$\frac{\sqrt{Msin\theta}}{(B)^{1/3}H^{2/3}} > 0.8$$

Disinfectant Decay Coefficient

A first order equation was used:

$$C = C_0e^{-kt}$$

Solving for k:

$$k = -\frac{\ln(\frac{C}{C_0})}{t}$$

k was found between sampling trips in the upper zone of stratified tanks. Values used in sample calculation:

$$Initial\ Concentration = C_0 = 0.55\ mg/L$$

$$Final\ Concentration = C = 0.4\ mg/L$$

$$Time\ Between\ Sampling = t = 14\ days$$

$$k = -\frac{\ln(\frac{0.4\ mg/L}{0.55\ mg/L})}{14\ d}$$

$$k_1 = \frac{0.023}{d}$$

Correcting for temperature:

$$k_2 = k_1 * \theta^{T_2 - T_1}$$

$$\theta = 1.03$$

$$T_1 = 27.58$$

$$T_2 = 20$$

$$k_2 = \frac{0.023}{d} * 1.03^{20-27.58}$$

$$k_2 = \frac{0.018}{d}$$

APPENDIX B

Water Quality, Total Coliform, and Heterotrophic Plate Count (HPC) Data

Table B.1: Water quality data for long term tank C

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
5/9/2011	1.5		2.54				
5/9/2011	6.5		2.62				
5/9/2011	11.5		2.28				
5/9/2011	16.5	AWL					
5/9/2011	21.5	AWL					
5/9/2011	26.5	AWL					
5/31/2011	1.5	14.5	2.48	3.05	0.06	0.009	0.303
5/31/2011	6.5	17.44	2.38	2.86	0.25	0.012	0.314
5/31/2011	11.5	18.85	2.52	2.46	0.33	0.012	0.319
5/31/2011	16.5	AWL					
5/31/2011	21.5	AWL					
5/31/2011	26.5	AWL					
6/8/2011	1.5	16.04	2.38	2.68	0.22	0.004	0.383
6/8/2011	6.5	27.1	2.26	2.46	0.15	0.006	0.341
6/8/2011	11.5	AWL					
6/8/2011	16.5	AWL					
6/8/2011	21.5	AWL					
6/8/2011	26.5	AWL					
6/16/2011	1.5	14.63	2.24	2.51	0.08	0.005	0.281
6/16/2011	6.5	20.52	2.16	2.43	0.07	0.007	0.338
6/16/2011	11.5	21.27	2.16	2.42	0.02	0.006	0.332
6/16/2011	16.5	AWL					
6/16/2011	21.5	AWL					
6/16/2011	26.5	AWL					

Table B.1: (Continued) Water quality data for long term tank C

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
6/22/2011	1.5	15.35	2.18	2.58	0.24	0.002	0.264
6/22/2011	6.5	20.27	2.02	2.41	0.16	0.004	0.31
6/22/2011	11.5	20.68	2	2.36	0.12	0.003	0.306
6/22/2011	16.5	AWL					
6/22/2011	21.5	AWL					
6/22/2011	26.5	AWL					
6/30/2011	1.5	20.95	2.12	2.13	0.36	0	0.284
6/30/2011	6.5	24.31	1.96	2.12	0.62	0.004	0.288
6/30/2011	11.5	AWL					
6/30/2011	16.5	AWL					
6/30/2011	21.5	AWL					
6/30/2011	26.5	AWL					
7/14/2011	1.5	20.99	1.96	2.08	0.52	0.007	0.256
7/14/2011	6.5	25.25	2	2	0.52	0.007	0.261
7/14/2011	11.5	AWL					
7/14/2011	16.5	AWL					
7/14/2011	21.5	AWL					
7/14/2011	26.5	AWL					
7/21/2011	1.5	19.25	2.32	2.49	0.46	0.006	0.359
7/21/2011	6.5	31.2	2.02	1.89	0.46	0.006	0.353
7/21/2011	11.5	31.46	2	1.9	0.49	0.006	0.355
7/21/2011	16.5	AWL					
7/21/2011	21.5	AWL					
7/21/2011	26.5	AWL					
8/4/2011	1.5	28.91	1.77	1.86	0.54	0.007	0.36
8/4/2011	6.5	29.75	1.78	1.86	0.44	0.008	0.359
8/4/2011	11.5	AWL					
8/4/2011	16.5	AWL					
8/4/2011	21.5	AWL					

Table B.1: (Continued) Water quality data for long term tank C

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
8/4/2011	26.5	AWL					
8/18/2011	1.5	24.12	1.96	2.34	0.43	0.007	0.293
8/18/2011	6.5	25.08	2.02	2.24	0.38	0.005	0.281
8/18/2011	11.5	AWL					
8/18/2011	16.5	AWL					
8/18/2011	21.5	AWL					
8/18/2011	26.5	AWL					
9/1/2011	1.5	22.93	1.93	2.07	0.52	0.006	0.307
9/1/2011	6.5	24.51	2.04	2.12	0.53	0.002	0.309
9/1/2011	11.5	AWL					
9/1/2011	16.5	AWL					
9/1/2011	21.5	AWL					
9/1/2011	26.5	AWL					
9/15/2011	1.5	20.14	2.15	1.97	0.44	0.004	0.294
9/15/2011	6.5	20.54	2.04	1.91	0.4	0.004	0.300
9/15/2011	11.5	AWL					
9/15/2011	16.5	AWL					
9/15/2011	21.5	AWL					
9/15/2011	26.5	AWL					

Table B.2: Total Coliform and heterotrophic plate count (HPC) data for long term tank C

Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml
5/31/2011	1.5	0	2
5/31/2011	6.5	0	0
5/31/2011	11.5	0	2
Average		0	1.33
6/16/2011	1.5	0	2
6/16/2011	6.5	0	0

Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml
6/8/2011	1.5	0	0
6/8/2011	6.5	0	0
6/8/2011	11.5	AWL	AWL
Average		0	0
6/22/2011	1.5	0	0
6/22/2011	6.5	0	0

Table B.2: (Continued) Total Coliform and heterotrophic plate count (HPC) data for long term tank C

Date	Height	Total Coliform	HPC		Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml			ft.	CFU/100 ml	MPN/ml
6/16/2011	11.5	0	2		6/22/2011	11.5	0	0
Average		0	1.33		Average		0	0
6/30/2011	1.5	0	6		7/14/2011	1.5	0	21
6/30/2011	6.5	0	19		7/14/2011	6.5	0	6
6/30/2011	11.5	AWL	AWL		7/14/2011	11.5	AWL	AWL
Average		0	12.5		Average		0	13.5
7/21/2011	1.5	0	6		8/4/2011	1.5	0	0
7/21/2011	6.5	0	2		8/4/2011	6.5	0	0
7/21/2011	11.5	0	2		8/4/2011	11.5	AWL	AWL
Average		0	3.33		Average		0	0
8/18/2011	1.5	0	0		9/1/2011	1.5	0	0
8/18/2011	6.5	0	0		9/1/2011	6.5	0	0
8/18/2011	11.5	AWL	AWL		9/1/2011	11.5	AWL	AWL
Average		0	0		Average		0	0
9/15/2011	1.5	0	0					
9/15/2011	6.5	0	0					
9/15/2011	11.5	AWL	AWL					
Average		0	0					

Table B.3: Water quality data for long term tank D

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
4/26/2011	1.5	7.58	1.67				
4/26/2011	8.5	7.72	1.58				
4/26/2011	15.5	8.61	1.46				
4/26/2011	29.5	9.09	1.43				
4/26/2011	43.5	9.67	1.44				
4/26/2011	57.5	10.06	1.46				

Table B.3: (Continued) Water quality data for long term tank D

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
4/26/2011	64.5	10.07	1.42				
4/26/2011	71.5	AWL					
Average in Dead Zone			1.442				
5/31/2011	1.5	11.25	1.57	1.6	0.21	0.002	0.281
5/31/2011	8.5	14.48	0.84				0.366
5/31/2011	15.5	16.56	0.73	0.79	0.28	0.001	0.362
5/31/2011	29.5	17.12	0.74				0.36
5/31/2011	43.5	17.73	0.72	0.83	0.25	0.003	0.355
5/31/2011	57.5	17.63	0.74				0.353
5/31/2011	64.5	17.53	0.75	0.82	0.31	0.006	0.349
5/31/2011	71.5	AWL					
Average in Dead Zone		16.842	0.736	0.813	0.280	0.003	0.356
6/8/2011	1.5	16.47	1.62	1.64	0.31	0.001	0.282
6/8/2011	8.5	24.34	0.68				0.346
6/8/2011	15.5	24.61	0.72	0.68	0.36	0.002	0.347
6/8/2011	29.5	25.08	0.7				0.347
6/8/2011	43.5	25.46	0.69	0.74	0.35	0.001	0.347
6/8/2011	57.5	25.65	0.69				0.348
6/8/2011	64.5	25.5	0.71	0.74	0.32	0.003	0.352
6/8/2011	71.5	AWL					
Average in Dead Zone		25.107	0.702	0.720	0.343	0.002	0.348
6/16/2011	1.5	14.78	1.75	1.92	0.15	0	0.218
6/16/2011	8.5	20.99	0.57				0.343
6/16/2011	15.5	21.7	0.59	0.58	0.08	0.002	0.337
6/16/2011	29.5	22.01	0.59				0.336
6/16/2011	43.5	22.61	0.6	0.67	0.03	0.002	0.341
6/16/2011	57.5	22.69	0.6				0.335
6/16/2011	64.5	22.68	0.59	0.74	0.09	0.003	0.336
6/16/2011	71.5	AWL					
Average in Dead Zone		22.113	0.594	0.663	0.067	0.002	0.337
6/22/2011	1.5	13.84	1.59	1.86	0.23	0.001	0.203

Table B.3: (Continued) Water quality data for long term tank D

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
6/22/2011	8.5	16.46	1.38				0.237
6/22/2011	15.5	18.31	0.51	0.58	0.23	0.002	0.336
6/22/2011	29.5	18.57	0.53				0.334
6/22/2011	43.5	19.06	0.54	0.59	0.24	0.005	0.336
6/22/2011	57.5	18.82	0.52				0.334
6/22/2011	64.5	18.8	0.53	0.6	0.27	0.004	0.332
6/22/2011	71.5	AWL					
Average in Dead Zone		18.337	0.526	0.590	0.247	0.004	0.334
6/30/2011	1.5	15.59	1.41	1.19	0.32	0.003	0.254
6/30/2011	8.5	23.05	0.51				0.335
6/30/2011	15.5	23.99	0.53	0.44	0.4	0.003	0.335
6/30/2011	29.5	24.6	0.54				0.333
6/30/2011	43.5	25.17	0.54	0.44	0.48	0.002	0.333
6/30/2011	57.5	25.34	0.57				0.334
6/30/2011	64.5	25.32	0.59	0.46	0.42	0.002	0.33
6/30/2011	71.5	AWL					
Average in Dead Zone		24.578	0.554	0.447	0.433	0.002	0.333
7/14/2011	1.5	16.38	1.66	1.49	0.41	0.002	0.233
7/14/2011	8.5	23.28	0.4				0.33
7/14/2011	15.5	24.62	0.4	0.42	0.56	0	0.331
7/14/2011	29.5	25.04	0.4				0.331
7/14/2011	43.5	25.61	0.41	0.42	0.56	0.003	0.335
7/14/2011	57.5	25.55	0.4				0.333
7/14/2011	64.5	25.42	0.39	0.44	0.56	0.001	0.329
7/14/2011	71.5	AWL					
Average in Dead Zone		24.920	0.400	0.427	0.560	0.001	0.332
7/21/2011	1.5	18.11	1.52	1.41	0.43	0.002	0.344
7/21/2011	8.5	31.19	0.38				0.411
7/21/2011	15.5	31.52	0.38	0.34	0.56	0.001	0.412
7/21/2011	29.5	32	0.38				0.411
7/21/2011	43.5	32.35	0.38	0.38	0.6	0.001	0.413

Table B.3: (Continued) Water quality data for long term tank D

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
7/21/2011	57.5	32.41	0.39				0.413
7/21/2011	64.5	32.14	0.39	0.36	0.56	0.002	0.412
7/21/2011	71.5	AWL					
Average in Dead Zone		31.935	0.383	0.360	0.573	0.001	0.412
8/4/2011	1.5	18.83	1.82	1.48	0.48	0.002	0.327
8/4/2011	8.5	29.54	0.26				0.416
8/4/2011	15.5	29.94	0.27	0.3	0.54	0.004	0.413
8/4/2011	29.5	30.51	0.25				0.417
8/4/2011	43.5	30.96	0.27	0.34	0.56	0.002	0.416
8/4/2011	57.5	31.1	0.27				0.417
8/4/2011	64.5	30.89	0.26	0.28	0.56	0.004	0.421
8/4/2011	71.5	AWL					
Average in Dead Zone		30.490	0.263	0.307	0.553	0.003	0.417
8/18/2011	1.5	18.12	1.97	2.19	0.6	0.004	0.297
8/18/2011	8.5	24.47	0.19				0.378
8/18/2011	15.5	25.38	0.2	0.34	0.8	0.001	0.376
8/18/2011	29.5	25.78	0.17				0.38
8/18/2011	43.5	26.22	0.19	0.28	0.76	0.002	0.381
8/18/2011	57.5	26.11	0.2				0.373
8/18/2011	64.5	25.97	0.2	0.26	0.76	0.001	0.38
8/18/2011	71.5	AWL					
Average in Dead Zone		25.655	0.192	0.293	0.773	0.001	0.378
9/1/2011	1.5	20.35	1.66	1.9	0.52	0.002	0.306
9/1/2011	8.5	26.57	0.26				0.382
9/1/2011	15.5	26.98	0.29	0.54	0.7	0.001	0.381
9/1/2011	29.5	27.29	0.29				0.379
9/1/2011	43.5	27.81	0.31	0.52	0.66	0.002	0.383
9/1/2011	57.5	27.97	0.31				0.381
9/1/2011	64.5	27.85	0.29	0.52	0.7	0.004	0.377
9/1/2011	71.5	AWL					
Average in Dead Zone		27.412	0.292	0.527	0.687	0.002	0.380

Table B.3: (Continued) Water quality data for long term tank D

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
9/15/2011	1.5	16.83	1.93	2.08	0.34	0	0.301
9/15/2011	8.5	17.78	1.92				0.302
9/15/2011	15.5	19	1.46	1.7	0.28	0	0.326
9/15/2011	29.5	19.83	1.48				0.324
9/15/2011	43.5	20.67	1.47	1.7	0.24	0.002	0.326
9/15/2011	57.5	20.82	1.49				0.329
9/15/2011	64.5	20.71	1.48	1.72	0.24	0	0.320
9/15/2011	71.5	AWL					
Average in Dead Zone		19.802	1.48	1.707	0.253	0.001	0.325

Table B.4: Total Coliform and heterotrophic plate count (HPC) data for long term tank D

Date	Height	Total Coliform	HPC	Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml		ft.	CFU/100 ml	MPN/ml
5/31/2011	1.5	0	0	6/8/2011	1.5	0	0
5/31/2011	15.5	0	0	6/8/2011	15.5	0	0
5/31/2011	29.5	0	0	6/8/2011	29.5	0	0
5/31/2011	43.5	0	6	6/8/2011	43.5	0	2
5/31/2011	57.5	0	0	6/8/2011	57.5	0	0
5/31/2011	64.5	0	0	6/8/2011	64.5	0	0
Average		0	1	Average		0	0.33
6/16/2011	1.5	0	161	6/22/2011	1.5	0	4
6/16/2011	15.5	0	100	6/22/2011	15.5	0	0
6/16/2011	29.5	0	166	6/22/2011	29.5	0	0
6/16/2011	43.5	0	108	6/22/2011	43.5	0	0
6/16/2011	57.5	0	71	6/22/2011	57.5	0	0
6/16/2011	64.5	0	8	6/22/2011	64.5	0	0
Average		0	102.3	Average		0	0.67
6/30/2011	1.5	0	6	7/14/2011	1.5	0	10
6/30/2011	15.5	0	4	7/14/2011	15.5	0	10
6/30/2011	29.5	0	4	7/14/2011	29.5	0	12

Table B.4: (Continued) Total Coliform and heterotrophic plate count (HPC) data for long term tank D

Date	Height	Total Coliform	HPC	Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml		ft.	CFU/100 ml	MPN/ml
6/30/2011	43.5	0	0	7/14/2011	43.5	0	30
6/30/2011	57.5	0	0	7/14/2011	57.5	0	15
6/30/2011	64.5	0	2	7/14/2011	64.5	0	12
Average		0	2.67	Average		0	14.8
7/21/2011	1.5	0	0	8/4/2011	1.5	0	0
7/21/2011	15.5	0	4	8/4/2011	15.5	0	2
7/21/2011	29.5	0	8	8/4/2011	29.5	0	0
7/21/2011	43.5	0	2	8/4/2011	43.5	0	2
7/21/2011	57.5	0	2	8/4/2011	57.5	0	0
7/21/2011	64.5	0	4	8/4/2011	64.5	0	4
Average		0	3.33	Average		0	1.33
8/18/2011	1.5	0	2	9/1/2011	1.5	0	0
8/18/2011	15.5	0	2	9/1/2011	15.5	0	2
8/18/2011	29.5	0	4	9/1/2011	29.5	0	2
8/18/2011	43.5	0	2	9/1/2011	43.5	0	0
8/18/2011	57.5	0	0	9/1/2011	57.5	0	0
8/18/2011	64.5	0	4	9/1/2011	64.5	0	4
Average		0	2.33	Average		0	1.33
9/15/2011	1.5	0	0				
9/15/2011	15.5	0	0				
9/15/2011	29.5	0	0				
9/15/2011	43.5	0	2				
9/15/2011	57.5	0	2				
9/15/2011	64.5	0	0				
Average		0	0.67				

Table B.5: Water quality data for long term tank E

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
4/26/2011	1.5	7.53	1.77				

Table B.5: (Continued) Water quality data for long term tank E

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
4/26/2011	8.5	7.69	1.71				
4/26/2011	22.5	8.39	1.59				
4/26/2011	29.5	9.39	1.53				
4/26/2011	43.5	9.37	1.51				
4/26/2011	50.5	9.18	1.5				
4/26/2011	64.5	9.09	1.55				
4/26/2011	71.5	9.31	1.54				
Average in Dead Zone			1.526				
5/31/2011	1.5	13.74	1.53	1.49	0.17	0.03	0.384
5/31/2011	8.5	14.89	1.56	1.38	0.2	0.031	0.383
5/31/2011	22.5	18	0.92	0.91	0.16	0.031	0.315
5/31/2011	29.5	18.89	0.97	0.98	0.13	0.025	0.316
5/31/2011	43.5	AWL					
5/31/2011	50.5	AWL					
5/31/2011	64.5	AWL					
5/31/2011	71.5	AWL					
Average in Dead Zone		18.445	0.945	0.945	0.145	0.028	0.316
6/8/2011	1.5	15.31	1.69	1.52	0.33	0.004	0.296
6/8/2011	8.5	21.75	1.38				0.319
6/8/2011	22.5	27.15	0.76	0.75	0.28	0.005	0.33
6/8/2011	29.5	27.49	0.76				0.331
6/8/2011	43.5	26.82	0.72	0.74	0.33	0.007	0.331
6/8/2011	50.5	27.5	0.77				0.331
6/8/2011	64.5	27.76	0.74	0.77	0.16	0.004	0.332
6/8/2011	71.5	28.12	0.77	0.82	0.18	0.004	0.333
Average in Dead Zone		27.473	0.753	0.770	0.238	0.005	0.331
6/16/2011	1.5	14.76	1.63	1.49	0.1	0.003	0.241
6/16/2011	8.5	16.99	1.58				0.245
6/16/2011	22.5	22.13	0.64	0.62	0.18	0.004	0.322
6/16/2011	29.5	22.94	0.65				0.322
6/16/2011	43.5	22.41	0.65	0.57	0.13	0.004	0.324

Table B.5: (Continued) Water quality data for long term tank E

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
6/16/2011	50.5	22.97	0.64				0.319
6/16/2011	64.5	22.94	0.65	0.64	0.18	0.003	0.319
6/16/2011	71.5	23.43	0.65	0.65	0.23	0.003	0.322
Average in Dead Zone		22.803	0.647	0.620	0.180	0.004	0.321
6/22/2011	1.5	14.35	1.49	1.61	0.15	0.007	0.235
6/22/2011	8.5	14.75	1.4				0.235
6/22/2011	22.5	19.49	0.61	0.69	0.26	0	0.316
6/22/2011	29.5	20.17	0.61				0.316
6/22/2011	43.5	19.46	0.62	0.67	0.11	0	0.329
6/22/2011	50.5	20.04	0.61				0.307
6/22/2011	64.5	20.33	0.61	0.7	0.13	0.003	0.314
6/22/2011	71.5	20.66	0.61	0.69	0.27	0	0.315
Average in Dead Zone		20.025	0.612	0.688	0.193	0.001	0.316
6/30/2011	1.5	18.18	1.41	1.33	0.39	0.01	0.202
6/30/2011	8.5	21.6	1.2				0.228
6/30/2011	22.5	24.88	0.57	0.57	0.32	0.007	0.332
6/30/2011	29.5	25.33	0.6				0.313
6/30/2011	43.5	24.96	0.6	0.6	0.37	0.003	0.313
6/30/2011	50.5	25.62	0.59				0.314
6/30/2011	64.5	25.45	0.6	0.63	0.35	0.005	0.317
6/30/2011	71.5	26.02	0.6	0.57	0.48	0.004	0.316
Average in Dead Zone		25.377	0.593	0.593	0.380	0.005	0.318
7/14/2011	1.5	17.63	1.39	1.35	0.22	0.002	0.288
7/14/2011	8.5	18.73	1.4				0.291
7/14/2011	22.5	25.84	0.38	0.37	0.51	0.005	0.3
7/14/2011	29.5	26.31	0.4				0.302
7/14/2011	43.5	25.8	0.39	0.42	0.49	0.004	0.302
7/14/2011	50.5	26.14	0.4				0.301
7/14/2011	64.5	26.14	0.39	0.43	0.49	0.005	0.297
7/14/2011	71.5	26.49	0.39	0.42	0.49	0.003	0.306

Table B.5: (Continued) Water quality data for long term tank E

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
Average in Dead Zone		26.120	0.392	0.410	0.495	0.004	0.301
7/21/2011	1.5	18.32	1.41	1.36	0.21	0.003	0.343
7/21/2011	8.5	19.13	1.39				0.347
7/21/2011	22.5	32.26	0.39	0.34	0.46	0.005	0.389
7/21/2011	29.5	32.85	0.37				0.393
7/21/2011	43.5	32.43	0.36	0.37	0.41	0.004	0.393
7/21/2011	50.5	32.84	0.35				0.391
7/21/2011	64.5	32.96	0.38	0.37	0.46	0.005	0.392
7/21/2011	71.5	33.3	0.36	0.36	0.48	0.003	0.395
Average in Dead Zone		32.773	0.368	0.360	0.453	0.004	0.392
8/4/2011	1.5	18.72	1.49	1.38	0.24	0.005	0.365
8/4/2011	8.5	22.55	1.22				0.376
8/4/2011	22.5	31.31	0.31	0.34	0.42	0.008	0.405
8/4/2011	29.5	31.54	0.32				0.404
8/4/2011	43.5	31.85	0.32	0.34	0.42	0.009	0.404
8/4/2011	50.5	31.51	0.32				0.409
8/4/2011	64.5	31.59	0.35	0.32	0.37	0.012	0.406
8/4/2011	71.5	31.79	0.31	0.34	0.4	0.009	0.412
Average in Dead Zone		31.598	0.322	0.335	0.403	0.010	0.407
8/18/2011	1.5	19.09	1.26	1.56	0.34	0.006	0.322
8/18/2011	8.5	19.61	1.24				0.325
8/18/2011	22.5	25.59	0.04	0.05	0.01	0.352	0.379
8/18/2011	29.5	26.04	0.05				0.387
8/18/2011	43.5	26.41	0.05	0.05	0.1	0.36	0.378
8/18/2011	50.5	26.16	0.03				0.384
8/18/2011	64.5	26.13	0.04	0.06	0.04	0.352	0.381
8/18/2011	71.5	26.45	0.04	0.14	0	0.354	0.380
Average in Dead Zone		26.130	0.042	0.075	0.038	0.355	0.382
9/1/2011	1.5	18.86	1.68	1.76	0.25	0.002	0.331
9/1/2011	8.5	19.34	1.72				0.327
9/1/2011	22.5	23.6	1.2	1.28	0.39	0.003	0.332

Table B.5: (Continued) Water quality data for long term tank E

Date	Height	Temperature	Total Chlorine	Monochloramine	Free Amonia	Nitrite	Nitrate
	ft.	°C	mg/L as Cl	mg/L as Cl	mg/L as N	mg/L as N	mg/L as N
9/1/2011	29.5	24.65	1.21				0.331
9/1/2011	43.5	25.59	1.2	1.21	0.27	0.002	0.338
9/1/2011	50.5	25.25	1.22				0.334
9/1/2011	64.5	25.38	1.22	1.22	0.27	0.002	0.330
9/1/2011	71.5	25.71	1.21	1.21	0.41	0.002	0.333
Average in Dead Zone		25.030	1.210	1.230	0.335	0.002	0.333
9/15/2011	1.5	16.27	1.42	1.14	0.27	0.002	0.322
9/15/2011	8.5	16.71	1.4				0.322
9/15/2011	22.5	19.97	0.94	1.03	0.25	0	0.348
9/15/2011	29.5	21.02	0.88				0.341
9/15/2011	43.5	20.38	0.93	0.97	0.27	0.002	0.340
9/15/2011	50.5	20.79	0.91				0.338
9/15/2011	64.5	20.91	0.95	1.01	0.24	0.002	0.347
9/15/2011	71.5	21.3	0.96	0.89	0.18	0	0.343
Average in Dead Zone		20.728	0.928	0.975	0.235	0.001	0.343

Table B.6: Total Coliform and heterotrophic plate count (HPC) data for long term tank E

Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml
5/31/2011	1.5	0	2
5/31/2011	8.5	0	0
5/31/2011	22.5	0	0
5/31/2011	29.5	0	4
5/31/2011	AWL		
5/31/2011	AWL		
Average		0	1.5
6/16/2011	1.5	0	124
6/16/2011	22.5	0	80
6/16/2011	43.5	0	56
6/16/2011	50.5	0	83

Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml
6/8/2011	1.5	0	2
6/8/2011	22.5	0	6
6/8/2011	43.5	0	0
6/8/2011	50.5	0	2
6/8/2011	64.5	0	0
6/8/2011	71.5	0	0
Average		0	1.67
6/22/2011	1.5	0	0
6/22/2011	22.5	0	0
6/22/2011	43.5	0	0
6/22/2011	50.5	0	0

Table B.6: (Continued) Total Coliform and heterotrophic plate count (HPC) data for long term tank E

Date	Height	Total Coliform	HPC	Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml		ft.	CFU/100 ml	MPN/ml
6/16/2011	64.5	0	146	6/22/2011	64.5	0	0
6/16/2011	71.5	0	97	6/22/2011	71.5	0	0
Average		0	97.67	Average		0	0
6/30/2011	1.5	0	6	7/14/2011	1.5	0	0
6/30/2011	22.5	0	4	7/14/2011	22.5	0	2
6/30/2011	43.5	0	4	7/14/2011	43.5	0	6
6/30/2011	50.5	0	0	7/14/2011	50.5	0	6
6/30/2011	64.5	0	0	7/14/2011	64.5	0	2
Date	Height	Total Coliform	HPC	Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml		ft.	CFU/100 ml	MPN/ml
6/30/2011	71.5	0	2	7/14/2011	71.5	0	2
Average		0	2.67	Average		0	3
7/21/2011	1.5	0	0	8/4/2011	1.5	0	0
7/21/2011	22.5	0	4	8/4/2011	22.5	0	0
7/21/2011	43.5	0	4	8/4/2011	43.5	0	4
7/21/2011	50.5	0	2	8/4/2011	50.5	0	0
7/21/2011	64.5	0	6	8/4/2011	64.5	0	0
7/21/2011	71.5	0	4	8/4/2011	71.5	0	2
Average		0	3.33	Average		0	1
8/18/2011	1.5	0	0	9/1/2011	1.5	0	0
8/18/2011	22.5	0	0	9/1/2011	22.5	0	0
8/18/2011	43.5	0	2	9/1/2011	43.5	0	0
8/18/2011	50.5	0	4	9/1/2011	50.5	0	0
8/18/2011	64.5	0	2	9/1/2011	64.5	0	0
8/18/2011	71.5	0	4	9/1/2011	71.5	0	0
Average		0	2	Average		0	0
9/15/2011	1.5	0	0				
9/15/2011	22.5	0	0				
9/15/2011	43.5	0	0				
9/15/2011	50.5	0	2				
9/15/2011	64.5	0	0				

Table B.6: (Continued) Total Coliform and heterotrophic plate count (HPC) data for long term tank E

Date	Height	Total Coliform	HPC	Date	Height	Total Coliform	HPC
	ft.	CFU/100 ml	MPN/ml		ft.	CFU/100 ml	MPN/ml
9/15/2011	71.5	0	0				
Average		0	0				

Table B.7: Water quality, total coliform, and heterotrophic plate count data for long term tank G

Date	Height	Temperature	Total Chlorine	Free Chlorine	Total Coliforms	HPC
	ft.	°C	mg/L as Cl	mg/L as Cl	CFU/100 ml	MPN/ml
6/28/2011	1.5	13.47	1.34	1.21	0	216
6/28/2011	7.5	13.69	1.22	1.19	0	
6/28/2011	13.5	13.37	1.23	1.23	0	248
6/28/2011	19.5	13.62	1.24	1.22	0	287
6/28/2011	25.5	13.38	1.35	1.21	0	311
6/28/2011	31.5	13.39	1.23	1.2	0	339
6/28/2011	37.5	13.41	1.35	1.25	0	257
6/28/2011	43.5	AWL				
Average					0	276
7/14/2011	1.5	14.92	0.96	0.84	0	12
7/14/2011	7.5	15.19	0.95	0.84	0	17
7/14/2011	13.5	14.88	0.9	0.84	0	4
7/14/2011	19.5	15.1	0.98	0.91	0	21
7/14/2011	25.5	15.25	0.95	0.89	0	17
7/14/2011	31.5	15.16	0.93	0.9	0	19
7/14/2011	37.5	AWL				
7/14/2011	43.5	AWL				
Average					0	15
7/21/2011	1.5	15.5	0.92	0.88	0	2
7/21/2011	7.5	15.49	0.96	0.83	0	0
7/21/2011	13.5	15.22	0.94	0.85	0	2
7/21/2011	19.5	15.57	0.91	0.86	0	0
7/21/2011	25.5	15.67	0.95	0.84	0	4
7/21/2011	31.5	23.83	0.92	0.87	0	2
7/21/2011	37.5	AWL				

Table B.7: (Continued) Water quality, total coliform, and heterotrophic plate count data for long term tank G

Date	Height	Temperature	Total Chlorine	Free Chlorine	Total Coliforms	HPC
	ft.	°C	mg/L as Cl	mg/L as Cl	CFU/100 ml	MPN/ml
7/21/2011	43.5	AWL				
Average					0	1.67
8/4/2011	1.5	15.98	1.12	1.07	0	0
8/4/2011	7.5	16.12	1.02	1.08		
8/4/2011	13.5	15.59	1.02	1.07	0	0
8/4/2011	19.5	16.09	1.1	1.04	0	0
8/4/2011	25.5	16.05	1.14	1.07	0	0
8/4/2011	31.5	15.82	1.17	1.13	0	0
8/4/2011	37.5	24.02	1.1	1.08	0	0
8/4/2011	43.5	AWL				
Average					0	0
8/16/2011	1.5	16.22	1.11	1.06	0	2
8/16/2011	7.5	16.4	1.11	1.05	0	0
8/16/2011	13.5	16.02	1.08	1.05	0	0
8/16/2011	19.5	16.27	1.11	1.05	0	0
8/16/2011	25.5	16.31	1.09	1.05	0	0
8/16/2011	31.5	16.14	1.1	1.03	0	4
8/16/2011	37.5	AWL				
8/16/2011	43.5	AWL				
Average					0	1

Table B.8: Water quality, total coliform, and heterotrophic plate count data for long term tank F

Date	Height	Temperature	Total Chlorine	Free Chlorine	Total Coliforms	HPC
	ft.	°C	mg/L as Cl	mg/L as Cl	CFU/100 ml	MPN/ml
6/3/2011	1.75	10.32	1.59	1.21	0	2
6/3/2011	5.25	10.19	1.74	1.47	0	0
6/3/2011	8.75	10.51	1.71	1.48	0	2
6/3/2011	15.75	13.95	1.49	1.28	0	4
6/3/2011	22.75	17.84	1.33	1.16	0	2
6/3/2011	29.75	AWL				
Average					0	2

Table B.8: (Continued) Water quality, total coliform, and heterotrophic plate count data for long term tank F

Date	Height	Temperature	Total Chlorine	Free Chlorine	Total Coliforms	HPC
	ft.	°C	mg/L as Cl	mg/L as Cl	CFU/100 ml	MPN/ml
6/9/2011	1.75	9.85	0.8	0.54	0	4
6/9/2011	5.25	9.72	0.81	0.57	0	6
6/9/2011	8.75	10.32	0.88	0.44	0	0
6/9/2011	15.75	10.34	0.83	0.59	0	2
6/9/2011	22.75	19.47	1.04	0.86	0	2
6/9/2011	29.75	AWL				
Average					0	2.8
6/17/2011	1.75	11.29	1.56	1.32	0	2
6/17/2011	5.25	11.04	1.6	1.29	5	2
6/17/2011	8.75	11.72	1.57	1.35	6	15
6/17/2011	15.75	12.21	1.58	1.34	0	0
6/17/2011	22.75	16.46	1.15	0.96	0	2
6/17/2011	29.75	AWL				
Average					2.2	4.2
6/23/2011	1.75	11.34	1.77	1.47	0	0
6/23/2011	5.25	11.23	1.71	1.45	0	0
6/23/2011	8.75	11.35	1.7	1.41	0	0
6/23/2011	15.75	11.61	1.25	1.02	0	0
6/23/2011	22.75	15.79	0.99	0.6	0	0
6/23/2011	29.75	AWL				
Average					0	0
6/29/2011	1.75	12.78	1.58	1.38	0	311
6/29/2011	5.25	12.33	1.6	1.42	0	324
6/29/2011	8.75	12.89	1.63	1.42	0	177
6/29/2011	15.75	13.41	1.61	1.42	0	299
6/29/2011	22.75	19.59	1.04	0.85	0	248
6/29/2011	29.75	AWL				
Average					0	271.8
7/13/2011	1.75	13.98	1.81	1.57	0	21
7/13/2011	5.25	13.74	1.81	1.62	0	15
7/13/2011	8.75	13.98	1.81	1.62	0	26
7/13/2011	15.75	14	1.79	1.59	0	26

Table B.8: (Continued) Water quality, total coliform, and heterotrophic plate count data for long term tank F

Date	Height	Temperature	Total Chlorine	Free Chlorine	Total Coliforms	HPC
	ft.	°C	mg/L as Cl	mg/L as Cl	CFU/100 ml	MPN/ml
7/13/2011	22.75	23.03	0.69	0.58	0	23
7/13/2011	29.75	AWL				
Average					0	22.2
7/20/2011	1.75	15.09	1.89	1.59	0	0
7/20/2011	5.25	14.72	1.93	1.63	0	0
7/20/2011	8.75	15.27	1.89	1.68	0	0
7/20/2011	15.75	16.31	0.76	0.64	0	2
7/20/2011	22.75	28.16	0.83	0.66	0	0
7/20/2011	29.75	AWL				
Average					0	0.4
8/3/2011	1.75	15.87	0.4	0.29	0	0
8/3/2011	5.25	15.47	0.4	0.28	0	0
8/3/2011	8.75	15.93	0.43	0.29	0	0
8/3/2011	15.75	16	0.42	0.31	0	0
8/3/2011	22.75	26.3	0.7	0.58	0	0
8/3/2011	29.75	AWL				
Average					0	0
8/17/2011	1.75	15.98	1.93	1.67	0	0
8/17/2011	5.25	15.52	1.98	1.71	0	0
8/17/2011	8.75	16.09	1.97	1.7	0	0
8/17/2011	15.75	16.09	1.98	1.71	0	0
8/17/2011	22.75	16.91	1.94	1.66	0	0
8/17/2011	29.75	AWL				
Average					0	0
8/31/2011	1.75	16.23	1.87	1.66	0	0
8/31/2011	5.25	16	1.87	1.64	0	2
8/31/2011	8.75	16.17	1.92	1.67	0	0
8/31/2011	15.75	16.41	1.9	1.76	0	0
8/31/2011	22.75	17.2	1.91	1.65	0	2
8/31/2011	29.75	AWL				
Average					0	0.8
9/14/2011	1.75	14.38	1.79	1.56	0	0

Table B.8: (Continued) Water quality, total coliform, and heterotrophic plate count data for long term tank F

Date	Height	Temperature	Total Chlorine	Free Chlorine	Total Coliforms	HPC
	ft.	°C	mg/L as Cl	mg/L as Cl	CFU/100 ml	MPN/ml
9/14/2011	5.25	14.11	1.72	1.53	0	2
9/14/2011	8.75	14.71	1.74	1.5	0	2
9/14/2011	15.75	14.53	1.75	1.52	0	0
9/14/2011	22.75	14.83	1.75	1.55	0	4
9/14/2011	29.75	AWL				
Average					0	1.6

APPENDIX C

Chlorine Decay Coefficient Data

Table C.1: Chlorine decay coefficient data for long term tank D

Initial Cl Concentration	Final Cl Concentration	Time	Average Temperature	k (1/d)	k (1/d)
mg/L	mg/L	days	˚C	at average temperature	at 20 ˚C
0.702	0.594	8.06	22.25	0.0207	0.0194
0.594	0.526	5.88	22.62	0.0201	0.0186
0.554	0.4	14.06	27.58	0.0231	0.0185
0.4	0.383	6.97	30.24	0.0155	0.0115
0.383	0.263	13.99	31.09	0.0269	0.0194
0.263	0.192	13.92	27.19	0.0226	0.018
				Average	0.0176

Table C.2: Chlorine decay coefficient used in CompTank for long term tank D

Average k at 20 ˚C	Average Temperature	Final k
(1/day)	˚C	(1/day)
0.0176	21.59	0.0184

Table C.3: Chlorine decay coefficient data for long term tank E

Initial Cl Concentration	Final Cl Concentration	Time	Average Temperature	k (1/d)	k (1/d)
mg/L	mg/L	days	˚C	at average temp	at 20 ˚C
0.753	0.647	8.05	23.01	0.0188	0.0172
0.647	0.612	5.9	23.83	0.0094	0.0084
0.612	0.593	7.99	22.28	0.0039	0.0036
0.593	0.392	14.08	28.51	0.0294	0.0229
0.392	0.368	6.98	30.95	0.0091	0.0066
0.368	0.322	13.99	32.06	0.0096	0.0067
				Average	0.0109

Table C.4: Chlorine decay coefficient used in CompTank for long term tank E

Average k at 20 ˚C	Average Temperature	Final k
(1/day)	˚C	(1/day)
0.0109	22.76	0.0118