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# Disinfection By-Product Reduction Study of a Small Central Florida Public Water System

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# DISINFECTION BY-PRODUCT REDUCTION STUDY FOR A SMALL CENTRAL FLORIDA PUBLIC WATER SYSTEM

by

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# ABSTRACT

The disinfection of water for potabilization has proven to be one of the most significant public achievements of the 20th century. Although chemical disinfectants are successfully utilized to inactivate acute pathogenic organisms, they may react with natural organic matter (NOM) to produce potentially-harmful disinfection by-products (DBPs). As a result, the United States Environmental Protection Agency regulates DBPs such as total trihalomethanes (TTHMs) and haloacetic acids (HAAs). The research herein is focused on the formation, removal, and control of TTHMs and HAAs in a small public water system (PWS) in Polk County, Florida (County). Pilot-scale tests were implemented to determine the efficacy of stripping TTHMs using single-pass spray and recirculating tray aeration systems, both operating at flows of 3 gallons per minute. In the spray aerator evaluation, an average TTHM reduction of 29.5% was recorded. With tray aeration, a 46.7% reduction of TTHMs was observed after a single pass through the assembly. The benefits of additional recirculation appeared to decrease significantly after four passes, at a TTHM removal of 85.5%. A raw water blending effort was conducted to model bypass around granular activated carbon (GAC) adsorption vessels. The results demonstrated the feasibility of a 50% blend in full-scale treatment operations. With this blend, chlorine residuals and HAA concentrations were able to be controlled throughout 48 hours of incubation at 30°C. From the data collected, a water quality plan was developed for the County's Waverly PWS. The plan to control the formation of DBPs integrated a recirculating tray aeration process for TTHM stripping complemented with GAC adsorption process for removing DBP precursors.

The estimated conceptual operating cost was approximated at $24,000 annually. This cost considered carbon replacement as well as the recirculation pump operation. If the recommended 50% GAC bypass is applied, the conceptual operating cost reduces to approximately $15,250 annually.

This thesis is dedicated to my family.  Their support was unfailing throughout my entire education.

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I thank God for everything I have been given in life, my family being the most important. My family has supported me endlessly through every venture I have taken and every setback I have experienced in life. Without question, my family is the most important thing in my life and I owe a great majority of my success to them.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AC1230CX | AquaCarb 1230 CX |
| AEL | Advanced Environmental Laboratories |
| BAC | Biological activated carbon |
| BDCM | Bromodichloromethane |
| $Cl_2$ | Elemental chlorine |
| $ClO_2$ | Chlorine dioxide |
| County | Polk County, Florida |
| D/DBPR | Disinfectant/disinfection by-products rule |
| DBCM | Dibromochloromethane |
| DBP | Disinfection by-product |
| DBPFP | Disinfection by-product formation potential |
| DHAA | Dihaloacetic acid |
| DI | De-ionized |
| DOC | Dissolved organic carbon |
| EBCT | Empty bed contact time |
| EPA | Environmental Protection Agency |
| FP | Formation potential |
| GAC | Granular activated carbon |
| gpd | Gallons per day |
| gpm | Gallons per minute |
| HAA | Haloacetic acid |
| HAAFP | Haloacetic acid formation potential |
| $HAA_5$ | Five regulated species of HAA |
| HOCl | Hypochlorous acid |
| hp | Horsepower |
| LRAA | Locational running annual average |
| MCL | Maximum contaminant level |
| MDF | Maximum daily flow |
| mg/L | Milligrams per liter |
| MRDL | Maximum residual disinfectant level |
| NaOCl | Sodium hypochlorite |
| NDMA | N-Nitrosodimethylamine |
| NOM | Natural organic matter |
| NPDOC | Non-purgeable dissolved organic carbon |
| $O_3$ | Ozone |
| ppb | Parts per billion |

| | |
|---|---|
| ppm | Parts per million |
| psi | Pounds per square inch |
| PWS | Public water system |
| QA | Quality assurance |
| QC | Quality control |
| RAA | Running annual average |
| RSSCT | Rapid small-scale column test |
| TOC | Total organic carbon |
| THM | Trihalomethane |
| TTHM | Total trihalomethanes |
| TTHMFP | Total trihalomethane formation potential |
| UC1240AW | UltraCarb 1240 AW |
| UCF | University of Central Florida |
| VFD | Variable-frequency drive |
| WTP | Water treatment plant |
| μg/L | Micrograms per liter |

# CHAPTER ONE: INTRODUCTION

Since its inception, disinfection in the realm of drinking water has saved countless lives. Proper disinfection techniques inactivate pathogenic organisms that spread infectious disease. Despite the benefits, effective disinfection may lead to the formation of undesirable substances known as disinfection by-products (DBPs). While the toxicity of some of these compounds remains to be discovered, some have been shown to be carcinogenic in laboratory settings and pose other health risks. As a result, the United States Environmental Protection Agency (EPA) implemented Stage 1 and Stage 2 of the Disinfectant and Disinfection By-Products Rule (D/DBPR) to safeguard public health. Maximum contaminant levels (MCLs) were established for several types of DBPs and maximum residual disinfectant levels (MRDLs) were created to regulate disinfectant residuals in the distribution system. Compliance became based on a locational running annual average (LRAA) as opposed to the previously-used running annual average (RAA). The organic DBPs specified in Stage 1 of the D/DBPR include four species of trihalomethane (THM), collectively referred to as total trihalomethanes (TTHMs) and five species of haloacetic acid (HAA), collectively referred to as $HAA_5$.

This thesis presents assessments of two pilot-scale aeration methods for THM removal, a blending study designed to simulate granular activated carbon (GAC) bypass, and water quality data from within Polk County's (County) Waverly Public Water System (PWS) located near Waverly, FL. The Waverly PWS is fed from two different facilities treating groundwater: the Waverly Water Treatment Plant (WTP) and the Hodge Street WTP. Because both systems disinfect water via free chlorine, the DBPs of concern in this research are THMs and HAAs.

Pilot-scale spray and tray aeration systems were evaluated and blending study trials were conducted to examine their respective effects on DBP reduction; the acquired data was considered along with GAC-related findings based on vendor-provided data generated using bulk raw water samples from the Hodge Street WTP. The aeration studies were performed to assess the feasibility of utilizing spray and tray aerators to strip THMs from the water stream. Pilot-scale spray aeration was investigated to evaluate its potential for County use, possibly as an operation prior to entering a water storage tank. Recirculating tray aeration was also analyzed on a pilot-scale for possible use by the County to recirculate treated water through a storage tank equipped with a tray aerator. Both methods aim to remove THMs but fail to address HAA formation or proactively reduce DBP formation. For precursor and HAA removal, the strategy of GAC adsorption was considered. The blending study was conducted to explore bypass options around a GAC operation and investigate the extent to which blending affects the DBP formation potential (DBPFP) of the water. Concurrently, two types of GAC were compared by Dr. Adam Redding using isotherm adsorption models and rapid small-scale column tests (RSSCTs), as presented in Appendix C. The data from each facet of this research was compiled and evaluated to identify options available to reduce DBPFP and control associated chlorine residual levels within the Waverly PWS, considering the D/DBPR. The research culminated in a water quality master plan which combines recirculating tray aeration with GAC adsorption to address both THM and HAA reduction. The conceptual master plan was based on technical and economic considerations related to integrating GAC and recirculating aeration technologies to meet the Waverly PWS's compliance needs.

# CHAPTER TWO: LITERATURE REVIEW

## Introduction to Groundwater

Water that exists in the pore spaces between sand, rocks, and other earthen media below the surface is known as groundwater. In the United States, about 35% of consumers of public water are supplied with groundwater (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2012). However, in Florida, about 17.7 million people or 93% of the population rely on groundwater for consumption as of 2012 (USGS, 2014). Hence, groundwater is an extremely valuable resource for Florida's population.

The Floridan Aquifer underlies the entire state of Florida, parts of southern Alabama and South Carolina, and southeastern Georgia. In total, it underlies approximately 100,000 square miles of the Southeastern United States and provides a source of drinking water for millions of people, both in urban and rural areas. The Floridan Aquifer is characterized by Karst topography; it is comprised of a sequence of carbonate rocks, particularly limestone and dolomite. The dissolution of carbonate rocks into water percolating into the reservoir creates numerous pores, fissures, and conduits that allow for greatly increased hydraulic conductivity when compared to many other subterranean reservoirs (USGS, 2015).

Groundwater has less particulate matter than surface water due to the filtration that occurs as the water percolates down toward the aquifer. However, it may still possess undesirable contaminants, anthropogenic or naturally-occurring. Some natural contaminants that may necessitate treatment include: metals, other inorganics such as arsenic, dissolved gasses, and a wide variety natural organic matter (NOM). NOM is an important component because it serves as a precursor for a variety of organic DBPs.

## Disinfection of Water and Aqueous Chlorine Chemistry

Because raw water may contain pathogenic organisms, effective disinfection is arguably the most important step in the treatment process. Proper disinfection of potable water should aim to achieve the following: (1) proper elimination or inactivation of pathogens during treatment (2) prevention of pathogen recontamination in the distribution system, and (3) minimizing the formation of disinfection by-products in the distribution system. Inactivation occurs when the microorganisms are altered so that they are unable to cause disease; they may be outright killed or simply lose their ability to reproduce while infecting a host. Several different compounds have proven efficient in the task of disinfection. Chemicals such as chlorine gas ($Cl_2$) and chlorine dioxide ($ClO_2$) disinfect by oxidation mechanisms. These substances kill or inactivate microbes by oxidizing enzymes which are essential to the organism's metabolism (Richards, 1996). Ultraviolet radiation, conversely, disinfects by damaging the nucleic acids of pathogens, preventing reproduction of the targeted organism (Crittenden, et.al., 2012).

First implemented in a United States public water system in 1909, free chlorine is the traditional disinfectant and is effective at inactivating a vast array of pathogens (Sawyer, McCarty, & Parkin, 2003). Chlorine is commonly added to water streams via injection of elemental chlorine gas ($Cl_2$) or a hypochlorite-containing bleach such as sodium hypochlorite (NaOCl). Free chlorine produces a residual which helps prevent recontamination in the distribution system. In aqueous solutions, both elemental chlorine and sodium hypochlorite react to form hypochlorous acid (HOCl). Equations (2-1) and (2-2) show the formation of HOCl by the means of $Cl_2$ and NaOCl addition.

$$\mathrm{Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-} \quad (2\text{-}1)$$

$$\mathrm{NaOCl + H_2O \rightarrow HOCl + Na^+ + OH^-} \quad (2\text{-}2)$$

The by-products formed, hydrochloric acid and sodium hydroxide, are a strong acid and a strong base, respectively. Hence, they ionize completely in aqueous solutions, often leading to changes in pH and/or alkalinity. Excess sodium hydroxide due to bleach addition, for example, will tend to cause an increase in pH and alkalinity (Crittenden et. al., 2012).

Hypochlorous acid is a weak acid; thus, it does not fully ionize in aqueous solutions. The degree of ionization and relative speciation between hypochlorous acid and its conjugate base, the hypochlorite ion, depends on pH. Equation (2-3) shows the dissociation of hypochlorous acid.

$$\mathrm{HOCl \leftrightarrow H^+ + OCl^-} \quad (2\text{-}3)$$

Free chlorine is considered the sum of the concentration of HOCl and $OCl^-$. The $pK_a$ of hypochlorous acid is 7.53 (Harris, 2009). In solutions with a pH below this level, hypochlorous acid prevails; above this level the hypochlorite ion quickly begins to dominate. Hypochlorous acid displays accelerated disinfection kinetics when compared to the hypochlorite ion and is typically the preferable species (Crittenden et. al., 2012). Hence, a slightly acidic pH is desirable (albeit not necessary) in processes where chlorine-based disinfection occurs. During disinfection with free chlorine, the species are ultimately reduced to chloride while pathogens are inactivated.

## Disinfection By-Products and Associated Regulations

Chemical disinfectants operate via oxidation-reduction chemistries. These reactions involve the transfer of electrons and can lead to the decomposition of compounds as well as the formation of new species. As the study of water treatment progresses, more by-products are likely to become regulated and current regulations may become stricter.

The EPA began to expand on their existing DBP regulations in 1998 with the issuing of Stage 1 of the D/DBPR (Crittenden et. al., 2012). fThe purpose of Stage 1 was to reduce exposure of the public to DBPs, thereby improving immediate and long-term public health. Table 1 shows the MCLs established by the rule, given in mg/L and parts per billion (ppb). 1 microgram per liter (µg/L) is equivalent to 1 ppb. In addition to establishing MCLs for certain DBPs, Stage 1 also established MRDLs for chlorine, chloramines, and chlorine dioxide. The MRDL for chlorine is 4.0 mg/L as $Cl_2$ (USEPA, 2006).

Table 1: Regulated DBPs under the EPA's D/DBPR

| By-Product | MCL under the D/DBPR | By-Product of |
|---|---|---|
| Total THMs (four species) | 0.080 mg/L or 80 ppb | Chlorine |
| Five haloacetic acids ($HAA_5$) | 0.060 mg/L or 60 ppb | Chlorine |
| Bromate ($BrO_3$-) | 0.010 mg/L or 10 ppb | Ozone |
| Chlorite ($ClO_2$-) | 1.0 mg/L or 1 ppm | Chlorine dioxide |

Stage 2 of the D/DBPR, enacted in 2006, tightened compliance monitoring for THMs and HAAs. It required utilities to conduct an initial distribution system evaluation to identify locations with the greatest DBP levels. In addition, it mandated that compliance of the new MCLs be assessed via LRAA as opposed to the RAA (USEPA, 2006). LRAAs require that the running annual average at each individual sampling location remain within the mandated MCLs. Using previous

RAA methods, compliance was determined based on an annual average of sampling sites throughout the entire system. The concentrations reported took the average of the entire distribution system. Hence, the LRAA provides better protection to public health and helps assure that the entirety of a system's consumers are receiving consistent DBP protection.

THMs and HAAs are halogenated organic molecules with one and two carbon atoms, respectively. While THMs strictly have three halogen atoms (and one hydrogen atom) attached to the single carbon atom, the regulated HAA species may possess one, two, or three halogen atoms. Of the halogens, the most commonly-found comprising halogenated DBPs are chlorine and bromine. Table 2 includes the specific DBP species of interest for the studies relating to this document. The four THMs and five HAA species are referred to as TTHMs and $HAA_5$, respectively. The TTHM concentration is found by adding together the individual concentrations of these four species; the same principle applies for the $HAA_5$ concentration. Other halogenated species such as iodinated DBPs exist but these listed have been specifically identified by the EPA for compliance testing.

Table 2: Chlorinated DBPs of Interest

| **Class of Compound** | **By-Product Name** | **Chemical Formula** | **By-Product of** |
|---|---|---|---|
| Trihalomethanes | Chloroform | $CHCl_3$ | Chlorine |
| | Bromodichloromethane (BDCM) | $CHBrCl_2$ | Chlorine |
| | Dibromochloromethane (DBCM) | $CHBr_2Cl$ | Chlorine |
| | Bromoform | $CHBr_3$ | Chlorine |
| Haloacetic acids | Dichloroacetic acid | $CHCl_2COOH$ | Chlorine |
| | Trichloroacetic acid | $CCl_3COOH$ | Chlorine |
| | Monochloroacetic acid | $CH_2ClCOOH$ | Chlorine |
| | Dibromoacetic acid | $CHBr_2COOH$ | Chlorine |
| | Monobromoacetic acid | $CH_2BrCOOH$ | Chlorine |

An important difference between THMs and HAAs is their relative volatilities. THMs are halogenated species of methane and are volatile. The most chlorinated of the species, chloroform, has the greatest volatility. As bromine atoms replace the chlorine atoms in the molecule, the volatility decreases due to bromine's increased mass and greater resistance to phase change. Bromoform, the most brominated of the THMs, may experience little, if any, volatilization with passive aeration methods, especially when compared to chlorine-containing THMs (Duranceau & Yoakum, 2017).

## Factors Affecting THM and HAA Formation

THMs and HAAs are formed in water by reduction-oxidation reactions that occur between free chlorine and NOM. Both physical and chemical aspects can influence the rate and magnitude of DBP formation. Physical factors include qualities such as temperature and chlorine contact time; chemical characteristics such as the water's NOM profile, free chlorine dose, and presence of certain inorganic constituents also impact THM and HAA formation. Because free chlorine is typically dosed to achieve a residual that persists in the distribution system, systems using free chlorine typically experience continuous DBP formation throughout their distribution systems. However, certain microbes have the ability to biodegrade HAAs and microbes that lend to HAA degradation have been found in distribution system conduits. Generally, though, as the time NOM is exposed to residual chlorine in the distribution system increases, the concentrations of THMs and HAAs in the water can be expected to increase as well.

When oxidizing, the disinfectant tends to attack NOM at carbon-carbon double-bonds and reduced heteroatoms (i.e. nitrogen or sulfur). Although both hydrophobic and hydrophilic NOM can contribute to the formation of these classes of DBP, one study demonstrated that hydrophobic fractions of NOM produced higher THM and HAA FPs in low-humic water. The same researchers found that hydrophilic NOM was more reactive with bromine than the corresponding hydrophobic fractions (Liang & Singer, 2003). Experimental evidence has suggested that HAA precursors tend to be of higher aromatic content than THM precursors (Rook, 1976). With respect to TTHMFP, it has been suggested that the molecular weight and physical properties of organic precursors may be more important than aromaticity (Karapinar, Uyak, & Topal, 2014). In addition, it was revealed that as the average molecular weight of NOM decreased, THM yield coefficients increased (Ozdemir, Toroz, & Uyak, 2013). In several studies, the formation of THMs increased while formation of HAAs decreased in response to increasing pH (Hung, B., Yemmireddy, & Huang, 2017). However, results in one study showed that concentrations of dihaloacetic acids (DHAAs) did increase under alkaline conditions (Hua & Reckhow, 2012). Lastly, temperature has shown to have a positive correlation with the formation of THMs and HAAs. The reaction kinetics of both compounds are temperature-sensitive and increase as water temperature increases.

## Common Methods to Control DBPs

As knowledge of DBPs increases, new DBPs are identified, and regulations tighten, the ability to control DBP levels will become an increasingly important aspect of water treatment. Some traditional strategies employed for chlorine-based DBPs include:

1. Removal of DBP precursors (NOM, bromide, etc.)
2. Use of alternate disinfectant (i.e. chloramines, ozone, chlorine dioxide)
3. Removal of DBPs after formation (i.e. aeration or adsorption)

4. Optimization of chlorine contact and water age (i.e. system management and flushing)

Multiple strategies can be used in conjunction, if necessary. The overall choice may depend on many variables. Each approach to reducing DBPs has a unique set of consequences and specifications that must be considered if the solution is to prove both effective and efficient.

The first technique, removal of precursors, is highly effective in DBP control as it proactively prevents the creation of the unwanted by-products. Precursor removal is a common technique for reducing DBP formation. Organic precursors can be removed through a variety of methods. Conventional treatment with coagulation, GAC adsorption, and ion exchange are viable strategies (Richards, 1996). Waters with higher UV absorbance have been shown to be better candidates for organic removal via coagulation with alum than low-absorbance waters (Liang & Singer, 2003). With ferric chloride, it was shown that coagulation was able to remove approximately 85% of the dissolved organic carbon (DOC) in a highly-organic Florida surface water (Duranceau and Yonge, 2012). GAC is a common and extremely effective solution for controlling precursors but can have limitations for economical removal if influent total organic carbon (TOC) levels are high (USEPA Technical Support Division, 1996).

Disinfectants other than free chlorine have become an increasingly popular choice in the United States. Each alternate disinfectant or disinfection approach will have different stipulations and effects that should be taken into consideration. For instance, disinfection with ozone and UV are not known to form THMs and HAAs yet neither of these disinfection processes provides a residual to protect the water from recontamination in the distribution system. Also, ozone can produce both organic (i.e. formadehyde) and inorganic (i.e. bromate) DBPs (Plummer & Edzwald, 2001).

Free chlorine can be carefully dosed with ammonia to form chloramines. The number of utilities using chloramines, also termed combined chlorine, rose to 30% in 2007 (Crittenden et. al., 2012). Although chloramines prevent the formation of the aforementioned DBPs, they have their own concerns. Retarded reaction kinetics, the creation of the toxic carcinogen N-Nitrosodimethylamine (NDMA), and possible chemical cost increases are some examples of consequences that may be incurred when utilizing combined chlorine for disinfection.

Once DBPs are formed, several methods exist to remove them from the water stream. These methods are generally dependent on the characteristics of the substance that is being targeted. For example, if the compound is known to be hydrophobic, adsorption with GAC or an ion exchange resin may be preferable. If the contaminant is volatile like THMs, air stripping may be a feasible method. Previous spray aeration conducted in Polk County has demonstrated a TTHM removal efficiency of approximately 50% when averaged between two tested spray nozzles (Duranceau & Smith, 2015). Additionally, a 43% reduction in TTHMFP over 96 hours was accomplished with multi-pass spray aeration (Duranceau & Yoakum, 2017).

DBP control can also be approached by proper management of chlorine contact and water age in the distribution system. Currently, the County aims to reduce DBP levels by managing these parameters. Chlorinated DBPs form following reaction kinetics; therefore, reducing the amount of time the water is in contact with free chlorine assists in reducing DBP levels. The County currently manipulates water age by utilizing automated flushing programs. Reducing volume in ground storage tanks also assists in decreasing water age and the time that DBPs are allowed to form. Although flushing programs may be effective at keeping DBP concentrations within compliance, improvement of the initial treatment process is often advantageous and should be investigated to minimize water loss during flushing protocols. Both plants that feed the Waverly PWS have the immediate ability to convert to combined chlorine, if necessary. Chemical storage tanks, piping, and valves have been installed should DBP issues force the County to implement combined chlorine.

## Air Stripping

In water treatment, it is often desirable to transfer contaminants from one phase to another. One such example is aeration techniques. The addition of gasses into the water is known as absorption while the removal of volatile substances from the water is known as desorption. While the general term ‘aeration’ refers to both absorption and desorption, air stripping specifically refers to desorption, converting matter from the liquid to gaseous phase and removing it from the water stream. Commonly stripped compounds during the treatment process include hydrogen sulfide, ammonia, and volatile organics (i.e. THMs).

Mass transfer between the liquid and gas phases requires a driving force such as a concentration gradient or pressure differential. The driving force in air stripping is primarily the difference between the existing and equilibrium concentrations in the two phases (Crittenden et. al., 2012). When the liquid remains in contact with a gas, a stationary film can form on each side of the interface, giving rise to the two-film model of mass transfer across an interface. Figure 1 shows the two-film model of air stripping. The concentration of solute in the air is less than the concentration in the bulk solution.

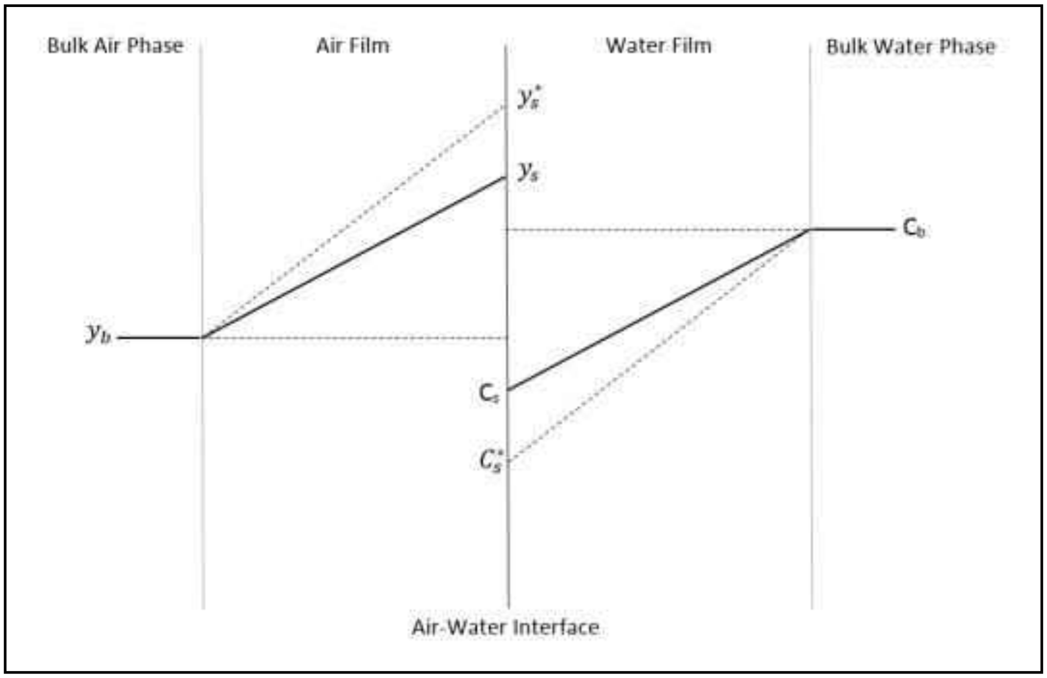

Figure 1: Diagram of the Two-Film Model for Stripping (Edzwald, 2001)

If the solute in the mixture is dilute, the separation of the substance between the liquid and gas interface is described by Henry's law:

$$H_{PX} = \frac{\mathrm{P}_A}{X_A} \tag{2-4}$$

Where $H_{PX}$ is termed Henry's constant, $P_A$ is the partial pressure of the solute above the liquid interface, $X_A$ is the mole fraction of solute in the liquid. In this form, the units of Henry's constant ($H_{PX}$) will be in terms of pressure (i.e. bar). A useful form of Henry's law occurs when the solute in both the gas and liquid phases is expressed as a concentration (Crittenden et. al., 2012).

$$H_{YC} = \frac{\mathrm{Y_A}}{\mathrm{C_A}} \tag{2-5}$$

Here, $H_{YC}$ is the dimensionless form of Henry's constant while $Y_A$ and $C_A$ are the gas phase and liquid phase concentrations of solute A, respectively. This dimensionless form is commonly used in environmental engineering; the greater its value, the more volatile a substance is and, consequently, the more prone the substance is to being stripped from the water stream. Factors that can influence Henry's constant include temperature, pH, and ionic strength or the solution (Richards, 1996). The values of two forms of Henry's constant are given in Table 3. The dimensionless values were taken from (Duranceau & Smith, 2015).

Table 3: Henry's Constant Values

| **Trihalomethane** | **Henry's Constant @ 20°C (atm)** | **Dimensionless Henry's Constant @ 23°C** |
|---|---|---|
| Chloroform | 170 | 0.148 |
| Bromodichloromethane | 118 | 0.095 |
| Dibromochloromethane | 47 | 0.035 |
| Bromoform | 35 | 0.024 |

Aerators exist in many different forms and may facilitate both absorption and desorption simultaneously, stripping an undesirable contaminant while allowing for the absorption of air to oxygenate the water. The type of aerator used often depends on the primary goal of the aeration, whether it be absorption, desorption, or both. For example, tray aerators allow water to fall onto consecutive trays to produce thin films of water and tend to be used for the purpose of releasing gases. Mechanical aspirators, conversely, disperse a gas stream into the water with the main goal of adding gasses to the water. Spray aerators commonly allow for absorption and desorption simultaneously by spraying water through a nozzle, creating small droplets and resulting in a relatively large liquid-air interface. Diffusion (fine bubble) aerators convey compressed air or ozone through porous diffusers submerged in the water; this allows small bubbles to travel through the water column, capturing volatile substances and transferring oxygen to the liquid phase during the bubbles' ascent (Richards, 1996).

The aeration assessments conducted in this study are focused on the stripping of THMs via spray and tray aerators. Important factors that affect the removal of contaminants include pH, water temperature, and the extent of the water-air interface. As the surface area of this interface increase, so does the ability of the solute to transfer across the interface and between phases. Therefore, when dealing with spray aeration, the average droplet diameter is important as is the travel distance of the droplet. In at least once instance, droplet travel distance appeared to be much more influential to THM removal than the diameter of the droplets (Brooke and Collins 2011). This same team found that spray aeration achieved THM removal rates of 20 to >99.5% while diffused aeration achieved THM removals ranging from 9 to >99.5%. In another past study, a single pass through a BETE TF10 spray nozzle was shown to remove approximately 55% and 48% of THMs at two different Central Florida locations (Duranceau and Smith 2012).

# CHAPTER THREE: EXISTING CONDITIONS

## Waverly Public Water System

The Waverly Public Water System (PWS #653-5707) is located in Polk County, Florida (County) and lies within the East Regional Utility Service Area. With over 600 service connections, the system services approximately 1,600 consumers. Source water for the Waverly PWS is groundwater from the Floridan Aquifer. The system distributes water provided by two separate production facilities: the Hodge Street WTP and the Waverly WTP. According to the County's 2017 capacity report, the entire Waverly system has an average daily flow rate of 138,000 gallons per day (gpd), only 32% of its permitted limit of 434,000 gpd (Polk County Utilities, 2017). The typical demand is such that, if necessary, one plant can feed the entire system while the other remains on standby. The location of the two plants that supply the Waverly PWS can be seen in Figure 2.

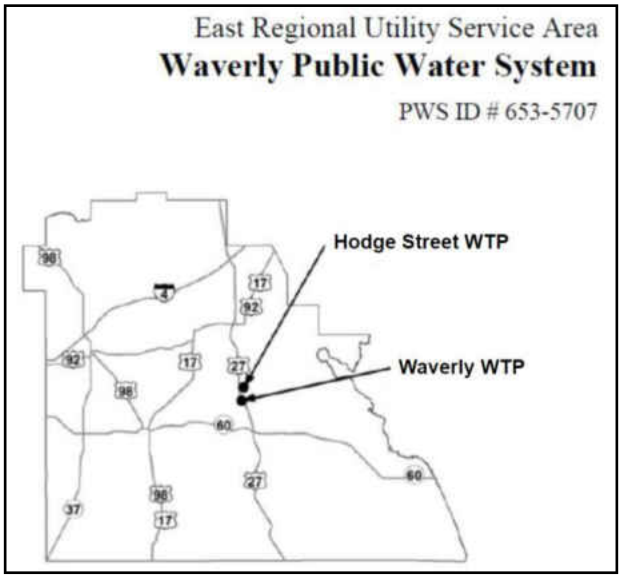

Figure 2: Waverly Public Water System

## Waverly Water Treatment Plant

The Waverly WTP is located at 860 ½ Thompson Nursery Road in Lake Wales, FL 33853 and is supplied raw groundwater by a single 12-inch diameter well. The well is cased to 168 feet and fully extends to a depth of 700 feet. Raw water is drawn from the well by a 100-horsepower (hp) pump with a rated capacity of 1,500 gallons per minute (gpm). The facility's treatment process consists of dosing blended poly-orthophosphate and sodium hypochlorite to the raw water for corrosion control and disinfection, respectively. Finished water is stored in two 30,000-gallon hydro-tanks. These larger hydro-tanks operate with an on pressure of 46 pounds per square inch (psi) and an off pressure of 60 psi.

The average monthly flow of the Waverly WTP is approximately 91,000 gpd and the maximum monthly average is almost 120,000 gpd. In the past 24 months, the maximum daily flow (MDF) experienced at the facility was 257,000 gpd. Table 4 displays average and extreme historical flow and process data recorded by the County over the last 24 months. A table displaying this data in greater detail can be found in Appendix A.

Table 4: Waverly WTP Flow and Chemical Process Data

| | **Monthly Avg. Flow** | **Monthly Max. Day Flow** | **POE Avg. Chlorine Residual** | **POE Max. Chlorine Residual** | **POE Phosphate Residual** |
|---|---|---|---|---|---|
| Average | 91,075 | 153,417 | 1.89 | 2.56 | 0.66 |
| Minimum | 54,800 | 75,000 | 1.61 | 2.09 | 0.45 |
| Maximum | 118,710 | 257,000 | 2.58 | 3.38 | 1.10 |

Table 5 shows the facility's raw and finished water quality. The table comes from Tetra Tech's 2017 Waverly evaluation and is a compilation of data acquired primarily by the University of Central Florida (UCF) and the County (Tetra Tech, 2017). Lastly, Figure 3 shows a simple diagram of the facility's treatment process.

Table 5: Waverly WTP Raw and Finished Water Quality

| Water Quality Parameter | Units | Raw Water | Finished Water |
|---|---|---|---|
| Temperature | °C | 24.5 | 26.1 |
| pH | - | 7.9 | 7.5 |
| Conductivity | µS/cm | 308 | 345 |
| Free Chlorine | mg/L | n/a | 1.89 |
| Oxidation Reduction Potential (ORP) | mV | -20 | 679 |
| Calcium | mg/L as $CaCO_3$ | 107 | 117 |
| Magnesium | mg/L | 13.4 | 13.2 |
| Total Hardness | mg/L as $CaCO_3$ | 162 | 159 |
| Alkalinity | mg/L as $CaCO_3$ | 143 | 142 |
| Iron | mg/L | 0.025 | 0.038 |
| Manganese | mg/L | n/a | 0.001 |
| Ortho-phosphate | mg/L | n/a | 1.3 |
| Chloride | mg/L | 8 | 18 |
| Sulfate | mg/L | 0.51 | 0.96 |
| TDS | mg/L | 151 | 188 |
| Total Sulfides | mg/L | 0.55 | n/a |
| Hydrogen Sulfide | mg/L | 0.2 | n/a |
| Turbidity | NTU | 0.07 | 0.55 |
| Color | CU | <5 | 3.8 |
| UV-254 | $cm^{-1}$ | 0.060 | 0.039 |
| NPDOC | mg/L | 1.76 | 1.73 |

n/a = not an applicable or tested parameter

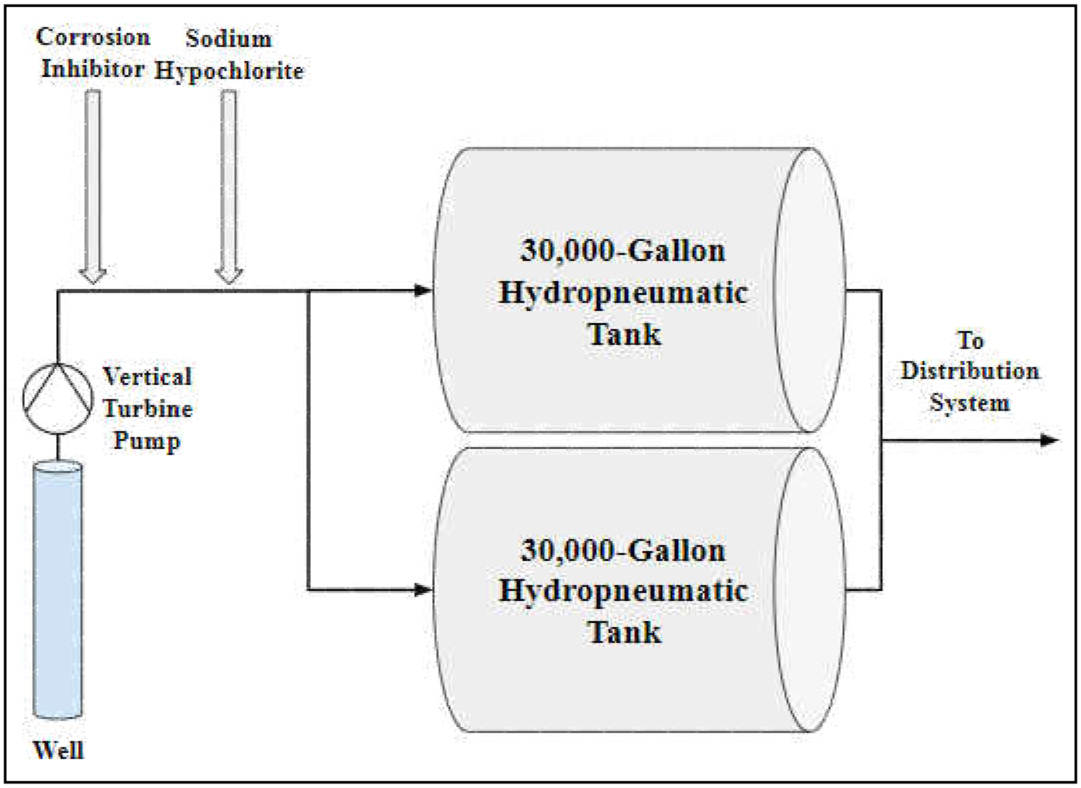

Figure 3: Simplified Waverly WTP Treatment Process Diagram

## Hodge Street Water Treatment Plant

The Hodge Street Water Treatment Plant is located at 253 Hodge St. in Waverly, FL 33877. The raw source water is supplied by a single groundwater well. The well possesses a 12-inch diameter casing down to 400 feet while the entirety of the boring extends down to a depth of 700 feet. The well is equipped with a 100 hp vertical turbine pump with a rated capacity of 1,500 gpm. A blended poly-orthophosphate is added for corrosion inhibition after which the water is disinfected with sodium hypochlorite. The disinfected water flows into a single 15,000-gallon hydro-pneumatic storage tank, or hydro-tank where it is stored before entering the distribution system. The on and off pressures of this tank are 30 and 70 psi, respectively.

The facility's historical raw and finished water quality, shown in Table 6, also comes from Tetra Tech's 2017 evaluation.

Table 6: Hodge Street WTP Raw and Finished Water Quality

| **Water Quality Parameter** | **Units** | **Raw Water** | **Finished Water** |
|---|---|---|---|
| Temperature | °C | 23.6 | 23.0 |
| pH | - | 7.7 | 7.6 |
| Conductivity | µS/cm | 350 | 356 |
| Free Chlorine | mg/L | n/a | 1.17 |
| Oxidation Reduction Potential (ORP) | mV | -47 | 626 |
| Calcium | mg/L as $CaCO_3$ | 132 | 108 |
| Magnesium | mg/L | 13.3 | 13.4 |
| Total Hardness | mg/L as $CaCO_3$ | 159 | 163 |
| Alkalinity | mg/L as $CaCO_3$ | 158 | 151 |
| Iron | mg/L | 0.04 | 0.03 |
| Manganese | mg/L | 0.01 | 0.002 |
| Ortho-polyphosphate | mg/L | n/a | 0.2 |
| Chloride | mg/L | 19 | 19 |
| Sulfate | mg/L | 0.77 | 2.07 |
| TDS | mg/L | 183 | 198 |
| Total Sulfides | mg/L | 0.41 | n/a |
| Hydrogen Sulfide | mg/L | 0.25 | n/a |
| Turbidity | NTU | 0.60 | 0.90 |
| Color | CU | 11.81 | 8.00 |
| UV-254 | $cm^{-1}$ | 0.11 | 0.04 |
| TOC | mg/L | 3.02 | n/a |
| NPDOC | mg/L | 2.96 | 1.84 |

n/a = not an applicable or tested parameter

The average monthly flow of the facility is just over 17,000 gpd and the maximum monthly average is approximately 60,000 gpd. The MDF from the facility in the last 24 months was more than 180,000 gpd. Table 7 shows extreme and average flow and process data from the past 24 months; Appendix A gives this data in greater detail. A process flow diagram of the facility is shown in Figure 4. The Hodge Street facility possesses one fourth of the storage volume of the Waverly WTP. Aside from this, the diagrams are very similar.

Table 7: Hodge Street WTP Flow and Chemical Process Data

| | **Monthly Avg. Flow** | **Monthly Max. Day Flow** | **POE Avg. Chlorine Residual** | **POE Max. Chlorine Residual** | **POE Phosphate Residual** |
|---|---|---|---|---|---|
| Average | 17,094 | 54,083 | 1.17 | 1.97 | 0.73 |
| Minimum | 133 | 3,000 | 0.41 | 0.73 | 0.51 |
| Maximum | 59,484 | 182,000 | 2.64 | 3.29 | 1.39 |

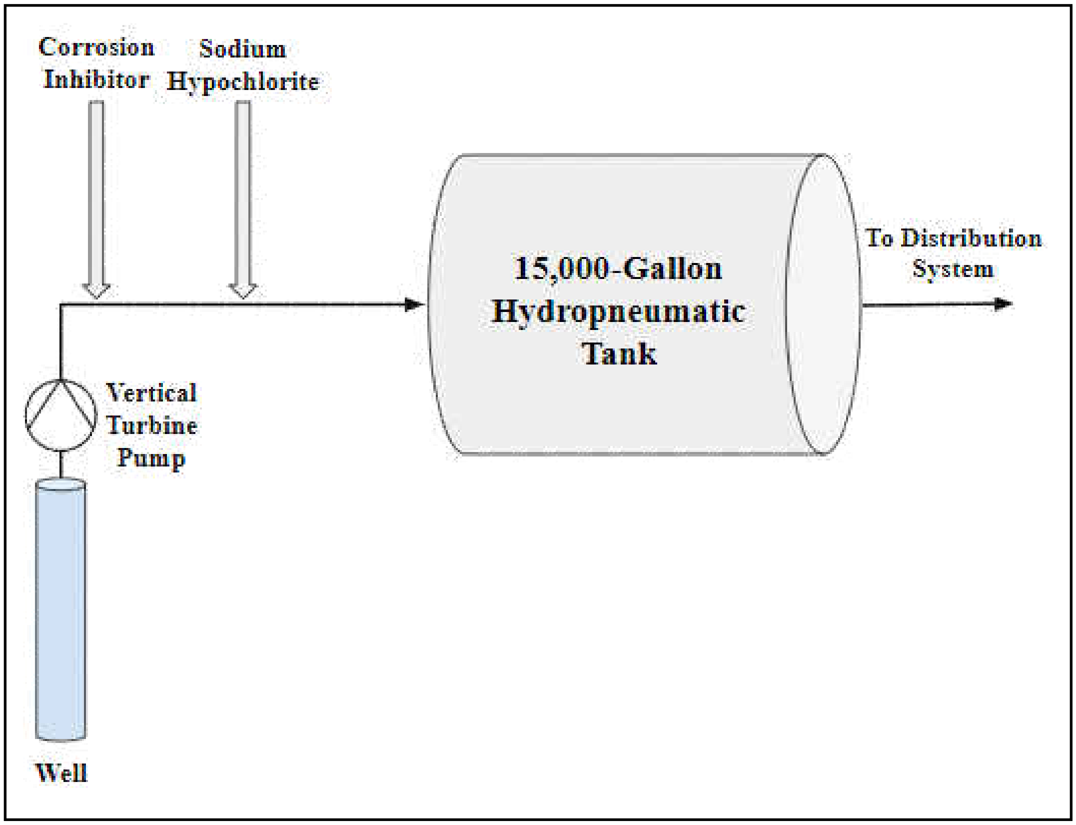

Figure 4: Simplified Hodge Street WTP Treatment Process Diagram

# CHAPTER FOUR: MATERIALS AND METHODS

## Overview of Studies

The objective of this research was to investigate methods to control DBP levels throughout the Waverly PWS with a particular focus on air stripping methods and GAC adsorption. Different studies were conducted, and data collected from the studies was compiled and used to develop a conceptual master plan for the County. The studies discussed herein include: (1) Assessing basic water quality and DBP information for the Hodge Street WTP, Waverly WTP, and distribution system points in the Waverly PWS, (2) Evaluating single-pass spray aeration's effects on THM concentration and FP as well as associated chlorine residual, (3) Evaluating the same THM and chlorine properties with recirculating tray aeration, and (4) Raw water blending study intended to model GAC bypass and its effects on HAA formation and chlorine residual.

## Standard Equipment and Protocols

Table 8 shows some of the additional standards that were kept constant across the different studies and trials of the research. Samples were collected and handled in accordance with Standard Methods 1060 B: Collection of Samples and 1060 C: Sample Storage and Preservation (American Public Health Association, 2017). An incubation temperature of 30°C was used for both THM and HAA analyses; this was to simulate summer conditions when elevated temperatures can lead to increased DBP levels in the distribution system. Samples assessed in the laboratory were brought to ambient laboratory temperature (20°C) before testing began.

Table 8: Miscellaneous Standards and Protocols

| Parameter | Standard Protocol |
|---|---|
| Water quality collections | 1-liter amber glass or plastic vessel |
| THM collections | 60-mL amber glass |
| HAA collections | 125-mL amber glass |
| Chlorine residual collections | 60-mL amber glass |
| Sample storage temperature | 4°C |
| Laboratory temperature | 20°C |
| THM incubation temperature | 30°C |
| HAA incubation temperature | 30°C |

## Methods, Equipment, and Chemical Reagents

A variety of chemical substances were used during the research. Table 9 shows the chemical reagents that were used throughout the research and a brief description of each. Table 10 provides a tabulated list of the tests conducted as well as some information regarding the location, methods, and equipment used.

Table 9: Chemical Reagents Used

| Chemical | Description |
|---|---|
| DPD free chlorine reagent | Powder pillows used in measuring free chlorine residual |
| pH standard solutions | For calibration of pH probe; includes standards of pH 4,7, and 10 |
| KCl standard solution | For calibration of conductivity probe |
| Sodium sulfite | Crystalline powder; used to make quenching solution to halt formation of THMs |
| Ammonium chloride | Crystalline powder; used to make quenching solution to halt formation of HAAs |
| Hexane | ACS-grade; used for liquid-liquid THM extractions |
| Trihalomethane calibration standard | 100 g/L stock solution; used in creation of standard curves and spikes in THM analyses |
| Sodium hypochlorite | Measured at 4.6%; used for simulating plant chlorination during blending assessment |
| Sulfuric acid | 0.185 N solution; used in titrations to calculate alkalinity |

Table 10: List of Methods and Equipment for Water Analyses

| Test | Test Location | Method | Equipment Description | Minimum Reporting Level | Preservation Technique |
|---|---|---|---|---|---|
| pH | UCF Laboratory/field | SM: 4500-H+ B. Electrometric Method | HACH HQ40D pH and temperature probe | 0.1 pH units | Analyze immediately |
| Temperature | UCF Laboratory/field | SM: 2550 B. Laboratory and Field Methods | HACH HQ40D pH and temperature probe | 0.1 °C | Analyze immediately |
| Free Chlorine | UCF Laboratory | HACH Method 8021 | HACH Spectrophotometer DR5000 | 0.02 mg/L as $Cl_2$ | Analyze immediately |
| $HAA_5$ | Advanced Environmental Laboratory (AEL) | SM:5710C | Agilent 6890N Network Gas Chromatograph | 3 µg/L | Ammonium chloride, 4 °C in the dark |
| TTHM | UCF Laboratory | SM: 6232 B: Liquid-Liquid Extraction Gas Chromatographic | Perkin Elmer Clarus 580 Gas Chromatographer | 8.0 µg/L TTHM | Sodium sulfite, 4 °C in the dark |
| Alkalinity | UCF Laboratory | SM: 2320 B. Titration Method | Sulfuric acid; glass burette; Accumet XL600 dual-channel analyzer | 5.0 mg/L as $CaCO_3$ | Analyze immediately |
| Conductivity | UCF Laboratory/field | SM: 2510 B. Laboratory Method | HACH HQ40D conductivity probe | 0.01 µS/cm | Analyze immediately |
| Turbidity | UCF Laboratory/field | SM: 2130 B. Nephelometric Method | HACH 2100N Laboratory Turbidity Meter | 0.01 NTU | Analyze immediately |
| Calcium | UCF Laboratory | SM: 3120 B. Inductively Coupled Plasma (ICP) Method | Perkin Elmer Optima 2100 DV | 0.01 mg/L | 2% Nitric Acid |
| Magnesium | UCF Laboratory | SM: 3120 B. Inductively Coupled Plasma (ICP) Method | Perkin Elmer Optima 2100 DV | 0.001 mg/L | 2% Nitric Acid |
| NPDOC | UCF Laboratory | SM: 5130 C. Persulfate-Ultraviolet or Heated-Persulfate Oxidation Method | Teledyne Tekmar Total Organic Carbon Fusion UV/Persulfate Analyzer | 0.01 mg/L | 2% Phosphoric Acid |
| UV-254 | UCF Laboratory | SM: 2120C Spectrophotometric Single-Wavelength Method | HACH Spectrophotometer DR5000 | 0.001 $cm^{-1}$ | Analyze immediately |

## TOC/GAC Analysis

The first site visit was to the Hodge Street facility on June 29, 2017. Water was collected in 2.5-gallon collapsible polyethylene vessels, kept refrigerated overnight at UCF, and transferred to Evoqua personnel the next day for TOC and GAC analyses at their laboratories. The full report generated by Evoqua's Dr. Adam Redding can be found in Appendix C. Results developed by his studies were used in design considerations for the master plan.

## Water Quality and Baseline DBP Data

Several site visits were made to the Waverly and Hodge Street facilities and surrounding distribution system to assess raw water quality and FP of DBPs in the finished waters. Formation curves were generated by collecting freshly chlorinated water samples from the facilities' hydro-tanks and incubating them to allow DBPs to form. In order to acquire freshly chlorinated water that was relatively free of DBPs, the hydro-tanks were flushed prior to collection. Periodic chlorine readings helped indicate when complete flushing had occurred. Each DBP sample was incubated for specific pre-designated time-period before being quenched with the exception of the time-zero points which were quenched immediately upon collection. The time points included in the Waverly DBP formation curve were: 0, 1, 4, 10, 22, 46, and 94 hours. The time points for the Hodge Street DBP formation curve included: 0, 2, 12, 24, and 48 hours. Time points were reflective of both logistics as well as each water's individual TTHMFP; it was preferable that the final time point measured be sufficiently long enough to begin to show somewhat asymptotic behavior in the curve.

## Spray Aeration

### *Purpose*

The effects of single-pass spray aeration on TTHM concentrations and formation potential were investigated. The feasibility of spray aeration as a control method for THMs in the Waverly PWS was explored. As HAA species are not removed effectively via aeration, analysis of these compounds was limited in the study.

### *Materials*

The nozzle used in the study was the BETE TF 10CFM brass spray nozzle, shown in Figure 5. The nozzle was chosen due its simplistic one-piece design, consistent spray pattern, and resistance to particulate fouling and plugging. Some of the nozzle's specifications are shown in Table 11.

Table 11: BETE Spray Nozzle Specifications

| Parameter | Value |
|---|---|
| Manufacturer | BETE |
| Model | TF 10 FCN |
| Material of construction | Brass |
| Nozzle/spray shape | Spiral/ full cone |
| Spray angle | 60 degrees |
| Rated flow | 4 gpm, 15.1 L/min |
| Standard pressure | 40 psi, 2.8 bar |

Figure 5: BETE Spray Nozzle

The tubing used to attach the spray nozzle to the Hodge Street hydro-tank's sampling port was a US Plastics braided PVC tubing. A clean 2000mL glass beaker was used to collect the spray-aerated droplets after they passed through the nozzle. Droplet fall distance was approximately 18 inches. Figure 6 shows a simple diagram of the assembly.

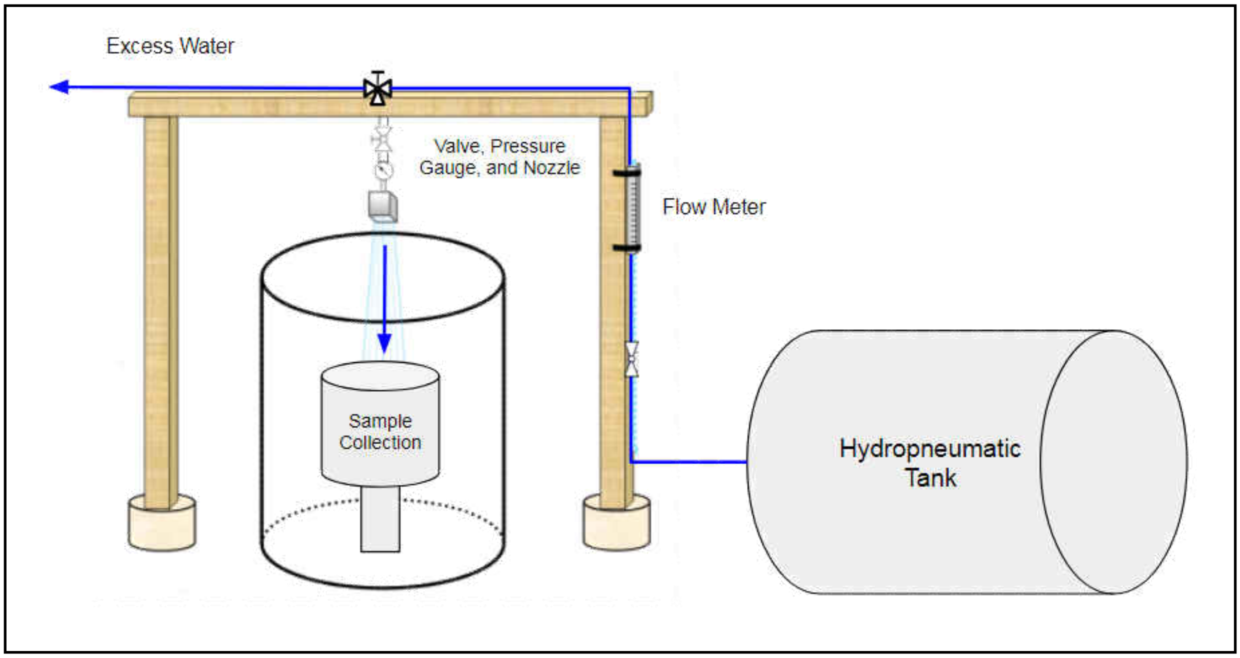

Figure 6: Spray Aeration Assembly (not to scale)

*Methods*

On August 14, 2017, a site visit was made to the Hodge Street facility. Unlike the generation of the baseline DBP curves, assessing the efficacy of spray aeration on THM reduction required that the water inside the hydro-tank (termed in-situ water) possess a sufficient concentration of THMs. To accomplish this, the hydro-tank was not flushed prior to spray aeration and collection. Instead, the in-situ water had been residing in the tank upward of 12 hours. The free chlorine residual of this in-situ water was 2.1 mg/L.

First, water was taken directly from the hydro-tank without being passed through the spray nozzle and collected in the 2000 mL glass beaker. This water was termed 'unaerated' and was transferred to the necessary amber glass vessels. The TTHMFP curve consisted of five different time points: 0, 4, 7, 24, and 48 hours with two samples taken for each time point. Therefore, ten (10) THM samples were collected. In addition, two (2) HAA samples were collected from the unaerated water.

The BETE spray nozzle was then attached to the hydro-tank's sampling port by the PVC tubing and a threaded PVC fitting. Water was passed through the spray nozzle once at a flow rate of 3 gpm and collected in the glass beaker. The pressure was measured to be 28 psi and was kept constant during the study. Once sufficient water had accumulated in the glass vessel, it was transferred to the appropriate amber glass vessels. Like the unaerated water, ten (10) mL THM samples and two (2) HAA samples were collected for the spray-aerated water.

The four (4) time-zero THM samples were quenched immediately upon collection using sodium sulfite while the other 16 THM samples were taken back to UCF labs and incubated at 30°C for their pre-designated time periods. Each sample was quenched after it had been incubated for its specified amount of time.

Of the four (4) total HAA samples collected, one (1) of the spray-aerated water's HAA samples was incubated at 30°C for 24 hours before quenching while the other remaining aerated sample was incubated for 48 hours. This same procedure was followed for the two (2) unaerated samples with quenching after 24 and 48 hours. Because the HAA species have extremely low volatility, it was expected that spray aeration would have unnoticeable effects on HAA concentrations. Samples which had been incubated for comparable periods of time were expected to have negligible differences in concentrations and could essentially be considered duplicates of each other, regardless of whether the sample had been aerated or not.

## Tray Aeration

### *Purpose*

This assessment analyzed the reduction of TTHM concentration and formation potential after aeration with a tray aerator. However, unlike the spray aeration which examined a single pass through the aerator, a recirculating assembly was designed to allow for successive passes to be made through the cascading, tray-type aerator. The DBP formation potentials of waters aerated for various periods of time were compared and respective chlorine residuals were also analyzed.

### *Materials*

A pilot-scale tray aerator was constructed for the purpose of assessing THM volatilization via tray aeration for the Waverly system's groundwater. The five trays that comprise the tray aerator were 55-centimeter (cm) long corrugated splash blocks. The width of these trays tapered in from 24 cm to 15 cm, giving each tray an approximate surface area of 0.11 square meters ($m^2$). With five trays, the entire configuration possesses a total tray surface area of 0.55 $m^2$. These trays were arranged in such a way that they allowed water to cascade through each successive tray and into a reservoir. The reservoir, a 55-gallon vessel manufactured by US Plastics, was equipped with a small Iwaki magnetic-driven centrifugal pump. The pump would allow for water in the reservoir to be recirculated back to the top of the tray aerator, allowing for multiple passes through the tray assembly. Trays were coated with clean aluminum foil to prevent the water from contacting non-NSF approved materials. A brief schematic of the tray aerator is shown in Figure 7; Figure 8 shows the trays from two different angles.

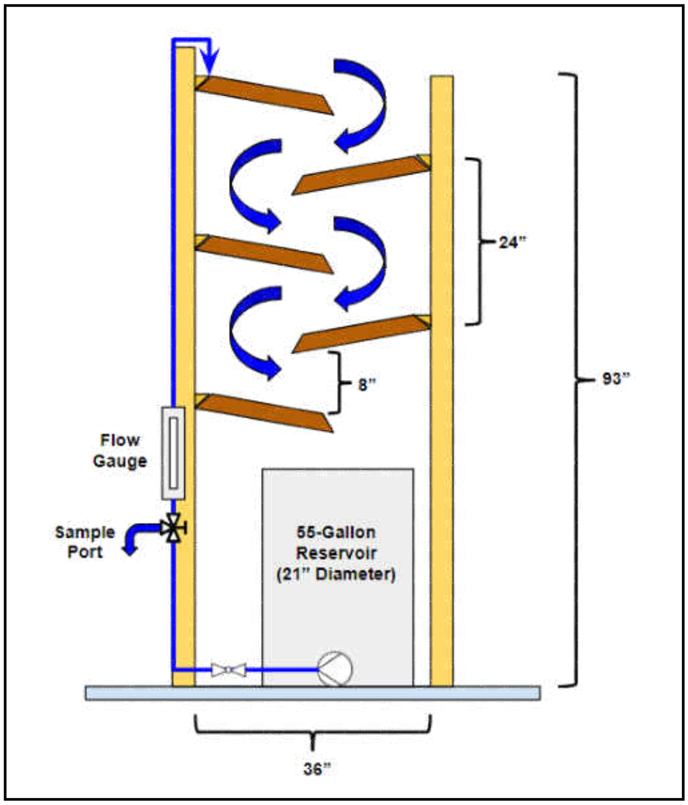

Figure 7: Simple Schematic of Tray Aerator

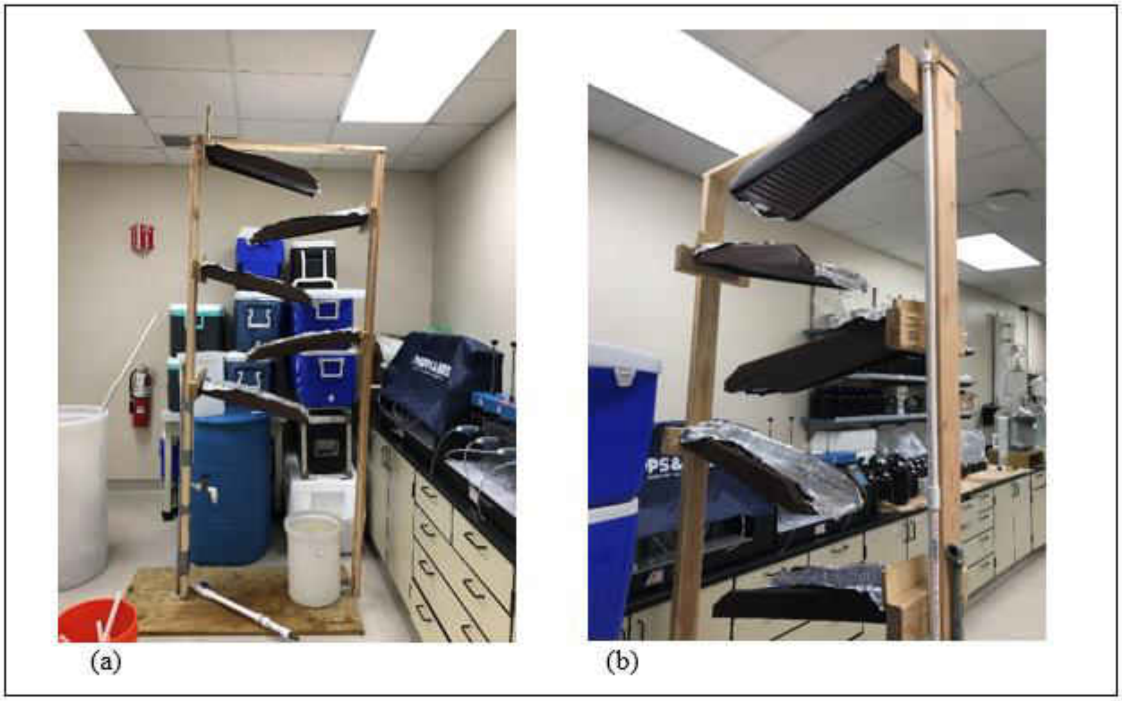

Figure 8: Tray Aerator from (a) Front (b) Side

*Methods*

On September 26, 2017, in situ water from the Hodge Street facility's hydro-tank was collected in a large drum. As with the spray aeration study, it was necessary to use water that had resided in the hydro-tank for sufficient time to possess an adequate concentration of THMs. Three (3) THM samples and one (1) HAA sample were collected and quenched immediately in the field to explore the in situ DBP levels prior to aeration. The samples and collected bulk water were transported to UCF laboratories where the study was conducted.

30 gallons of the water was transferred to the aerator's 55-gallon reservoir in a manner that minimized turbulence and aeration. Three (3) time-zero THM samples and one (1) time-zero HAA sample were collected and quenched immediately prior to the study's commencement. Once tray

aeration was initiated, THM samples were taken in triplicate every ten (10) minutes and quenched along with two (2) free chlorine readings. Because the pump operated at three (3) gpm and the reservoir contained 30 gallons of chlorinated water, every ten (10) minutes constituted a volumetric turnover of the reservoir, herein defined as a 'pass'. Three (3) THM samples continued to be collected and quenched after each pass until six (6) passes had occurred. At this point, the triplicate THM samples were collected, quenched, and the water was left to recirculate for an additional hour.

After 12 passes (two hours of recirculation) had occurred, six (6) THM samples and three (3) HAA samples were collected and analyzed; six (6) free chlorine samples were also taken to monitor chlorine consumption over time. Two (2) of the THM samples and one (1) HAA sample were quenched immediately. The same number of samples (two THMs and one HAA) were quenched at a later time, after being incubated for approximately 12 hours. The last set was quenched after approximately a full day of incubation had passed. This procedure was repeated after the water had recirculated through the tray aerator for 12 hours (72 passes). Monitoring the THM re-formation in the aliquots which had been aerated for two (2) and 12 hours helped gauge the degree to which air stripping impacted the water's ability to create THM species after they have been removed.

## Simulation of GAC Bypass Study

### *Purpose*

This study aimed to gain a better understanding of the DBP and chlorine-related effects of various raw water blends. The conceptual master plan specific to Hodge Street includes an opportunity to complement granular activated carbon (GAC) adsorption treatment for the effective removal of organic precursors with aeration technologies for the removal of formed THMs. However, passing the entirety of the facility's supply water through the GAC adsorption vessels is neither necessary nor cost-effective. Therefore, different bypass ratios should be examined to determine a feasible flow that could be slip-streamed around the GAC vessels. To investigate the characteristics and impacts of bypass blending, an evaluation consisting of two trials was conducted. The trials assessed DBP formation potential and chlorine consumption for Hodge Street's raw water and for various blended raw water ratios.

### *Materials*

Raw groundwater from the Hodge Street WTP was collected in 20-L low-density polyethylene collapsible vessels. To represent water which had passed through GAC adsorption, distilled water from the UCF laboratory was used as it is virtually free of organics. The choice to blend the raw water with de-ionized water as opposed to water that had been passed through GAC was made due to time constraints within the project's scope. Chlorination was accomplished with a laboratory-grade sodium hypochlorite solution. Both the Waverly and Hodge Street WTPs accomplish disinfection by injection sodium hypochlorite into the water stream.

### *Methods*

On December 8, 2017, a site visit to the Hodge Street Water Treatment Plant (WTP) was made. Raw groundwater was pumped to the surface via the facility's well, collected in plastic vessels, and returned to UCF's laboratories. The vessels were kept at 4°C until initiation of testing, at which point the vessels were warmed up to ambient laboratory temperature (≈ 20°C). The water was not chlorinated or chemically altered prior to commencement of testing. Three (3) different ratios of raw water to de-ionized (DI) water were chosen for the first trial: 1:0 (100% raw), 3:1 (75% raw), and 1:1 (50% raw). When creating the different blend ratios, DI water was used to simulate GAC-treated water as it is virtually free of NOM.

The hypochlorite solution was standardized and found to be 4.6% pure. The dose of hypochlorite solution was then adjusted until an initial free chlorine reading of approximately 3 mg/L was obtained in a 200 mL sample of raw water. When the raw water was dosed at 6.5 mg/L, the free chlorine residual after the initial chlorine demand was satisfied was 3.4 mg/L. Thus, a chlorine dose of 6.5 mg/L was used for the first trial of this study.

Four (4) liters of each blend were produced and dosed with identical amounts of hypochlorite solution and initial free chlorine readings were taken after the solution had been allowed to mix for about 20 seconds on a magnetic stir plate. Because protected ground water supplies are essentially free of DBPs prior to disinfection, initial THM and HAA concentrations were assumed to be zero. Aliquots were prepared for each of the three blends to allow for one (1) THM and two (2) free chlorine samples to be quenched every 24 hours, for up to 96 hours (12 samples for each blend). Four (4) HAA samples (one for each blend with a duplicate for the 100% raw water) were collected and quenched with ammonium chloride after 24 hours of incubation. The samples were incubated at 30°C until their designated quenching times to simulate summer-time conditions and encourage DBP formation. Quenched THM and HAA samples were placed in a walk-in cooler at 4°C. HAA analysis was conducted off-site by Advanced Environmental Laboratories (AEL), 528 Northlake Blvd., No. 1016, Altamonte Springs, FL (32701).

Another site visit to the Hodge Street facility was made on February 22, 2018 to conduct a second trial. Raw water was gathered in five (5)-gallon plastic vessels and brought back to UCF laboratories. This trial differed from the first in the following ways:

1. Increased focus on water quality data (NPDOC, UV-254, alkalinity)
2. Increased focus on HAA concentrations (no THMs)
3. Two different chlorine doses were analyzed (6.5 mg/L and 3.25 mg/L)
4. Only 100% raw water and the 50% blend were analyzed

The water was stored at 4°C and brought to ambient temperature (20°C) before performing laboratory tests. First, four (4) liters of the 50% blend was prepared in a large plastic container and a water quality assessment was conducted. One (1) liter of the blend was then taken for NPDOC, UV-254, and other analyses. Next, the 50% blend was dosed at 3.25 mg/L of free chlorine; this dose is half of the 6.5 mg/L dose used in the first trial. After 20 seconds on a stir plate, the free chlorine residual was measured. As the initial chlorine measurements were being taken, two (2) free chlorine samples were taken for future readings, one to be read at the 24-hour mark and one at the 48-hour mark. Also, two (2) HAA samples were collected to be read at the 24- and 48-hour marks. After these samples were collected, the plastic container that had held the blend was emptied and cleaned. The same procedure was followed using the first trial's chlorine dose of 6.5 mg/L.

After both chlorine doses had been applied to the 50% blend and the necessary aliquots were collected, the undiluted raw water was prepared and the procedure was repeated as with the 50% blend. The lower chlorine dose of 3.25 mg/L was added and, after the one (1) NPDOC sample, two (2) free chlorine samples, and two (2) HAA samples were taken, the plastic container was emptied and cleaned, the water was replaced, and the higher chlorine dose of 6.5 mg/L was added with the same sample collections being made for a fourth time.

## Field and Laboratory Quality Control

The quality assurance (QA) and quality control (QC) parameters were derived in accordance with Standard Methods SM: 1010B Statistics and SM: 1020B Quality Control. Two types of control charts commonly used in laboratories: accuracy (means) charts for QC samples and precision (range) charts for replicate or duplicate analyses (American Public Health Association, 2017).

### *Accuracy*

The average and standard deviation of spiked THM samples were used in the creation of the accuracy chart. Percent recovery was calculated for each spiked sample processed by the GC using Equation (3-1).

$$\%\ Recovery = \left(\frac{C_{sample+spike} - C_{sample}}{C_{spike}}\right) \times 100\% \qquad (4\text{- }1)$$

Warning and control levels were established to assess consistency of spiking methods and GC analysis. The upper and lower warning limits were defined as plus or minus two standard deviations from the mean while the control limits were plus or minus three standard deviations, as shown in Equations (3-2) and (3-3).

$$UWL = \mu + 2s \ and \ LWL = \mu - 2s \qquad (4\text{-}2)$$

$$UCL = \mu + 3s \ and \ LCL = \mu - 3s \qquad (4\text{-}3)$$

In these equations, μ is the mean and s is the standard deviation of the data set. Data points that fell outside of the control limits were considered illegitimate and disregarded.

*Precision*

The industrial "I-statistic" is calculated using Equation (3-4); its helps monitor variations of replicates and duplicates during THM analyses. Unlike accuracy charts, only upper warning and control limits are meaningful in precision charts.

$$I = \frac{|sample\ result - duplicate\ result|}{(sample\ result + duplicate\ result)} \tag{4-4}$$

$$UWL = I_{avg} + 2s \tag{4-5}$$

$$UCL = I_{avg} + 3s \tag{4-6}$$

As with the accuracy charts, values that fell outside of the control limits were not considered. If any two successive points exceeded the warning limits, a control violation was declared.

Many of the data gathered for this research was compiled from several different sources, including the County, previous UCF studies, and private firms. Consequently, it was necessary to rely on the historical data provided and assume that the data had been evaluated with a sufficient QA protocol. Judgement was exercised concerning which sources were most reliable and historical data was sometimes cross-referenced to assess consistency.

# CHAPTER FIVE: RESULTS AND DISCUSSION

## Basic Water Quality and Baseline DBP Data

### *TOC Data and GAC Findings*

Evoqua's testing showed that the Hodge Street facility's raw water had an average TOC concentration of 3.6 mg/L. While both GACs tested were able to adsorb the vast majority of the raw water's organics, the coal-based UC1240AW demonstrated an advantage both in the RSSCTs and isotherm adsorption tests when compared to the AC1230CX. The UC1240AW appeared to keep effluent TOC levels lower for longer periods of time. A complete report detailing the results of the study can be found in Appendix C.

### *Raw Water Quality*

Table 12 shows raw water quality data collected in the field. Basic water quality parameters were assessed on-site during site visits. The raw water was taken prior to the disinfection process; therefore, free chlorine is not included in the table.

Table 12: Raw Water Quality – Field Data

| **Water Quality Parameter** | **July 2017** | **August 2017** | **December 2017** | **February 2018** |
|---|---|---|---|---|
| Temperature (°C) | 27.5 | 27.3 | 24.9 | 22.8 |
| pH | 7.40 | 7.52 | 7.61 | 7.73 |
| Conductivity (µS/cm$^2$) | 336 | 363 | 350 | 338 |
| Dissolved oxygen (mg/L) | 1.0 | 1.7 | 2.2 | 2.0 |
| Turbidity (NTU) | 0.33 | 0.55 | 0.30 | 0.19 |

Table 13 shows additional data regarding some of the organic and inorganic constituents of the raw water. Apart from the TOC measurement, the values were derived from tests conducted at UCF's laboratories.

Table 13: Raw Water Quality - Laboratory Data

| Water Quality Parameter | Average Value |
|---|---|
| TOC* (mg/L) | 3.6 |
| Non-purgeable dissolved organic carbon (NPDOC) (mg/L) | 2.7 |
| Calcium (mg/L) | 41.3 |
| Magnesium (mg/L) | 8.6 |
| Alkalinity (mg/L as $CaCO_3$) | 153 |
| UV-254 | 0.104 |

*Conducted by Evoqua Water Technologies

*Hodge Street WTP Water Quality*

Table 14 shows the basic water quality data recorded on the initial site visit to the Hodge Street WTP. Table 15 contains data from a more detailed water quality assessment in which water residing in the hydro-tank for a considerable period was analyzed along with four different points in the distribution system. During the sampling event, the entire Waverly PWS was being fed water solely from the Hodge Street facility; the Waverly facility was on standby.

Table 14: Hodge Street WTP Water Quality (July 2017)

| Water Quality Parameter | Well (Raw) | Raw w/ Polymer | Chlorinated | POE |
|---|---|---|---|---|
| Temperature (°C) | 27.5 | 27.3 | 27.3 | 28.2 |
| pH | 7.40 | 7.46 | 7.47 | 7.43 |
| Conductivity (µS/cm$^2$) | 336 | 349 | 368 | 392 |
| Dissolved Oxygen (mg/L) | 1.0 | 1.4 | 2.7 | 3.0 |
| Turbidity (NTU) | 0.33 | 0.17 | 0.69 | 0.50 |
| Free Chlorine (mg/L) | 0.0 | 0.0 | 2.2 | 0.9 |

Table 15: Hodge Street WTP and System Data during Hodge Street-Only Operation

| Parameter/Sample | In-Situ | HS Site #0 (POE) | HS Site #1 | HS Site #2 | HS Site #3 |
|---|---|---|---|---|---|
| pH | 7.64 | 7.49 | 7.47 | 7.44 | 7.47 |
| Temperature (°C) | 26.3 | 26 | 24.9 | 25.2 | 25.6 |
| Turbidity (NTU) | 2.26 | 0.56 | 0.94 | 1.71 | 0.16 |
| Conductivity (µS/cm$^2$) | 400 | 403 | 362 | 366 | 404 |
| Dissolved oxygen (mg/L). | 5.59 | 5.35 | 5.73 | 5.69 | 4.32 |
| Free chlorine (mg/L) | 2.1 | 2.0 | 0.7 | 1.0 | 0.6 |
| NPDOC (mg/L) | 2.46 | 2.48 | 1.97 | 2.35 | 1.76 |
| Calcium (mg/L) | 41.2 | 41.4 | 40.3 | 41.1 | 40.5 |
| Magnesium (mg/L) | 8.8 | 8.7 | 9.1 | 8.9 | 9.0 |
| Alkalinity (mg/L as $CaCO_3$) | 157 | 167 | 148 | 150 | 148 |
| UV-254 (cm$^{-1}$) | .07 | .069 | .04 | .054 | .045 |
| TTHM concentration (ppb) | 45 | 57 | 46 | 93 | 72 |
| $HAA_5$ concentration (ppb) | 65 | 72 | 41 | 68 | 60 |

### *Waverly WTP Water Quality*

During the site visit to the Waverly WTP, a basic water quality assessment was conducted with water that had been residing in the hydro-tank for some time. The tank was flushed, and an additional assessment was conducted. Also, three distribution system points were analyzed. The data gathered from the event is shown in Table 16. During the time of sampling, the entire Waverly PWS was being supplied with water from the Waverly WTP; the Hodge Street facility was in standby at the time.

Table 16: Waverly WTP and System Data during Waverly-Only Operation

| **Water Quality Parameter** | **In Situ** | **Flushed Tank (POE)** | **W Site #1** | **W Site #2** | **W Site #3** |
|---|---|---|---|---|---|
| Temperature (°C) | 26.2 | 26.4 | 27.8 | 26.9 | 27.3 |
| pH | 7.6 | 7.6 | 7.55 | 7.54 | 7.5 |
| Conductivity (µS/cm$^2$) | 368 | 374 | 381 | 371 | 382 |
| Dissolved oxygen (mg/L) | 1.57 | 4.01 | 1.8 | 2.94 | 1.4 |
| Free chlorine (mg/L) | 3.2 | 3.8 | 2.1 | 2.3 | 1.5 |
| TTHM concentration (ppb) | 41 | 22 | 46 | 52 | 58 |

*DBP Assessments*

A profile of the THM species distribution is shown in Figure 9. The primary component was chloroform at 81% by mass. Chloroform is the most volatile of the EPA's regulated THMs. Its prevalence suggests that aeration methods are a viable option for removal of formed THMs.

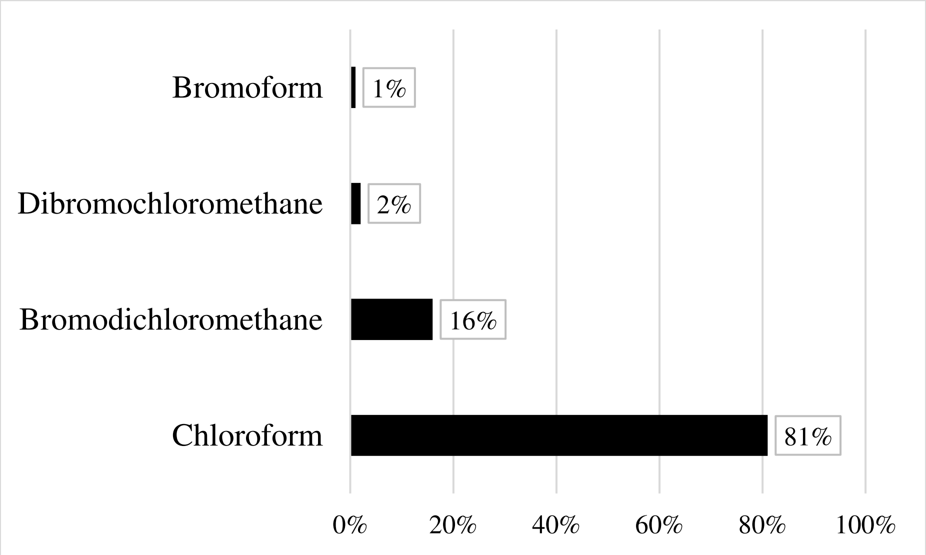

Figure 9: TTHM Species Distribution

The DBP curves created for the two facilities showed discrepancies between their TTHMFPs. Although both waters had comparable initial TTHM concentrations, they exceeded the EPA's mandated MCL after different periods of elapsed incubation time. The Waverly facility's water exceeded the 80 ppb MCL after approximately 35 hours as shown in Figure 10. Hodge Street's curve, shown in Figure 11, reached this same level after just over 15 hours. Ambient and water temperatures were comparable during the two site collections. The chlorine residuals in the flushed Waverly and Hodge Street hydro-tanks were 3.8 mg/L and 3.3 mg/L, respectively.

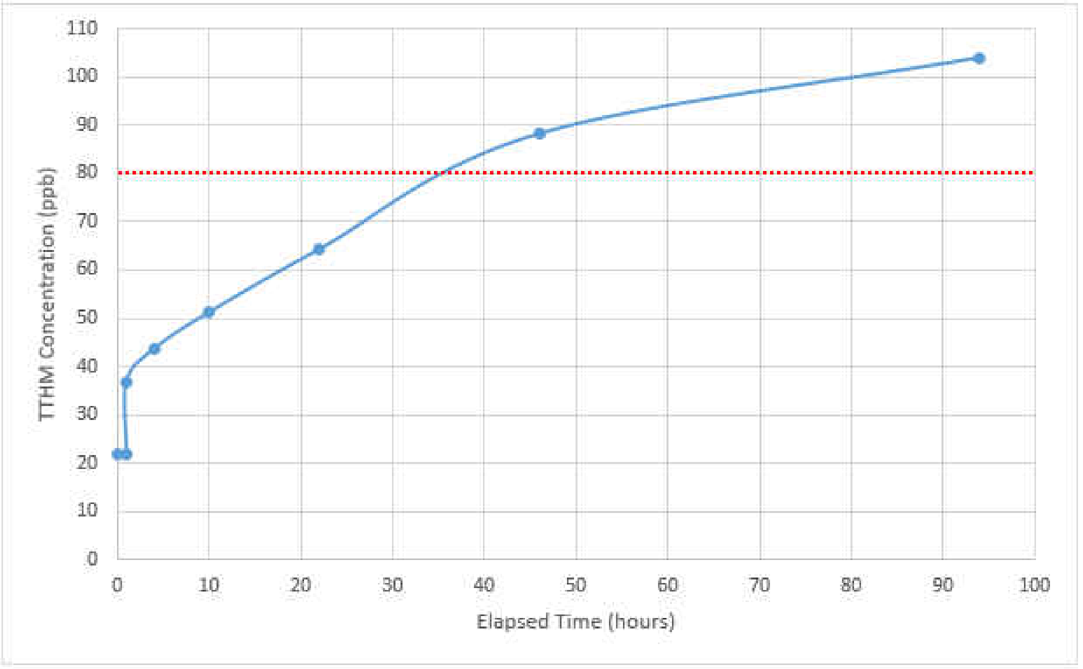

Figure 10: Waverly WTP Baseline THM Formation Curve

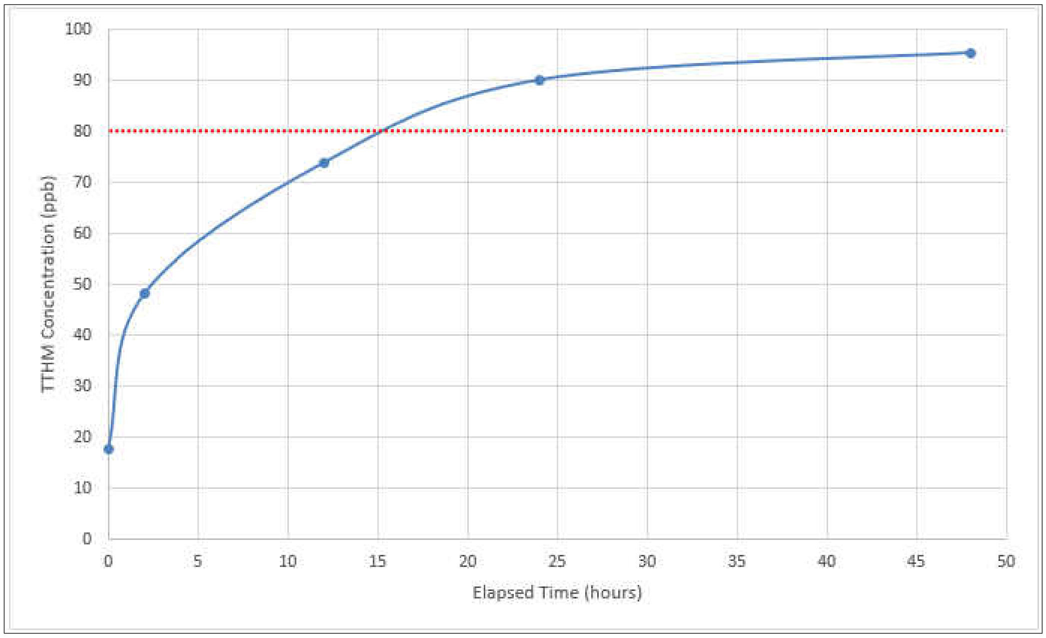

Figure 11: Hodge Street WTP Baseline THM Formation Curve

Figure 12 and Figure 13 illustrate the formation of the HAA species at the Waverly and Hodge Street WTPs, respectively. After approximately two days of incubation, both waters remained below the regulatory MCL of 60 ppb. The Waverly WTP's water, after two days of incubation at 30°C, possessed an $HAA_5$ concentration 49 ppb while Hodge Street's water had an $HAA_5$ concentration of 59 ppb. When comparing the initial formation curves, TTHM concentrations reach the EPA's MCL sooner than the $HAA_5$ concentrations. This hints that TTHM levels may be more at risk of MCL violations than $HAA_5$ concentrations.

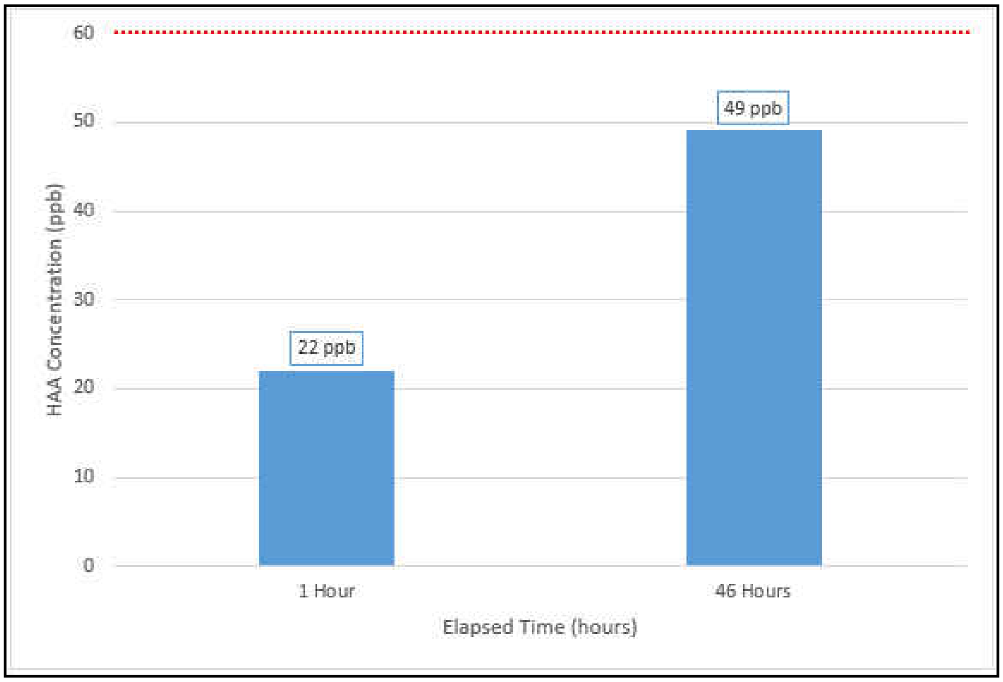

Figure 12: Waverly WTP Baseline HAA Formation

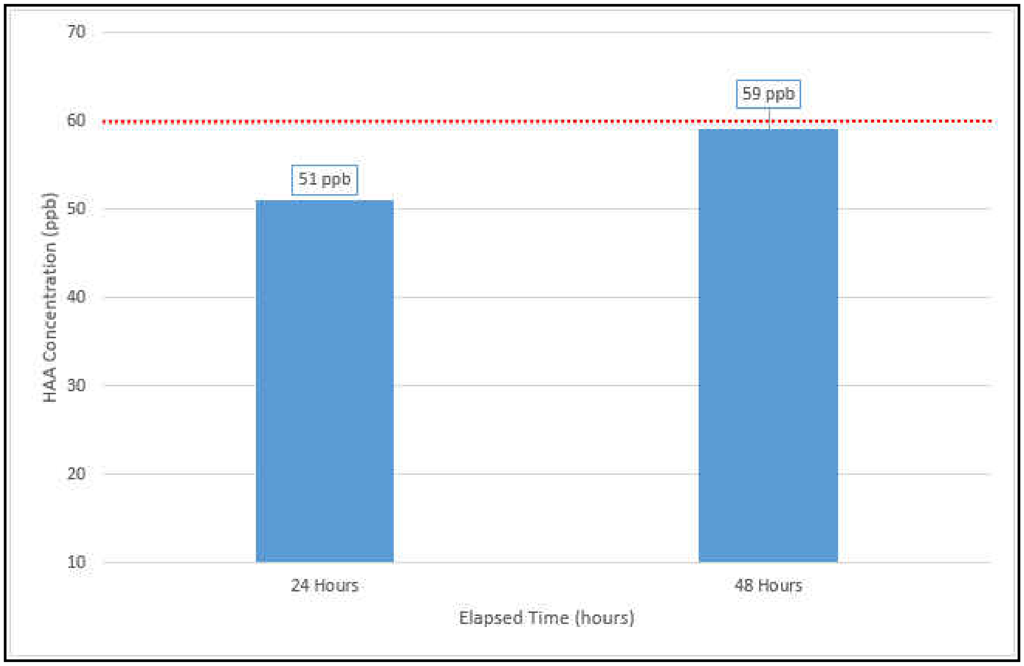

Figure 13: Hodge Street WTP Baseline HAA Formation

## Single-Pass Spray Aeration Assessment

Table 17 shows the water quality data that was obtained from the Hodge Street WTP during the spray aeration evaluation. To better evaluate the effects of the spray aeration on Hodge Street water quality, each water quality parameter was analyzed for both the spray-aerated and unaerated samples. The unaerated samples were labeled *Chlorinated Unaerated* and water that was passed through the spray aerator was defined as *Chlorinated Aerated*. Aside from dissolved oxygen concentration, basic water quality characteristics did not appear to be altered significantly with single-pass spray aeration.

Table 17: Hodge Street WTP Water Quality during Spray Aeration Study

| **Water Quality Parameter** | **Well (Raw)** | **Raw w/ Polymer** | **Chlorinated Unaerated** | **Chlorinated Aerated** | **POE** |
|---|---|---|---|---|---|
| Temperature (°C) | 27.3 | 27.4 | 27.4 | 27.1 | 29.2 |
| pH | 7.52 | 7.49 | 7.51 | 7.68 | 7.63 |
| Turbidity (NTU) | 0.55 | 1.06 | 0.58 | 0.68 | 1.05 |
| Conductivity (µS/cm$^2$) | 363 | 362 | 402 | 406 | 393 |
| Dissolved oxygen (mg/L) | 1.7 | 2.1 | 4.4 | 7.6 | 3.1 |
| Free chlorine (mg/L) | 0 | 0 | 2.4 | 2.6 | 1.5 |

Table 18 displays the TTHM concentrations of both the aerated and unaerated waters over the course of 48 hours. Figure 14 offers a graphical representation of this data. The unaerated water taken from the hydro-tank exceeded the EPA’s TTHM MCL after 7 hours. Passing the sample once through the spray aerator allowed the water to remain under the MCL for 17 hours. The water that was passed through the spray aerator experienced an immediate 29.5% reduction in TTHM concentration and a 15.7% reduction in TTHMs formed after 48 hours.

Table 18: Spray Aeration Effects on TTHM Concentration

| **Condition** | **Elapsed Time (hours)** | **TTHM Concentration (ppb)** |
|---|---|---|
| Unaerated | 0 | 44 |
| | 4 | 57 |
| | 7 | 82 |
| | 24 | 106 |
| | 48 | 108 |
| Aerated | 0 | 31 |
| | 4 | 41 |
| | 7 | 59 |
| | 24 | 87 |
| | 48 | 91 |

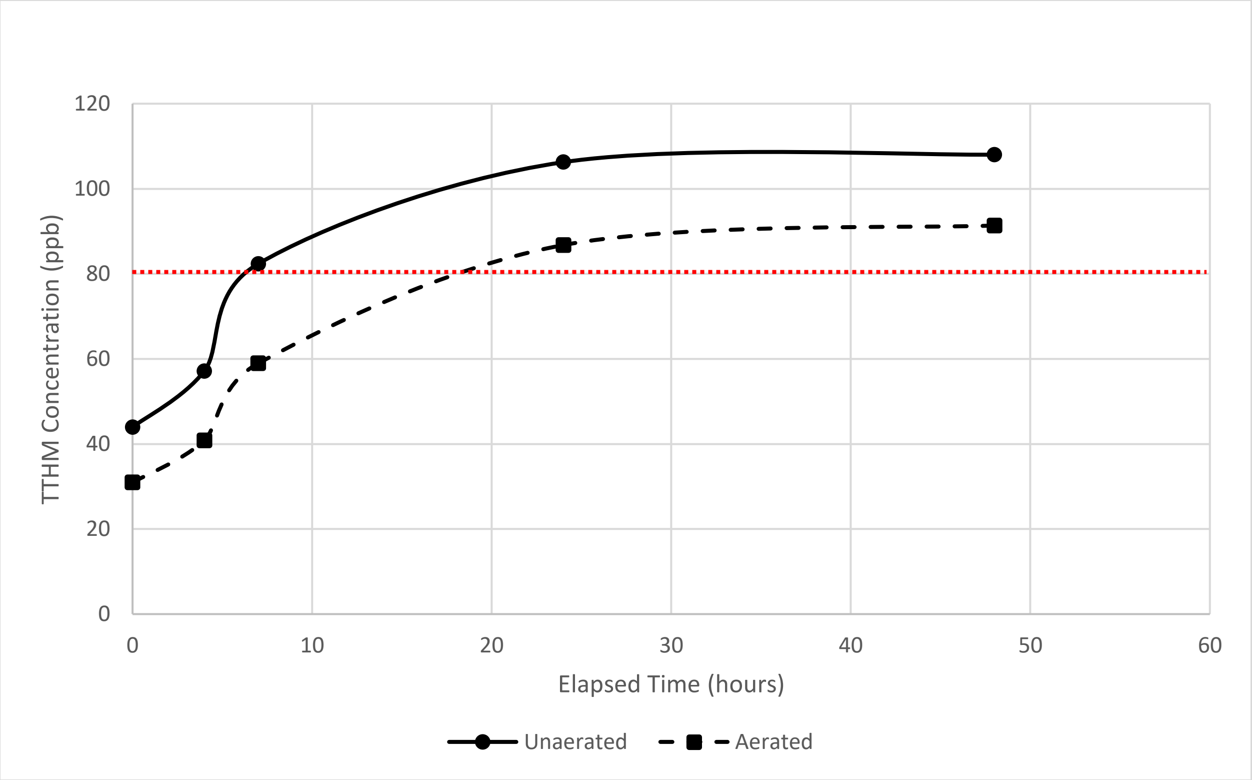

Figure 14: Spray Aerated vs Unaerated THM Formation

The concentrations given in Table 19 demonstrate that $HAA_5$ concentrations were unaffected by spray aeration; samples which had been incubated for equal periods of time had very similar concentrations regardless of whether they were aerated or not.

When the baseline DBP formation curves were generated, the hydro-tanks were flushed beforehand to allow for water collection immediately after chlorination before DBPs have had the chance to form. Conversely, for studies focused on removal such as this, it was necessary to use water which already possessed a certain concentration of DBPs. Water with a considerable residence time in the hydro-tank was used for this purpose. The TTHM concentration of this in situ water was 44 ppb. As a result, it is expected that the aeration DBPFP curves achieve MCL concentrations noticeably sooner than the baseline DBP curves. This discrepancy illustrates the importance of optimizing chlorine contact time and how, if mismanaged, variances in chlorine contact time can greatly affect DBP concentrations in the water.

Table 19: Hodge Street WTP in Situ HAA Data

| **Elapsed Time (hours)** | **Aerated $HAA_5$ Concentration (ppb)** | **Unaerated $HAA_5$ Concentration (ppb)** | **Average $HAA_5$ Concentration (ppb)** |
|---|---|---|---|
| 24 | 64 | 67 | 66 |
| 48 | 77 | 74 | 76 |

## Tray Aeration Assessment

The field samples taken prior to the assessment indicated an in situ TTHM concentration of 64 ppb, 20 ppb more than the in situ TTHM levels recorded during the spray aeration evaluation. Because ambient temperatures were comparable during the two months, the increase in concentration was attributed mostly to a greater detention time within the hydro-tank. Table 20 presents the TTHM removal and free chlorine residual as a result of successive passes through the tray aerator. The data is illustrated in Figure 15. The data displays a diminishing reduction of THMs after each successive pass indicating that, after 3 passes or so, additional passes have limited benefits. The TTHM concentration fell below detection after five passes. Free chlorine residual did not appear to be impacted noticeably by THM volatilization.

Table 20: TTHM Concentration and Chlorine Residual vs Number of Tray Passes

| **Sample** | **TTHM Concentration (ppb)** | **TTHM Removal Efficiency (%)** | **Free Chlorine Concentration (mg/L)** |
|---|---|---|---|
| Field sample | 64 | - | 2.8 |
| 0 passes | 62 | - | 1.6 |
| 1 pass | 33 | 46.7 | 1.5 |
| 2 passes | 19 | 69.4 | 1.5 |
| 3 passes | 12 | 80.6 | 1.5 |
| 4 passes | 9 | 85.5 | 1.5 |
| 5 passes | < 8 | > 85.5 | 1.5 |
| 6 passes | < 8 | > 85.5 | 1.4 |

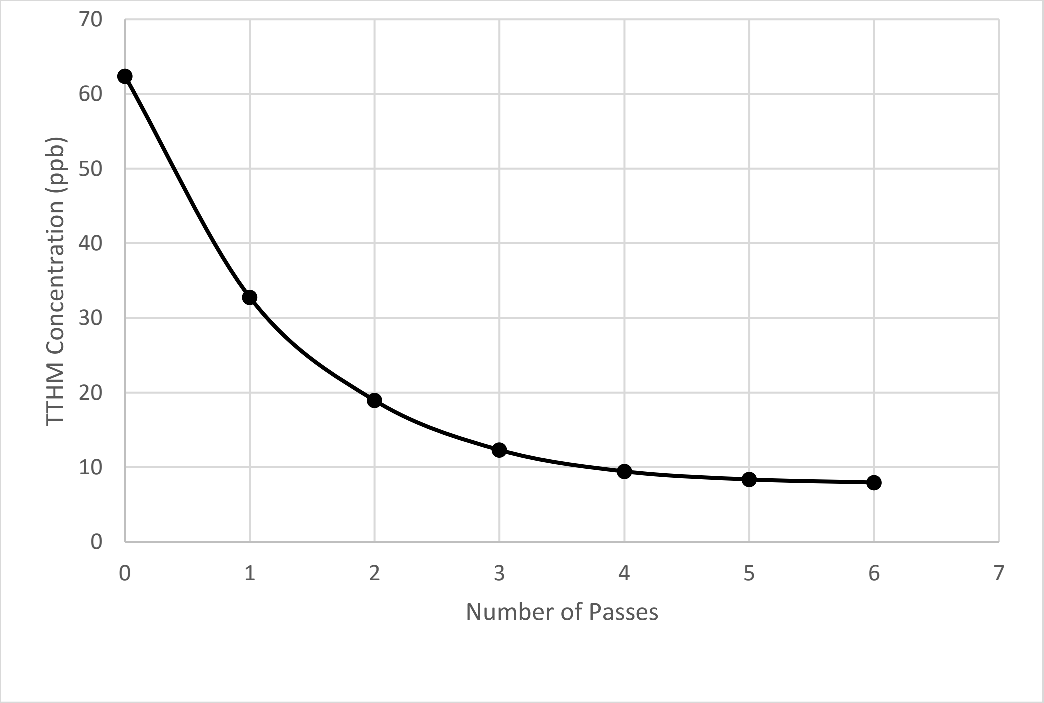

Figure 15: TTHM Concentration vs Number of Tray Passes

Results of the DBP re-formation analyses are shown in Table 21 while the re-formation of THMs is illustrated specifically in Figure 16 and Figure 17. While initial TTHM concentrations were unchanged between 2 hours and 12 hours of aeration, they had different re-formation capabilities. Free chlorine levels dropped to 0.05 mg/L after 12 hours of aeration, demonstrating the impracticality of such a lengthy tray aeration cycle in realistic operation.

Table 21: Re-formation Potential of Aerated Water

| **Aeration Time (hours)** | **Incubation Time (hours)** | **TTHM Concentration (ppb)** | **$HAA_5$ Concentration (ppb)** | **Free Chlorine Concentration (mg/L)** |
|---|---|---|---|---|
| 2 | 0 | < 8 | 59 | 1.20 |
| | 16 | 38 | 73 | 0.62 |
| | 22 | 52 | 75 | 0.48 |
| 12 | 0 | < 8 | 61 | 0.05 |
| | 14 | < 8 | 69 | 0.02 |
| | 29 | 10 | 69 | 0.01 |

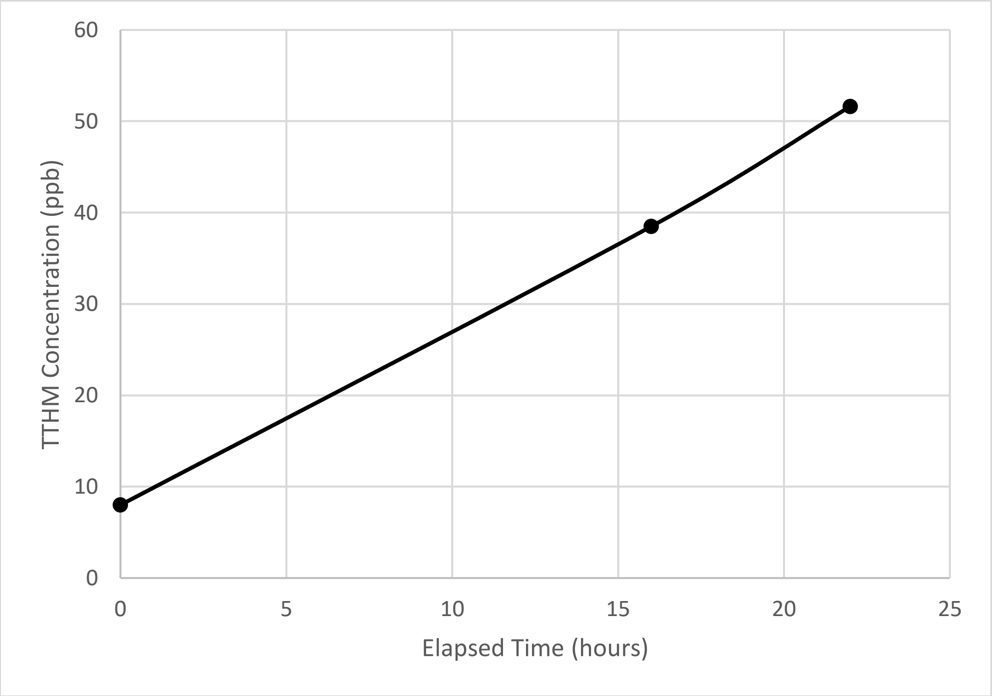

Figure 16: Re-formation Potential after 2-Hour Aeration (12 Passes)

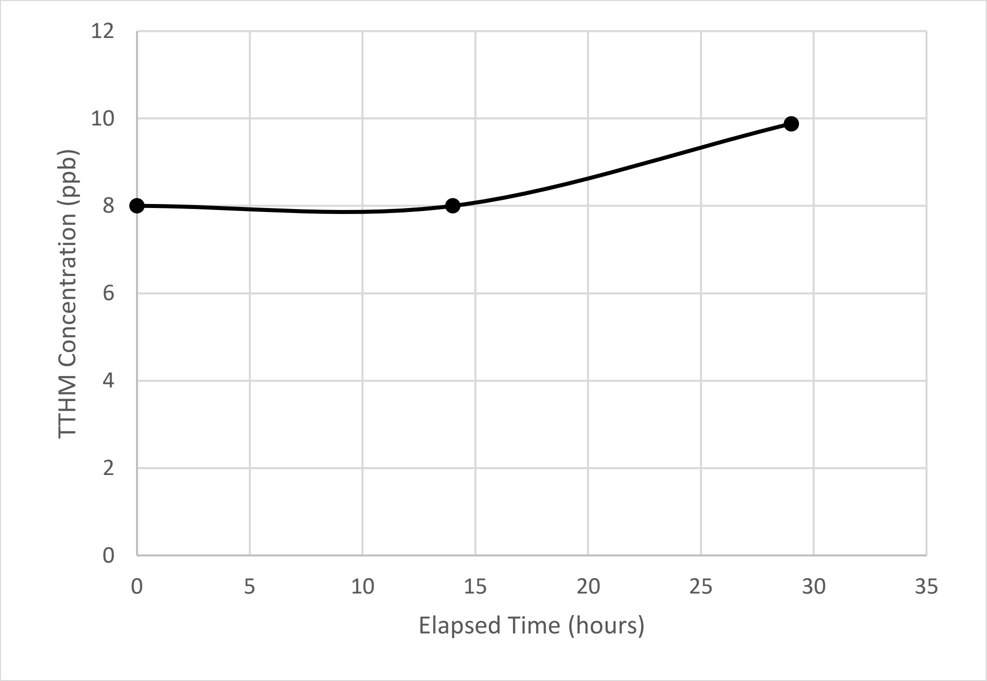

Figure 17: Re-formation Potential after 12-Hour Aeration (72 Passes)

Water that had been incubated after 2 hours of recirculation (12 passes) generated an average re-formation of 2 ppb of TTHMs per hour over 22 hours, rising to 52 ppb. After the water had been passed recirculated for 12 hours (72 passes), its THM formation rate was significantly less (an average of 0.069 ppb per hour over 29 hours) as was the ultimate TTHM concentration that was achieved. After over a full day of incubation, the 12-hour aerated sample possessed a non-detectable level TTHMs. This indicates that after a certain amount of aeration time, the TTHM formation potential of water becomes nearly exhausted. However, it is not feasible for a full-scale system to recycle water through a tray aerator 72 times. When analyzing the collected data, two to three passes appears to be the optimal choice for a realistic engineering design.

## GAC Bypass and Blending Simulation

### *Chlorine Demand*

To assess the feasibility of integrating GAC adsorption with aeration, each sample tested was initially dosed with sufficient sodium hypochlorite to provide a theoretical free chlorine concentration of 6.5 mg/L. The difference between this dose and the initial free chlorine residuals of each sample is the water's chlorine demand; chlorine demands for each sample are shown in Table 22. Typically, greater concentrations of NOM and inorganics such as sulfides correlate with a larger chlorine demand. The 100% raw water had the greatest chlorine demand, 3.1 mg/L, while the 50% blend's demand was only 2 mg/L. The 75% blend's demand fell between the two values at 2.1 mg/L.

Table 22: Initial Chlorine Demands

| | **100% Raw** | **75% Raw** | **50% Raw** |
|---|---|---|---|
| Chlorine Demand (mg/L) | 3.1 | 2.1 | 2.0 |

Chlorine consumption of the 100%, 75%, and 50% blended waters was monitored over 96 hours. The data is displayed in Table 23 and illustrated in Figure 18. The free chlorine residual in the 100% raw water dropped below 1 mg/L after 24 hours and was exhausted after 96 hours. Conversely, the 50% blend possessed a 2.4 mg/L chlorine residual after 96 hours. The chlorine residuals for the 75% blend tended to fall almost directly between the two extrema.

Table 23: Chlorine Consumption Over 96 Hours

| | **Free Chlorine (mg/L)** | | |
|---|---|---|---|
| **Elapsed Time (hours)** | **100% Raw** | **75% Raw** | **50% Raw** |
| 0 | 3.4 | 4.4 | 4.5 |
| 24 | 0.9 | 2.1 | 3.4 |
| 48 | 0.4 | 1.6 | 2.8 |
| 72 | 0.2 | 1.4 | 2.7 |
| 96 | 0.0 | 1.1 | 2.4 |

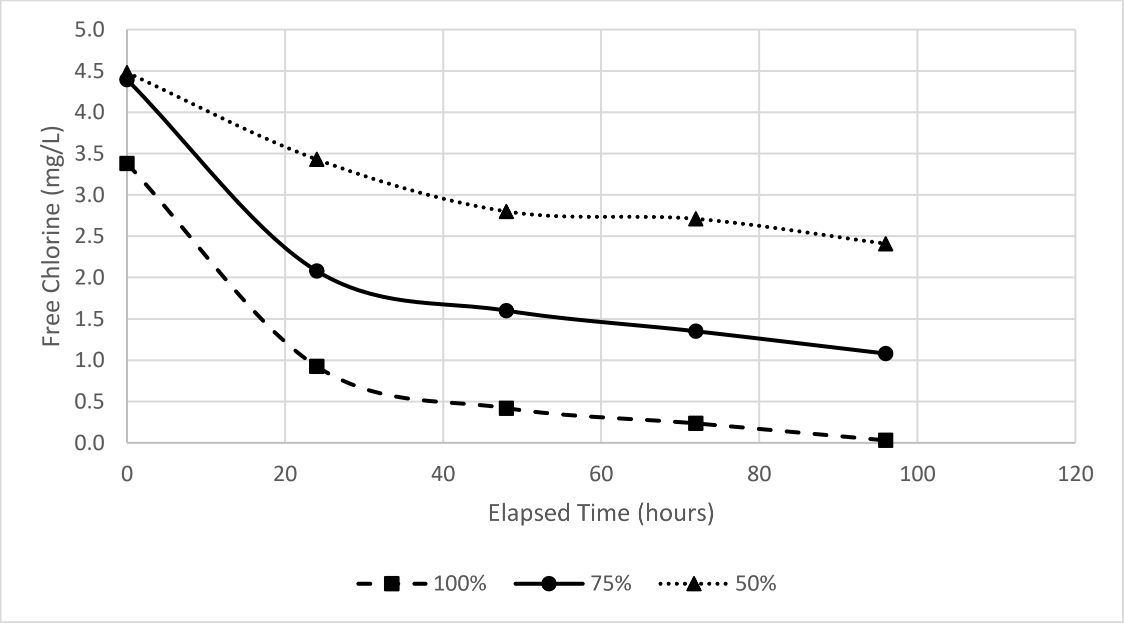

Figure 18: Chlorine Consumption of Various Raw Water Blends

When two different chlorine doses were applied, initial chlorine demands changed. As shown in Table 24, a lower chlorine dose corresponded with lower chlorine demands for both the 100% raw water and the 50% blend. The 75% blend was not studied in subsequent simulations.

Table 24: Initial Chlorine Demands of Different Doses

| | **6.5 mg/L Chlorine Dose** | | **3.25 mg/L Chlorine Dose** | |
|---|---|---|---|---|
| | **100% Raw** | **50% Raw** | **100% Raw** | **50% Raw** |
| Chlorine Demand (mg/L) | 3.2 | 1.7 | 2.2 | 1.4 |
| % of Chlorine Dose | 49% | 26% | 66% | 42% |

Chlorine consumption of the 100% and 50% waters at the two different chlorine doses is included in Table 25. The demand curves were conducted over 48 hours as opposed to the 96-hour curves used in the first trial. Figure 19 shows the demand curve for the higher chlorine dose, while Figure 20 displays the demand curve of the lower chlorine dosage. Both the 100% raw water and the 50% blend had a free chlorine residual remaining after 48 hours when the 6.5 mg/L chlorine dose was applied. Conversely, when dosed at 3.25 mg/L of free chlorine, the 100% raw water had a residual of 0.02 mg/L after 24 hours while the 50% blend possessed a residual of 0.5 mg/L after the same 24-hour period.

Table 25: Free Chlorine Residual of Different Doses Over 48 Hours

| | **6.5 mg/L Chlorine Dose** | | **3.25 mg/L Chlorine Dose** | |
|---|---|---|---|---|
| **Elapsed Time (hours)** | **100% Raw** | **50% Raw** | **100% Raw** | **50% Raw** |
| 0 | 3.3 | 4.8 | 1.1 | 1.9 |
| 24 | 1.2 | 3.3 | 0.02 | 0.5 |
| 48 | 0.6 | 2.7 | 0.02 | 0.3 |

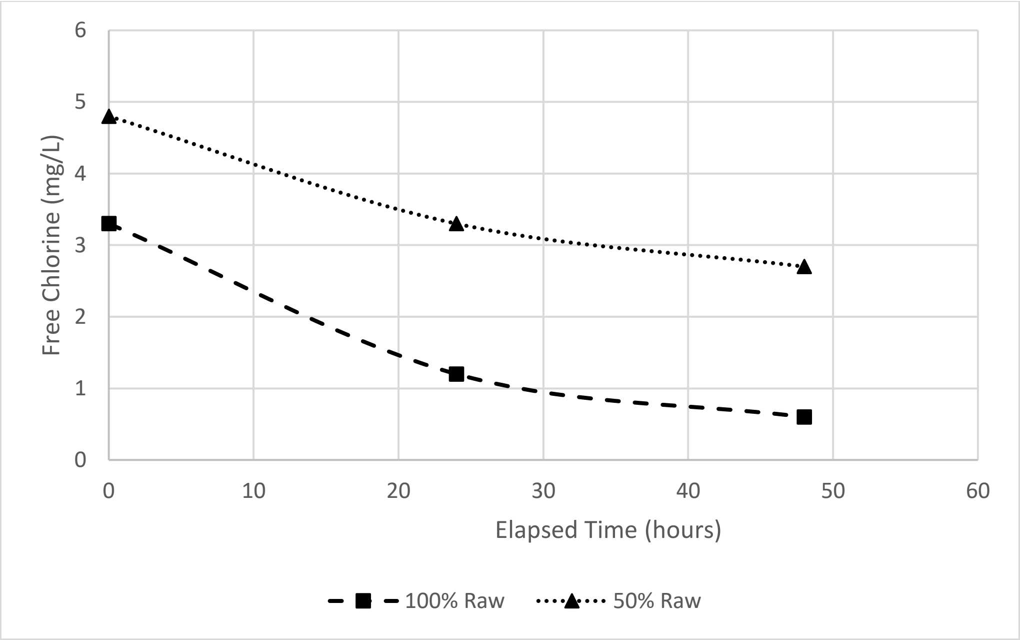

Figure 19: 6.5 mg/L Chlorine Dose

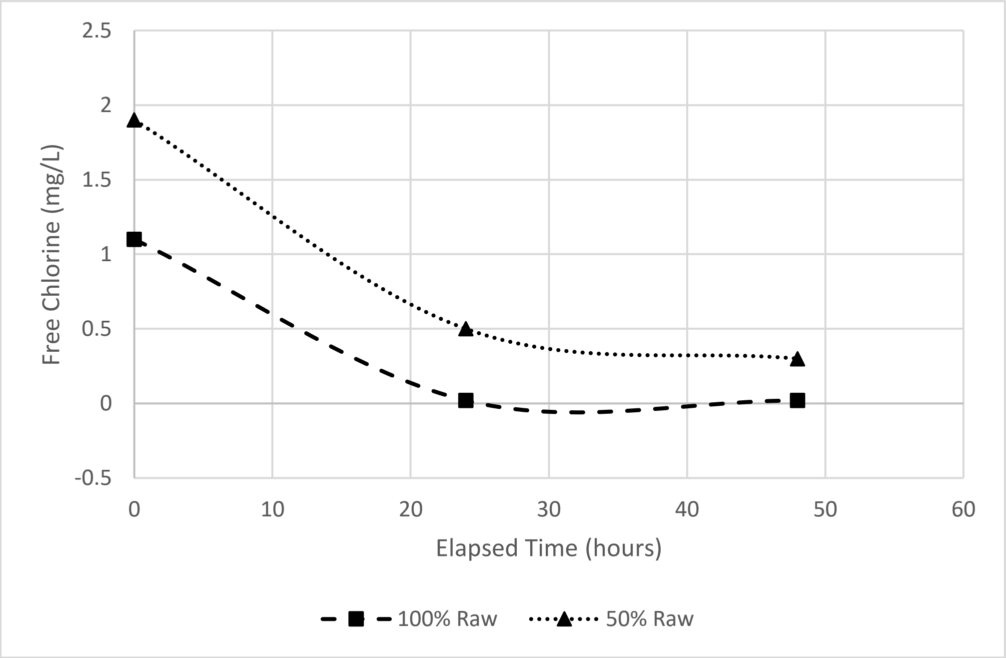

Figure 20: 3.25 mg/L Chlorine Dose

*TTHM Analysis*

A slightly larger chlorine residual was used than what is typically aimed for at the Hodge Street facility (3.4 mg/L vs 3.0 mg/L). This required the previously-mentioned chlorine dose of 6.5 mg/L. Because of these factors, both DBP formation kinetics and ultimate concentrations were greater than what is typically experienced at the facility. The THM formation over 96 hours is displayed in Table 26 and conveyed graphically in Figure 21.

The 100% raw water exceeded the established TTHM MCL of 80 ppb after approximately 17 hours, the 75% blend after approximately 26 hours, and the 50% blend after approximately 42 hours. After the test period concluded, the formation curves possessed an upward trend, indicating that formation of THMs was still occurring.

Table 26: TTHM Concentrations Over 96 Hours with 6.5 mg/L Chlorine

| **Elapsed Time (hours)** | **TTHM Concentration (ppb)** | | |
|---|---|---|---|
| | **100% Raw** | **75% Raw** | **50% Raw** |
| 0 | 0 | 0 | 0 |
| 24 | 101 | 75 | 58 |
| 48 | 124 | 108 | 85 |
| 72 | 138 | 111 | 93 |
| 96 | 146 | 123 | 102 |

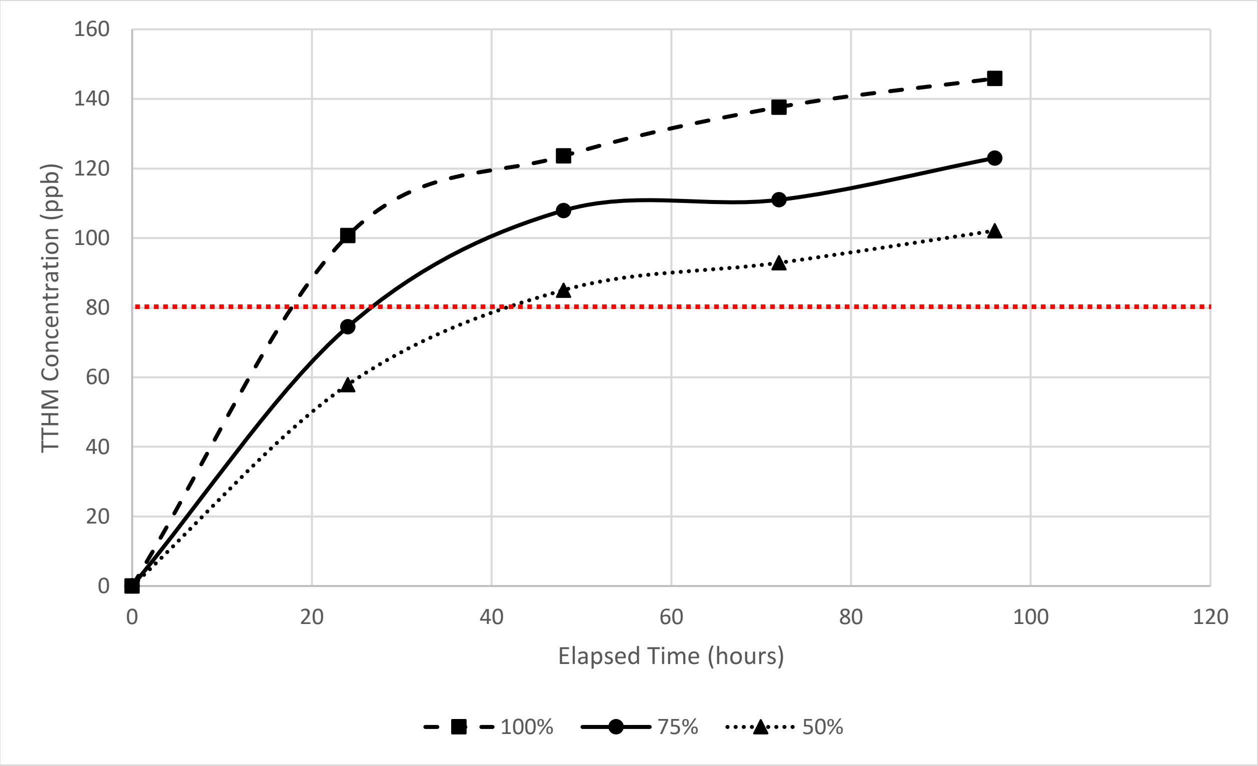

Figure 21: THM Formation of Blended Waters

Figure 22 shows the previously constructed baseline THM formation curve collected from the Hodge Street facility. This water was chlorinated by the facility's disinfection process and collected from the plant's hydro-pneumatic tank. As the time-zero value indicates, this water had resided in the hydro-tank long enough to allow a concentration of 18 ppb of TTHMs to be present. Because this water was not diluted, it should be compared with the 100% raw water's curve in Figure 21. The historical curve surpasses the MCL sooner than the study's 100% raw water curve, but this can be partially attributed to the fact that the water collected from the hydro-tank already had a measurable concentration of THMs.

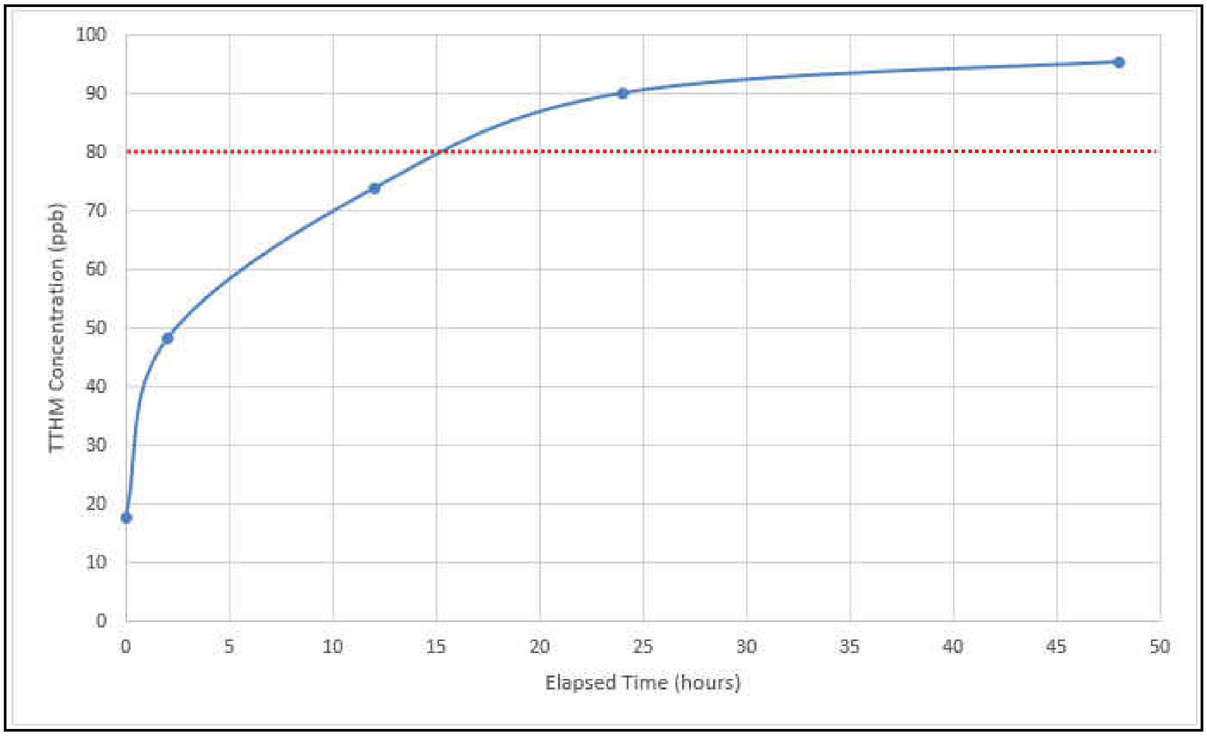

Figure 22: Pre-established Hodge Street THM Curve (August 2017)

*HAA Analysis*

The first HAA analysis was conducted using the same incubation temperature as the THM curves (6.5 mg/L and 30°C). Four (4) HAA samples were transported from UCF to AEL for analysis. Each water had a single sample incubated for 24 hours with a duplicate for the 100% raw water. Results indicated that 24 hours after chlorination, the MCL of 60 ppb had not been exceeded by any sample. After 24 hours, the 100% raw water had an $HAA_5$ concentration of 56 ppb, the 75% blend had a concentration of 44 ppb, and the 50% blend had a concentration of 33 ppb. Table 27 conveys this data while Figure 23 relates the values graphically to the MCL.

Table 27: 24-Hour HAA Formation

| | **100% Raw** | **100% Raw Duplicate** | **75% Raw** | **50% Raw** |
|---|---|---|---|---|
| **24-Hour $HAA_5$ Concentration (µg/L)** | 56 | 55 | 44 | 33 |

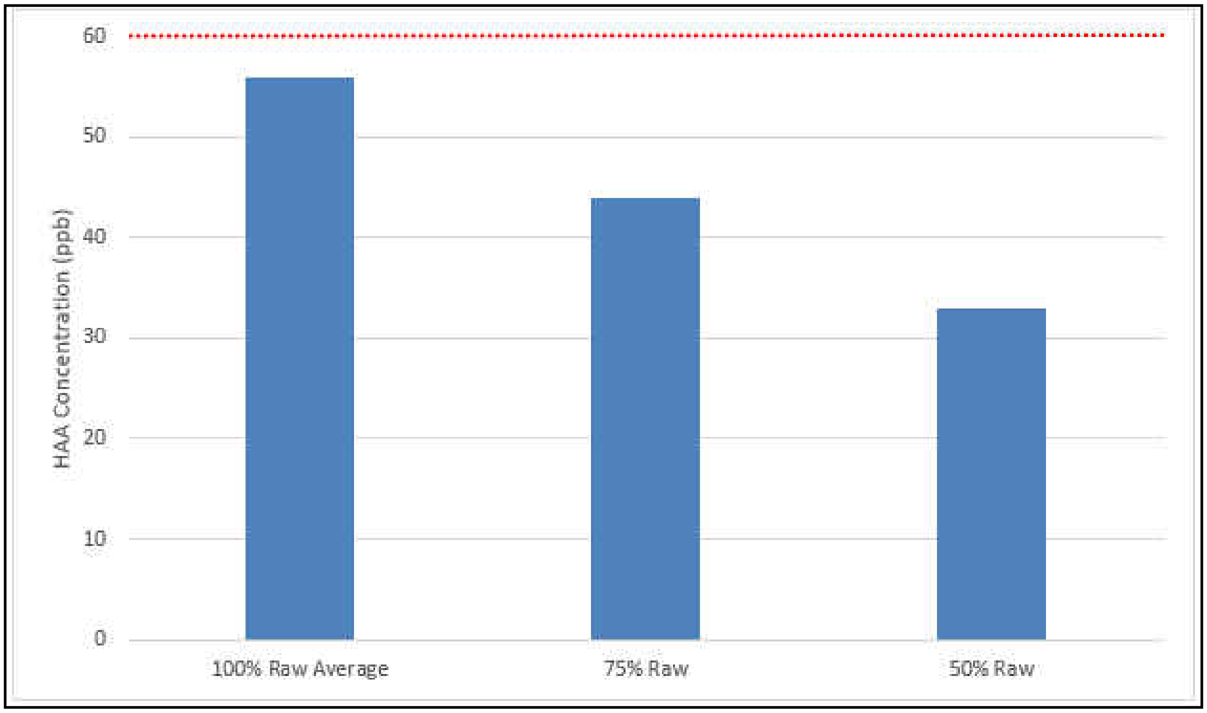

Figure 23: 24-Hour HAA Formation

When the effects of the two chlorine doses were compared, the 100% raw water dosed with 6.5 mg/L of chlorine possessed the same $HAA_5$ concentration after 24 hours as it did in the first trial (55 ppb). After 48 total hours of incubation, this 100% raw water's $HAA_5$ concentration increased to 72 ppb. This was the singular sample to exceed the 60 ppb MCL. The 50% blend that received the 6.5 mg/L chlorine dose experienced an increase of only two ppb between the 24-hour and 48-hour incubation periods. When the lower chlorine dose of 3.25 mg/L was applied to the waters, negligible changes in the $HAA_5$ concentrations occurred between the 24-hour and 48-hour incubation periods. This re-formation data is summarized in Table 28 and shown graphically in Figure 24 and Figure 25.

Table 28: $HAA_5$ Re-formation at Different Blends and Chlorine Doses

| | **6.5 mg/L Chlorine Dose** | | **3.25 mg/L Chlorine Dose** | |
|---|---|---|---|---|
| **Elapsed Time (hours)** | **100% Raw Water** | **50% Raw Water** | **100% Raw Water** | **50% Raw Water** |
| 24 | 55 ppb | 44 ppb | 14 ppb | 27 ppb |
| 48 | 72 ppb | 46 ppb | 14 ppb | 27 ppb |

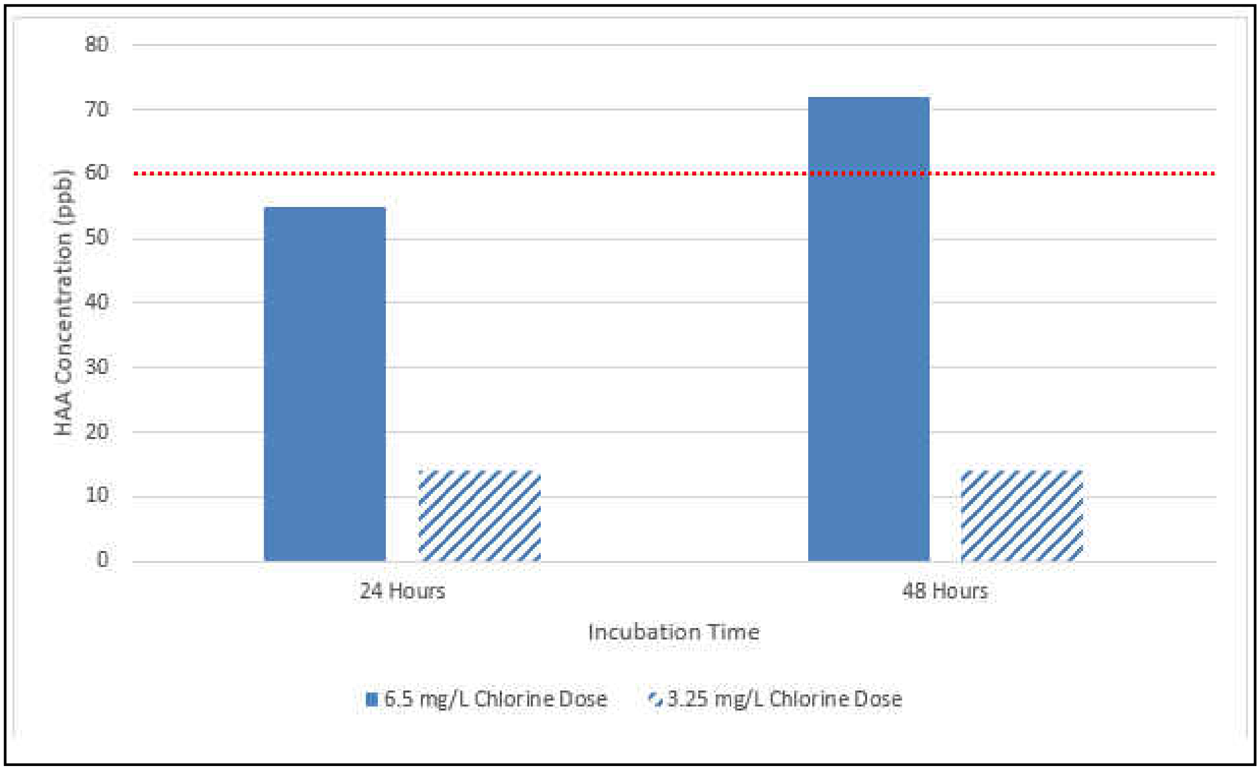

Figure 24: HAA Formation of 100% Raw Water

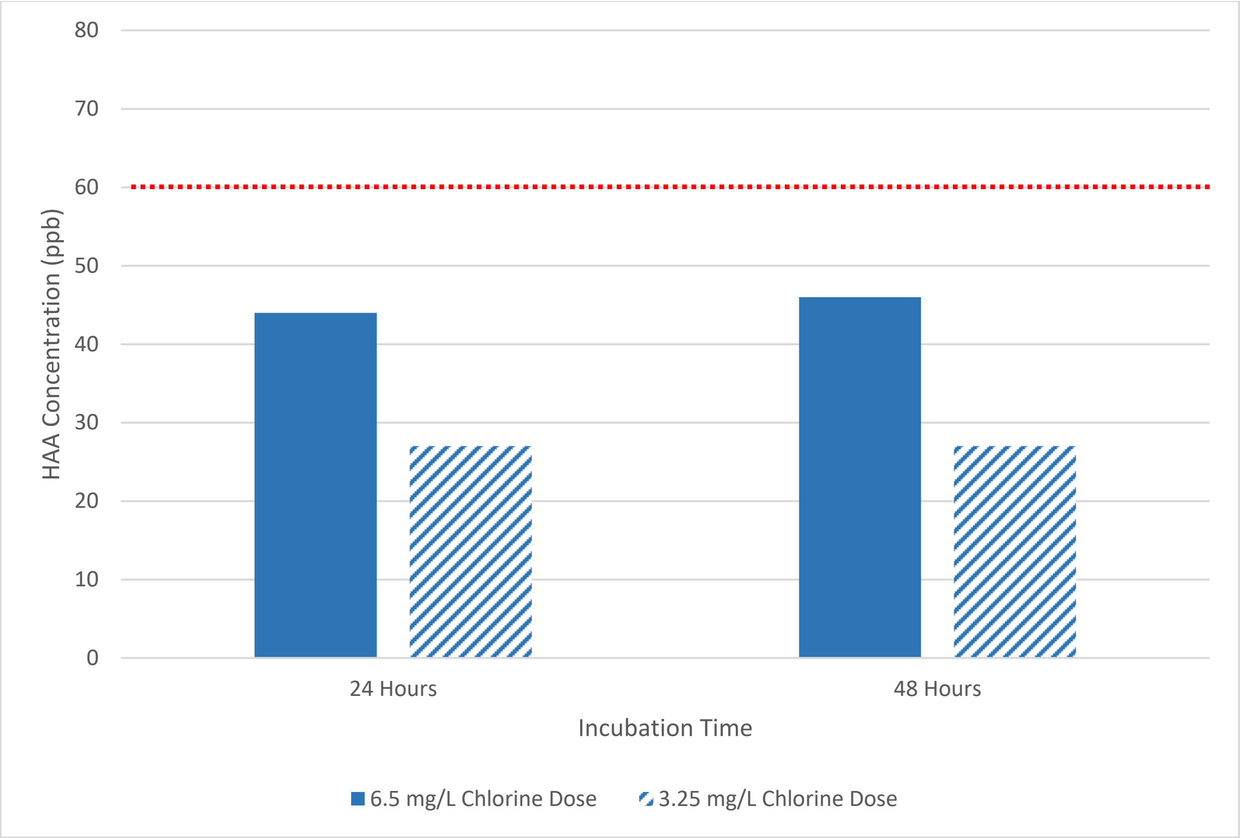

Figure 25: HAA Formation of 50% Blend

## Statistical Analysis

Accuracy and precision control charts were constructed as according to the methods described in the previous chapter. The THM samples prepared via liquid-liquid hexane extraction and analyzed by gas chromatography were analyzed for precision and accuracy. The QC charts for precision is shown in Figure 26 while Figure 27 displays the control chart for accuracy. One data point exceeded the control limit in the precision chart and was discarded from the data.

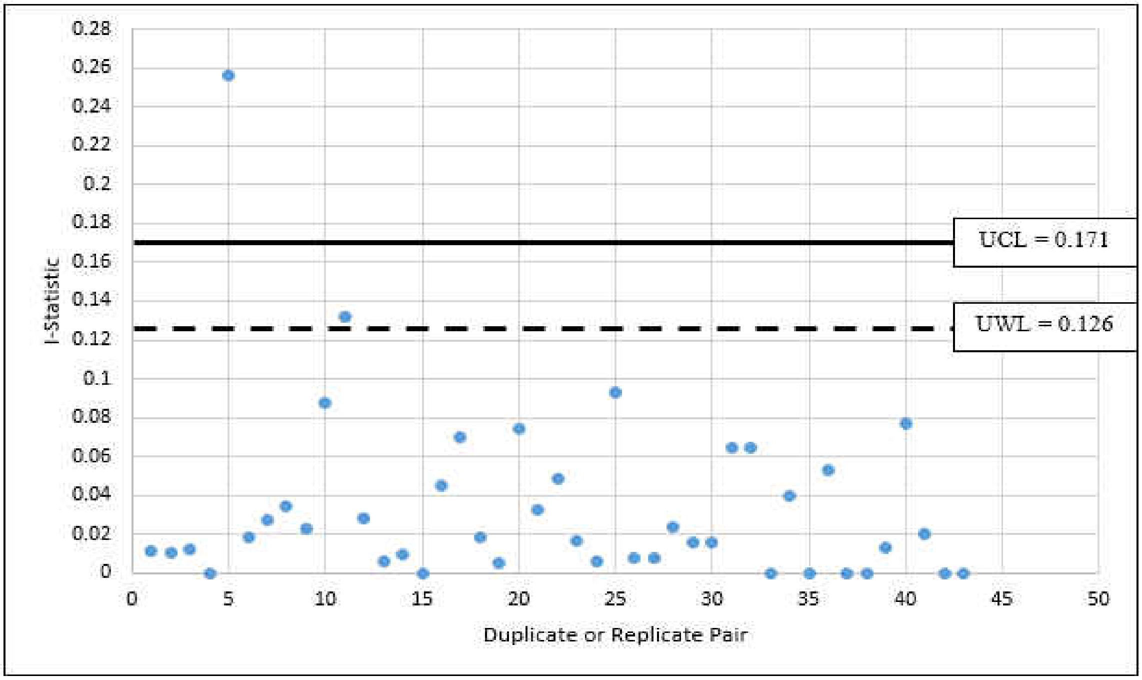

Figure 26: Control Chart for THM Precision

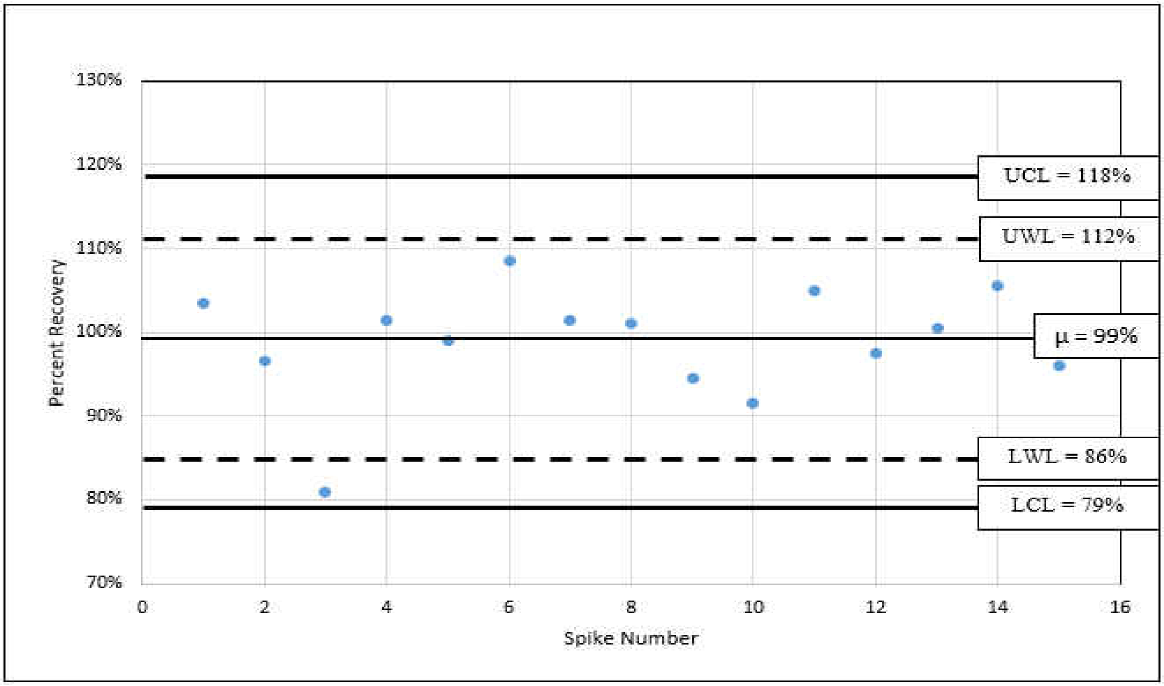

Figure 27: Control Chart for THM Accuracy

# CHAPTER SIX: CONCEPTUAL COST CONSIDERATIONS

## Conceptual Plan

Upon completion of the studies, a conceptual plan was developed for the Waverly PWS. Hodge Street's current treatment process is shown in Figure 28 accompanied by some brief notes in Table 29. It is compared with two suggested systems (one temporary and one master). Each process option has some pros and cons listed and was given an overall rating. The first improvement suggested for the Hodge Street WTP is the addition of a 100,000 to 150,000-gallon ground storage tank, based on fire flow requirements; the ground storage tank should be equipped with a tray aerator and an internal recycle line to allow for recirculating aeration. Table 30 conveys a few notes about the theoretical system and a general schematic is shown in Figure 29. This improvement would greatly reduce the TTHM concentrations in the distribution system; however, the formation of the HAA species is not curtailed by this option. Also, this option only removes formed DPBs and does not pre-emptively reduce DBPFP. Therefore, a master plan that addresses both DBPs as well as DBPFP was also developed. The master plan compliments the suggested recirculating tray aeration with the addition of a side-stream GAC adsorption operation, as shown in Figure 30. Some pros and cons of the master plan are presented in Table 31. The carbon adsorption upstream of the storage tank will remove organic precursors as well as certain dissolved substances and inorganics, effectively reducing the FP of both THMs and HAAs. In addition, the GAC's removal of these substances should greatly reduce chlorine consumption rate and, consequently, distribution system flushing. Water may also be bypassed around the GAC vessels as needed to reduce carbon utilization and reduce costs.

Table 29: Hodge Street Option 1: Current Operations

| **PROS** | **CONS** |
|---|---|
| Simplest operation | Does not remove NOM or synthetic organics |
| No recycle expenses | No aeration for volatile compound removal |
| No additional capital costs or materials needed | May struggle in maintaining EPA compliance |
| OVERALL RATING | ○ |

○ NEEDS IMPROVEMENT ◐ GOOD ● EXCELLENT

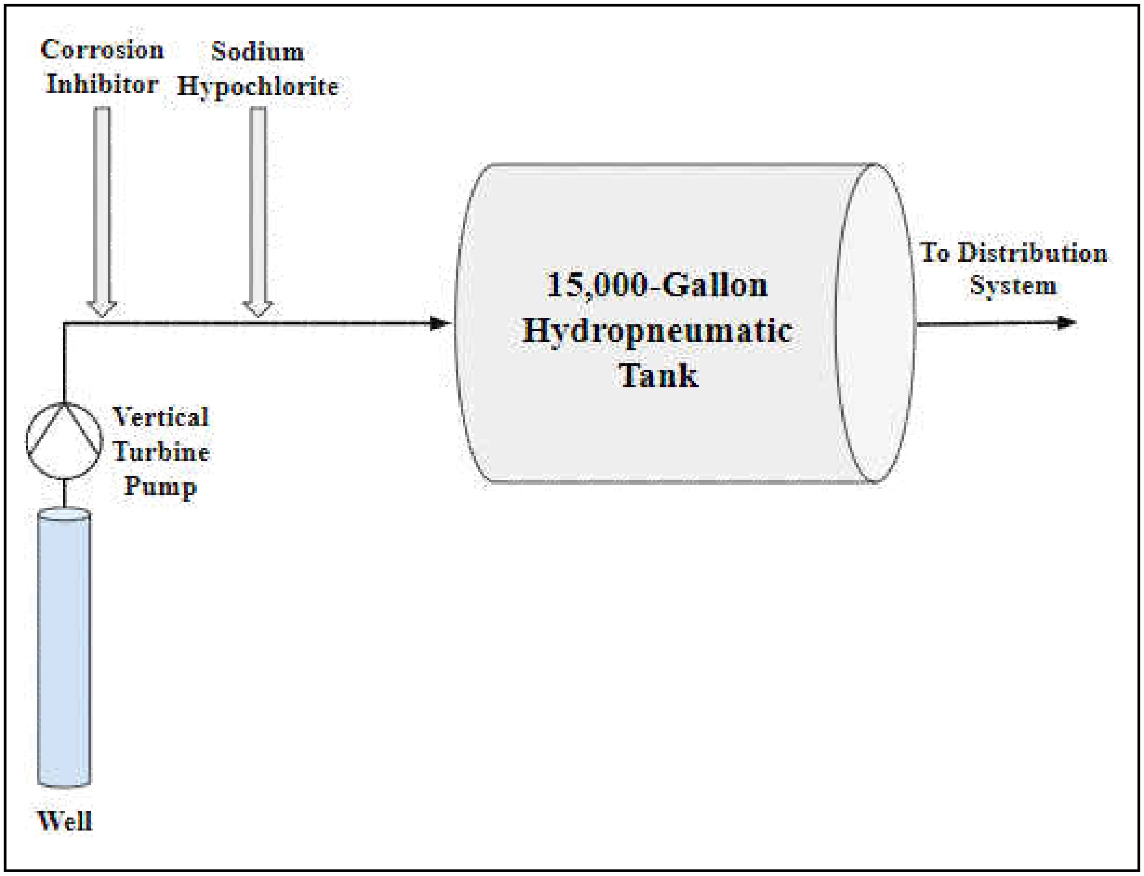

Figure 28: Hodge Street WTP Current Operations

Table 30: Hodge Street Option 2: Ground Storage Tank with Recirculating Tray Aeration

| PROS | CONS |
|---|---|
| Relatively simple operation | Captial costs will be incurred |
| Provides aeration for THM control | Does not address HAA formation or removal |
| Recirculation is variable to allow for system flexibility | Does not remove NOM or synthetic organics; only removes THMs after they are formed |
| OVERALL RATING | ◐ |

○ NEEDS IMPROVEMENT ◐ GOOD ● EXCELLENT

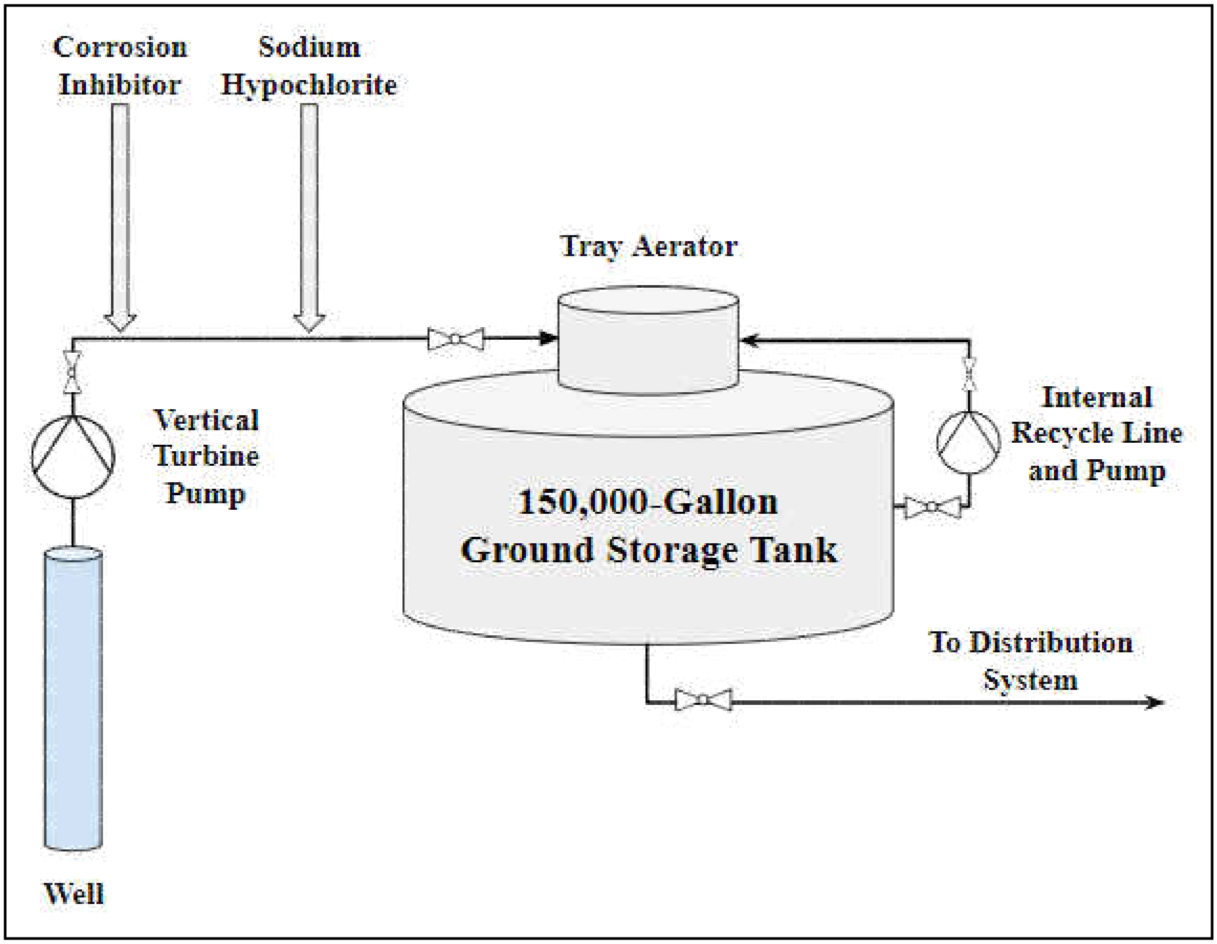

Figure 29: Hodge Street WTP with Recirculating Ground Storage Tank

Table 31: Hodge Street Option 3: Master Plan with Aeration and Adsorption

| PROS | CONS |
|---|---|
| Provides the best control for variable influent | More operational attention is needed |
| Controls formation of THMs and HAA | Greatest capital costs |
| Bypass allows for system flexibility | |
| OVERALL RATING | ● |

○ NEEDS IMPROVEMENT ◐ GOOD ● EXCELLENT

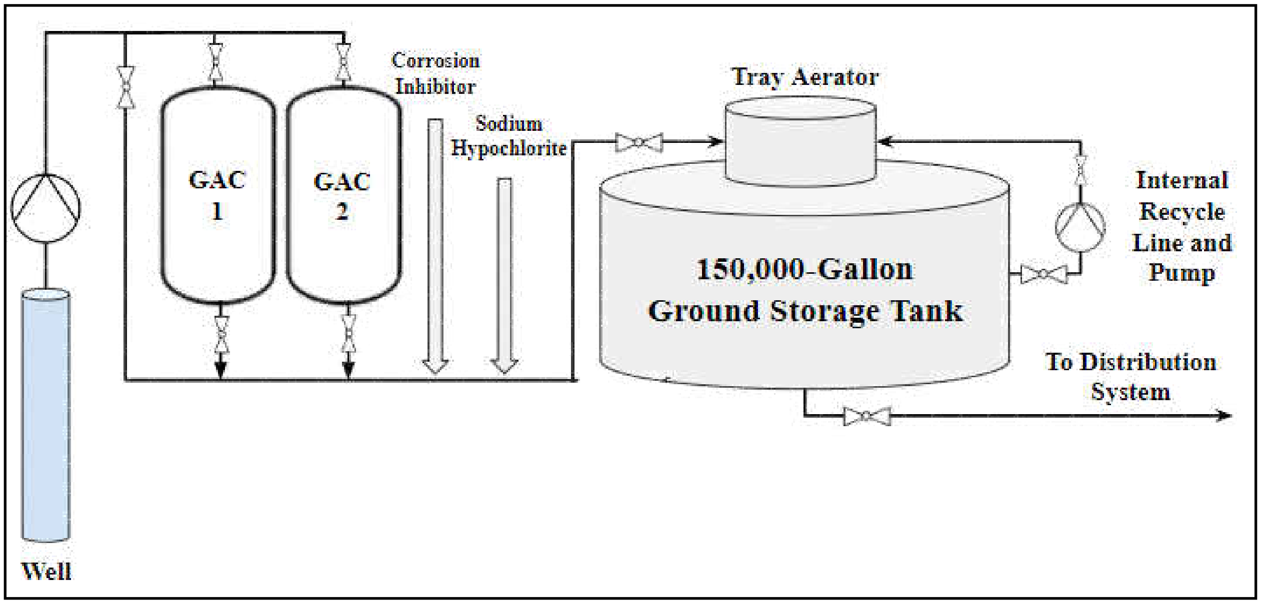

Figure 30: Hodge Street WTP Master Plan with Aeration and Adsorption

The installation of variable frequency drive (VFD) motors on pumps should be considered as it will allow for increased control over a broader range of flow demands. The VFD addition may be coupled with flow throttling via valves for maximum control in regulating the bypass and blending around the GAC operation. Another area of interest regarding the GAC process is its ability to operate in biological mode. The growth of specific microbes can support NOM removal either with or without the assistance of pre-ozonation or other pre-oxidizing processes. The ability of favorable microbes to grow onto GAC media is highly dependent on the water's chemistry and, thus, water quality should be analyzed to determine which microbial species can be supported. Additional studies may wish to expound on biological operation and explore its efficacy at removing organic compounds and/or inorganic nutrients. Lastly, multiple tray aerators with differing surface areas could have their stripping efficacies compared to determine the most appropriately-sized tray aerator for the improved system.

Previous studies conducted by UCF have investigated the efficacy of using BAC adsorption to remove DBP precursor material. Pilot and full scale tests were conducted at the Babson Park WTP #2 and the Imperial Lakes WTP, both in Polk County, FL. The pilot runs demonstrated an approximate average removal of 40% of the influent dissolved organic carbon (DOC). Full scale monitoring at the two facilities revealed an average DOC removal of 55%. The conclusion was that BAC adsorption could be a viable treatment option for the Babson Park #2 facility (Duranceau & Yoakum, 2017). However, differences in water chemistry (i.e. sulfide species/concentrations, organic and inorganic profiles) can impact BAC's removal efficacies. Therefore, it cannot be assumed the DBP precursor removal experienced at the Hodge Street facility by BAC will be equal to the reductions experienced at the Babson Park #2 facility.

Table 32 displays an example of a schedule for operating the internal recycle pump. A batch-type concept may be implemented where pre-determined flows of water are pumped into a ground storage tank and ceased before the water in the hydro-tank begins to be recirculated through the aerator. The entire volume of the ground storage tank need not be filled entirely; smaller batches of water may be chosen for recirculation, depending on current daily demand or other factors. The recycling periods should occur when the potable water demand is not particularly high. It is recommended that times be altered to best suit the system and its demands. 12 hours has been chosen in this example because, at a recirculation flow of 250 gpm, it would take 12 hours to recycle the maximum monthly average flow (60,000 gpd) three times. These 12 hours could be divided into three periods of four hours, four periods of three hours, or in a way that best suits the operators. A batch-type concept is flexible for small systems, allowing the volume of water being recirculated as well as the recirculation periods to be adjusted to allow for operational freedom.

Table 32: Example Recirculating Operation Schedule

| **Time** | **Recirculating Aeration Status** |
|---|---|
| 12:00 am – 2:00 am | Off |
| 2:00 am – 6:00 am | On |
| 6:00 am – 12:00 pm | Off |
| 12:00 pm – 4:00 pm | On |
| 4:00 pm – 8:00 pm | Off |
| 8:00 pm – 12:00 am | On |
| 11:00 pm – 12:00 am | Off |

## Economic Comparison

The maximum monthly average flow for the Hodge Street plant is about 60,000 gpd, which equates to approximately 42 gpm if the water flows continuously. However, in reality, this is not how the plant operates. If the pump is run for four hours a day, the flow through the GAC vessels would be approximately 250 gpm. The well pump at the Hodge Street WTP is rated at 1,500 gpm, suggesting that the selected flow rate and time of pump operation seem appropriate to provide the facility with 60,000 gallons of water in a day.

When looking to reduce carbon usage, the ability to bypass water around the GAC reactors and blend with the treated water is an effective and economical option. The operational flow of 250 gpm (flowing 4 hours per day) would result in a carbon utilization rate of 24 lbs. per day to meet the maximum average monthly demand. Using the unit price of $2 per lb. of carbon, this equates to approximately $18,000 per year (Redding, 2017).

When considering different GAC contactor units, there may be considerable capital cost differences, depending on size and manufacturer. If influent TOC remains relatively constant, the carbon usage will vary directly with the total amount of water passed through the GAC beds. Table 33 shows theoretical effluent TOC concentrations and carbon utilization that would result at different bypass percentages while using the previously-described flow regime of 250 gpm pumped over 4 hours. Additional evaluations are recommended to explore what TOC reduction is satisfactory for sufficiently limiting DBP formation and to minimize the amount of water passed over the beds. This will result in lower annual carbon replacement costs. The system can also be implemented as a seasonal operation, if necessary. Because water temperature increases and DBP levels rise during the months from May to October, the choice of when to run the system as described or keep it on standby can be made by the County as needed.

Table 33: Bypass Percentage vs Effluent TOC and Carbon Utilization

| % Bypass | Flow to GAC (gpm) | Flow Bypassing GAC (gpm) | Effluent TOC (mg/L) | Daily Carbon Utilization (lbs.) | Annual Carbon Cost |
|---|---|---|---|---|---|
| 100% | 0 | 250 | 3.60 | 0 | $ 0 |
| 90% | 25 | 225 | 3.31 | 2 | $ 1,460 |
| 80% | 50 | 200 | 3.02 | 5 | $ 3,650 |
| 70% | 75 | 175 | 2.73 | 7 | $ 5,110 |
| 60% | 100 | 150 | 2.44 | 10 | $ 7,300 |
| 50% | 125 | 125 | 2.15 | 12 | $ 8,760 |
| 40% | 150 | 100 | 1.86 | 15 | $ 10,950 |
| 30% | 175 | 75 | 1.57 | 17 | $ 12,410 |
| 20% | 200 | 50 | 1.28 | 19 | $ 13,870 |
| 10% | 225 | 25 | 0.99 | 22 | $ 16,060 |
| 0% | 250 | 0 | 0.70 | 24 | $ 17,520 |

The three different treatment strategies should be compared with regard to their economic feasibility. For the purposes of this document, the capital analysis assumes that each strategy will result in similar capital costs; consequently, the analysis used in this report will focus on operational considerations. Because the operation of the 1,500 gpm well pump is dependent upon demand and is identical with each treatment method, its cost will not be included. The recycle pump, on the other hand, may operate 9-14 hours a day recirculating water through the aerator and its cost must be considered. As previously mentioned, the storage tank may undergo a recirculation cycle with smaller volumes of water to lessen wear on the pump and associated costs. Recirculating the maximum monthly average flow (60,000 gpd) three times through the tray aerator would take 12 hours at a flow rate of 250 gpm. The calculations for the cost of running the recycle pump 12 hours a day at 80 psi with a pump efficiency of 70% are shown here in equation (6-1):

$$250\,\frac{gal}{min} * \left(\frac{60\,min}{hour}\right) * 12\,hours * \left(\frac{8.345\,lbs}{gal}\right) = 1{,}502{,}100\,lbs \qquad (6\text{-}1)$$

$$1{,}502{,}100\,lbs * (80\,psi) * \left(\frac{2.31\,ft\,head}{psi}\right) = 277{,}588{,}080\,ft - lbs$$

$$277{,}588{,}080\,ft - lbs * \left(\frac{kWh}{2{,}655{,}220\,ft - lbs}\right) = \frac{104.5\,kWh}{.7} = 149.3\,kWh$$

$$149.3\,kWh * \left(\frac{\$0.12}{kWh}\right) = \frac{\$17.92}{day} * \left(\frac{365\,days}{year}\right) = \frac{\$\,6{,}541}{year}\ or\ \approx \$\,6{,}500\,annually$$

Thus, the annual costs for GAC adsorption are more than the two aeration costs. Even if 50% of the influent is bypassed around the GAC beds, the cost remains nearly double that of spray and tray aeration. More water may be bypassed to keep the cost of GAC treatment competitive with the other two methods; however, the DBP formation potential of Hodge Street water may cause compliance issues if there is a sufficient TOC concentration in the effluent. The annual costs of each strategy are presented in Table 34.

Table 34: Economic Comparison of Alternate Strategies

| **Treatment Strategy** | **Recirculation Costs ($/year)** | **Carbon Replacement Costs ($/year)** | **Annual Costs ($/year)** |
|---|---|---|---|
| Spray aeration | $ 6,500 | n/a | $ 6,500 |
| Tray aeration | $ 6,500 | n/a | $ 6,500 |
| GAC adsorption | n/a | $ 17,520 | $ 17,520 |
| GAC + aeration | $ 6,500 | $ 17,520 | $ 24,020 |

# CHAPTER SEVEN: CONCLUSIONS AND RECOMMENDATIONS

The findings from the compilation of studies and recommended responses are as follows:

- The County's raw water, particularly from the Hodge Street WTP, has a considerable immediate chlorine demand. Studies of the facility's raw water have shown instances where an initial free chlorine dose of 6.5 mg/L falls to a residual of 3.1 mg/L within one minute. On more than one occasion, the free chlorine residual decreased by more than 1 mg/L between Hodge Street's hydro-tank and the facility's POE, indicating stagnation. Other times, the drop in free chlorine between the same two points was only 0.1 mg/L. Investigation of the Waverly PWS and development of a protocol for mapping the water quality throughout the system is recommended. A protocol of this sort would provide a more detailed and accurate representation of the water chemistry at different points throughout the distribution system. Water quality mapping may be implemented via sample collection and/or use of a computerized hydraulic model. It is recommended that these samples be taken repeatedly at different times of the year and day, ensuring that sufficient samples be taken during worse-case conditions for DBPs (Mid-day during late summer).
- On average, chloroform comprised over 80% of the THM species in the Waverly system's finished water, followed by BDCM (≈ 16%), DBCM (≈ 2%), and lastly bromoform (≤ 1%). This distribution suggests favorable volatilization potential with proper aeration methods.
- Single-pass spray aeration demonstrated an initial average TTHM removal of 29.5%, a reduction of 17.9% after 24 hours of incubation at 30°C, and a 15.7% reduction after 48

hours of incubation. Chloroform and bromoform experienced the greatest and least amount of volatilization, respectively. The single pass through a quality spray aerator increased the time the water remained within compliance levels for an additional ten hours; this may prove an opportunity for small-system utilities that slightly exceed TTHM limits or have seasonal THM issues and chloroform as the primary THM species. However, it is not likely to provide sufficient THM reduction for full-scale application at the Hodge Street facility.

- Stripping via tray aeration showed an immediate TTHM reduction of 46.7% after a single pass. Diminishing returns existed with each subsequent pass. After four passes, 85.5% of the initial TTHMs had been removed; further passes brought TTHM concentrations down to non-detectable levels. The data collected during the evaluation suggests that, after three or four passes, THMs are mitigated for current conditions. Utilization of a ground storage tank with a recirculating tray aerator for batch-type removal of THMs at the Hodge Street facility appears feasible. It is recommended that the volume of water used for recirculation and other operating parameters be adjusted as needed to accommodate for seasonal and demand fluctuations.
- Neither single-pass spray aeration nor recirculating tray aeration appeared to have a significant effect on the water's free chlorine residuals. Free chlorine levels diminished at considerable rates, whether aeration was occurring or not.
- The blending study showed that the chlorine dose applied to the water had a considerable impact on instantaneous chlorine demand as well as DBP formation kinetics. Elevated chlorine doses were shown to water's initial chlorine demand and noticeably accelerate by-

product formation. Data reported herein suggests that a 50% bypass across the planned GAC operation can keep chlorine costs manageable and provide a sufficient reduction of DBPFP. Even when exposed to a chlorine dose of 6.5 mg/L, the 50% blend endured approximately 42 hours of contact time before the TTHM concentration exceeded 80 ppb. The lower chlorine dose of 3.25 mg/L, when applied to the 50% blend, had an $HAA_5$ concentration of 27 ppb and a free chlorine residual of 0.3 mg/L after 48 hours of incubation. Thus, according to the findings, remaining below the 4 mg/L maximum residual disinfectant level (MRDL) while applying a 50% bypass appears to be an appropriate option for providing safe chlorine residuals in the distribution system while effectively reducing DBP formation.

- The proposed master plan recommends the combination of recirculating tray aeration and GAC adsorption. This strategy shows promise for effectively and efficiently removing both formed DBPs as well as their precursors. The plan suggests using UC1240AW carbon in the adsorption vessels with a 50% bypass around the GAC units. It is recommended that the recirculating storage tank be operated in such a manner as to allow for three passes through the tray aerator assembly.
- Associated operational costs were based on providing the maximum monthly average flow of 60,000 gpd. The proposed master plan has a conceptual operating cost of approximately $24,000 annually for carbon replacement and operation of the recirculation pump. However, if the recommended 50% bypass around the GAC is implemented, carbon costs are cut in half and the conceptual operating cost is reduced to approximately $15,250 annually.

# APPENDIX A: PLANT AND SYSTEM DATA

Table A.1: Hodge Street WTP Flow and Process Data

| | Monthly Avg. Flow | Monthly Max. Day Flow | 12-MADF Flow | POE Avg. Chlorine Residual | POE Max. Day Chlorine Residual | POE Phosphate Residual | Remote Phosphate Residual |
|---|---|---|---|---|---|---|---|
| Feb '16 | 1,138 | 22,000 | 28,975 | 0.79 | 1.37 | 1.13 | 1.27 |
| Mar '16 | 1,548 | 26,000 | 23,402 | 0.73 | 1.30 | 1.18 | 1.16 |
| Apr '16 | 133 | 3,000 | 14,642 | 0.72 | 1.90 | 1.39 | 1.28 |
| May '16 | 1,097 | 15,000 | 11,746 | 0.53 | 1.00 | 0.75 | 0.76 |
| Jun '16 | 600 | 7,000 | 8,366 | 0.63 | 1.49 | 0.85 | 0.86 |
| Jul '16 | 3,226 | 13,000 | 6,230 | 0.49 | 0.73 | 0.86 | 0.86 |
| Aug '16 | 1,935 | 36,000 | 1,902 | 0.54 | 1.10 | 0.88 | 0.88 |
| Sep '16 | 750 | 5,000 | 1,939 | 0.82 | 2.18 | 0.72 | 0.72 |
| Oct '16 | 2,177 | 5,000 | 1,161 | 0.56 | 0.82 | 0.82 | 0.85 |
| Nov '16 | 2,433 | 31,000 | 1,290 | 0.41 | 0.74 | 0.63 | 0.64 |
| Dec '16 | 194 | 5,000 | 1,292 | 0.57 | 1.10 | 0.64 | 0.63 |
| Jan '17 | 613 | 6,000 | 1,325 | 0.45 | 0.81 | 0.77 | 0.75 |
| Feb '17 | 250 | 4,000 | 1,258 | 0.91 | 1.66 | 0.62 | 0.61 |
| Mar '17 | 48,258 | 137,000 | 5,225 | 1.32 | 2.55 | 0.70 | 0.64 |
| Apr '17 | 29,867 | 91,000 | 7,668 | 1.19 | 2.61 | 0.65 | 0.59 |
| May '17 | 59,484 | 134,000 | 12,627 | 1.91 | 2.57 | 0.59 | 0.64 |
| Jun '17 | 34,767 | 96,000 | 15,436 | 2.11 | 2.76 | 0.51 | 0.61 |
| Jul '17 | 22,516 | 182,000 | 17,074 | 1.35 | 2.30 | 0.59 | 0.65 |
| Aug '17 | 55,516 | 119,000 | 21,625 | 2.21 | 3.04 | 0.52 | 0.56 |
| Sep '17 | 51,667 | 108,000 | 25,810 | 2.64 | 3.29 | 0.53 | 0.55 |
| Oct '17 | 14,129 | 44,000 | 26,825 | 1.61 | 3.26 | 0.59 | 0.59 |
| Nov '17 | 21,633 | 38,000 | 28,403 | 1.71 | 2.23 | 0.52 | 0.56 |
| Dec '17 | 31,258 | 73,000 | 31,041 | 1.85 | 3.19 | 0.55 | 0.57 |
| Jan '18 | 25,065 | 98,000 | 33,118 | 1.94 | 3.20 | 0.55 | 0.58 |
| | | | | | | | |
| **Average** | 17,093.92 | 54,083.33 | 13,682.50 | 1.17 | 1.97 | 0.73 | 0.74 |
| **Minimum** | 133.33 | 3,000.00 | 1,161.20 | 0.41 | 0.73 | 0.51 | 0.55 |
| **Maximum** | 59,483.87 | 182,000.00 | 33,117.81 | 2.64 | 3.29 | 1.39 | 1.28 |

Table A.2: Waverly WTP Flow and Process Data

| | **Monthly Avg. Flow** | **Monthly Max. Day Flow** | **12-MADF Flow** | **POE Avg. Chlorine Residual** | **POE Max. Day Chlorine Residual** | **POE Phosphate Residual** | **Remote Phosphate Residual** |
|---|---|---|---|---|---|---|---|
| Feb '16 | 94,690 | 158,000 | 212,846 | 1.77 | 2.09 | 1.18 | 1.26 |
| Mar '16 | 99,000 | 158,000 | 74,221 | 1.92 | 2.31 | 0.98 | 1.16 |
| Apr '16 | 98,800 | 136,000 | 79,481 | 1.98 | 2.69 | 1.10 | 1.26 |
| May '16 | 109,839 | 172,000 | 84,270 | 1.80 | 2.49 | 0.63 | 0.75 |
| Jun '16 | 105,167 | 175,000 | 89,525 | 1.94 | 2.44 | 0.73 | 0.86 |
| Jul '16 | 102,000 | 147,000 | 93,292 | 1.96 | 2.72 | 0.70 | 0.86 |
| Aug '16 | 118,710 | 184,000 | 99,708 | 1.79 | 2.50 | 0.79 | 0.88 |
| Sep '16 | 105,650 | 142,000 | 101,042 | 1.95 | 2.80 | 0.67 | 0.73 |
| Oct '16 | 104,403 | 138,000 | 103,161 | 1.71 | 2.71 | 0.70 | 0.83 |
| Nov '16 | 114,533 | 165,000 | 104,538 | 1.61 | 2.34 | 0.62 | 0.66 |
| Dec '16 | 109,339 | 144,000 | 105,537 | 1.86 | 2.40 | 0.58 | 0.64 |
| Jan '17 | 109,887 | 145,000 | 106,063 | 1.72 | 2.30 | 0.51 | 0.63 |
| Feb '17 | 100,679 | 141,000 | 106,553 | 1.93 | 2.35 | 0.55 | 0.62 |
| Mar '17 | 75,097 | 257,000 | 104,523 | 1.87 | 2.57 | 0.50 | 0.60 |
| Apr '17 | 94,633 | 206,000 | 104,181 | 1.71 | 2.89 | 0.45 | 0.57 |
| May '17 | 68,000 | 165,000 | 100,627 | 1.67 | 2.36 | 0.62 | 0.63 |
| Jun '17 | 54,800 | 79,000 | 96,488 | 1.77 | 2.84 | 0.56 | 0.65 |
| Jul '17 | 72,935 | 146,000 | 94,019 | 2.07 | 2.85 | 0.56 | 0.62 |
| Aug '17 | 55,613 | 80,000 | 88,660 | 1.91 | 2.24 | 0.52 | 0.56 |
| Sep '17 | 55,117 | 75,000 | 84,507 | 1.99 | 2.77 | 0.51 | 0.54 |
| Oct '17 | 97,500 | 203,000 | 83,921 | 2.58 | 3.38 | 0.53 | 0.58 |
| Nov '17 | 88,567 | 193,000 | 81,786 | 2.08 | 2.69 | 0.58 | 0.60 |
| Dec '17 | 65,935 | 107,000 | 78,100 | 1.78 | 2.16 | 0.63 | 0.63 |
| Jan '18 | 84,910 | 166,000 | 75,979 | 1.93 | 2.45 | 0.66 | 0.64 |
| | | | | | | | |
| **Average** | 91,075.17 | 153,416.67 | 98,042.83 | 1.89 | 2.56 | 0.66 | 0.74 |
| **Minimum** | 54,800.00 | 75,000.00 | 74,221.31 | 1.61 | 2.09 | 0.45 | 0.54 |
| **Maximum** | 118,709.68 | 257,000.00 | 106,553.42 | 2.58 | 3.38 | 1.10 | 1.26 |

# APPENDIX B: LABORATORY RESULTS

Table A.3: Hodge Street WTP Baseline GC Results

| **Sample Name** | **Chloroform Conc. (ppb)** | **BDCM Conc. (ppb)** | **DBCM Conc. (ppb)** | **Bromoform Conc. (ppb)** | **TTHM Conc. (ppb)** |
|---|---|---|---|---|---|
| 0 hour | 14.5 | 0.9 | 1.2 | 1.0 | 18 |
| 2 hour | 38.5 | 7.7 | 1.0 | 1.0 | 48 |
| 12 hour | 58.6 | 12.4 | 1.8 | 1.0 | 74 |
| 24 hour | 70.9 | 14.8 | 2.2 | 1.0 | 89 |
| 24 hour dup | 72.6 | 15.2 | 2.3 | 1.0 | 91 |
| 48 hour | 75.3 | 16.5 | 2.5 | 1.0 | 95 |
| 48 hour rep | 76.6 | 16.6 | 2.5 | 1.0 | 97 |
| 48 hour spike | 120.7 | 69.8 | 57.5 | 54.8 | 303 |

Table A.4: Waverly WTP Baseline GC Results

| **Sample Name** | **Chloroform Conc. (ppb)** | **BDCM Conc. (ppb)** | **DBCM Conc. (ppb)** | **Bromoform Conc. (ppb)** | **TTHM Conc. (ppb)** |
|---|---|---|---|---|---|
| In situ | 32.8 | 6.0 | 0.8 | 0.7 | 40 |
| In situ dupe | 33.8 | 6.2 | 0.8 | 0.7 | 41 |
| t=0 hour | 17.5 | 2.6 | 0.7 | 0.7 | 21 |
| t=0 hour dup | 17.4 | 2.6 | 0.7 | 0.7 | 21 |
| t=1 hour tank | 10.9 | 2.1 | 0.7 | 0.7 | 27 |
| t=1 hour tank rep | 12.8 | 2.1 | 0.7 | 0.7 | 16 |
| t=1 hour tank spike | 56.2 | 48.1 | 50.9 | 54.2 | 209 |
| t=1 hour tank dup | 22.7 | 3.8 | 0.7 | 0.7 | 28 |
| t=1 hour bottle | 29.2 | 6.7 | 1.1 | 0.7 | 38 |
| t=1 hour bottle dup | 27.9 | 6.3 | 1.0 | 0.7 | 36 |
| t=4 hours | 32.6 | 7.8 | 1.3 | 0.7 | 42 |
| t=4 hours dup | 34.5 | 8.2 | 1.3 | 0.7 | 45 |
| t=4 hours dup rep | 33.9 | 8.0 | 1.3 | 0.7 | 44 |
| t=4 hours dup spike | 79.2 | 57.6 | 54.2 | 55.6 | 247 |
| t=10 hour | 43.4 | 9.8 | 1.6 | 0.7 | 56 |
| t=10 hour dup | 36.9 | 8.0 | 1.3 | 0.7 | 47 |
| t=22 hour | 44.6 | 9.1 | 1.4 | 0.7 | 56 |
| t=22 hour dup | 57.2 | 12.6 | 2.2 | 0.7 | 73 |
| t=46 hour | 71.5 | 15.4 | 2.6 | 0.7 | 90 |
| t=46 hour rep | 68.1 | 14.3 | 2.4 | 0.7 | 85 |
| t=46 hour spike | 111.5 | 64.9 | 55.2 | 54.4 | 286 |
| t=46 hour dup | 70.4 | 15.1 | 2.7 | 0.7 | 89 |
| t=94 hour | 82.7 | 16.5 | 2.8 | 0.7 | 103 |
| t=94 hour dup | 84.5 | 17.1 | 2.9 | 0.7 | 105 |
| Site 2 | 45.0 | 9.0 | 1.5 | 0.7 | 56 |
| Site 2 dup | 45.3 | 8.8 | 1.4 | 0.7 | 56 |
| Site 2 dup rep | 28.6 | 5.5 | 0.7 | 0.7 | 35 |
| Site 2 dup spike | 78.2 | 60.3 | 59.3 | 61.6 | 259 |
| Site 3 | 41.6 | 8.4 | 1.3 | 0.7 | 52 |
| Site 3 dup | 41.2 | 8.3 | 1.3 | 0.7 | 52 |
| Site 4 | 35.5 | 6.8 | 1.0 | 0.7 | 44 |
| Site 4 dup | 58.1 | 11.8 | 2.1 | 0.7 | 73 |

Table A. 5: Spray Aeration GC Data

| **Sample Name** | **Chloroform Conc. (ppb)** | **BDCM Conc. (ppb)** | **DBCM Conc. (ppb)** | **Bromoform Conc. (ppb)** | **TTHM Conc. (ppb)** |
|---|---|---|---|---|---|
| Unaerated t=0 hour | 37.3 | 6.9 | 1.1 | 0.7 | 46 |
| Unaerated t=0 hour dup | 34.0 | 6.3 | 1.0 | 0.7 | 42 |
| Unaerated t=4 hour | 49.4 | 9.2 | 1.7 | 0.7 | 61 |
| Unaerated t=4 hour dup | 42.4 | 8.5 | 1.4 | 0.7 | 53 |
| Unaerated t=7 hour | 65.5 | 15.5 | 2.4 | 0.7 | 84 |
| Unaerated t=7 hour dup | 63.3 | 14.4 | 2.2 | 0.7 | 81 |
| Unaerated t=24 hour | 84.3 | 18.9 | 2.9 | 0.7 | 107 |
| Unaerated t=24 hour dup | 83.5 | 18.6 | 2.9 | 0.7 | 106 |
| Unaerated t=48 hour | 92.8 | 19.2 | 3.3 | 0.7 | 116 |
| Unaerated t=48 hour dup | 83.0 | 13.2 | 3.1 | 0.7 | 100 |
| Aerated t=0 hour | 25.3 | 3.5 | 0.3 | 0.7 | 30 |
| Aerated t=0 hour dup | 27.0 | 4.1 | 0.3 | 0.7 | 32 |
| Aerated t=4 hour | 31.2 | 5.9 | 1.3 | 0.7 | 39 |
| Aerated t=4 hour dup | 33.2 | 7.9 | 1.2 | 0.7 | 43 |
| Aerated t=7 hour | 47.8 | 10.0 | 1.6 | 0.7 | 60 |
| Aerated t=7 hour dup | 46.5 | 9.2 | 1.4 | 0.7 | 58 |
| Aerated t=24 hour | 70.2 | 14.1 | 2.3 | 0.7 | 87 |
| Aerated t=24 hour dup | 69.6 | 13.8 | 2.2 | 0.7 | 86 |
| Aerated t=48 hour | 81.6 | 15.4 | 2.5 | 0.7 | 100 |
| Aerated t=48 hour dup | 68.8 | 11.5 | 1.6 | 0.7 | 83 |

Table A.6: Tray Aeration GC Data

| Sample Name | Chloroform Conc. (ppb) | BDCM Conc. (ppb) | DBCM Conc. (ppb) | Bromoform Conc. (ppb) | TTHM Conc. (ppb) |
|---|---|---|---|---|---|
| field1 | 51.2 | 9.9 | 1.7 | 1.0 | 64 |
| field2 | 51.8 | 10.0 | 1.8 | 1.0 | 65 |
| field3 | 50.4 | 9.7 | 1.7 | 1.0 | 63 |
| t=0 | 49.8 | 11.4 | 2.1 | 1.0 | 64 |
| t=0 dup | 47.1 | 10.6 | 1.9 | 1.0 | 61 |
| t=0 dup rep | 48.0 | 10.9 | 1.9 | 1.0 | 62 |
| t=0 dup spike | 88.4 | 59.9 | 57.3 | 59.8 | 265 |
| t=0 trip | 48.5 | 10.9 | 1.9 | 1.0 | 62 |
| t=10 | 22.0 | 4.9 | 0.6 | 1.0 | 29 |
| t=10 dup | 25.2 | 5.5 | 1.0 | 1.0 | 33 |
| t=10 trip | 25.7 | 5.1 | 0.9 | 1.0 | 33 |
| t=20 | 14.0 | 2.7 | 1.0 | 1.0 | 19 |
| t=20 rep | 14.4 | 2.9 | 1.0 | 1.0 | 19 |
| t=20 spike | 59.9 | 50.2 | 53.8 | 57.1 | 221 |
| t=20 dup | 14.1 | 2.9 | 1.0 | 1.0 | 19 |
| t=20 trip | 5.0 | 1.0 | 1.0 | 1.0 | 8 |
| t=30 | 9.3 | 1.5 | 1.0 | 1.0 | 13 |
| t=30 dup | 8.2 | 1.4 | 1.0 | 1.0 | 12 |
| t=30 trip | 9.1 | 1.4 | 1.0 | 1.0 | 13 |
| t=30 trip rep | 9.2 | 1.4 | 1.0 | 1.0 | 13 |
| t=30 trip spike | 51.7 | 44.9 | 50.5 | 55.3 | 202 |
| t=40 | 6.7 | 1.0 | 1.0 | 1.0 | 10 |
| t=40 dup | 6.0 | 1.0 | 1.0 | 1.0 | 9 |
| t=40 trip | 6.7 | 1.0 | 1.0 | 1.0 | 10 |
| t=50 | 5.5 | 1.0 | 1.0 | 1.0 | 8 |
| t=50 dup | 5.0 | 1.0 | 1.0 | 1.0 | 8 |
| t=50 dup rep | 5.0 | 1.1 | 1.0 | 1.0 | 8 |
| t=50 dup spike | 47.0 | 42.6 | 47.9 | 53.1 | 191 |
| t=50 trip | 5.6 | 1.0 | 1.0 | 1.0 | 9 |
| t=60 | 5.1 | 1.0 | 1.0 | 1.0 | 8 |
| t=60 dup | 4.9 | 1.0 | 1.0 | 1.0 | 8 |
| t=60 trip | 4.9 | 1.0 | 1.0 | 1.0 | 8 |
| t=120 | 5.0 | 1.0 | 1.0 | 1.0 | 8 |
| t=120 rep | 5.0 | 1.0 | 1.0 | 1.0 | 8 |

| | | | | | |
|---|---|---|---|---|---|
| t=120 spike | 54.1 | 49.0 | 54.4 | 60.2 | 218 |
| t=120 dup | 5.0 | 1.0 | 1.0 | 1.0 | 8 |
| t=120+16 | 32.7 | 4.0 | 1.0 | 1.0 | 39 |
| t=120+16 dup | 32.3 | 3.9 | 1.0 | 1.0 | 38 |
| t=120+22 | 41.6 | 5.1 | 0.7 | 1.0 | 48 |
| t=120+22 dup | 48.2 | 6.2 | 0.9 | 1.0 | 56 |
| t=120+22 dup rep | 42.6 | 5.6 | 0.9 | 1.0 | 50 |
| t=120+22 dup spike | 85.3 | 51.6 | 52.1 | 56.0 | 245 |
| t=12 | 5.0 | 1.0 | 1.0 | 1.0 | 8 |
| t=12 dup | 5.0 | 1.0 | 1.0 | 1.0 | 8 |
| t=12+14 | 4.6 | 1.0 | 1.0 | 1.0 | 8 |
| t=12+14 dup | 4.8 | 1.0 | 1.0 | 1.0 | 8 |
| t=12+29 | 6.9 | 1.0 | 1.0 | 1.0 | 10 |
| t=12+29 rep | 6.9 | 1.0 | 1.0 | 1.0 | 10 |
| t=12+29 spike | 56.3 | 47.2 | 51.6 | 55.8 | 211 |
| t=12+29 dup | 6.9 | 1.0 | 1.0 | 1.0 | 10 |

Table A.7: Chlorine Demand Curve from Hodge Street WTP (July 2017)

| **Elapsed Time (hours)** | **Free Chlorine (mg/L)** |
|---|---|
| 0 | 2.4 |
| 2 | 1.04 |
| 12 | 0.52 |
| 24 | 0.2 |
| 48 | 0.02 |
| 72 | 0.01 |

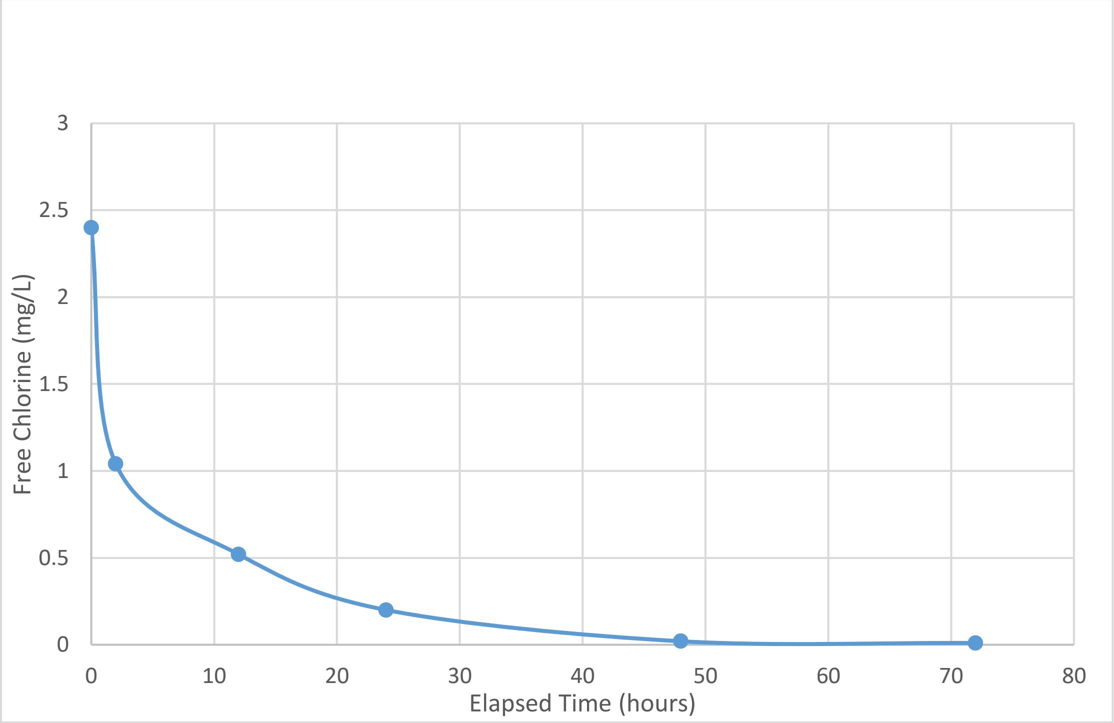

Figure A.1: Chlorine Demand Curve from Hodge Street WTP (July 2017)

Table A.8: Chlorine Demand Data from Hodge Street WTP (August 2017)

| **Elapsed Time (hours)** | **Free Chlorine (mg/L)** |
|---|---|
| 0 | 3.3 |
| 4 | 1.73 |
| 7 | 1.47 |
| 24 | 0.9 |
| 48 | 0.37 |

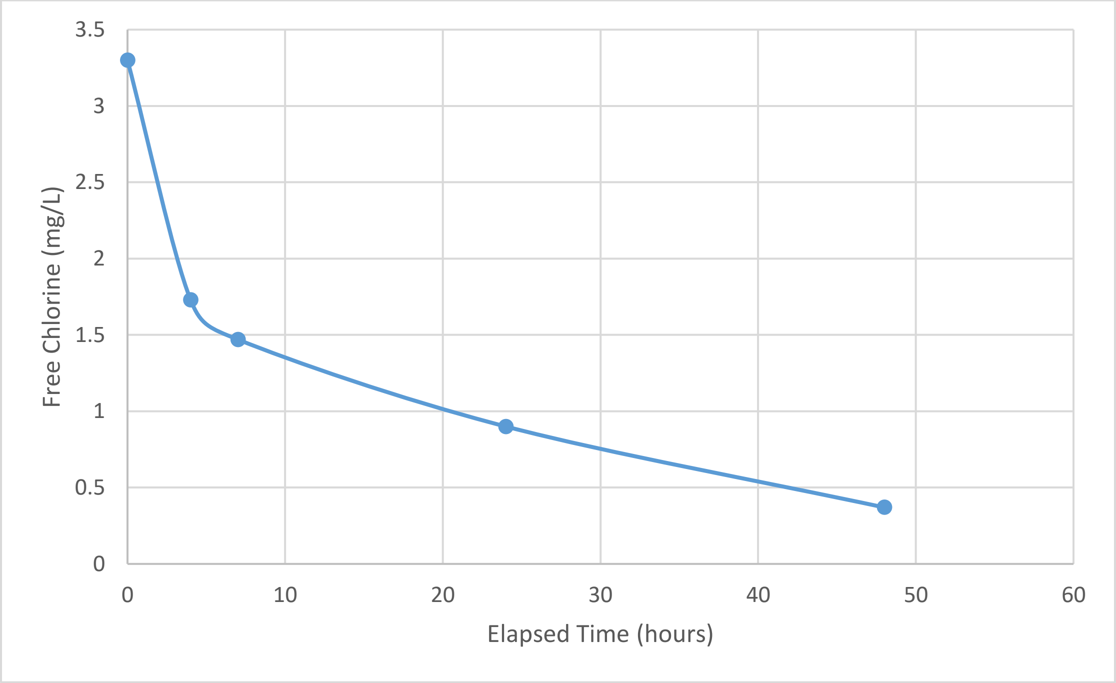

Figure A.2: Chlorine Demand Curve for Hodge Street WTP (August 2017)

Table A.9: Chlorine Demand Data for Waverly WTP (October 2017)

| **Elapsed Time (hours)** | **Free Chlorine (mg/L)** |
|---|---|
| 0 | 3.7 |
| 1 | 3.2 |
| 4 | 2.7 |
| 10 | 2.3 |
| 22 | 1.8 |
| 46 | 1.6 |

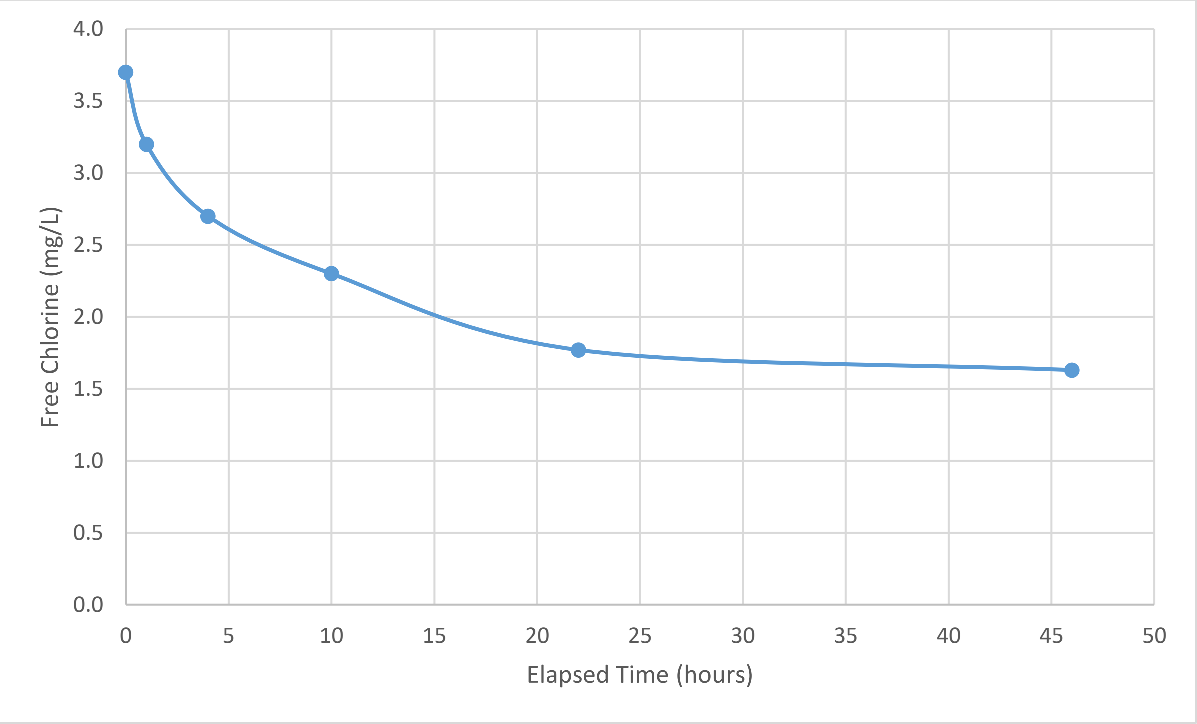

Figure A.3: Chlorine Demand Curve for Waverly WTP (October 2017)

# APPENDIX C: EVOQUA’S TOC AND GAC STUDIES REPORT

# TOC AND GAC STUDIES

## Isotherm Adsorption and Rapid Small-Scale Column Tests for the Removal of Total Organic Carbon from Groundwater Using Granular Activated Carbons

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Prepared by: Adam Redding, PhD, Evoqua Water Technologies LLC, Bellefonte, PA 16823

### Executive Summary

The work herein aimed to predict the performance of granular activated carbon (GAC) adsorbers using both isotherm adsorption tests and the Rapid Small-Scale Column Test (RSSCT) when that GAC is treating groundwater for the removal of total organic carbon (TOC) To that end, GAC performance was measured with two (2) GAC types: virgin Westates® AquaCarb® 1230CX (AC1230CX) and virgin Westates UltraCarb® 1240AW (UC1240AW). The influent water for testing was provided by Polk County via the University of Central Florida to Evoqua Water Technologies LLC on 30 June 2017. The full-scale-size GACs were ground to <325 US Mesh for isotherm tests and 170 × 200 US Mesh size grains for the RSSCTs.

Isotherm tests indicated similar TOC capacities for the UC1240AW and AC1230CX carbons, with UC1240AW having a slightly higher capacity. Results implied that at an influent concentration of ~3.6 mg/L the UC1240AW carbon would have a capacity of 128 mg TOC / g GAC. At this same influent concentration, the AC1230CX material would have a capacity of 113 mg TOC / g GAC.

UC1240AW provided markedly more-favorable removal of TOC in RSSCTs. Using 2.0 mg/L as a point of comparison, breakthrough to this level with UC1240AW occurred at 60 days versus the same level of breakthrough with AC1230CX at 24 days. Both GACs appeared to reach a plateau with regards to removal at ~80 days although UC1240AW continuously removed TOC to a level below 2.5 mg/L while AC1230CX removed TOC steadily at 2.7 mg/L.

## 1. Overview and Objective

GAC is widely used in water purification for the removal of synthetic and naturally occurring organic compounds from groundwater and surface water. During the disinfection of drinking water using chlorine, harmful byproducts can form via reaction of that chlorine with natural organic matter (NOM). Removal of NOM prior to disinfection is one method by which the formation of disinfection by-products (DBPs) can be controlled. GAC is applied for this purpose where the concentration of NOM is measured as TOC and the GAC performance measured as TOC reduction.

Adsorption isotherms provide a measure of the equilibrium capacity for a given adsorbent at a given adsorbate concentration. These tests are limited thus to estimating carbon performance in terms of ultimate sorption capacity. Since adsorption is allowed to occur over several days, with the goal of reaching equilibrium, isotherm tests cannot be used to infer adsorption kinetics. Tests of adsorption kinetics have demonstrated that carbons with a high equilibrium capacity may concurrently have unfavorable kinetics; conversely a low equilibrium capacity carbon may display relatively fast kinetics (Newcombe et al., 2002). For this reason, RSSCTs are preferred over isotherm tests as a more accurate lab-scale predictor of full-scale performance (Rangel-Mendez and Cannon, 2005).

RSSCTs offer a method for the prediction of full-scale activated carbon performance by mimicking the dynamics of a full-scale GAC bed. By reducing the size of the bed and the carbon grains, a relatively small water sample (10 gal - 100 gal) is required per test and that the test can be conducted in a matter of days or weeks. As a progression in the development of a GAC application, RSSCTs are often applied prior to commencing pilot studies, where pilot studies would use the full-scale grains under full-scale hydraulic loading rates.

The objective of this work was to use isotherms and RSSCTs to estimate the potential full-scale performance of two GACs, AC1230CX and UC1240AW, for removal of TOC from a groundwater sample as supplied by Polk County.

## 2. Experimental Methods

### 2.1. Activated Carbon Material and Preparation

Virgin UltraCarb 1240AW (Lot 26630) and virgin AC1230CX (Lot 27062) was acquired from Evoqua Water Technologies in June 2017. UC1240AW is offered as 12×40 US Mesh and AC1230CX is offered as 12×30 US Mesh-size material at full-scale grain size. GAC for use in isotherms was prepared by grinding the as-received GAC, wet-sieving using a 325-US mesh sieve (0.044 mm), and then collecting the fraction passing that size. GAC for use in RSSCTs was prepared by grinding the as-received GAC and then wetsieving it using a 170-US mesh (0.090 mm) sieve combined with a 200-US mesh (0.075 mm) sieve to obtain the 170×200 fraction. In wet-sieving, the surface of the sieve is rinsed with distilled water to remove fines and prevent particles from adhering to each other or the surface of the mesh. Dry-sieving is not adequate as electrostatics prevent the correct particle size from passing the mesh. After rinsing with about 5 L of additional distilled water per gram of ground GAC, the samples were dried under vacuum at 105°C for 24 hours before storage. After preparation the samples were stored in a vacuum desiccator. This storage technique aims to minimize exposure to atmospheric oxygen and moisture, decreasing the potential for a change in surface chemistry due to oxidation (Li and Knappe, 2002).

### 2.2 Isotherm Tests

Isotherm tests for TOC adsorption were conducted per ASTM D5919, Standard Practice for Determination of Adsorptive Capacity of Activated Carbon by a MicroIsotherm Technique for Adsorbates at ppb Concentrations (ASTM, 2014). GAC was ground and wet-sieved to <325 US mesh and test bottles were held at 20°C for 5 days while being stirred via magnetic stir bar. Final TOC concentrations ranged from 1.2 to 3.3 mg/L across GAC dosages ranging from 2 to 50 mg/L.

### 2.3. Rapid Small-Scale Column Tests

RSSCTs were used as a measure of fixed-bed GAC adsorption performance for contaminant removal. The RSSCTs were performed similarly to the American Society for Testing and Materials (ASTM) Standard Practice D6586, assuming proportional diffusivity scaling.

Specifically, the ratio of the empty-bed contact times was set equal to the ratio of the grain diameters between the small-scale and large-scale grains. At the small-scale, 0.36 mL of the ground GAC was used per test, and thus each BV was equal to 0.36 mL. For a broad range of compounds the work of Crittenden and colleagues (Crittenden et al., 1986 and 1991) has demonstrated this approach and that RSSCTs are useful for predicting fullscale and pilot-scale adsorber performance. Detailed calculations for the RSSCT scaling are included in Appendix I.

To compare with the full-scale, ~76 BV were processed through the RSSCT in 1 hour at an RSSCT contact time of ~0.80 minutes (Table 1), versus 4 BV per hour at the full scale contact time of 15 minutes. The small-scale columns were constructed of polycarbonate with stainless steel fittings and polytetrafluoroethylene (PTFE) interconnecting tubing (Figure 1).

The tests of AC1230CX and UC1240AW were run concurrently using the same influent water that was refrigerated during testing at 4°C.

**Table 1**: Full-scale operating conditions compared to RSSCTs.

| | | | Small-Scale | | |
|---|---|---|---|---|---|
| | Full-Scale | | AC1230CX | UC1240AW | |
| Bed Diameter | 12 | ft | 0.48 | 0.48 | cm |
| Fill Weight* | 40,000 | lb | 0.148 | 0.145 | g |
| Apparent Density | 0.50 | g/cc | 0.41 | 0.38 | g/cc |
| Bed Depth | 12.6 | ft | 2.0 | 2.0 | cm |
| Bed Volume** | 1428 | ft$^3$ | 0.36 | 0.36 | mL |
| Hydraulic Loading | 6.3 | gpm/ft$^2$ | 0.67 | 0.67 | gpm/ft$^2$ |
| Empty-Bed Contact Time | 15.0 | min | 0.73 | 0.79 | min |
| Particle Size | 12 × 30 or 12 × 40 | US Mesh | 200 × 400 | 200 × 400 | US Mesh |

cm – centimeter, g – gram, lb – pound, cc – cubic centimeter, ft – foot, gpm – gallon-per-minute, mL/min – milliliters-per-minute, US – United States.

*Assuming an apparent density of 0.50 g/cc.

**Assuming media backwashed and drained to 92% of apparent density.

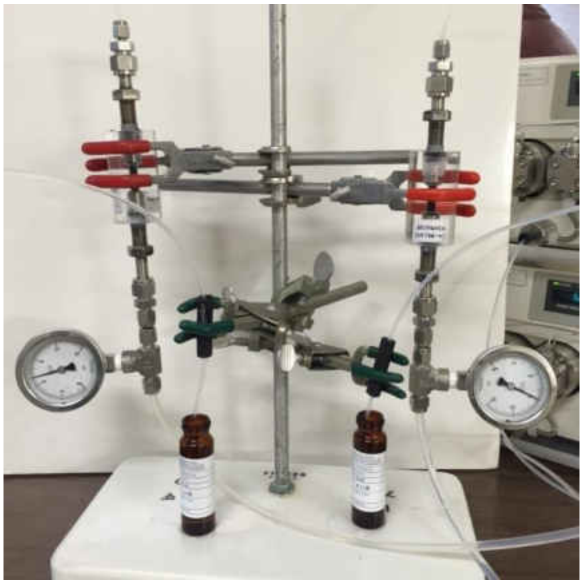

**Figure 1.** Example of RSSCT columns as typically configured. The GAC beds are visible within the red clamps. Shown also are the pressure gauges, located on the lower end of the columns since operation is in an up-flow direction.

## 2.4. Analytical

Analytical for the isotherm samples was conducted in the Evoqua Warrendale, PA laboratory using a Teledyne Tekmar Lotix Model 15-1600-000 combustion type analyzer. Analytical for the RSSCT samples was conducted by Eurofins-Eaton Analytical (Monrovia, CA) and samples were collected in containers provided by this laboratory (Table 2). Samples were refrigerated at 4°C until shipment on-ice to the laboratory. All appropriate temperatures and sample hold times were maintained. Influent samples for TOC analysis were collected at two points near the beginning and end of the test run. Eight (8) effluent samples per GAC were collected, spread across the ~20,000 BV test duration.

Analytical results for the RSSCT are included in Appendix II.

**Table 2.** Details of Applied Analytical Methods

| Analytical | Compound | Reporting Limit (Typ.) | Sample Size | Preservative |
|---|---|---|---|---|
| SM5310B | Total Organic Carbon (TOC) | 0.1 mg/L | 1 × 125 mL Brown Amber Bottle | Sulfuric Acid |

mg/L – milligrams-per-liter, mL – milliliter

## 2.5. Water Source

The water sample for testing was received in multiple 2.5-gal low-density polyethylene collapsible bags by Evoqua on June 30th, 2017, with the sample having been collected from Polk County and refrigerated by University of Central Florida personnel the previous day. The samples were kept refrigerated at 4°C until use in testing.

## 3. Results and Discussion

### 3.1. TOC Isotherms

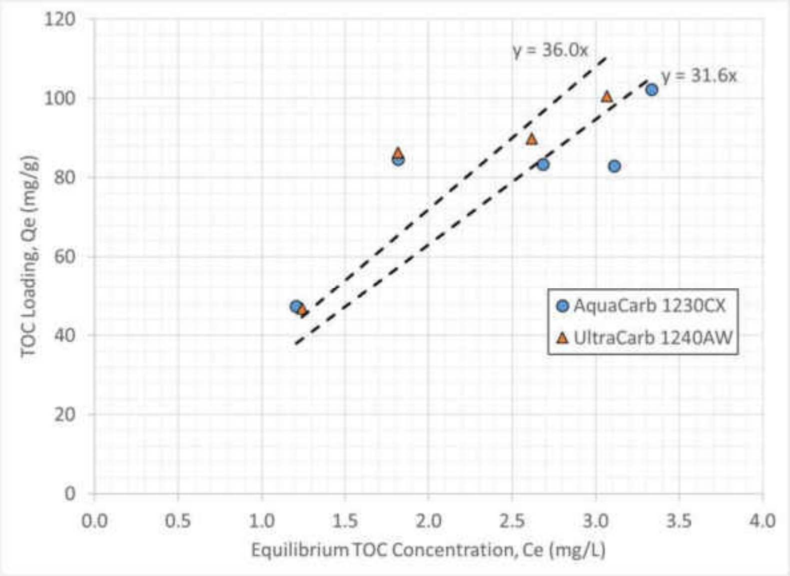

**Fig. 2 –** Equilibrium loading of TOC on two activated carbons as compared to equilibrium concentration of TOC in the source water.

Across the range of equilibrium TOC concentrations (1.3 mg/L to 3.3 mg/L) the isotherm curves for both GACs appear to be linear with respect to TOC loading (Figure 2). The TOC in the as-received sample of TOC was measured as 3.6 mg/L. UC1240AW provided 12% greater loading than AC1230CX across the range of equilibrium TOC concentration. Both isotherm curves trend toward the origin (0,0) implying that all of the compounds comprising the TOC were indeed adsorbable. Conversely if an isotherm curve intersects the x-axis, the point of intersection indicates the portion of the TOC that is not adsorbable.

From the isotherm curve constants, usage rates can be estimated assuming the water influent to the GAC system has a TOC of 3.6 mg/L as measured in the control water sample. This usage rate assumes a flow of 500 gallons-per-minute (gpm) and a goal of 100-percent removal of the TOC. Greater flow rates would increase the usage rate by the corresponding multiple of the flow, e.g. 1000 gpm would amount to twice the usage rate at 500 gpm.

<u>Example Usage Rate Estimate for 500 gpm of Flow – 100% TOC Reduction</u>

Given:
Flow = 500 gpm
Influent TOC Concentration = 3.6 mg/L

For UC1240AW:
$Q_e$ (mg/g) = 36 × $C_e$ (mg/L)

1) Loading of TØC: $36 \cdot 3.6\,{}^{mg}/_{L} = 130\ mg\ TOC/g\ carbon$

2) Usage Rate:

$$\left(\frac{500\ gal}{min}\right)\left(\frac{3.785\ L}{gal}\right)\left(\frac{1440\ min}{day}\right)\left(\frac{3.6\ mg\ TOC}{L}\right)\left(\frac{g\ GAC}{130\ mg\ TOC}\right)\left(\frac{lb}{453\ g}\right)(1.75)$$

$$\approx \frac{290\ lb\ GAC}{day}$$

The factor of "1.75" in the above equation is applied to roughly account for difference between the amount of adsorbate loading achieved at equilibrium and the adsorbate loading achieved at breakthrough. Since at initial breakthrough the GAC at the forward edge of the mass transfer zone is not exposed to the full influent concentration the loading of adsorbate is considerably less than that at equilibrium with the influent.

To estimate a changeout frequency, the calculated usage rate (above) must be applied against the weight of GAC in a given vessel. A "40,000 lb" GAC vessel is sized with a bed volume of ~1428 $ft^3$ assuming an average apparent GAC density of 28 $lb/ft^3$; when using a low density GAC however such as UC1240AW the fill weight is approximately 28,000 lb. Using this weight of UC1240AW and the usage rate above, the bed life can be estimated as ~96 days to breakthrough of TOC.

## 4. RSSCTs

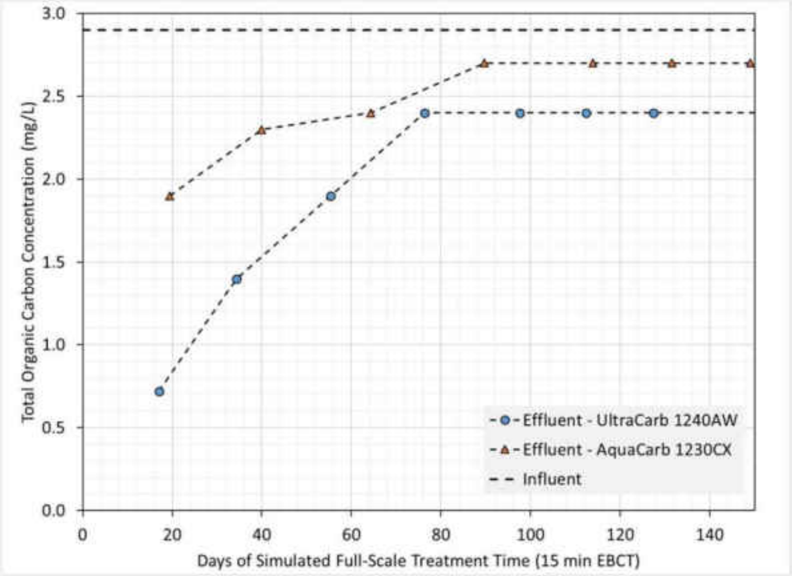

**Fig. 3 –** Breakthrough of TOC in terms of simulated service time in RSSCTs scaled for a 15minute EBCT.

The performance of UC1240AW for removal of TOC in RSSCTs was noticeably more-favorable than that of AC1230CX (Figure 3). Using 2.0 mg/L as a point of comparison, breakthrough to this level with UC1240AW occurred at 60 days versus the same level of breakthrough with AC1230CX at 24 days. Both GACs appeared to reach a plateau with regards to removal at ~80 days although UC1240AW continuously removed TOC to a level below 2.5

mg/L while AC1230CX removed TOC steadily at 2.7 mg/L. The steady removal of TOC beyond initial breakthrough suggests that capacity remains in the GAC but that the mass transport rate is too slow for a greater portion of the TOC to be adsorbed.

In comparing the results of the RSSCTs to the isotherm usage rate estimate, the isotherm approach appears to markedly over-predict the GAC performance. It should be noted however that although the isotherm curves did not indicate a non-adsorbable fraction, that fraction may still have been present since none of the GAC dosages removed TOC below a level of 1.1 mg/L.

Biological activity is a common occurrence in GAC beds when removing TOC and this activity can offer extended and continuous reduction of TOC. RSSCTs cannot simulate this phenomenon since several weeks are typically required for biogrowth to occur. Instead a pilot study using full-scale carbon grains is the best approach for determining the efficacy of biological activity.

## 4. Conclusions

- UC1240AW offered a slightly higher capacity for TOC in isotherm tests.
- The estimated usage rate from the isotherm test was 290 lb/day of GAC, equating to ~96 days until TOC breakthrough.
- UC1240AW performed most-favorably in RSSCTs, providing 50% removal of TOC until approximately 40 days of scaled operation.
- The estimate based on isotherm results appeared to over-predict the expected GAC performance.

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