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INVESTIGATING THE REMOVAL OF TOTAL TRIHALOMETHANES BY TRAY AND
SPRAY AERATION PROCESSES AT TWO CENTRAL FLORIDA GROUNDWATER
TREATMENT FACILITIES

by

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B.S. Environmental Engineering, University of Central Florida, 2019

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Civil, Environmental, and Construction Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Summer Term
2021

Major Professor: Steven J. Duranceau

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ABSTRACT

An investigation has been completed that assessed the efficiency of tray and spray aeration processes on the removal of regulated total trihalomethanes (TTHMs) at two publicly owned potable groundwater treatment facilities located in Polk County, Florida: the Providence and Van Fleet water treatment plants (WTPs). Finished water from each of these facilities was fed to a pilot-plant that could be operated as either a tray, spray, or combined configuration. A series of four pilot aerator configurations were tested at each WTP. Test 1 evaluated the tray aerator operated in a recirculated multiple-pass mode. It was shown that three passes across the same tray aerator configuration was effective in reducing 96-hour TTHM formation by 48% and 63% at the Providence and Van Fleet WTPs, respectively. Test 2 (a) measured the effect of increased tray surface area on TTHM reduction. It was shown that increasing the tray aerator surface area by 40% decreased the 96-hour TTHM formation at the Providence and Van Fleet WTPs by 25% and 66%, respectively. Test 2 (b) evaluated the effectiveness of spray aeration on TTHM reduction, resulting in a decrease of 14% in the 96-hour TTHM concentrations at both WTPs. Test 2 (c) combined tray and spray aeration integrated with an increased tray surface area. A 22% and 25% decrease in 96-hour TTHM concentrations was observed with this combined configuration at the Providence and Van Fleet WTPs, respectively. The five regulated haloacetic acid (HAA5) disinfection by-product concentrations were found to be largely unaffected by aeration. Results of this study indicated that the implementation of more surface area within the existing tray aeration units would reduce 96-hour TTHM formation concentrations. The addition of a recirculation pump would aid in reducing 96-hour TTHM formation but could be limited by the operation of the ground storage tank at each site.

This thesis is dedicated to my family. Their never-ending love and support are treasured.

ACKNOWLEDGMENTS

My sincere gratitude goes to my family and friends. The ongoing support received from both parties was tremendously helpful throughout my graduate studies. Without them, I would not be where I am today.

This work would not have occurred without the support of several of my professors and colleagues at the University of Central Florida. My appreciation goes to Dr. Steven Duranceau, who served as my committee chair and graduate advisor. He allowed me not only the opportunity to perform this research, but also provided his time, extensive knowledge, and guidance throughout my graduate studies. Additional appreciations are given to Dr. Anwar Sadmani and Dr. Woo Hyoung Lee for serving on my thesis committee. Further thanks are given to each of the members in the University of Central Florida's (UCF) Water Quality Engineering Research Group for their assistance in performing this work: Eric Barnes, Paula Campesino, Jessica Cormier, Devon Higgins, Kylie Izquierdo, Courtney Powell, Tulsi Shukla and Nino Stea. Additional appreciation is given to Devon Higgins of the Water Quality Engineering Research Group for providing a helping hand during each of the multiple on-site visits.

One individual working for the Polk County Utilities Division should be recognized for his ongoing support. Specifically, thanks are owed to Raymond Freeman for his assistance during visits on-site, and his willingness to help with any matter.

Research presented herein is based upon work supported by project authorization number 1620-8A07. Funding for this project was provided by Polk County. Any opinions, findings, conclusions, or recommendations expressed in this material do not necessary reflect the views of the funding agency, but those of the author.

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LIST OF ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
µg/L	Micrograms per Liter
µs/cm	Microsimens per Centimeter
AEL	Advanced Environmental Laboratories
ANSI	American National Standards Institute
BDL	Below Detection Level
BrO ₃ ⁻	Bromate
Ca(OCl) ₂	Calcium Hypochlorite
CCl ₂ COOH	Trichloroacetic Acid
CDC	Center for Disease Control
CH ₂ BrCOOH	Monobromoacetic Acid
CH ₂ ClCOOH	Monochloroacetic Acid
CHBr ₂	Bromoform
CHBr ₂ Cl	Dibromochloromethane
CHBr ₂ COOH	Dibromoacetic Acid
CHBrCl ₂	Bromodichloromethane
CHCl ₂ COOH	Dichloroacetic Acid
CHCl ₃	Chloroform
Cl ₂	Chlorine
ClO ₃ ⁻	Chlorate
cm ⁻¹	Inverse Centimeter
CO ₂	Carbon Dioxide

CR-54	County Road-54
D/DBPR	Disinfectants and Disinfection By-Products Rule
DBP	Disinfection By-Product
DOC	Dissolved Organic Carbon
EPA	Environmental Protection Agency
ESEI	Environmental Systems Engineering Institute
ft ²	Square Feet
GAC	Granular Activated Carbon
gpm	Gallons per Minute
GST	Ground Storage Tank
GWR	Ground Water Rule
HAA	Haloacetic Acid
HAA ₅	Total Haloacetic Acids
HCl	Hydrochloric Acid
HOCl	Hypochlorous Acid
HSP	High Service Pump
IDSE	Initial Distribution System Evaluation
LLDPE	Linear Low Density Polyethylene
LRAA	Local Running Annual Average
MCL	Maximum Contaminant Level
MG	Million Gallons
mg/L	Milligrams per Liter
MGD	Million Gallons per Day

MRDL	Minimum Residual Disinfectant Level
mV	Millivolts
Na ₂ SO ₃	Sodium Sulfite
NaClO	Sodium Hypochlorite
NDMA	N-Nitrosodimethylamine
NERUSA	Northeastern Regional Utility Service Area
NH ₃	Ammonia
NH ₄ Cl	Ammonia Chloride
NOM	Natural Organic Matter
NSF	National Sanitation Foundation
NTU	Nephelometric Turbidity Unit
POE	Point of Entry
psi	Pounds per Square Inch
PtCo	Platinum Cobalt Units
PVC	Polyvinyl Chlorine
RAA	Running Annual Average
RPD	Relative Percent Difference
SDWA	Safe Drinking Water Act
THM	Trihalomethane
TTHM	Total Trihalomethanes
UCF	University of Central Florida
WTP	Water Treatment Plant

CHAPTER 1: INTRODUCTION

The Safe Drinking Water Act (SDWA) is a federal law that requires the United States Environmental Protection Agency (EPA) to set standards for drinking water quality that includes disinfection requirements. The EPA mandates that public water systems must disinfect water for two purposes: for pathogen inactivation (primary disinfection) and to maintain a disinfectant residual within the distribution system (secondary disinfection). One of the first reported uses of chlorination for the disinfection of water supplies in the United States was in 1908 in Jersey City, New Jersey (Leal, 1909). According to the Centers for Disease Control (CDC), disinfection of water supplies using filtration and chlorine is one of the ten greatest public health achievements of the 20th Century (CDC, 1999). Chlorine is the most common form of disinfectant used to prevent waterborne disease in the United States; three of the most common chlorine-containing substances used in water treatment are chlorine gas, sodium hypochlorite (NaClO), and calcium hypochlorite ($\text{Ca}(\text{OCl})_2$). Although these chemicals were found to inactivate waterborne pathogens, by-products of chlorination were also discovered. In 1974 J.J. Rook revealed that chlorine reacts with natural organic matter (NOM) to form disinfection by-products (DBPs); since that time many DBPs have been identified in addition to those found originally in Rotterdam (Rook, 1974; Richardson et al., 2007; Howe et al. 2012).

Due to the identified risks associated with the presence of DBPs in drinking water supplies, the EPA ratified Stage 1 and Stage 2 of the Disinfectant and Disinfection By-Products Rules (D/DBPR) in 1998 and 2006, respectively. These rules were designed to reduce the public's exposure to DBPs. Stage 1 of the D/DBPR established the maximum contaminant levels (MCL) for the four species of trihalomethanes (THMs), jointly referred to as Total Trihalomethanes (TTHMs), the five species of haloacetic acids (HAAs), jointly referred to as HAA5, and the

regulated the maximum residual disinfectant levels (MRDLs) for disinfectants. Stage 2 of the D/DBPR strengthened monitoring requirements for DBPs. For TTHMs, the MCL is set at 80 µg/L, measured by a locational running annual average (LRAA). HAA5s are regulated at 60 µg/L, also monitored through an LRAA. Water systems are required to maintain a MRDL less than 4.0 mg/L as free Cl₂.

Polk County Utilities produces and distributes nearly 2.78 billion gallons of drinking water per year to its Northeast Regional Utility Service Area (NERUSA). This service area covers approximately 72 square miles and is composed six water treatment plants (WTPs) and is supplied by 17 wells. Prior evaluations showed that several WTPs in the NERUSA region can produce elevated levels of DBPs (ESEI, 2019), specifically trihalomethanes.

This research was performed to evaluate several measures to reduce the formation potential of TTHMs at Polk County's Providence and Van Fleet WTPs. The research in this thesis focused on three major goals: (1) to document a number of water quality parameters including DBP concentrations for the Providence and Van Fleet WTPs as well as a pumping station in the NERUSA; (2) to operate pilot-scale tray and spray aeration under four different configurations and alternative operating modes at the two largest WTPs in the region; and, (3) to provide concepts for existing process modifications that would help reduce TTHM formation in the NERUSA water distribution system (as measured by 96-hr formation concentrations); limited opinions of probable modification costs would be developed where possible.

CHAPTER 2: LITERATURE REVIEW

An Overview of Drinking Water Disinfection

The protection of drinking water supplies through chlorination was one of the largest and most significant public health breakthroughs in the modern age (CDC, 1999). Prior to disinfection, waterborne diseases were a leading cause of death in the 19th century. Multiple Cholera outbreaks around the world wiped nearly 1% of the world's population in the 1800s. Since the adoption of proper disinfection practices, occurrences of waterborne diseases have been significantly reduced.

One of the first documented outbreaks of waterborne diseases was in London, England, when physician John Snow traced the epicenter of a cholera breakout to a contaminated water pump (Snow, 1854). In 1881, German-born physicist and microbiologist Robert Koch showed that pure cultures of bacteria such as cholera and typhoid could successfully be inactivated by hypochlorite solutions (Howard-Jones, 1984). Chlorination was applied sporadically in England's water supplies in the late 19th century. A well-documented case of disinfection practices was in 1897 when Sims Woodhead used hypochlorous acid (HOCL) to sterilize water supplies, reducing the extent of a Typhoid outbreak (Davy, 1898). Drinking water chlorination was used by the United States in 1908, when calcium hypochlorite ($\text{Ca}(\text{OCl})_2$) was imparted into a New Jersey public water supply (Leal, 1909). By the mid-20th century, many water purveyors in the United States practiced disinfection (Baker, 1914).

Chlorination of water was understood to produce by-products, but analytical methods in the early 20th century were not advanced enough to determine so. DBPs were not discovered until 1974, when J.J. Rook revealed that the chlorination of drinking water results in the formation of potentially carcinogenic by-products. Rook's research was focused on haloforms, specifically

trihalomethanes (Rook, 1974). Rook's findings lead to further research into the health effects and later regulation of DBPs.

EPA Regulatory Efforts

Shortly after the discovery of trihalomethanes, congress developed the Safe Drinking Water Act (SDWA). The SDWA, promulgated in 1974, established the MCLs for several compounds and impurities suspected to cause adverse health effects when consumed. The SDWA set the MCL of TTHMs at 100 µg/L, or 100 parts per billion (ppb) (USEPA, 1979). TTHMs are the sum of chloroform, bromoform, bromodichloromethane, and dibromochloromethane concentrations. As further research progressed into drinking water disinfection, it was discovered that additional DBPs such as haloacetic acids were suspected to be carcinogenic when consumed (Kim et. Al, 2002). Of the compounds in the haloacetic acid family, five compounds were considered for the highest risk to humans - monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid, and dibromoacetic acid.

In response to these findings, the EPA issued the Stage 1 D/DBPR in 1998, thus lowering the MCL for TTHMs to 80 µg/L and establishing the MCL for HAA5s at 60 µg/L (USEPA, 1998). Stage 1 of the D/DBPR also established the MRDLs for disinfectants. Monitoring of DBPs was performed through a running annual average (RAA) of four samples taken quarterly within the distribution system.

Stage 2 of the D/DBPR was established in 2006 and it tightened monitoring requirements for utilities. A local running annual average (LRAA) was established (USEPA, 2006a). To determine the sampling locations for LRAA compliance, utilities are required to conduct an initial distribution system evaluation (IDSE) and identify four locations with the highest DBP risk. Each quarter, these four sampling locations undergo DBP testing. DBP concentrations are averaged over

the last four calendar quarters at each respective location. Each location's LRAA must fall below the respective MCLs, or a violation has occurred. If a violation above the MCL occurs, the water utility must notify its customers within 30 days with an ordinance on the breach.

Table 2-1: Regulated DBPs and Associated Mean Residual Disinfectant Levels (MRDLs)

Chemical Class	Disinfection by-Product	Chemical Formula	MCL (mg/L)
Trihalomethanes	Chloroform	CHCl ₃	0.08
	Bromodichloromethane	CHBrCl ₂	
	Dibromochloromethane	CHBr ₂ Cl	
	Bromoform	CHBr ₃	
Haloacetic Acids	Monochloroacetic Acid	CH ₂ ClCOOH	0.06
	Dichloroacetic Acid	CHCl ₂ COOH	
	Trichloroacetic Acid	CCl ₃ COOH	
	Monobromoacetic Acid	CH ₂ BrCOOH	
	Dibromoacetic Acid	CHBr ₂ COOH	
Other	Bromate	BrO ₃ ⁻	0.01
	Chlorate	ClO ₃ ⁻	1.0
Regulated Disinfectants		MRDL (mg/L)	
Chlorine		4.0 as Cl ₂	
Chlorine Dioxide		0.8	
Chloramines		4.0 as Cl ₂	

Established in 2006, the groundwater rule (GWR) set forth the protection of public water systems using groundwater as their source. The GWR encourages that disinfection is provided to at least 4-log (99.99%) removal and inactivation of viruses. Suppliers not meeting 4-log removal are required to undergo routine source water monitoring. The level of log inactivation is based on the concept of delivered dose, "CT". C represents the disinfectant residual concentration, while T is the contact time for disinfection. Water purveyors responsible for determining the CT based on several monitoring parameters, such as pH, disinfectant residual, and temperature. The EPA has developed tables to determine log inactivation numbers based on CT values (USEPA, 2006b).

Health Effects

Since the discovery of DBPs, epidemiological studies have suggested a correlation between the consumption of chlorinated water and adverse health effects (Hrudey et al., 2015). Responses in mammals to DBP exposure, specifically chloroform, include depression of the central nervous system, hepatotoxicity, teratogenicity, and carcinogenicity. (Wagner et al., 2017). These responses were observed in rats and mice, who were administered a high level of chloroform. Long term exposure to DBPs have not been fully studied in humans but it has been studied extensively in lab animals (Boorman, 1999). Mice and rats were used due to their similar genetic patterns shared with humans (NCI, 1976). Studies undertaken have shown that brominated DBPs pose a higher toxicity as compared to other by-product counterparts (Chuang et. al., 2019). Epidemiologic studies have suggested an association with cancer of the large intestine and bladder when water with chloroform is consumed (ASTDR, 1997). According to the World Health Organization (WHO) the health risks “from these by-products are extremely small in comparison to the risks associated with inadequate disinfection” (WHO, 2017).

Chlorination and Chlorinated DBP Formation in Water Distribution Systems

Water treatment processes are relied upon to remove undesirable contaminants in source water. The majority of contaminants, both chemical and biological, are present in raw water supplies prior to treatment. Unlike other pollutants, DBPs form during the treatment process. DBPs are formed when chemical disinfectants interact with natural organic matter (NOM). DBP formation is influenced by several factors, including pH, temperature, contact time, disinfectant type, disinfectant dose, bromide presence and concentration of NOM (Crittenden et al., 2012). This section will focus on chlorination and chlorinated DBPs as this research investigated primarily TTHMs and HAA5s. Alternative disinfectants such as chlorine, chloramine, ozone, chlorine

dioxide, and UV irradiation are not presented herein; information on these alternative disinfectants and their associated by-products can be found elsewhere (Nieuwenhuijsen et al., 2000; Richardson et al., 2007; Selbes et al., 2018; Couri et al., 1982)

The effects of pH on the formation of chlorinated DBPs is significant (Cecchetti et al., 2014). Alkaline water tends to form higher percentages of THMs, while acidic waters possess the tendency to form higher fractions of HAAs (Liang et al., 2003). Studies have shown that neutral waters (pH ~7) tend to produce the highest levels of DBPs due to the uniform speciation of organics (Kim et al., 2003). Elevated water temperatures speed up reaction rates and the subsequent formation of DBPs (Singer, 1994). The formation of chloroform in a water source at 35°C was shown to be nearly three times higher than that at 15° C (Zhang et al., 2013). Extensive distribution systems increase water age and chlorine contact time which intensifies DBP formation. The highest level of THMs are likely to be observed at the end of the distribution system since contact time is largest at this point. This is not true for HAAs, as they are more likely to degrade biologically (Singer, 1994). The endpoint locations in a distribution system are frequently identified by the IDSE conducted by water distributors, as these points are where LRAA compliance sampling is undertaken.

Water age is a major factor in water quality deterioration within the distribution system. The primary mechanism for water quality deterioration in the distribution system is from interactions between the pipe wall and the bulk water itself. As the bulk water travels through the distribution system, it undergoes various chemical, physical, and aesthetic transformations that may impact water quality. Many water systems are designed to maintain pressures and quantities needed to meet future demands or to provide extra reserves for fire flow, power outages and other emergencies (such as hurricanes).

Rooks' findings in 1974 introduced evidence that THM formation is initiated by the presence of hydroxide ions in water (Rook, 1974). Further research confirmed this, as HOCl, a commonly used disinfectant, reacts with electron rich portions in NOM (Bond et al., 2012). Both TTHM and HAA5 formations have been shown to occur rapidly in the first few hours, and then the reactions slow and taper out over time as NOM is consumed and disinfectant residual is depleted (Fakour et al., 2018; Vogt et al., 1981).

Higher doses of disinfectant allow more DBPs to form. The presence DBP formation relies heavily on NOM concentration and speciation. NOM is composed of two parts: humic and non-humic fractions. The bulk of NOM falls into the humic fraction, which is composed further into high molecular weight organic molecules, humic and fulvic acids. These two acids are the principal NOM components that contribute to DBP formation (Matilainen et al., 2010). NOM is slow oxidizing by nature, and its solubility varies with pH. Humic acids tend to form more DBPs than fulvic acids due to their higher carbon content (Nikolaou et al., 2004).

Bromide's presence in source water has been shown to have a large impact on the TTHM formation potential of water (Hua et al., 2006). The bromide ion was shown to be a strong halogenating oxidant, reacting with more organic matter than HOCl. The presence of bromide affects the speciation of TTHMs. Symons and others demonstrated that hypobromous acid competes with hypochlorous acid and their subsequent reactions with NOM. HOCl forms larger quantities of chloroform, while hypobromous acid forms more brominated DBPs, such as bromoform (Symons et al., 1993). Studies have been performed that model the effect of several water quality parameters on the subsequent TTHM formation potential of a water supply (Brett et al., 1979; Stevens et al., 1976; Wang et al., 2015). It was shown that TTHM content can vary significantly in the distribution system due to differences in the aforementioned parameters.

Temperature and pH were shown to be the two more significant factors related to TTHM formation in water distribution systems. Also, higher water temperatures often cause a higher chlorine demand, requiring an increased disinfectant dose that can result in higher DBP formation potential

Managing the Formation of Chlorinated DBPs

As regulations of DBPs have been strengthened, many utilities have changed their disinfectant practices to comply with new regulations. Several strategies for the management of chlorinated DBP concentrations in drinking water have been developed:

1. Decrease in the amount of disinfectant added
2. Efficient management of the distribution system
3. Removal or reduction of DBP precursors (NOM)
4. Reduction of TTHMs following formation

Decreasing the amount of disinfectant has been shown to reduce the amount of DBPs formed. However, this management strategy has its limitations. Established in the D/DBPR rules, MRDLs should be maintained within a distribution system. The EPA states that public water utilities must maintain a free chlorine residual less than 4 mg/L and at least 0.2 mg/L within its distribution system (USEPA, 2006a). Disinfection is achieved in two steps: primary and secondary disinfection. Primary disinfection is performed for the purpose of pathogen inactivation, preventing microorganisms such as: *Cryptosporidium parvum*, *Escherichia coli*, *Girardi lamblia*, *Salmonella typhi* and *Vibrio cholerae* from spreading diseases. Secondary disinfection is performed to maintain a residual within the distribution system to limit biofilm growth. For groundwater systems the purpose of primary disinfection is to provide 4-log reduction of virus. Hence, the proper management of chlorine dose along with the corresponding residual is crucial to compliance for public water purveyors.

Control of DBPs can also be achieved by the effective management of water quality in the distribution system. This technique aims to optimize DBP formation factors such as chlorine residual maintenance, pH, and water age. Adjusting pH before or after chlorination may help to control the rate and prevalence of DBP formation. Temperature adjustment is a possible reduction technique, as colder waters hinder DBP formation rates (Zhang et al., 2013), but due to its high cost, it is not economically practical. Since DBP formation is an ongoing reaction between NOM and chlorine, it is important for a water purveyor to deliver water efficiently with minimal water age to the consumer's tap. Water age is the time it takes for water to travel from a treatment plant to a specific point in the distribution system. To reduce the water age in a system, flushing can be employed to help minimize DBP concentrations at the tail ends of a distribution system. The reduction in size of ground storage tanks (GSTs) can assist in the reduction of water age and subsequent DBP concentrations; however, a change in storage volume may impact fire flow emergency storage requirements and hence should be considered in such a strategy. Strategic placement of valves in the distribution system could prove useful to manage water age. Closing distribution system valves (purposefully or accidentally) can result in dead-ends unless there is an ability to flush the system. In an effort to reduce hydraulic retention times, the utility may modify pressure zone boundaries or pressure set points at pumping stations or manage valve placement.

The removal of organic precursors is an effective way to control DBPs. Numerous studies have been conducted to show the effectiveness of treatment processes that can remove DBP precursor matter. Organic DBP precursors can be effectively removed through several technologies such as granular activated carbon (GAC) filtration, membrane filtration, and the enhancement of coagulation, flocculation and sedimentation processes (Hendricks, 2010; Symons et al., 1981; Taylor, 1987). Although these treatment processes are effective in NOM removal, the

implementation and application of these processes require additional cost for construction, operation, and maintenance. If preventative techniques for the reduction of TTHM formation are unavailable, or not economically sound, post-formation removal of DBPs may be necessary. The technique of posttreatment reduction is widely used due to its potential to lower TTHM concentrations at an economically attractive cost. Posttreatment reduction can be achieved by means of GAC filtration, biologically active GAC filtration or aeration processes (Symons et al., 1981). Both GAC filtration techniques can effectively remove both TTHMs and HAA5s but come at elevated operating costs, as the replacement of activated carbon is required frequently.

Air stripping processes are widely employed by water treatment plants for the removal of volatile compounds such as hydrogen sulfide or carbon dioxide. The air stripping process agitates water using spray nozzles or allows water to cascade over a series of trays. Implementation of the aeration process has been shown to lower TTHM concentrations in water, partly due to its ability to remove hydrogen sulfide, a volatile chemical that consumes chlorine (Cecchetti et al., 2014). The use of conventional tray and spray aeration processes for chloroform reduction is relatively new.

Air Stripping

Air stripping processes work by converting matter from the liquid phase to the gaseous phase, resulting in removal from the water column. The aeration process can be described by the two-film theory (Equation 2-1), which details the mass transport of a volatile component(s) from water. In this theory, the solute is transferred from the liquid interface to the air-liquid interface through diffusion. The driving force in this reaction is the concentration gradient between the two phases. When the concentration of gas in water exceeds that in air, the two-film model holds true as shown in Figure 2-1.

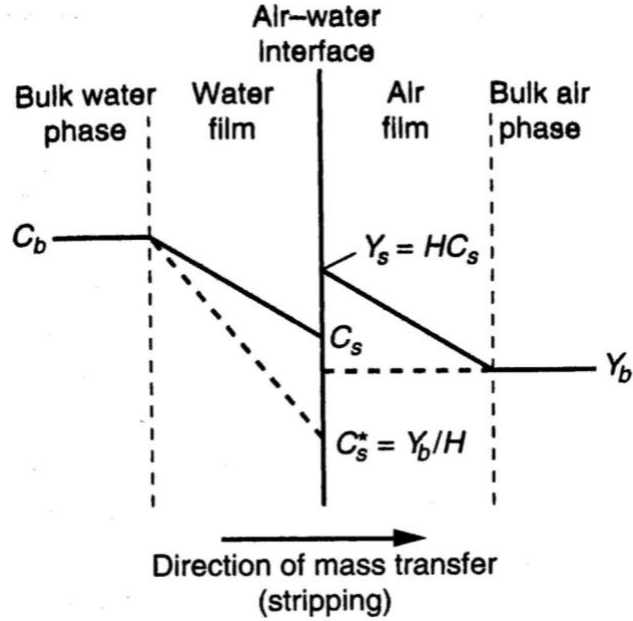


Figure 2-1: Two-Film Theory For the Air-Water Interface

(Crittenden et al., 2012)

$$J = K_L \left(C_b - \frac{Y_b}{H} \right)$$

Equation 2-1

Where:

J is the flux of constituent over the air-water interface

K_L is the total mass transfer coefficient

C_b is the liquid phase concentration of the constituent in the bulk solution

Y_b is the gas phase concentration of the constituent in the bulk solution

H is Henry's law constant

Effectiveness of the air stripping process is determined by the Henry's Law Constant, which represents the proportion of the partial pressure of a volatile constituent in air to the fluid phase concentration of the same constituent in water (Munz et al., 1989). Henry's Law is shown in Equation 2-2 (Crittenden et al., 2012).

$$P_g = HX_g$$

Equation 2-2

Where:

P_g is the partial pressure of the THM species

H is Henry's constant

X_g is the molar concentration of the THM species in water

The Henry's Law constants at 23° and 1 atm are shown for the four regulated THM species in Table 2-2. As with other factors influencing DBP formation, Henry's law constants can be influenced by temperature, pH, and ionic strength. Species possessing larger Henry's Law constants are more volatile and can therefore be stripped easier. Chloroform possesses the largest Henry's Law constant and is the most volatile THM species; however, bromoform has the lowest Henry's law constant and therefore would be more difficult to convert from the liquid phase to the gaseous phase.

Table 2-2: Henry's Law Constants for THM Species of Concern

TTHM	Henry's Law Constant
Chloroform	0.148
Bromodichloromethane	0.095
Dibromochloromethane	0.035
Bromoform	0.024

(Nicholson et al., 1984)

Variations in pH do not directly affect Henry's constant, but it does affect the ionization of certain compounds. Species such as carbon dioxide (CO₂) and ammonia (NH₃) are likely to be in the ionized form at certain pH levels and un-ionized at others. The un-ionized species are volatile and can be removed. As temperature increases, so does the Henry's constant, which makes species more available for stripping. Henry's constant is affected by the ionic strength when dissolved solids are very high, for example, a concentrate stream from reverse osmosis treatment (Gossett,

1987). Natural waters can contain a portion of NOM and other dissolved solids, but these concentrations are not significant enough to affect Henry's constant (Nicholson et al., 1984). The presence of surfactants in high concentrations, as compared to the concentrations of volatile compounds, can hinder the ability of these compounds to volatilize. Surfactants can accumulate at the air-water interface and lower the molar fraction of volatile compounds available. In natural water supplies, surfactant concentrations are often undetectable (Crittenden et al., 2012).

Tray and Spray Aerators

Numerous types of air stripping systems exist; two commonly used systems in drinking water for the removal of volatile compounds are thin-film contactors and droplet contactors. In this work, tray and spray aerators were relied upon for collecting removal efficiency data. The tray aerator represents a thin-film technology, and the spray aerator is considered a droplet contactor.

Thin-film contactors act by agitating and disturbing the flow of water by creating a thin film, maximizing the surface area of water in contact with the atmosphere. A multiple-tray aerator is a thin-film contactor that distributes water at the top of a tower, allowing water to cascade down levels of trays. Multiple levels of solid or perforated trays are stacked on top of each other before water is collected in a basin at the bottom of the trays (Scott et al., 1955). Many studies have documented that aeration in general is capable of removing TTHMs (Sherant, 2008; Brooke & Collins, 2011; Gosh et al., 2015). Another study determined that recirculation through an existing full-scale cascade tray aeration unit results showed an approximate 40 µg/L TTHM reduction in the distribution system (Yoakum & Duranceau, 2018). Additionally, a pilot component performed as part of the Yoakum and Duranceau (2018) study showed that >85% of TTHMs in the storage tank could be reduced to below the detection limit after five passes through a tray aerator placed above the reservoir unit.

Droplet contactors work in a similar way that thin-film contactors do, producing small droplets that increase the surface area available for mass transfer. Spray aeration has been shown as a successful management practice for TTHM reduction. Studies have found spray aeration to be effective in removing more than 80% of TTHMs depending on operating conditions (Cecchetti et al. 2014, Brooke & Collins 2011; Duranceau & Smith., 2016; Rodriguez & Duranceau., 2019).

Duranceau and Smith (2016) assessed the optimal configuration of spray nozzles and its effect on THM removal from a water source. It was shown that spray aeration processes were successful in affecting the reformation potential of a source water, as the final TTHM concentrations of treated water were lower than the TTHM content initially present. Spray aeration using multiple passes was shown to reduce TTHM concentrations in a Central Floridan water supply by up to 99% after five passes (Yoakum & Duranceau, 2018).

In many Central Floridan groundwater treatment systems, tray aeration and chlorination are the primary treatment method. If these systems experience elevated levels of DBPs, then adjustments to their existing system may be an attractive cost-effective alternative as this approach removes the need for further infrastructure, as compared to alternative technologies such as nanofiltration, ozone and GAC treatment. This study investigates the optimization of existing aeration infrastructure to remove formed TTHMs to meet EPA Stage 2 D/DBPR regulatory mandates.

CHAPTER 3: EXISTING CONDITIONS

Polk County is the fourth largest county in Florida by land coverage. To distribute safe drinking water to its residents effectively, the County's water service areas are divided into 15 separate regions. The largest of these regions (by water demand) is the NERUSA, where nearly 2.9 billion gallons of drinking water was distributed to its residents in 2019. Water in the NERUSA region is treated by six different WTPs which are fed by 17 different groundwater wells pulling water from the Upper Floridan aquifer. Previous evaluations provided data on a number of groundwater wells that feed several WTPs in the NERUSA region (ESEI, 2019). It was shown that the two largest WTPs in the region, Providence WTP and Van Fleet WTP, are capable of producing elevated levels of disinfection-by-products, that given enough time would exceed the regulatory maximum contaminant level of 80 ppb. Table 3-1 displays data obtained from the 2017 to 2019 County annual water quality reports for the NERUSA region showed that TTHM concentrations have been increasing yearly and are approaching the MCL of 80 ppb.

Table 3-1: NERUSA DBP Compliance Results (2017 to 2019)

Year	Free Chlorine (mg/L)		TTHM (ppb)		HAA5 (ppb)	
	Range	RAA	Range	LRAA	Range	LRAA
2019	0.2 – 3.6	2.0	22 – 100	76	13 – 56	49
2018	0.2 – 3.6	1.8	21 – 100	76	9 – 57	48
2017	0.4 – 3.6	1.7	21 – 90	73	8 – 43	39

(Polk County Utilities, 2017; Polk County Utilities, 2018; Polk County Utilities, 2019)

Both Providence and Van Fleet WTPs rely on cascade tray aeration for the removal of sulfide and other dissolved gasses, a poly-orthophosphate based corrosion inhibitor for corrosion control and iron sequestration, and sodium hypochlorite for primary and secondary disinfection. The CR-54 booster pump station is located in-between Providence and Van Fleet WTPs, as shown

in Figure 3-1. Water quality and DBP evaluations were performed at this location to assess DBP formation at the main pumping station within the NERUSA distribution system.

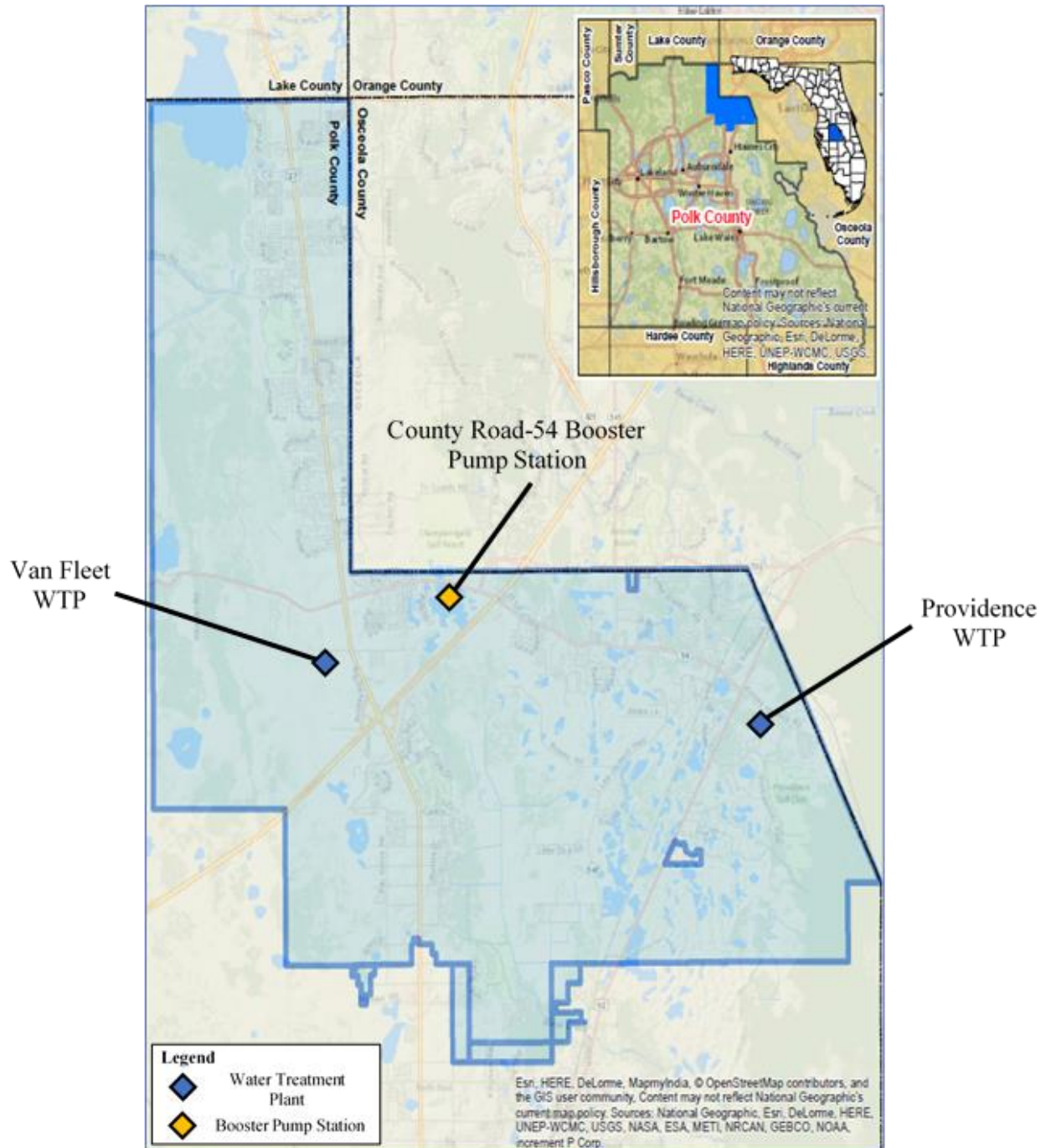


Figure 3-1: Location of NERUSA and Areas of Interest
(Adapted from: Polk County Utilities 2015 NERUSA Master Plan)

Providence WTP

Providence WTP is permitted to distribute 10 million gallons per day (MGD) of potable groundwater to residents (Polk County Utilities, 2015). Providence WTP is located at 801 Kinney Harmon Road Davenport, Florida. This WTP is fed by 5 groundwater wells: Oak Hills well 1, Oak Hills well 2, Oak Hills well 3, Providence well 5, and Providence well 6. Providence wells 5 and 6 are located on-site. Water is pumped in from the surrounding area for Oak Hills wells no. 1, 2 and 3. Well Information shown in Table 3-2.

Table 3-2: Providence WTP Well Information

Well	Capacity (gpm)	Depth (ft.)
Oak Hills 1	1,500	1,050
Oak Hills 2	2,100	780
Oak Hills 3	1,700	820
Providence 5	1,750	750
Providence 6	1,500	750

Providence WTP sits on approximately 4 acres. The site has been master planned for expansion, including an additional 2.0 million gallons (MG) GST along with another high service pump (HSP). Water that flows to Providence WTP is blended with corrosion inhibitor and chlorine before flowing to a 7,000 gpm tray aerator. Water is collected in the GST where additional chlorine is dosed before it flows to one of the four on-site HSPs rated between 3,475 gpm and 1,737 gpm.

Table 3-3: Providence WTP Operating Information in 2020

Parameter	Value
Average Chlorine Residual [Pre/Post] (mg/L)	1.28 / 2.44
Average Corrosion Inhibitor Dose (mg/L)	1.00
Average Tank Height (ft.)	21.5



Figure 3-2: Providence WTP Ground Storage Tank with Tray Aerator and High Service Pump Station

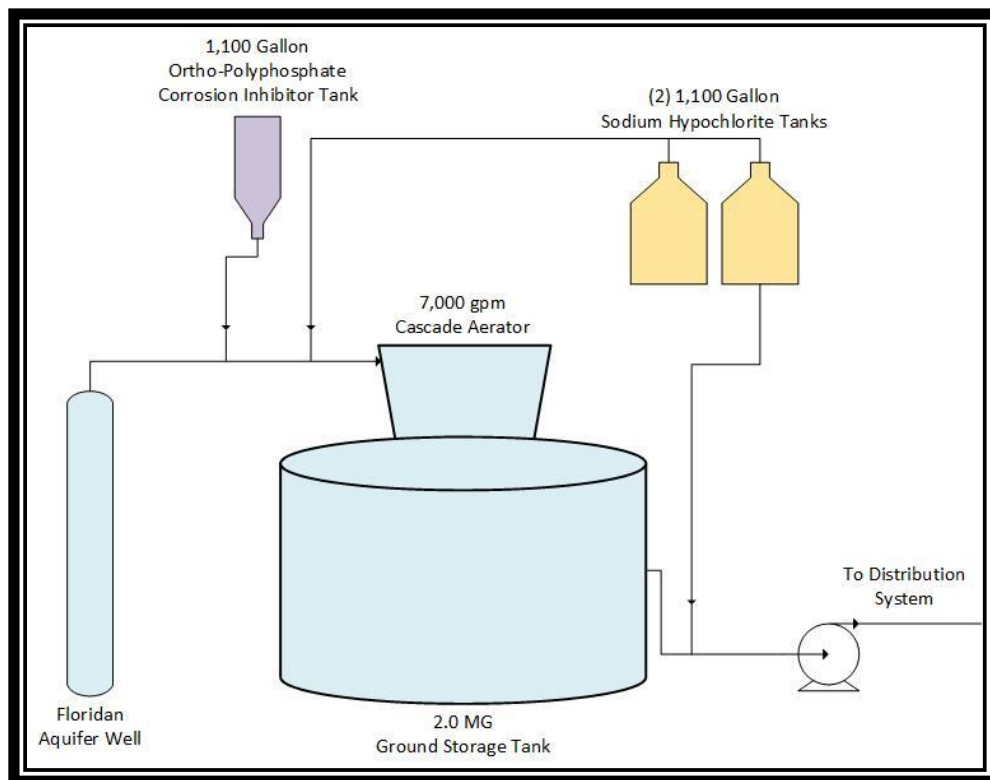


Figure 3-3: Providence WTP Process Schematic

Van Fleet WTP

The Van Fleet WTP is located at 2850 Waverly Barn Road in Davenport, Florida and is permitted to distribute a 5.8 MGD of treated groundwater (Polk County Utilities, 2015). The Van Fleet WTP is fed by four groundwater wells: Bella Toscana, Tierra del Sol, US Homes and Van Fleet. The Van Fleet well is situated on-site, while the other wells are pumped in from off-site locations in proximity of the facility. Information on these wells are presented in Table 3-4.

Table 3-4: Van Fleet WTP Well Information

Well	Capacity (gpm)	Depth (ft.)
Bella Toscana 2	1,367	253
Tierra del Sol	1,256	537
U.S. Homes	916	510
Van Fleet	3,000	255

The Van Fleet WTP and associated facilities are arranged on approximately 3 acres. The site has been master planned for expansion, including an additional 1.0 MG GST and another HSP. Water at the Van Fleet WTP is dosed with chlorine before flowing to a tray aerator rated at 5,000 gpm. Water is then collected in the GST where additional chlorine is dosed along with corrosion inhibitor before heading to one of the four HSPs on-site. Three HSPs are rated at 2,600gpm and one is rated at 1,000 gpm. Operating information for Van Fleet WTP in 2020 is included in Table 3-5.

Table 3-5: Van Fleet WTP Operating Information in 2020

Parameter	Value
Average Chlorine Residual [Pre/Post] (mg/L)	1.59 / 2.38
Average Corrosion Inhibitor Dose (mg/L)	1.00
Average Tank Height (ft.)	23.5



Figure 3-4: Van Fleet WTP With Chemical Storage Shelter

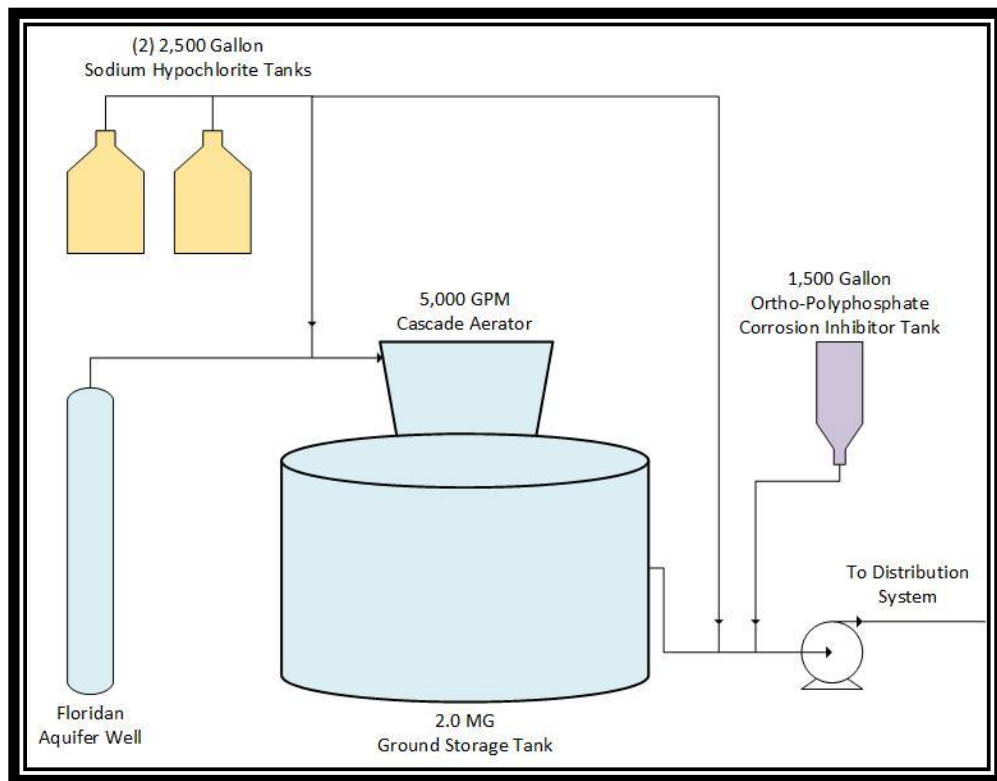


Figure 3-5: Van Fleet WTP Process Schematic

County Road-54 Booster Pump Station

The CR-54 booster pump station is located west of Interstate 4 along County Road-54. The facility was constructed to increase pressure within the distribution system and to serve as a location for emergency water storage.

The CR-54 booster pump station sits on a ~ 1.5 acre site. This location has a 1.5 MG GST that feeds water to back to distribution system using three HSPs rated for 2,950 gpm each. Water flows to this location from Providence WTP and Ovation WTP, both neighboring sites. Water is pumped from this location west, towards the Van Fleet side of the distribution system. Chlorine can be added at two locations, both before water enters the GST and as water exits the tank. The CR-54 booster pump station does not currently run with the sodium hypochlorite tanks in line, as the chlorine residual of the incoming water is sufficient without the need of additional chlorination. Corrosion inhibitor is not added at this location. There is currently not an aeration process in place at the CR-54 booster pump station, but it would be possible to retrofit aerator stripping technology at this location. Operating information from the year of 2020 is included in Table 3-6.

Table 3-6: CR-54 Booster Pump Station Operating Information in 2020

Parameter	Value
Average Chlorine Residual [Pre/Post] (mg/L)	N/A
Average Corrosion Inhibitor Dose (mg/L)	N/A
Average Tank Height (ft.)	14.1



Figure 3-6: County Road-54 Booster Pump Station with Sodium Hypochlorite Tanks

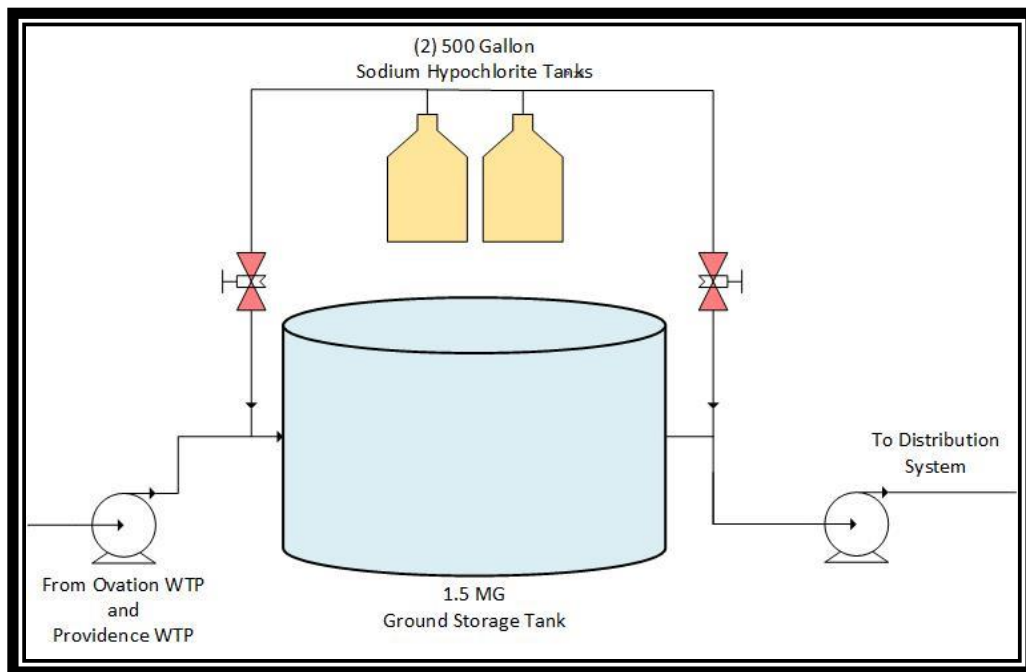


Figure 3-7: County Road-54 Booster Pump Station Process Schematic

CHAPTER 4: MATERIALS AND METHODS

This chapter presents a detailed description of the experimental procedures and materials used throughout this study. Standard methods for the analysis of drinking water, described further in this section, were applied for the determination of precision and accuracy. Quality assurance and control measures were used to assess the acceptability of analytical methods.

Experimental Plan

This research was conducted to evaluate several measures for the reduction of the TTHM formation potential at two WTPs in Polk County. To perform this task three goals were developed; (1) collecting a number of water quality parameters at Providence WTP, Van Fleet WTP and the CR-54 booster pump station; (2) operate a pilot-scale tray and spray aeration unit under four different configurations at Providence and Van Fleet WTPs; and, (3) provide a concept for process modifications aiding in the reduction of TTHM formation within the NERUSA water distribution system.

Initial Water Quality Evaluations

Samples at the Providence WTP, Van Fleet WTP and the County Road-54 booster pump station were collected and transported to UCF's environmental engineering laboratory for water quality analysis and for in-situ TTHM and HAA analysis. TTHM and water quality samples were obtained at three locations from each of the WTPs: water entering the GST, water exiting from the outlet of the lowest tray in the aeration process and water exiting the ground storage tank. At the CR-54 booster pump station, samples were collected from two locations: water entering and exiting the GST. Background operating information was obtained for each of the three locations to gain a further understanding of the daily conditions experienced at the sites.

Following the completion of the initial water quality evaluation, two additional sampling events at each of the aforementioned locations were conducted. These visits were performed to gain a further understanding of basic water quality parameters, as well as TTHM and HAA contents over time through diurnal variations. These events represent different sampling conditions: WTPs under low organic loading and WTPs under high organic loading. Low organic loading denotes the WTPs running with their typical well rotations in effect. High organic loading represent the WTPs operating with their lesser used, higher TTHM forming wells in rotation. High organic loading was conducted to evaluate the worst-case water quality and DBP concentrations present at each of the sampling locations. During each operating condition, samples were taken at two different times: morning and afternoon, corresponding to high and low flows, respectively. During the low organic sampling event, no operational changes were made at the three locations. Two days prior to the high organic sampling, the lesser used wells were put into lead, or priority, allowing ample time to fill the GSTs with the higher TTHM forming water.

At each of the WTPs, water is fed to the GST from several wells in the surrounding area. Prior evaluations in the NERUSA region show that water quality varies greatly from well to well (ESEI, 2019). For the County to ensure an adequate supply of water is provided to each WTP, a combination of several wells are used to feed the GSTs. During operation, one well is kept in lead mode, indicating that the GST will be filled mostly with its water. Several other wells are kept in lag mode, only pulling water when necessary (periods of high demand). The County operates with its wells possessing higher water quality in lead mode, while the wells with lower water quality are kept in lag mode. For the low organic sampling, WTPs were run with their typical well rotations in lead and lag configurations. During the high organic sampling, WTPs operated with their lesser used wells in lead.

Pilot Unit Construction

To evaluate the effectiveness of tray and spray aeration on TTHM removal from a treated and chlorinated groundwater supply, a pilot-scale tray and spray aeration unit was constructed. The pilot-scale aeration unit was designed to reflect a full-scale tray aerator in operation at each testing location. The pilot-scale unit was designed so that it could easily be modified to serve solely as a spray aeration unit, or as a combined tray and spray aeration unit. The pilot-scale aeration unit was run in a series of four different field tests performed at both the Providence and the Van Fleet WTPs, for a total of eight tests between the two locations. Field test 1 was conducted to assess the effect of recirculation on TTHM removal. Field test 2, conducted in three parts, evaluated TTHM removal through different configurations of the aeration pilot.

Field Test 1 – Recirculated Tray Aeration

Field Test 2 (a) – One-Pass Expanded Tray Aeration

Field Test 2 (b) – One-Pass Spray Aeration

Field Test 2 (c) – One-Pass Modified Tray with Spray Aeration

The pilot-scale aeration unit consists of a series of trays that allow water to cascade down into a storage tank. The skeleton of the unit was made using 2" x 4" plywood pieces and the base was made with two 2' x 4' plywood sheets. Metal reinforcement bars were added to the legs of the unit for stability. The storage tank is a 55-gallon linear low-density polyethylene (LLDPE) plastic drum obtained from United States Plastic Corporation® (1390 Neubrecht Road, Lima, OH 45801). Water from the storage tank was pumped to the inlet of the highest tray using an 2/7 horsepower Iwaki MD-70RLZT pump, manufactured by Iwaki America (5 Boynton Road, Holliston MA 01746). Schedule 40 polyvinyl chloride (PVC) tubing was used for pipe connections. A Brooks® 4UN11 Flowmeter, produced by Brooks® Instrument (407 West Vine Street, Hatfield PA 19440)

was placed after the pump to monitor the flowrate through the system. A T-shaped PVC ball valve was installed directly before to the flowmeter. The trays used were corrugated brown plastic splash blocks obtained from a hardware store. Each tray measures 22-inches long. The trays expand out from a width of 6 inches to 9 inches, giving each tray a surface area of 1.18 ft². Vertical drops for a full-scale tray aeration unit typically range between 12 and 30 inches. Full-scale water application rates range from 20 to 30 gpm/ft² (Crittenden et al., 2012; Faust & Aly, 1998). Application rates for the pilot aeration unit were selected to provide dimensional similitude to a full-scale unit. Prior to operation, plastic splash guards were added to the smaller portion of the trays to reduce water loss during operation. Each of the trays were wrapped in aluminum foil, to prevent water contact with non-National Sanitation Foundation (NSF) / American National Standards Institute (ANSI) approved materials. NSF/ANSI Standard 61 applies to drinking water components. The splash blocks before and after modification are shown in Figure 4-1.



Figure 4-1: Unmodified Splash Block (Left) and Modified Splash Block (Right)

Field Test 1 – Recirculated Tray Aeration

Field test 1 focuses on assessing the effect of multiple volumetric turnovers, herein defined as “passes”, through a pilot tray aeration unit on TTHM reduction. This condition aims to reflect recirculation of the full-scale ground storage tank while no pumping to the distribution system is present. Currently, the WTPs do not practice recirculation within the GSTs. With five trays in operation, the pilot aeration unit possesses a surface area of 0.55 m². 30 gallons of source water was run through the aeration unit at a flow of 3 gpm. This flow was selected to simulate the Providence WTP and the Van Fleet WTP running at peak flow conditions (1800 gpm and 2400 gpm, respectively). The constructed tray aeration pilot and its schematic with approximate dimensions are included in figure 4-2.

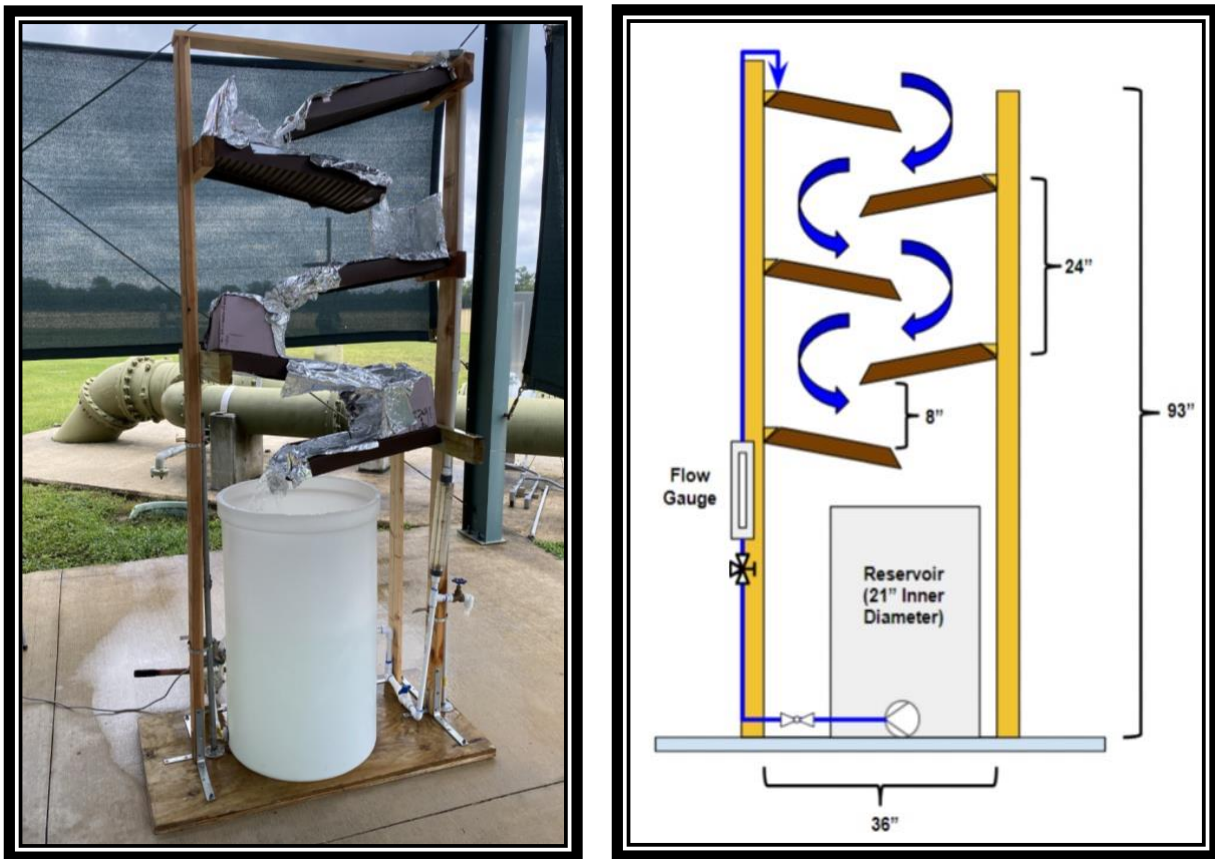


Figure 4-2: Tray Aerator Pilot Unit (Left) and Schematic (Right)

Field Test 2 (a) – One-Pass Expanded Tray Aeration

This field test is the first of the configuration experiments. Field test 2 (a) entails running 30 gallons of source water through the pilot tray aeration unit with five trays in operation at a flow of 3.0 gpm. The same process was repeated with seven trays in operation. This condition reflects running the ground storage tank with additional trays in effect but with no pumping to the distribution system present. With the addition of two extra trays, the total surface area of the unit increases to 0.77 m². A photo and schematic of the pilot aeration unit is shown with seven trays in operation is shown in Figure 4-3.

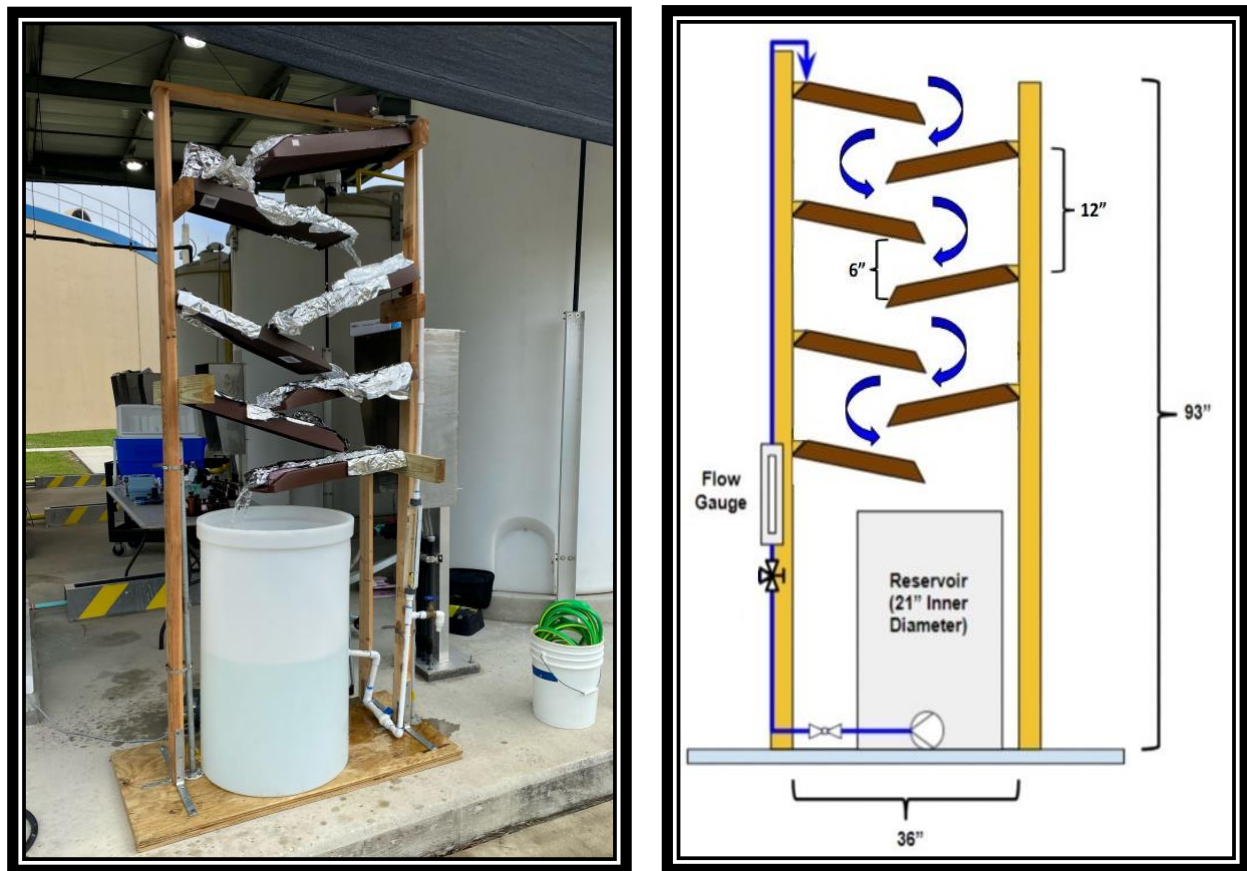


Figure 4-3: Tray Aerator Pilot with Seven Trays (Left) and Schematic (Right)

Field Test 2 (b) – One-Pass Spray Aeration

The spray aeration pilot utilizes the same 55-gallon LLDPE drum and Iwaki pump as the tray aeration unit. Water is pumped using schedule 40 PVC piping from the drum to a GridBee® spray nozzle produced by IXOM Watercare (3225 Highway 22, Dickinson, ND 58601). Prior evaluations have shown that GridBee® spray nozzles are highly effective in spray aeration processes (Duranceau & Smith, 2016). A pressure gauge was put directly before the nozzle to monitor water pressure leaving the unit. 30 gallons of source water was used for spray aerator testing. Flowrates of 2 gpm (7 psi) and 3 gpm (13 psi) were utilized for this study. This condition introduces spray aeration to the GST. The spray aeration pilot unit in operation is shown in Figure 4-4 (left) and the GridBee® spray nozzle with its pressure gauge is shown in Figure 4-4 (right).



Figure 4-4: Spray Aeration Unit (Left) and GridBee® Spray Nozzle (Right)

Field Test 2 (c) – One-Pass Modified Tray with Spray Aeration

Field test 2 (c) presents a modification of field test 2 (a). For this test, a BETE® spray nozzle was added to the inlet of the highest tray. The BETE® spray nozzle, (50 Greenfield St, Greenfield, MA 01301), selected operates in a full-cone spray pattern. A full-cone spray pattern was favored in this test, due to the spatial constraints present in the aeration pilot unit. This test was performed to assess the effect of combining tray and spray aeration with increased surface area. 30 gallons of water obtained from the point of entry (POE) sampling tap was used. A flow of 3.0 gpm was used for this test. This testing condition reflects running a modified ground storage tank that combines spray and tray aeration with no pumping to the distribution system present. The BETE® spray nozzle is shown prior to installation (left) and in operation (right) in Figure 4-5.

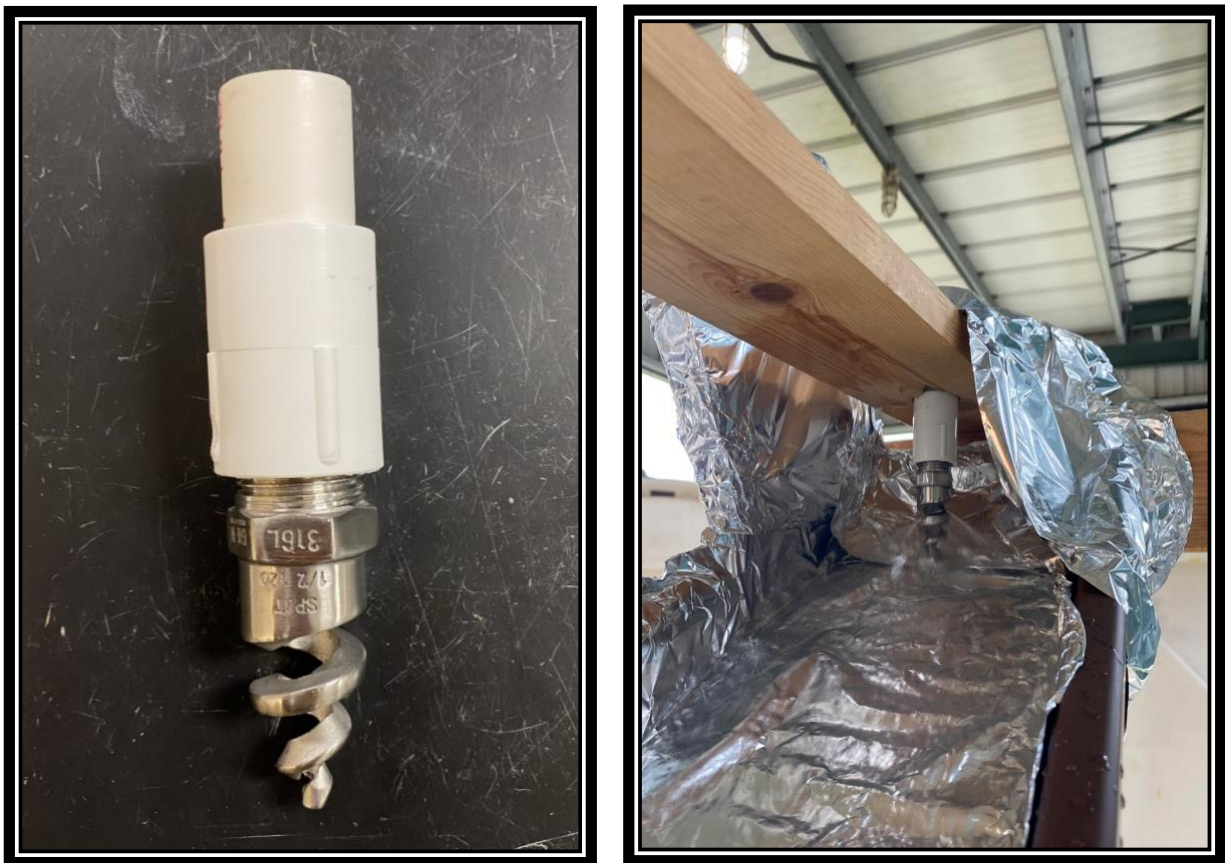


Figure 4-5: BETE® Spray Nozzle (Left) and BETE® Spray Nozzle in Operation (Right)

Source Water Location

Water obtained during piloting events was collected from a hose connected to the POE sampling tap at each of the respective WTPs. During each of the piloting events, the drum and pilot unit piping were flushed out two times with water obtained from the POE prior to operation. Water from the POE was then put into the drum until it reached the 30 gallon mark before testing began. As the drum was filling up, samples were collected to establish a baseline for chlorine residual, TTHM, HAA5, and water quality. These samples were relied on to assess the effect of no additional treatment on water exiting the WTPs. Following the completion of each field testing subset, water samples were collected from a stream coming off the outlet of the lowest tray [field tests 1, 2 (a), 2 (c)] and from the GridBee® spray nozzle outlet [field test 2(b)].

The same procedures for flushing were utilized for each of the field tests. Upon flushing and gathering of baseline samples, the flowmeter was adjusted to its respective flowrate and the pump was activated. Detailed data on the source water quality is included in the results section of this document.

Field Test Sampling

During each field test several parameters were monitored: pH, temperature, free chlorine residual, non-purgeable dissolved organic carbon (DOC), UV-254, TTHMs and HAA5. Samples collected on-site for pH, temperature and free chlorine residual were measured directly in the field, while samples collected for TTHMs, HAA5, DOC and UV-254 were measured at UCF's environmental engineering laboratories. TTHM samples were quenched using 1 mL of TTHM quenching reagent. This reagent was prepared at UCF by adding 10 grams of sodium sulfite (Na_2SO_3) to 100 mL of deionized (DI) water. HAA5 samples were quenched in 60-mL vials containing 5 grams of ammonium chloride (NH_4Cl) provided by Advanced Environmental

Laboratories (AEL) (380 Northlake Blvd #1048, Altamonte Springs, FL 32701). Both TTHM and HAA5 samples were checked for air bubbles prior to capping.

For each field test performed at the WTPs, a total of 14 bottles were collected. Eight bottles were collected for TTHM analysis: 0-hr., 24-hr., 48-hr., and 96-hr. marks, each in duplicate. Four bottles for chlorine analysis were taken: 24-hr., 48-hr., and 96-hr. marks, duplicated at the 48-hr. mark only. One 250-mL bottle was taken for HAA sampling and one 250 mL bottle was taken for water quality sampling.

TTHM samples were quenched following the respective holding time for each sample. HAA5 samples were taken at the 96-hr. mark only. Chlorine residual samples were read after their respective holding times. Water quality samples were read as soon as possible, not exceeding the one-week mark, as set by *Standard Methods for the Examination of Water and Wastewater*. Chlorine residual, TTHM and HAA5 sample that have yet to be quenched were incubated in a Thermo Scientific Heratherm™ (168 3rd Avenue, Waltham, MA 02451) incubator at 30°C to imitate the warmest distribution system conditions and project worst-case DBP formation. Water quality samples, together with samples that have been quenched were stored in a refrigerator at 4°C until an analysis was performed. Sample analyses were performed on-site or at UCF's environmental engineering laboratories with the exception of HAA5 samples. HAA5 samples were sent to AEL to protect the safety of those involved in the analytical procedures. The methodology and equipment used when performing water quality analysis are summarized in Table 4-1.

Table 4-1: Analytical Methods Used During Testing

Test	Location Analyzed	Equipment and Method Used	Minimum Detection Level
Free chlorine	On-site	Hach Spectrophotometer DR5000 Hach Method 8021	0.02 mg/L as Cl ₂
Temperature	On-site	Hach Pocket Pro+ Multi Meter SM: 2550 B	0.01 °C
pH	On-site	Hach Pocket Pro+ Multi Meter SM: 4500-H ⁺ B	0.01 pH Units
Conductivity	On-site	Hach Pocket Pro+ Multi Meter SM: 2510 B	0.01 µS/cm
Oxidation Reduction Potential	On-site	Hach Pocket Pro+ Multi Meter SM: 2580 B	-999 mV
Total Sulfide	On-site	Hach DR900 Hach Method 8131	0.01 mg/L
Turbidity	On-site	Hach 2100Q Portable Turbidimeter SM: 2130 B	0.01 NTU
TTHM	UCF Lab	Perkin Elmer 580 Clarus Gas Chromatographer SM 6232 B	3 ppb (chloroform) 0.7 ppb (other THMs)
UV-254	UCF Lab	RealTech P300 UV254 Meter SM: 5910 B	0.001 cm ⁻¹
Color (True)	UCF Lab	Hach Spectrophotometer DR5000 SM 2120 C	1.0 PtCo
DOC	UCF Lab	Teledyne Tekmar Total Organic Carbon Fusion SM: 5310 C	0.25 mg/L
Metals	UCF Lab	Inductively Coupled Plasma (ICP) SM: 3120 B	Calcium: 0.01 mg/L Iron: 0.004 mg/L Magnesium: 0.03 mg/L Manganese: 0.005 mg/L Silica: 0.02 mg/L Sodium: 0.03 mg/L
Anions	UCF Lab	Dionex ICS-1100 SM: 4110 B	Chloride: 0.004 mg/L Sulfate: 0.018 mg/L
HAAs	AEL	Agilent 6890N Network Gas Chromatograph EPA 552.2	0.20 µg/L

Quality Assurance / Quality Control

Method 1020 B from *Standard Methods for the Examination of Water and Wastewater* was used to maintain the quality of data obtained. Glassware used for sample collection was washed with laboratory grade detergent, rinsed with 1:1 hydrochloric acid (HCL) and rinsed thoroughly with distilled water prior to being ashed in a furnace at 400°C for a minimum of two hours. Reagents relied upon for analytical laboratory procedures were analytical grade or a higher equivalent.

When collecting chlorine residual samples, one bottle out of every five was used for purposes of providing a duplicate analysis. When reading chlorine residual, one bottle out of every five was replicated. As detailed in the previous section, during sample collection for chlorine residual, five 60-mL bottles were collected and labeled as follows: 0-hour, 24-hour, 48-hour, 48-hour (duplicate), and 96-hour. For replicate purposes, the 96-hour bottle was read twice. For the construction of the precision control chart, both replicates and duplicates are considered as duplicates. For TTHM analyses, a minimum of every 5th sample was replicated, duplicated, and spiked for maintaining instrument precision and accuracy. Equations 4-1 through 4-5 were employed for the calculations corresponding to quality control and quality assurance. Control and warning levels were determined for the first ten duplicate/replicate samples analyzed. For other water quality tests, a minimum of one in every five samples were replicated, duplicated, and spiked, where appropriate, to confirm the quality of data obtained.

Duplicates and replicates were used to generate precision control charts. These charts were used to monitor fluctuations in sampling techniques and equipment readings. Sample precision was calculated using the relative percent difference (RPD), shown in Equation 4-1. A violation of precision control arises when a single data point fell outside of the control limit, or when

consecutive samples exceed the warning limit. Samples failing precision control are not included in the data sets. No samples were excluded from the precision data sets.

The percent recovery was calculated for spiked samples to monitor the accuracy of equipment used. An accuracy control chart was generated using the percent recoveries for the spiked samples. Upper and lower warning levels were calculated using Equation 4-4 (Upper warning levels were set at two standard deviations higher than the mean, while lower warning levels were set two standard deviations lower than the mean). Equation 4-5 was used for the upper and lower control levels (upper control levels were set three standard deviations above the mean while lower control levels were set three standard deviations below the mean). A violation of accuracy control occurs when two successive results fall outside of the warning limits, or seven successive points fall either above or below the mean. Any data points incurring an accuracy violation were not included in the data sets. No violations were observed for accuracy control. Precision and control charts can be found in the results section of this document.

$$RPD = \frac{|sample\ result - duplicate\ result|}{(sample\ result + duplicate\ result)/2} * 100 \quad \text{Equation 4-1}$$

$$\% Recovery = \frac{quantity\ measured}{quantity\ added} * 100 \quad \text{Equation 4-2}$$

$$\bar{R} = d_2 s \quad \text{Equation 4-3}$$

$$WL = \bar{R} \pm 2s(R) \quad \text{Equation 4-4}$$

$$CL = \bar{R} \pm 3s(R) \quad \text{Equation 4-5}$$

Where:

RPD = relative percent difference

\bar{R} = mean range

d_2 = factor to convert s to the mean range (1.128 was used for duplicates)

WL = warning level

CL = control level

$s(R)$ = standard deviation of the range

D_4 = factor to convert the mean range to CL (3.267 was used for duplicates)

CHAPTER 5: RESULTS AND DISCUSSION

Initial Site Visits

The three locations of interest, the Providence WTP, Van Fleet WTP, and the County Road-54 booster pump station were visited several times at the onset of research activities to gain a better understanding of the existing water quality for a number of parameters, including DBP concentrations present within the water system.

During the first visit, TTHM profiles were generated for samples taken at the Providence WTP, Van Fleet WTP and the CR-54 booster pump station. A profile of TTHM concentrations present in each location obtained during the July 3, 2020 sampling event are shown in Figures 5-1, 5-2 and 5-3. These figures represent TTHM concentrations during this water quality screening exercise.

At the Providence WTP, shown in Figure 5-1, water exits the GST with a TTHM concentration of 50 ppb. The on-site tray aerator was successful in the reduction of TTHM concentrations, lowering the magnitude from 44 ppb entering the unit to 16 ppb at the outlet of the lowest tray. Figure 5-2 displays that water exiting the GST located at the Van Fleet WTP has a TTHM concentration of 35 ppb. The tray aeration unit on-site reduced concentrations from 31 ppb entering the process to 6 ppb leaving the lowest tray. At the CR-54 booster pump station, Figure 5-3, TTHM concentrations entering the GST were at 15 ppb. Water exited the GST at 28 ppb, indicating an increase of 13 ppb at this location.

Results indicate that TTHM concentrations exiting the three locations may be reduced by the improvement of the tray aeration process and/or the decrease in residence time within the GSTs. Results indicate that residence time of in the GST is likely between 5 and 15 hours.

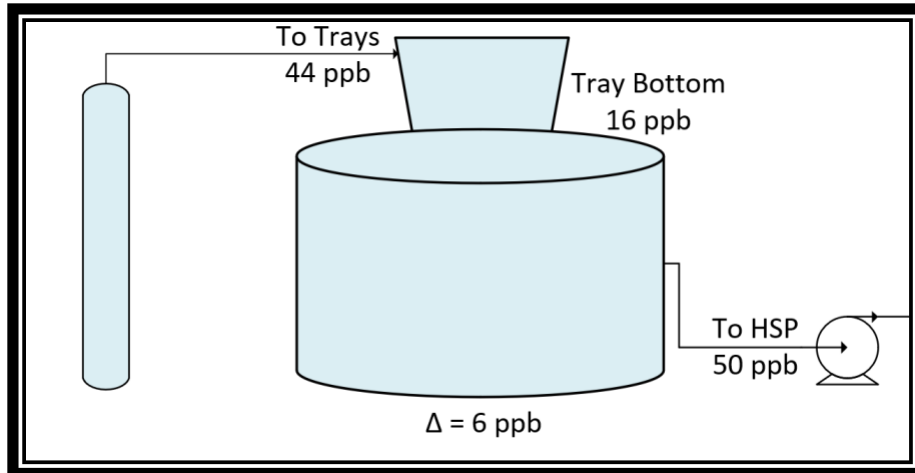


Figure 5-1: TTHM Profile of Providence WTP

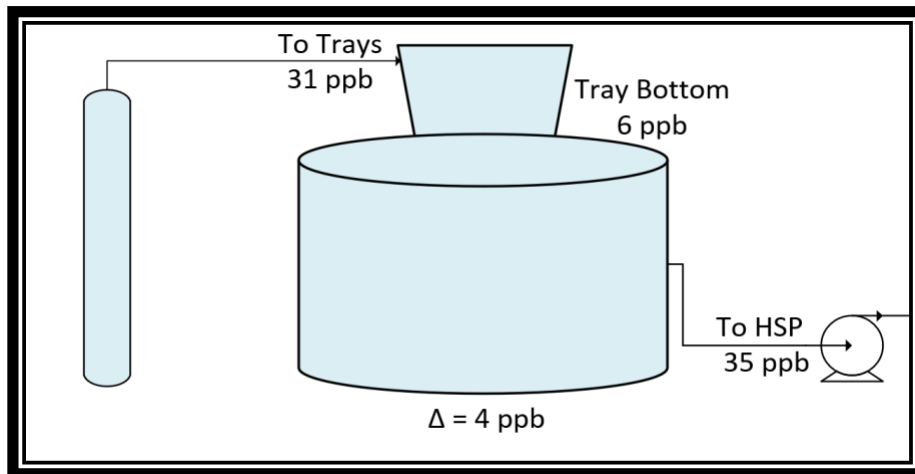


Figure 5-2: TTHM Profile of Van Fleet WTP

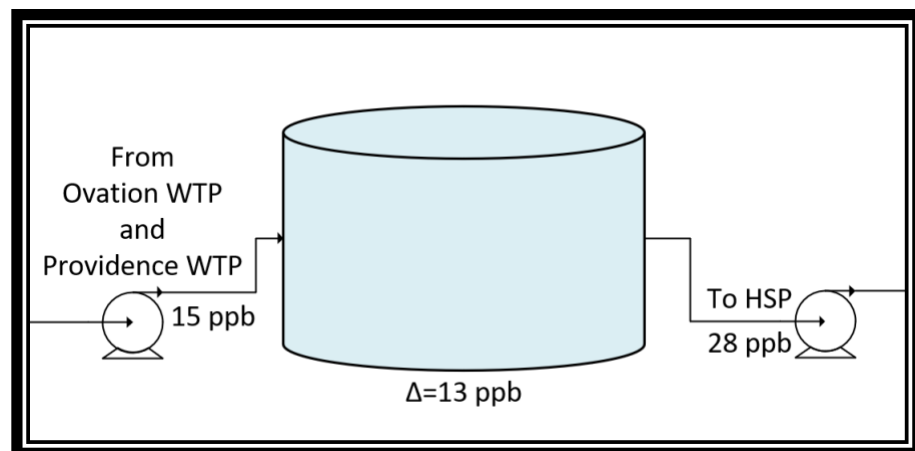


Figure 5-3: TTHM Profile of 54 Booster Pump Station

Sampling events conducted during low organic and high organic loadings were performed on July 20, 2020 and July 23, 2020, respectively. On each date, samples were taken at two different times for each location. The morning sampling time, displayed on the left side of each sampling date column in Tables 5-1 and 5-2, was taken at a period of high demand for each location (increased flow in and out of GSTs). The afternoon samples were taken at a period of low flow at the three locations, displayed on the right side of each sampling date column in each of these tables.

At Providence WTP, altering the well rotations from low organic to high organic loading resulted in a 25% increase in TTHM concentrations at the POE sampling tap. At Van Fleet, a 31% increase in TTHM concentrations was observed from shifting the well rotations from low organics to high organics. The free chlorine residual was observed to be lower on the July 23 sampling event at both the Providence and Van Fleet WTPs. This is likely due to the increased hydrogen sulfide demand of the source water. At the Providence and Van Fleet WTPs, DOC entering the tank on the July 23 sampling date was 34% higher, and 26% higher, respectively, than the July 20 sampling date. Table 5-1 displays the water quality and DBP results from these sampling events at the Providence WTP and the Van Fleet WTP. Due to the increased cost with HAA5 analysis, samples were only taken during the July 23 afternoon sampling event, to establish worst-case HAA5 concentrations.

It was determined that the CR-54 booster pump station is not an area of concern for TTHM formation. Table 5-2 displays the associated water quality and DBP results from July 20, 2020 and July 23, 2020 sampling events at this location. Between the two sampling dates, TTHM concentrations exiting the GST increased by 5%. DOC concentrations exiting the GST remained similar for both sampling dates. It should be noted that TTHM concentrations in the afternoon sampling were increased by more than double from the morning sampling. Aeration studies

conducted do not include this location, as TTHM concentrations exiting this location did not rise higher than 33 ppb.

Table 5-1: TTHM, HAA5 and Water Quality Data from Providence and Van Fleet WTPs

Parameter	Providence				Van Fleet			
Sampling Date	7/20/2020		7/23/2020		7/20/2020		7/23/2020	
Flow	High	Low	High	Low	High	Low	High	Low
TTHM (ppb)	37.6	45.4	55	56.7	29.7	26.9	38.9	37.5
HAA5 (ppb)	N/A	N/A	N/A	41.5	N/A	N/A	N/A.	17.3
pH	7.94	7.84	7.96	7.87	8.07	7.76	8.01	7.96
Temperature (°C)	27.5	29.5	27	29.2	26.8	27.4	27.2	28
Conductivity (µs/cm)	395	310	364	339	301	340	412	335
Free Chlorine (mg/L)	2.1	2.3	1.97	2	1.91	1.8	1.7	1.76
DOC (mg./L)	1.51	1.55	2.02	2.03	1.13	1.11	1.42	1.25

Table 5-2: TTHM, HAA5 and Water Quality Data from 54 Booster Pump Station

Parameter	54 Booster In				54 Booster Out			
Sampling Date	7/20/2020		7/23/2020		7/20/2020		7/23/2020	
Flow	High	Low	High	Low	High	Low	High	Low
TTHM (ppb)	14.3	30.4	12.9	28.6	8.0	31.2	15.5	32.5
HAA5 (ppb)	N/A	N/A	N/A	12.2	N/A	N/A	N/A	12.9
pH	7.78	7.69	7.83	7.69	7.75	7.76	7.80	7.74
Temperature (°C)	27.1	27.8	25.4	28.3	26.8	27.4	25.8	27.9
Conductivity (µs/cm)	319	380	324	299	362	309	316	306
Free Chlorine (mg/L)	1.91	1.87	1.46	1.34	2.06	2.00	1.53	1.58
DOC (mg./L)	1.01	1.35	1.04	1.22	1.00	1.22	1.03	1.22

Field Test 1 – Recirculated Tray Aeration

In the Final Report by UCF’s Environmental Systems Engineering Institute (ESEI) provided to Polk County on March 4, 2019, chlorine decay and TTHM formation potential curves were presented for the wells feeding the Providence and Van Fleet WTPs (ESEI, 2019). These chlorine decay and TTHM formation potential curves were used to demonstrate baseline conditions for Field test 1.

One pass was selected based on the possibility of recirculating the ground storage tank for a single volumetric turnover. Three passes were studied to determine the effectiveness of several tank turnovers on TTHM removal. It was demonstrated that TTHM reduction was effective using three passes. For three passes, 96-hour TTHM samples at the Providence WTP possessed a concentration of 109.1 ppb. At the Van Fleet WTP, the 96-hour TTHM concentration was 56.1 ppb. Baseline TTHM samples at the Providence WTP had a concentration of 209 ppb after 96-hours. At Van Fleet the 96-hour TTHM baseline concentration was 152.4 ppb. Data indicated that baseline samples reached the MCL after approximately 15 hours at the Providence WTP and 20 hours at the Van Fleet WTP. Source water quality parameters for each WTP at the 0-hour mark are shown in table 5-3.

Table 5-3: Source Water Quality for Field Test 1

WTP Name	Parameter	Value	Units
Providence	pH	7.77 ± 0.64	pH
	Temperature	28.0 ± 1.6	°C
	Conductivity	339 ± 51	µs/cm
Van Fleet	pH	7.97 ± 0.88	pH
	Temperature	25.2 ± 1.9	°C
	Conductivity	301 ± 48	µs/cm

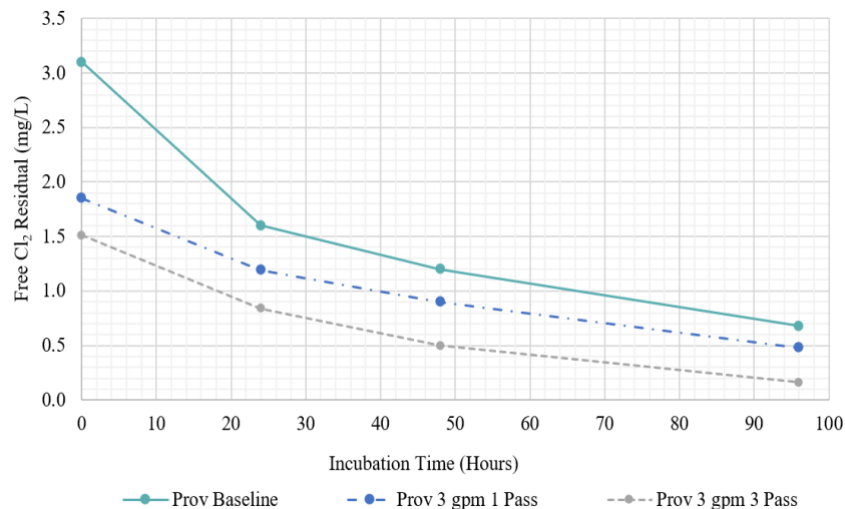


Figure 5-4: Free Chlorine as a Function of Sample Incubation Time and Number of Recirculation Passes [Providence Field Test 1]

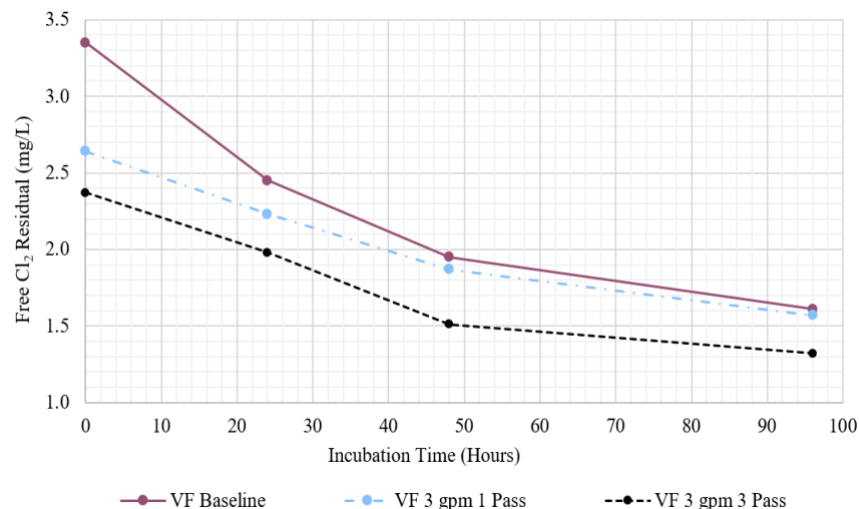


Figure 5-5: Free Chlorine as a Function of Sample Incubation Time and Number of Recirculation Passes [Van Fleet Field Test 1]

Table 5-4: 96-Hour HAA5 Formation Results by Number of Recirculation Passes [Field Test 1]

WTP Name	Test Name	Incubation Time (hrs.)	Chlorine Residual (mg/L)	HAA5 (ppb)
Providence	Baseline	96	0.73	85.6
	3 gpm 1 Pass	96	0.48	60.5*
	3 gpm 3 Pass	96	0.16	42.5*
Van Fleet	Baseline	96	1.61	59.6
	3 gpm 1 Pass	96	1.57	67.0
	3 gpm 3 Pass	96	1.32	71.1

* Denotes samples taken at the 168-hour mark

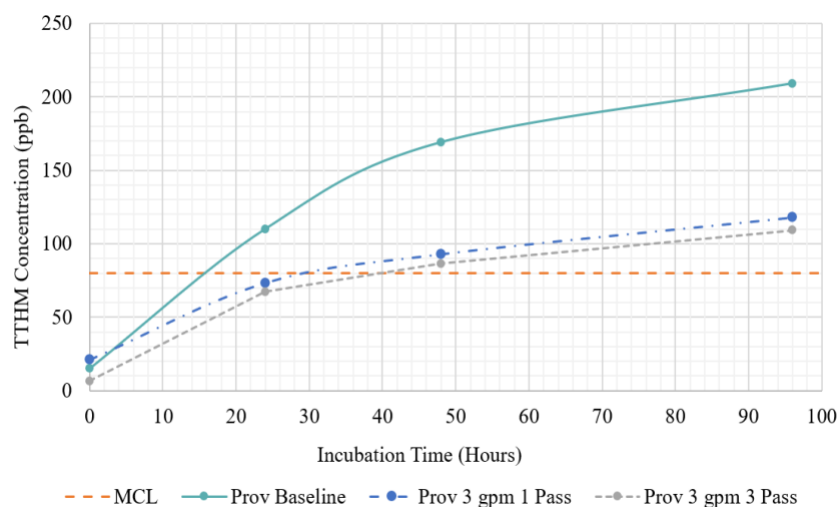


Figure 5-6: TTHM Formation as a Function of Sample Incubation Time and Number of Recirculation Passes [Providence Field Test 1]

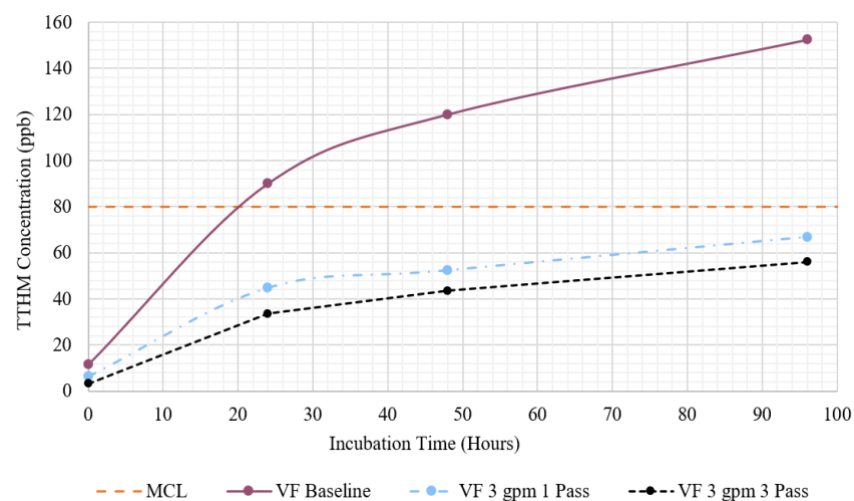


Figure 5-7: TTHM Formation as a Function of Sample Incubation Time and Number of Recirculation Passes [Van Fleet Field Test 1]

Table 5-5: 96-Hour TTHM Formation Results by Number of Recirculation Passes [Field Test 1]

WTP Name	Test Name	DOC (mg/L)	Incubation Time (hrs.)	TTHM (ppb)	Estimated Time to Reach MCL (hrs.)
Providence	Baseline	N/A	96	208.6	15
	3 gpm 1 Pass	2.15	96	118.1	31
	3 gpm 3 Pass	2.09	96	109.1	40
Van Fleet	Baseline	N/A	96	152.4	20
	3 gpm 1 Pass	1.06	96	66.8	N/A
	3 gpm 3 Pass	0.97	96	56.1	N/A

Field Test 2 (a) – One-Pass Expanded Tray Aeration

Baseline samples from the POE were taken to establish TTHM curves of treated water leaving the WTPs. Samples were also collected after operating the pilot using either five or seven trays in series. For field test 2 (a), the tray aeration unit was operated for 10 minutes, allowing one volumetric turnover of water.

Aeration using five trays provided an equivalent loading rate to the full scale WTP tray aeration process. Seven trays were used to assess the impact of additional surface area on the reduction in TTHM formation. It was demonstrated that aeration with seven trays in operation was more effective at reducing simulated TTHM formation in the water system. At the Providence WTP, seven trays in operation resulted in a 96-hour TTHM concentration of 85.7 ppb, at the Van Fleet WTP, a 96-hour concentration of 75.7 ppb was observed. Baseline samples reached 114.1 ppb at the Providence WTP and 85.6 ppb at Van Fleet WTP following 96 hours of incubation. Data indicated that baseline samples reached the MCL after approximately 24 hours at the Providence WTP and 80 hours at the Van Fleet WTP. With seven trays in operation, samples at the Providence WTP reached the MCL after 76 hours. Samples at the Van Fleet WTP remained below 80 ppb after 96 hours of incubation with seven trays in operation.

Table 5-6: Source Water Quality For Field Test 2 (a)

WTP Name	Parameter	Value	Units
Providence	pH	7.87 ± 0.22	pH
	Temperature	26.2 ± 1.2	°C
	Conductivity	490 ± 25	µs/cm
Van Fleet	pH	7.97 ± 0.29	pH
	Temperature	25.2 ± 0.9	°C
	Conductivity	301 ± 16	µs/cm

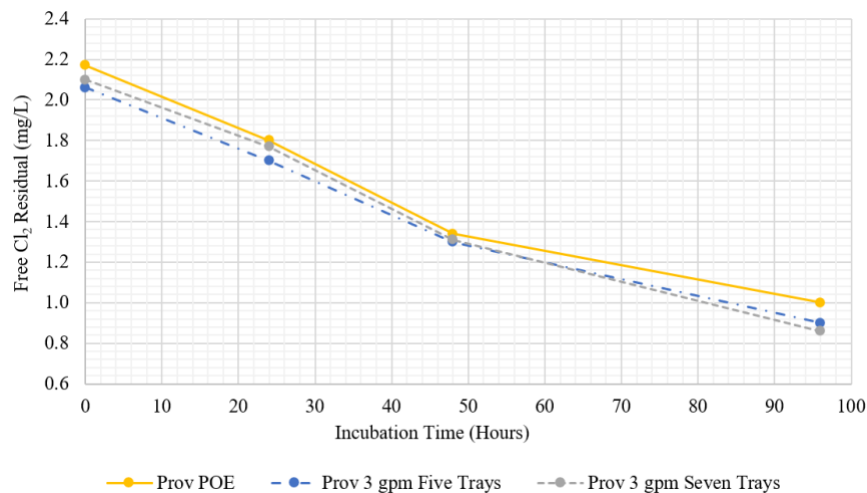


Figure 5-8: Free Chlorine as a Function of Sample Incubation Time and Number of Trays Operating [Providence Field Test 2 (a)]

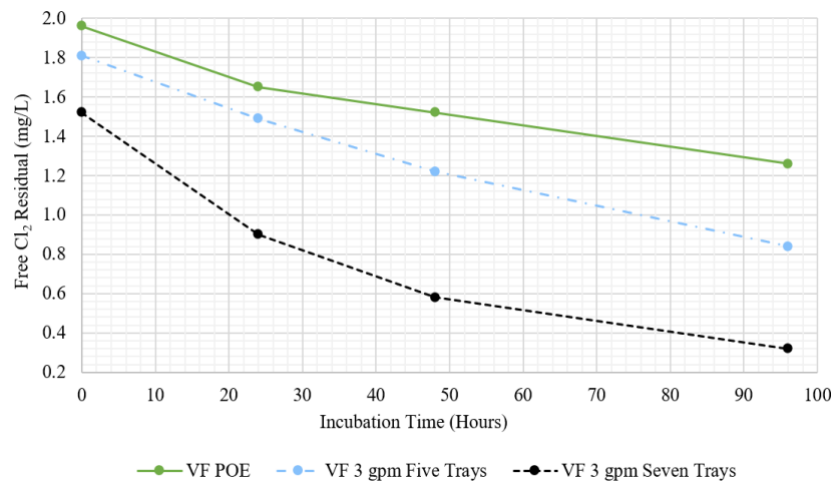


Figure 5-9: Free Chlorine as a Function of Sample Incubation Time and Number of Trays Operating [Van Fleet Field Test 2 (a)]

Table 5-7: 96-Hour HAA5 Formation Results by Number of Trays Operating [Field Test 2 (a)]

WTP Name	Test Name	Incubation Time (hrs.)	Chlorine Residual (mg/L)	HAA5 (ppb)
Providence	POE	96	1.00	59.6
	3 gpm Five Trays	96	0.90	67.0
	3 gpm Seven Trays	96	0.86	71.1
Van Fleet	POE	96	1.26	40.0
	3 gpm Five Trays	96	0.85	51.2
	3 gpm Seven Trays	96	0.32	49.1

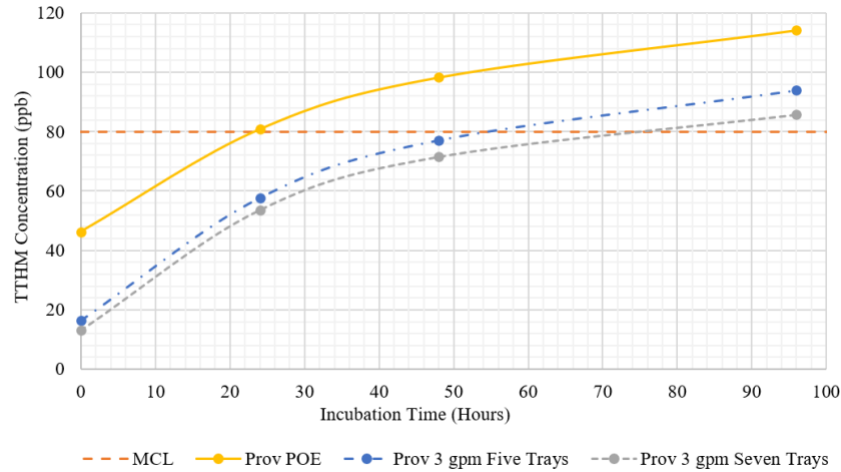


Figure 5-10: TTHM Formation as a Function of Sample Incubation Time and Number of Trays Operating [Providence Field Test 2 (a)]

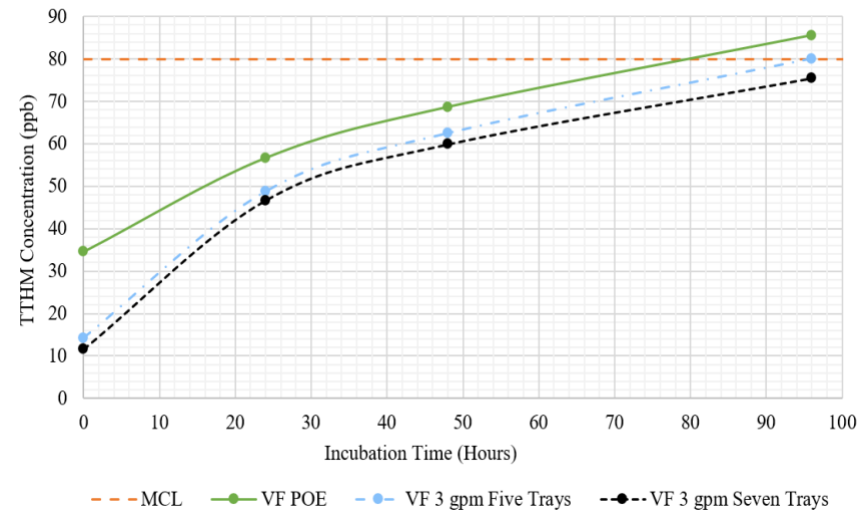


Figure 5-11: TTHM Formation as a Function of Sample Incubation Time and Number of Trays Operating [Van Fleet Field Test 2 (a)]

Table 5-8: 96-Hour TTHM Formation Results by Number of Trays Operating [Field Test 2 (a)]

WTP Name	Test Name	DOC (mg/L)	Incubation Time (hrs.)	TTHM (ppb)	Estimated Time to Reach MCL (hrs.)
Providence	POE	2.33	96	114.1	24
	3 gpm Five Trays	2.15	96	93.9	54
	3 gpm Seven Trays	2.09	96	85.7	76
Van Fleet	POE	1.88	96	85.6	80
	3 gpm Five Trays	1.58	96	80.1	96
	3 gpm Seven Trays	1.56	96	75.5	N/A

Field Test 2 (b) – One-Pass Spray Aeration

Sample collection in field test 2 (b) was based on operation of the pilot for one volumetric turnover of water. A duration of 15 minutes allowed for one volumetric turnover at 2.0 gpm. Operation at 3.0 gpm required 10 minutes for one full volumetric turnover. Baseline samples were obtained prior to piloting. Additional samples were taken after one volumetric turnover occurred at a flow of 2.0 and 3.0 gpm.

Spray aeration was tested using a single pass, to assess the effects of a Gridbee® spray nozzle on TTHM reduction at the two WTPs under investigation. Data indicates that the reduction in TTHM formation was slightly more effective at 3.0 gpm when compared to 2.0 gpm. At the Providence and the Van Fleet WTPs, spray aeration at a flow of 3.0 gpm resulted in 96-hour TTHM concentrations of 82.8 ppb and 73.8 ppb, respectively. POE samples at the Providence WTP reached the MCL after approximately 51 hours of incubation. At the Van Fleet WTP, it took nearly 78 hours to reach the MCL. Using a flow of 3.0 gpm and a Gridbee® spray nozzle, samples reached the MCL after 88 hours. Samples at Van Fleet WTP did not reach the MCL after 96 hours of incubation.

Table 5-9: Source Water Quality for Field Test 2 (b)

WTP Name	Parameter	Value	Units
Providence	pH	7.81 ± 0.19	pH
	Temperature	25.8 ± 0.7	°C
	Conductivity	377 ± 55	µs/cm
Van Fleet	pH	7.15 ± 0.11	pH
	Temperature	24.7 ± 1.2	°C
	Conductivity	303 ± 22	µs/cm

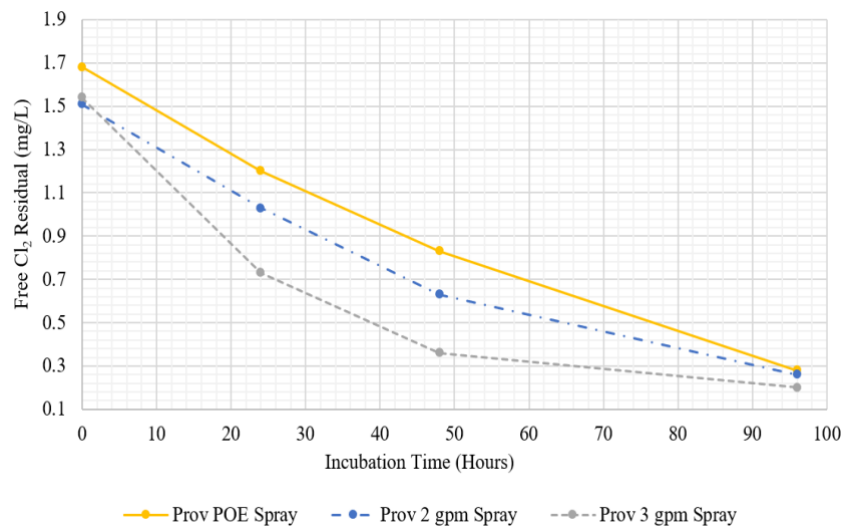


Figure 5-12: Free Chlorine as a Function of Sample Incubation Time for Spray Aeration [Providence Field Test 2 (b)]

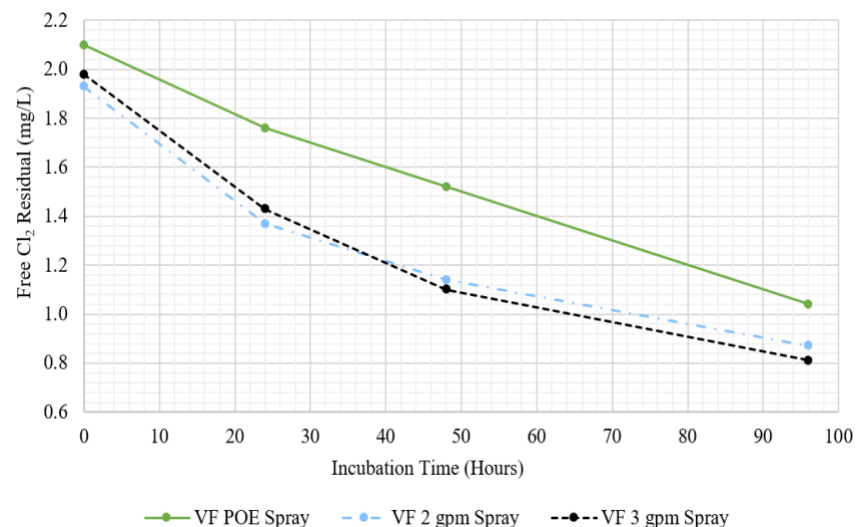


Figure 5-13: Free Chlorine as a Function of Sample Incubation Time for Spray Aeration [Van Fleet Field Test 2 (b)]

Table 5-10: 96-Hour HAA5 Formation Results for Spray Aeration [Field Test 2 (b)]

WTP Name	Test Name	Incubation Time (hrs.)	Chlorine Residual (mg/L)	HAA5 (ppb)
Providence	POE Spray	96	0.28	61.2
	2 gpm Spray	96	0.26	65.1
	3 gpm Spray	96	0.20	61.8
Van Fleet	POE Spray	96	1.04	45.0
	2 gpm Spray	96	0.87	46.3
	3 gpm Spray	96	0.81	46.4

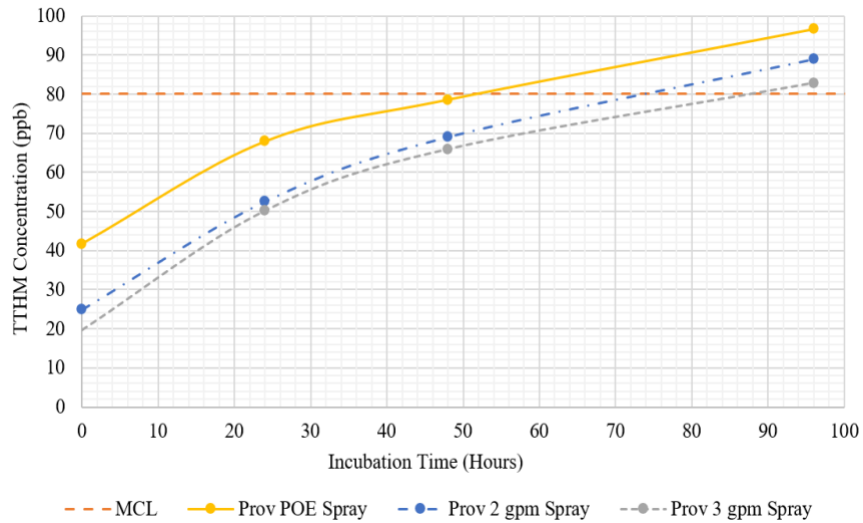


Figure 5-14: TTHM Formation as a Function of Sample Incubation Time for Spray Aeration [Providence Field Test 2 (b)]

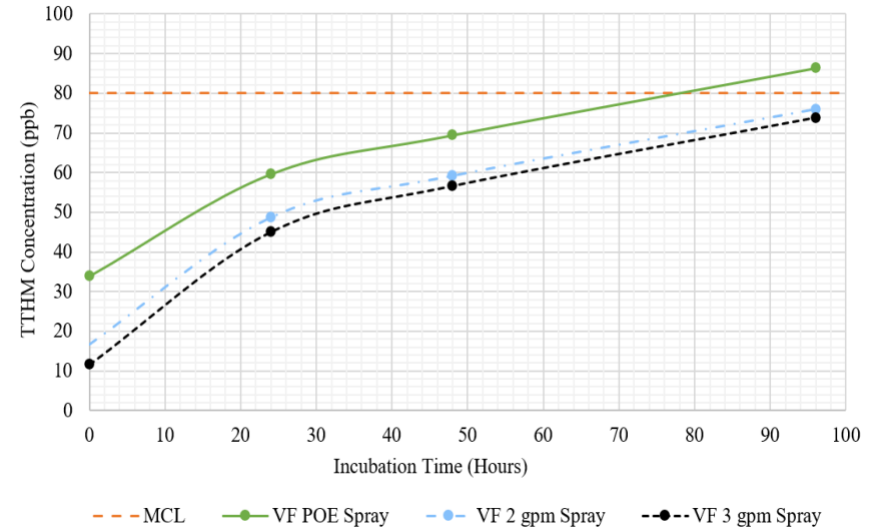


Figure 5-15: TTHM Formation as a Function of Sample Incubation Time for Spray Aeration [Van Fleet Field Test 2 (b)]

Table 5-11: 96-Hour TTHM Formation Results for Spray Aeration [Field test 2 (b)]

WTP Name	Test Name	DOC (mg/L)	Incubation Time (hrs.)	TTHM (ppb)	Estimated Time to Reach MCL (hrs.)
Providence	POE Spray	2.13	96	96.7	51
	2 gpm Spray	1.96	96	88.9	73
	3 gpm Spray	2.01	96	82.8	88
Van Fleet	POE Spray	1.64	96	86.3	78
	2 gpm Spray	1.59	96	75.9	N/A
	3 gpm Spray	1.58	96	73.8	N/A

Field Test 2 (c) – One-Pass Modified Tray with Spray Aeration

In field test 2 (c), each sample collection activity was performed with the pilot operating for 10 minutes, allowing for one volumetric turnover of the reservoir through the modified tray-spray pilot. Baseline samples were obtained from the POE sampling tap to establish TTHM curves of treated water leaving the WTPs.

Combined tray and spray aeration were integrated with increased surface area to determine the effectiveness of these processes together. A BETE® full-cone nozzle was utilized for spray aeration. It was demonstrated that combined spray and tray aeration with seven trays in operation was an effective TTHM reduction method. With seven trays in operation for the combined tray-spray aeration pilot, the 96-hour TTHM concentration at the Providence WTP was 68.4 ppb. At Van Fleet, a concentration of 55.7 was shown for the same conditions. Baseline samples from the POE reached 87.6 ppb at the Providence WTP and 69.5 ppb at the Van Fleet WTP following 96 hours of incubation. Data indicated that baseline samples reached the MCL after 60 hours of incubation at Providence WTP and they did not reach the MCL at Van Fleet WTP. With the combination of a BETE® nozzle and seven trays in operation, samples at Providence WTP did not reach the MCL after 96 hours. No samples at Van Fleet reached the MCL.

Table 5-12: Source Water Quality for Field Test 2 (c)

WTP Name	Parameter	Value	Units
Providence	pH	7.92 ± 0.43	pH
	Temperature	25.7 ± 1.1	°C
	Conductivity	374 ± 23	µs/cm
Van Fleet	pH	8.17 ± 0.34	pH
	Temperature	25.0 ± 0.9	°C
	Conductivity	315 ± 15	µs/cm

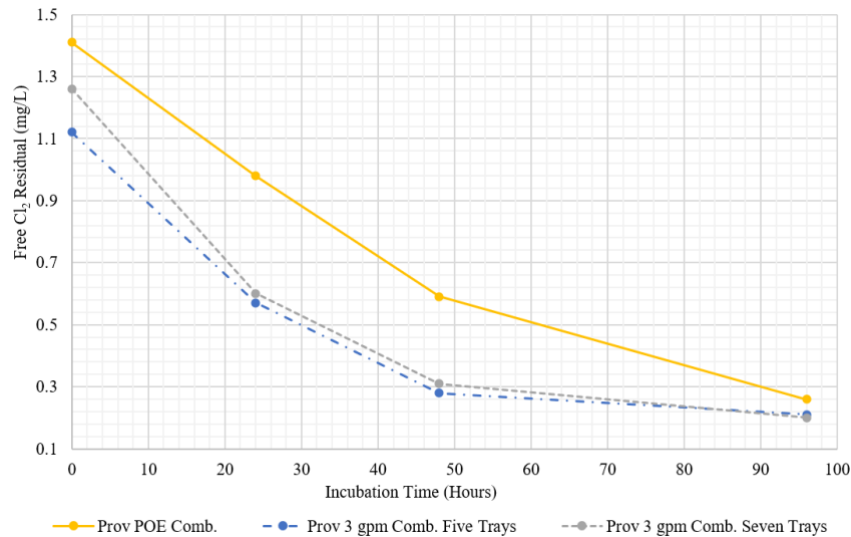


Figure 5-16: Free Chlorine as a Function of Sample Incubation Time for the Modified Tray-Spray Pilot [Providence Field Test 2 (c)]

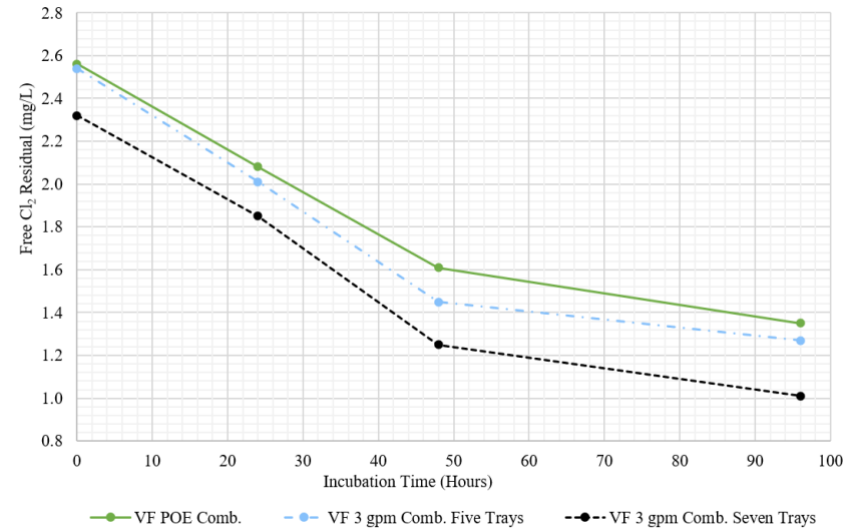


Figure 5-17: Free Chlorine as a Function of Sample Incubation Time for the Modified Tray-Spray Pilot [Van Fleet Field Test 2 (c)]

Table 5-13: 96-Hour HAA5 Formation Results for the Modified Tray-Spray Pilot [Field Test 2 (c)]

WTP Name	Test Name	Incubation Time (hrs.)	Chlorine Residual (mg/L)	HAA5 (ppb)
Providence	POE Combined	96	0.26	58.2
	3 gpm Combined Five Trays	96	0.21	57.7
	3 gpm Combined Seven Trays	96	0.20	60.5
Van Fleet	POE Combined	96	1.35	37.8
	3 gpm Combined Five Trays	96	1.27	35.9
	3 gpm Combined Seven Trays	96	1.01	37.1

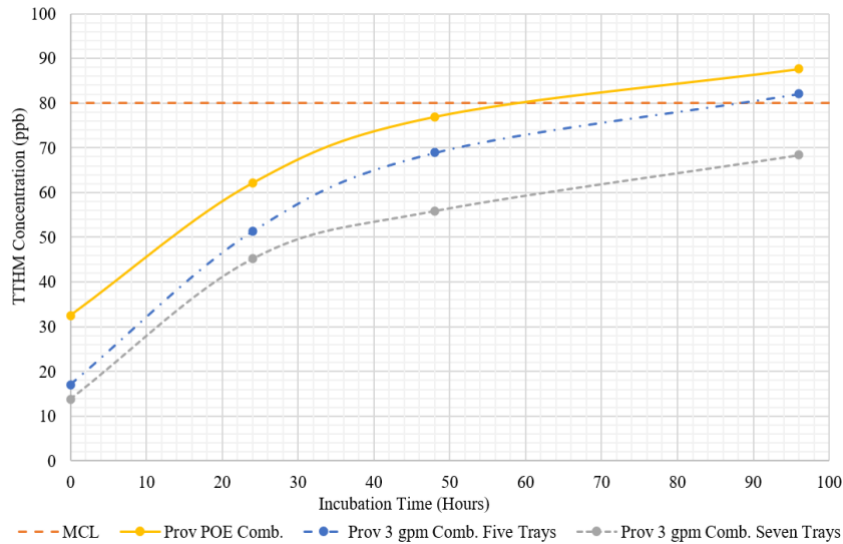


Figure 5-18: TTHM Formation as a Function of Sample Incubation Time for the Modified Tray-Spray Pilot [Providence Field Test 2 (c)]

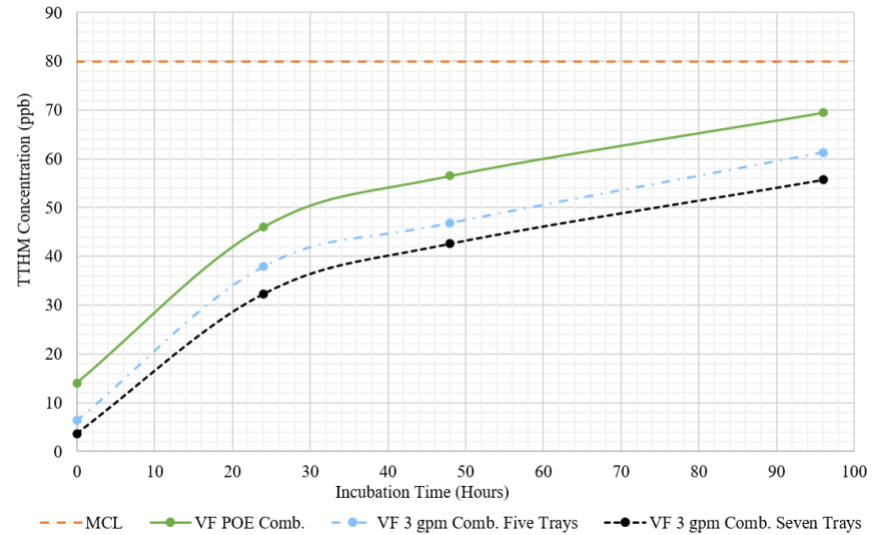


Figure 5-19: TTHM Formation as a Function of Sample Incubation Time for the Modified Tray-Spray Pilot [Van Field Test 2 (c)]

Table 5-14: 96-Hour TTHM Formation Results for the Modified Tray-Spray Pilot [Field Test 2 (c)]

WTP Name	Test Name	DOC (mg/L)	Incubation Time (hrs.)	TTHM (ppb)	Estimated Time to Reach MCL (hrs.)
Providence	POE Combined	2.12	96	87.6	60
	3 gpm Combined Five Trays	1.98	96	82.1	88
	3 gpm Combined Seven Trays	1.87	96	68.4	N/A
Van Fleet	POE Combined	1.15	96	69.5	N/A
	3 gpm Combined Five Trays	1.09	96	61.3	N/A
	3 gpm Combined Seven Trays	1.04	96	55.7	N/A

Field Testing Summary

At the Providence and Van Fleet WTPs a series of four aeration tests were implemented at each location. The primary purpose of these tests was to examine the efficiency of tray and spray aeration on TTHM formation within the distribution system assuming a 96-hr water age.

The 96-hour DBP and chlorine decay results for field tests 1 and 2 (a, b and c) are presented in Table 5-15. TTHM formation reduction by means of aeration was shown to be effective at both Providence WTP and Van Fleet WTP. Of the TTHMs in water obtained from the POE sampling tap at Providence WTP, approximately 87% were shown to be chloroform. At the Van Fleet WTP, TTHMs present in water collected from the POE were shown to be comprised primarily of chloroform (64%). The source water feeding Providence WTP was shown to have a higher TTHM formation potential, as compared to the Van Fleet WTP, based on DOC, sulfur, and iron content.

Haloacetic acid formation was not significantly impacted by aeration. Throughout the study, HAA5 levels for the Providence system remained near or exceeded the regulated LRAA level of 60 µg/L for the conditions tested in the field. Consequently, at the Van Fleet WTP, HAA samples collected did not rise above 60 µg/L. Data indicated that HAA5 concentrations generated by the Providence WTP had the propensity to rise above the MCL. Despite this concern, HAA5 concentrations historically collected by the County for LRAA monitoring requirements did not exceed the MCL. Based on the data collected in this research, there appears to be no correlation between increased aeration and its impact on HAA5 concentrations.

Free chlorine residual was shown to reduce by less than 19% as aeration intensified. Actual chlorine decay curves within the distribution system might differ from the results presented due to the complex chemistry associated with the distribution system.

Table 5-15: Summary of TTHM Reductions at 0-hour and 96-hour Marks for Aeration Experiments

WTP Name	Field Test	Test Name	0-hour TTHM Reduction (%)	96-hour TTHM Reduction (%)
Providence	1	Baseline	-	-
		3 gpm 1 Pass	N/A	43
		3 gpm 3 Pass	56	48
	2 (a)	POE	-	-
		3 gpm Five Trays	65	17
		3 gpm Seven Trays	72	25
	2 (b)	POE Spray	-	-
		2 gpm Spray	40	8
		3 gpm Spray	52	14
	2 (c)	POE Combined	-	-
		Combined Five Trays	47	6
		Combined Seven Trays	57	22
Van Fleet	1	Baseline	-	-
		3 gpm 1 Pass	44	56
		3 gpm 3 Pass	72	63
	2 (a)	POE	-	-
		3 gpm Five Trays	59	6
		3 gpm Seven Trays	66	12
	2 (b)	POE Spray	-	-
		2 gpm Spray	51	12
		3 gpm Spray	65	14
	2 (c)	POE Combined	-	-
		Combined Five Trays	55	12
		Combined Seven Trays	74	20

At the Providence WTP, it was demonstrated that a single pass through the pilot aeration unit (field test 1) did not significantly impact 0-hour TTHM formation as compared to the baseline formation potential curve. Two additional passes through the aeration unit decreased 0-hour TTHM concentrations by 56%. Increasing the surface area from 0.55 m² to 0.77 m² [field test 2 (a)], assisted in reducing 0-hour TTHM formation content by 72%. Spray aeration with a Gridbee® spray nozzle [field test 2 (b)] was shown to be less effective at TTHM formation reduction than tray aeration. At a flow of 2 gpm, 0-hour TTHM concentrations were reduced by 40%. At 3 gpm, TTHM formation concentrations were reduced by 52%. The combination of spray and tray aeration [field test 2 (c)] decreased 0-hour TTHM formation concentrations by 47% with five trays in operation and by 57% with seven trays in operation. That being stated, it is believed that recirculation within the full-scale GST may not be feasible as currently designed and operated due to the continuous and elevated water demand of the system.

At Van Fleet WTP, the reduction in TTHM formation was shown to be lower. Field test 1 reduced 0-hour TTHM formation by 44% after one pass, after 3 passes, a reduction of 72% was observed as compared to the baseline formation potential curve. Field test 2 (a) reduced 0-hour TTHM formation by 59% with 5 trays in operation and by 66% with seven trays in operation. Field test 2 (b) reduced 0-hour TTHM formation by 51% at a flow of 2 gpm and by 65% at a flow of 3 gpm. Field test 2 (c) reduced 0-hour TTHM concentrations by 55% with 5 trays in operation and by 74% with seven trays in operation.

The TTHM formation concentration at the 96-hour mark were shown to be lower than the baseline (POE) samples, but at differing percentages than the 0-hour TTHM samples. Data suggests that the TTHM reformation potential was impacted by aeration.

TTHM Speciation

Of the four TTHM species chloroform, bromodichloromethane, dibromochloromethane and bromoform, it was shown that chloroform was the most prevalent DBP produced at each of the WTPs. Figures 5-20 and 5-21 display the relative percentages of each species composing TTHMs. These figures were generated by totaling the TTHM concentrations for each species present in baseline/POE (un-aerated) samples in field tests 1 - 2 (a, b, and c). The same calculations were performed for treated (aerated) samples. TTHM samples from both the 0-hour and 96-hour marks were used to assess the effects of re-formation on the TTHM distribution.

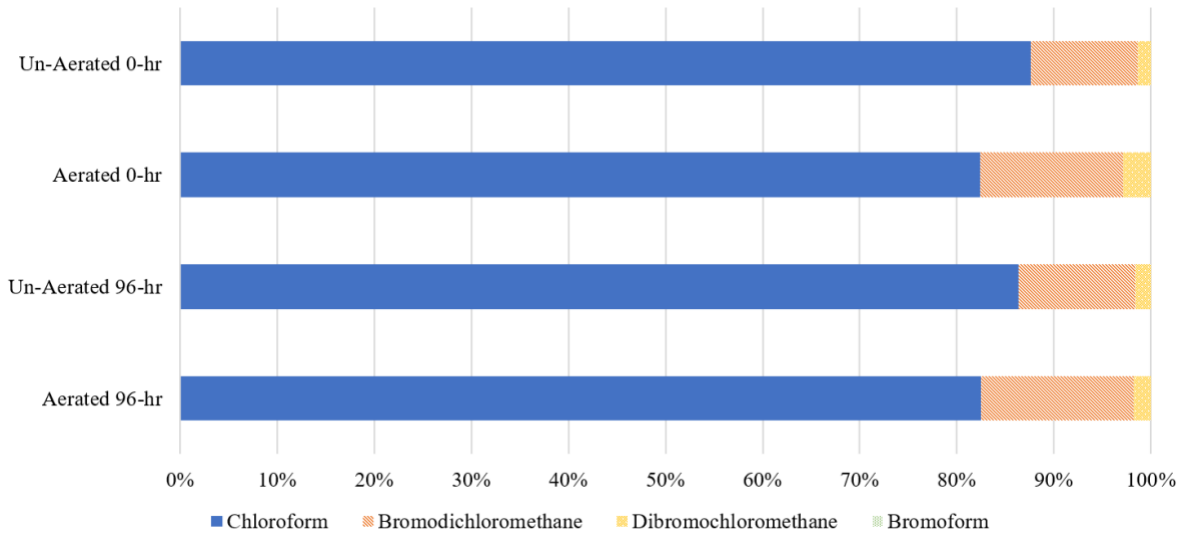


Figure 5-20: TTHM Speciation at Providence WTP

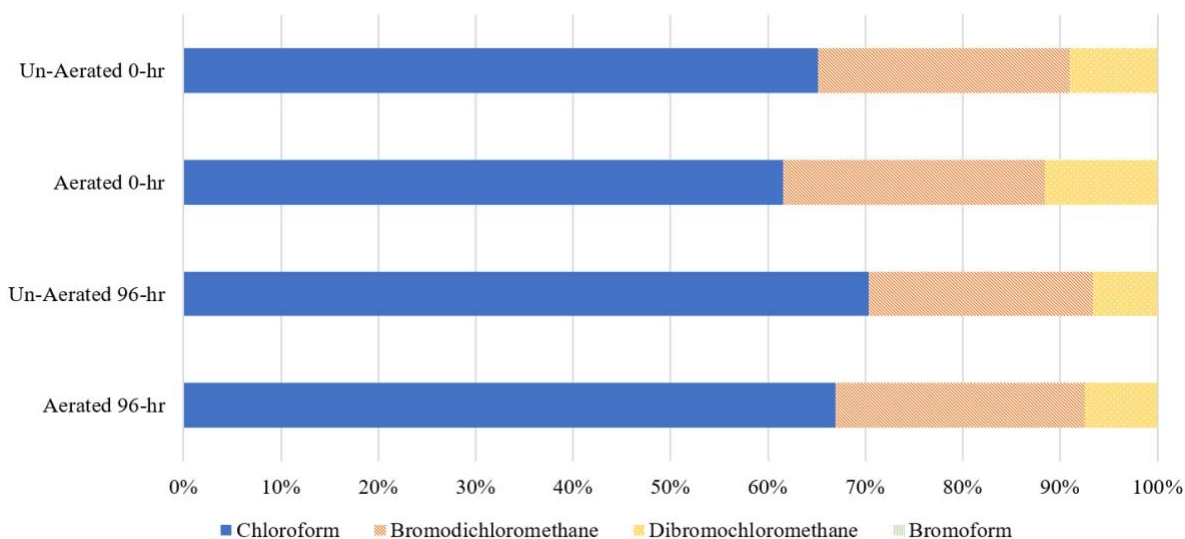


Figure 5-21: TTHM Speciation at Van Fleet WTP

At the Providence WTP, un-aerated TTHM samples at the 0-hour and 96-hour marks were composed of 87% and 85% chloroform, respectively. Following aeration, both 0-hour and 96-hour chloroform concentrations were reduced to 82%. Bromodichloromethane accounted for 11% of the TTHMs at both the 0-hour and 96-hour marks for the un-aerated water samples. For the aerated water samples, bromodichloromethane represented 15% of the TTHMs formed at both the 0-hour and 96-hour marks. Bromoform concentrations remained below the detection level (BDL) of 0.7 ppb for the samples measured.

At the Van Fleet WTP, the dominant TTHM species were chloroform and bromodichloromethane. Aeration reduced 0-hour chloroform percentages from 64% to 62% and 96-hour chloroform percentages from 70% to 67%. Aeration had less than a 5% impact on both bromodichloromethane percent speciation for both 0-hour and 96-hour samples. Bromoform concentrations remained BDL of 0.7 ppb for the samples measured.

Data suggests that immediately following aeration chloroform concentrations are reduced at larger quantities as compared to aerated samples incubated for 96 hours. Aerated samples

incubated for longer than 96 hours may result in similar TTHM speciation to that of an un-aerated sample. Of the TTHMs formed, Chloroform concentrations were shown to decrease by the largest percentage following aeration. Data aligns with the concept of Henry's Law, since chloroform is the easiest THM species to be stripped out of water due to its large Henry's Law constant.

Quality Assurance and Quality Control

Precision control charts were generated for free chlorine, and TTHM analyses. These charts are presented in Figures 5-23 and 5-24, respectively. An accuracy control chart was generated for TTHM analysis in Figure 5-25. For the free chlorine precision control chart, one value was observed above the warning level. For the TTHM precision chart, two samples were observed above the warning level. No two consecutive samples in the free chlorine or TTHM precision control charts exceeded the warning level and no samples exceeded the control level, indicating no violations in precision control. The TTHM accuracy chart displayed two samples below the lower warning level. No two consecutive samples were observed to fall above or below the control limits. No systematic trends above or below the average were observed, indicating no violations in accuracy control.

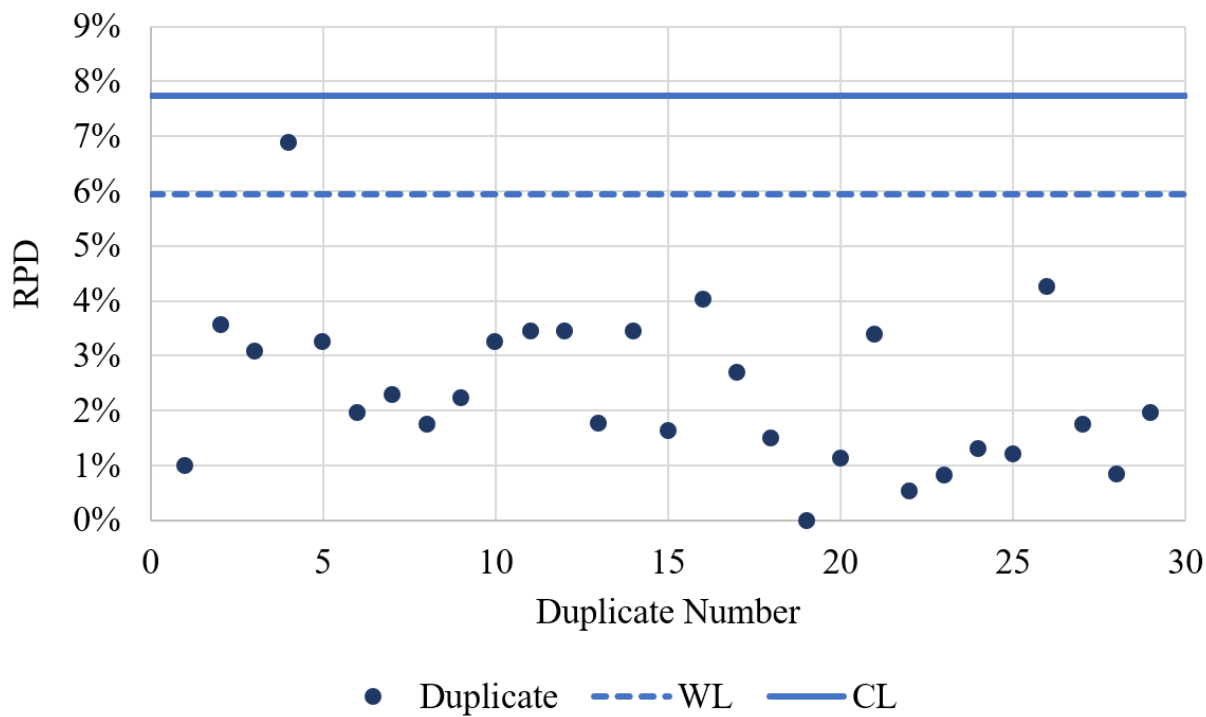


Figure 5-22: Free Chlorine Precision Control Chart

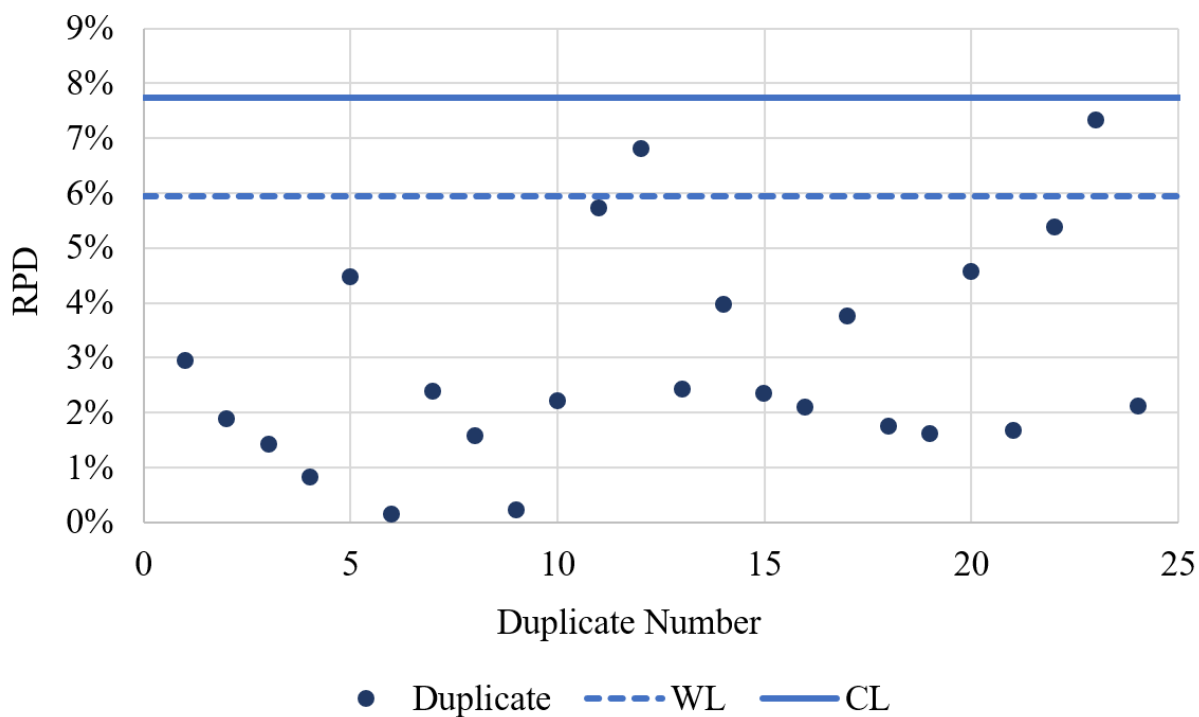


Figure 5-23: TTHM Precision Control Chart

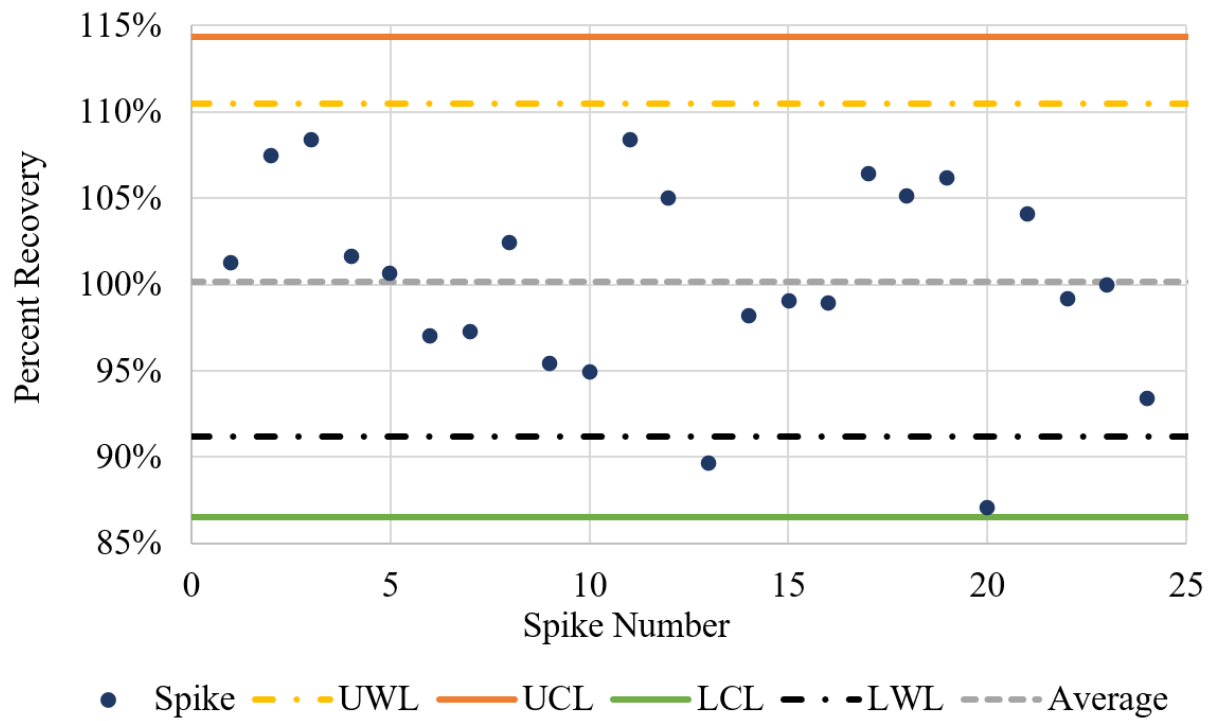


Figure 5-24: TTHM Accuracy Control Chart

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

An analysis into the effectiveness of tray and spray aeration processes was conducted at two WTPs in the NERUSA of Polk County, Florida. This chapter presents the general conclusions and recommendations based on findings of this research. Recommendations of enhancements to the operational practices and existing aeration infrastructure are contained herein.

The effectiveness of current tray aeration process was shown to vary at each WTP, due to differing incoming source water characteristics. Source water quality impacts the quantity of TTHMs formed. Control of source water quality can be achieved through the monitoring of well rotations. Table 6-1 presents water quality parameters related to DBP formation, specifically TTHMs, for each of the wells feeding the Providence and the Van Fleet WTPs. Optimizing well rotations to rely on lower forming DBP supplies will aid in the management of TTHM levels within the water system. Two water quality parameters for determining the extent of precursor NOM in a groundwater supply are NOM (as measured by DOC) and UV-254. Sulfide and iron concentrations should also be considered as important water quality parameters to monitor, as the amount of chlorine necessary for proper disinfection purposes is dependent on these demand-causing substances. Based on the levels of DOC, UV-254, sulfide and iron observed in this study, Table 6-1 was prepared to identify the highest-quality groundwater well supply that would produce the lowest TTHM formation potential. This data was supported by prior work performed at UCF ESEI laboratories (ESEI, 2019).

Table 6-1: Well Operational Parameters

WTP Name	Well Name	DOC (mg/L)	UV-254 (cm⁻¹)	Sulfide (mg/L)	Iron (mg/L)	Proposed Operational Priority
Providence	Providence Well 5	1.81	0.070	0.13	0.090	2
	Providence Well 6	1.70	0.066	0.15	<0.005	1
	Oak Hills Well 1	2.23	0.068	0.16	0.067	3
	Oak Hills Well 2	2.71	0.099	0.30	0.048	5
	Oak Hills Well 3	2.36	0.075	0.40	0.075	4
Van Fleet	Bella Toscana 2	0.92	0.036	N/A	N/A	2
	Tierra del Sol	0.41	0.016	N/A	N/A	1
	U.S. Homes	1.24	0.049	0.02	<0.005	3
	Van Fleet	2.38	0.081	0.15	0.006	4

Aeration studies conducted were shown to reduce 0-hour TTHM formation concentrations between 40% and 74%. The addition of one or more “rings” or “levels” of trays on the full-scale unit was shown to provide an economical and beneficial approach to TTHM reduction at the both WTPs, specifically the Providence WTP. Improvement of the tray aeration process at the Van Fleet WTP is also believed to be beneficial. Results indicate that spray aeration was effective in reducing TTHM formation concentrations, but less when compared to other aeration techniques. The County does not currently have spray aeration processes in effect and the implementation of spray aerators would add increased capital costs if applied. With this in mind, cost considerations for spray aeration are not included herein.

The addition of a recirculation pump to the GST was shown to be a feasible option for the reduction of TTHM concentrations. If recirculation was to be employed, the level of the GST would need to be adjusted accordingly. Minimizing the level of water within the tank allows for a volumetric turnover to occur faster. Additional testing and coordination will be required if the GST

levels were adjusted to allow recirculation. Fire flow demands will need to be met when adjustments to the tank are applied.

Recirculation within the GST would be achieved by the addition of two horizontal split-case pumps. A Pentair Aurora 328B Vertical Inline pump from Pentair (5500 Wayzata Boulevard Suite 900 Golden Valley, MN 55416), or equivalent, could be used for recirculation purposes. The 10x10x14 inch pump is recommended to operate at a maximum of 1200 rpm and would function between 40 and 50 horsepower. One pump is necessary for recirculation purposes, but two pumps would be installed to ensure redundancy in the process. A conceptual opinion of probable capital cost for acquisition of the recirculation pump is provide in Table 6-2. Estimates were developed with the following assumptions: (1) the County has enough power on-site to operate the pumps, (2) the construction will not damage the existing GST structures; and (3) that construction for the upgrade will not impact existing plant facilities. The implementation of a recirculation pump of this size would result in one volumetric turnover of water within the GST in approximately 4.2 hours if the tank was kept at a level of 0.75 MG (3/8 the maximum volume of the GST).

Table 6-2: Opinion of Probable Capital Cost Assessment for GST Recirculation Pump

Component	Number of Units	Unit Cost (\$)	Total Cost (\$)
Pump	2	75,000	150,000
Pentair Aurora 328B			
Process Equipment	1	50,000	50,000
Process Piping			
Fixtures / Fittings			
Electrical Systems			
Instrumentation and Controls			
Installation	1	200,000	200,000
Construction Equipment			
Labor			
Engineering Design			
Inspection / Testing			
Total			\$400,000

Based on the ongoing work that supported the development of this thesis, the County implemented improvements to the existing tray aeration unit at the Providence WTP. Figure 6-6 presents a schematic of the updated tray design that the County replaced existing tray aeration infrastructure with. The original tray aeration unit at Providence WTP had 36 trays in operation, the County's modification doubled the number of trays to 72. Enhancements to the tray aerator at the Providence WTP cost \$68,640. Reflected in this cost are design, installation, and labor fees. The improved aeration process was designed to fit in the existing footprint of the aeration unit. It is recommended that sampling is performed with the new trays in operation to determine the efficiency and to gain an understanding of water quality parameters, specifically free chlorine, in the new aeration process.

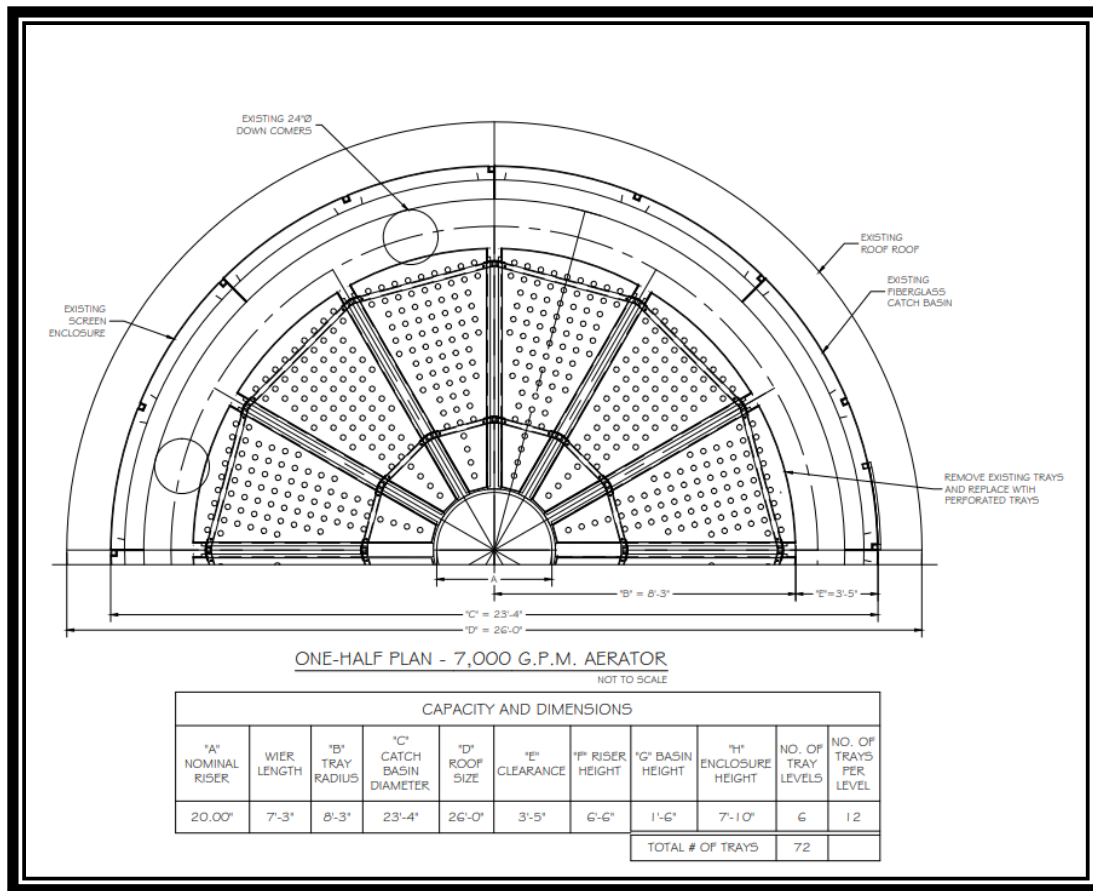


Figure 6-1: Schematic of New Tray Aerator Design

Data obtained in this research suggests that the combination of increasing surface area available for aeration, the optimization of well rotations and the implementation of a recirculation pump will reduce TTHM formation to allow the distribution levels to remain below the regulated level of 80 µg/L for a system with a residence time less than 96 hours. The effectiveness of aeration techniques was shown to be dependent on source water quality parameters, which should be understood prior to the implementation of aeration. The employment of aeration techniques described presented a practical approach to reducing TTHM concentrations for the two WTPs in this study.

APPENDIX A: DATA LOG SHEETS

Table A-1: Initial Site Visit Data Sheet

Date:	
-------	--

Location / Time:		Flow
Turbidity:		
pH:		In:
Conductivity ($\mu\text{S}/\text{cm}$)		Out:
Free Chlorine (mg/L)		
UV-254 (cm^{-1})		

Location / Time:		Flow
Turbidity:		
pH:		In:
Conductivity ($\mu\text{S}/\text{cm}$)		Out:
Free Chlorine (mg/L)		
UV-254 (cm^{-1})		

Location / Time:		Flow
Turbidity:		
pH:		In:
Conductivity ($\mu\text{S}/\text{cm}$)		Out:
Free Chlorine (mg/L)		
UV-254 (cm^{-1})		

Location / Time:		Flow
Turbidity:		
pH:		In:
Conductivity ($\mu\text{S}/\text{cm}$)		Out:
Free Chlorine (mg/L)		
UV-254 (cm^{-1})		

Location / Time:		Flow
Turbidity:		
pH:		In:
Conductivity ($\mu\text{S}/\text{cm}$)		Out:
Free Chlorine (mg/L)		
UV-254 (cm^{-1})		

Table A-2: Aeration Pilot Sampling Data Sheet

Test Time Collected

		CL ₂ Reading (mg/L)	TTHM Quenched?
CL ₂ Residual	0 hr		
	24 hr		
	48 hr		
	96 hr		

Test Time Collected

		CL ₂ Reading (mg/L)	TTHM Quenched?
CL ₂ Residual	0 hr		
	24 hr		
	48 hr		
	96 hr		

Test Time Collected

		CL ₂ Reading (mg/L)	TTHM Quenched?
CL ₂ Residual	0 hr		
	24 hr		
	48 hr		
	96 hr		

Table A-3: Aeration Pilot Water Quality Data Sheet

Test:		Flow
Date:		
		In:
Temperature (°c)		Out:
pH		
Conductivity (µs/cm)		
Free Chlorine (mg/L)		
UV-254 (cm ⁻¹)		
TOC		
HAA ₅ Collected?		

Test:		Flow
Date:		
		In:
Temperature (°c)		Out:
pH		
Conductivity (µs/cm)		
Free Chlorine (mg/L)		
UV-254 (cm ⁻¹)		
TOC		
HAA ₅ Collected?		

Test:		Flow
Date:		
		In:
Temperature (°c)		Out:
pH		
Conductivity (µs/cm)		
Free Chlorine (mg/L)		
UV-254 (cm ⁻¹)		
TOC		
HAA ₅ Collected?		

APPENDIX B: TTHM, FREE CHLORINE AND HAA5 DATA

Table B-1: TTHM and Free Chlorine Data

WTP Name	Field Test	Test Name	Incubation Time (hrs.)	Free Chlorine Residual (mg/L)	Chloroform (µg/L)	Bromodichloromethane (µg/L)	Dibromochloromethane (µg/L)	Bromoform (µg/L)	TTHM (µg/L)
Providence	1	Baseline	0	3.09	11.1	2.9	0.8	BDL	14.8
			24	1.62	97.2	11.9	1.3	BDL	110.4
			48	1.2	146.5	19.8	2.5	BDL	168.8
			96	0.73	182.0	23.4	3.2	BDL	208.6
		3 gpm 1 Pass	0	1.85	16.9	3.5	0.7	BDL	21.1
			24	1.19	63.6	9.0	0.8	BDL	73.4
			48	0.90	81.1	10.8	1.0	BDL	92.9
			96	0.48	103.9	13.0	1.2	BDL	118.1
		3 gpm 3 Pass	0	1.51	4.3	1.6	0.7	BDL	6.6
			24	0.84	59.2	7.4	0.7	BDL	67.3
			48	0.50	76.5	9.0	0.8	BDL	86.3
			96	0.16	97.9	10.5	0.7	BDL	109.1

Table B-1: (Continued)

WTP Name	Field Test	Sample Name	Incubation Time (hrs.)	Free Chlorine Residual (mg/L)	Chloroform (µg/L)	Bromodichloromethane (µg/L)	Dibromochloromethane (µg/L)	Bromoform (µg/L)	TTHM (µg/L)
Providence	2 (a)	POE	0	2.17	38.2	7.1	1.0	BDL	46.3
			24	1.80	68.5	10.9	1.4	BDL	80.8
			48	1.34	83.5	13.0	1.7	BDL	98.2
			96	1.00	98.1	14.2	1.8	BDL	114.1
		3 GPM Five Trays	0	2.06	13.6	2.5	0.4	BDL	16.5
			24	1.70	49.3	7.3	0.9	BDL	57.5
			48	1.30	66.9	9.0	1.2	BDL	77.1
			96	0.90	82.7	9.9	1.3	BDL	93.9
		3 GPM Seven Trays	0	2.10	14.9	2.7	0.4	BDL	18.0
			24	1.77	46.2	6.6	0.7	BDL	53.5
			48	1.31	62.3	8.1	1.0	BDL	71.4
			96	0.86	74.9	10.1	0.7	BDL	85.7
		POE Spray	0	1.68	33.7	6.9	1.1	BDL	41.7
			24	1.20	57.3	9.6	1.0	BDL	67.9
			48	0.83	66.8	10.4	1.4	BDL	78.6
			96	0.28	83.3	12.0	1.4	BDL	96.7
	2 (b)	2 gpm Spray	0	1.51	20.2	4.1	0.6	BDL	24.9
			24	1.03	44.4	7.1	1.0	BDL	52.5
			48	0.63	59.5	8.4	1.2	BDL	69.1
			96	0.26	77.2	10.3	1.4	BDL	88.9
		3 gpm Spray	0	1.54	15.8	3.4	0.6	BDL	19.8
			24	0.73	42.5	6.7	1.0	BDL	50.2
			48	0.36	57.1	7.9	1.1	BDL	66.1
			96	0.20	72.1	9.4	1.3	BDL	82.8

Table B-1: (Continued)

WTP Name	Field Test	Sample Name	Incubation Time (hrs.)	Free Chlorine Residual (mg/L)	Chloroform (µg/L)	Bromodichloromethane (µg/L)	Dibromochloromethane (µg/L)	Bromoform (µg/L)	TTHM (µg/L)
Providence	2 (c)	POE Combined	0	1.41	26.7	5.0	0.8	BDL	32.5
			24	0.98	52.4	8.5	1.2	BDL	62.1
			48	0.59	65.6	9.9	1.4	BDL	76.9
			96	0.26	75.8	10.4	1.4	BDL	87.6
		Combined Five Trays	0	1.26	14.5	2.8	0.4	BDL	17.7
			24	0.60	44.8	6.6	1.0	BDL	52.4
			48	0.31	60.2	8.3	1.1	BDL	69.6
			96	0.20	76.7	10.3	1.4	BDL	88.4
		Combined Seven Trays	0	1.12	11.5	2.0	0.3	BDL	13.8
			24	0.57	38.8	5.6	0.8	BDL	45.2
			48	0.28	48.6	6.4	0.9	BDL	55.9
			96	0.21	60.5	7.0	0.9	BDL	68.4
Van Fleet	1	Baseline	0	3.35	8.7	2.0	0.7	BDL	11.4
			24	2.45	63.0	19.8	7.5	BDL	90.3
			48	1.95	84.0	27.8	8.6	BDL	120.4
			96	1.61	112.7	30.8	8.9	BDL	152.4
		3 gpm 1 Pass	0	2.64	3.5	1.7	1.2	BDL	6.4
			24	2.23	30.5	9.5	3.5	BDL	43.5
			48	1.87	37.8	10.8	3.8	BDL	52.4
			96	1.57	48.9	13.4	4.5	BDL	66.8
		3 gpm 3 Pass	0	2.37	1.1	1.4	0.7	BDL	3.2
			24	1.98	22.5	8.2	2.9	BDL	33.6
			48	1.51	30.0	10.1	3.5	BDL	43.6
			96	1.32	40.3	11.9	3.9	BDL	56.1

Table B-1: (Continued)

WTP Name	Field Test	Sample Name	Incubation Time (hrs.)	Free Chlorine Residual (mg/L)	Chloroform (µg/L)	Bromodichloromethane (µg/L)	Dibromochloromethane (µg/L)	Bromoform (µg/L)	TTHM (µg/L)
Van Fleet	2 (a)	POE	0	1.96	22.7	9	2.9	BDL	34.6
			24	1.65	38.5	14.1	4.1	BDL	56.7
			48	1.52	47.3	16.7	4.7	BDL	68.7
			96	1.26	60.6	19.8	5.2	BDL	85.6
		3 GPM Five Trays	0	1.81	9.7	3.4	1.3	BDL	14.4
			24	1.49	34.9	10.8	3.1	BDL	48.8
			48	1.22	45.9	13	3.6	BDL	62.5
			96	0.84	60.6	15.5	4.0	BDL	80.1
		3 GPM Seven Trays	0	1.52	8.0	2.6	1.0	BDL	11.6
			24	0.90	33.1	10.5	3.1	BDL	46.7
			48	0.58	43.6	12.7	3.6	BDL	59.9
			96	0.32	56.3	15.1	4.1	BDL	75.5
	2 (b)	POE Spray	0	2.10	22.5	8.7	2.7	BDL	33.9
			24	1.76	40.7	14.8	4.1	BDL	59.6
			48	1.52	48.1	16.7	4.5	BDL	69.3
			96	1.04	61.7	19.5	5.1	BDL	86.3
		2 gpm Spray	0	0.93	7.8	2.8	1.0	BDL	11.6
			24	1.37	31.8	10.2	3.0	BDL	45.0
			48	1.14	40.9	12.2	3.5	BDL	56.6
			96	0.87	55.2	14.6	4.0	BDL	73.8
		3 gpm Spray	0	1.98	10.7	4.3	1.6	BDL	16.6
			24	1.43	33.9	11.3	3.4	BDL	48.6
			48	1.10	42.2	13.1	3.8	BDL	59.1
			96	0.81	56.1	15.6	4.2	BDL	75.9

Table B-1: (Continued)

WTP Name	Field Test	Sample Name	Incubation Time (hrs.)	Free Chlorine Residual (mg/L)	Chloroform (µg/L)	Bromodichloromethane (µg/L)	Dibromochloromethane (µg/L)	Bromoform (µg/L)	TTHM (µg/L)
Van Fleet	2 (c)	POE Combined	0	2.56	8.6	3.8	1.6	BDL	14.0
			24	2.08	33.1	9.5	3.4	BDL	46.0
			48	1.61	40.7	11.7	4.1	BDL	56.5
			96	1.35	50.9	13.9	4.7	BDL	69.5
		Combined Five Trays	0	2.54	3.5	2.0	0.8	BDL	6.3
			24	2.01	26.1	8.4	3.4	BDL	37.9
			48	1.45	33.1	10.2	3.5	BDL	46.8
			96	1.27	44.3	12.9	4.1	BDL	61.3
		Combined Seven Trays	0	2.32	1.1	1.8	0.8	BDL	3.7
			24	1.85	20.9	8.4	3.0	BDL	32.3
			48	1.25	31.7	10.2	0.7	BDL	42.6
			96	1.01	39.6	12.2	3.9	BDL	55.7

Table B-2: 96-hour HAA5 Data

WTP Name	Field Test	Sample Name	Bromoacetic Acid (ppb)	Chloroacetic Acid (ppb)	Dibromoacetic Acid (ppb)	Dichloroacetic Acid (ppb)	Trichloroacetic Acid (ppb)	HAA5 (ppb)
Providence	1	Baseline	BDL	3.3	BDL	44.49	37.77	85.6
		3 gpm 1 Pass	BDL	BDL	BDL	32.09	28.43	60.5*
		3 gpm 3 Pass	BDL	BDL	BDL	25.58	16.91	42.5*
	2	POE	1.02	1.65	BDL	26.76	30.18	59.6
		3 gpm Five Trays	BDL	0.98	BDL	35.96	30.99	67.0
		3 gpm Seven Trays	BDL	0.98	BDL	40.47	30.67	71.1
	3	POE Spray	BDL	2.70	BDL	31.33	27.20	61.2
		2 gpm Spray	BDL	1.28	BDL	32.01	31.81	65.1
		3 gpm Spray	BDL	1.26	BDL	30.83	29.67	61.8
	4	POE Combined	BDL	2.33	BDL	29.21	26.65	58.2
		Combined Five Trays	BDL	1.31	BDL	29.90	26.44	57.7
		Combined Seven Trays	BDL	2.63	BDL	30.63	27.23	60.5
Van Fleet	1	Baseline	BDL	2.10	1.51	33.61	18.95	54.1
		3 gpm 1 Pass	BDL	BDL	1.05	19.36	14.60	35.0
		Van Fleet 3 gpm 3 Pass	BDL	BDL	1.06	21.56	14.28	36.9
	2	POE	BDL	3.10	1.10	21.99	13.78	40.0
		3 gpm Five Trays	BDL	4.33	1.41	30.09	15.32	51.2
		3 gpm Seven Trays	BDL	3.80	1.32	29.76	14.18	49.1
	3	POE Spray	0.89	2.45	1.09	24.53	16.02	45.0
		2 gpm Spray	0.88	2.57	1.35	26.59	14.89	46.3
		3 gpm Spray	0.84	2.57	1.37	27.01	14.61	46.4
	4	POE Combined	BDL	BDL	1.09	22.10	14.59	37.8
		Combined Five Trays	BDL	3.63	0.99	18.11	13.16	35.9
		Combined Seven Trays	BDL	BDL	1.26	21.92	13.97	37.2

*Denotes samples taken at the 168-hour mark

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