

OZONE AND GAC TREATMENT OF A CENTRAL FLORIDA GROUNDWATER FOR
SULFIDE AND DISINFECTION BY-PRODUCT CONTROL

by

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ABSTRACT

This study evaluated the combination of ozone and granular activated carbon (GAC) treatment for the removal of sulfide and disinfection byproduct (DBP) precursors in drinking water at the pilot-scale. The research conducted was performed at the Auxiliary (Aux) and Main Water Treatment Plants (WTPs) in Sanford, Florida. Both WTPs rely upon groundwater sources that contain total sulfide ranging from 0.02 to 2.35 mg/L and total organic carbon (TOC) ranging from 0.61 to 2.20 mg/L. The Aux WTP's raw water contains, on average, 88% more sulfide and 24% more TOC than the Main WTP. Haloacetic acids (HAA₅) and total trihalomethanes (TTHMs) comprise the regulated forms of DBPs. HAA₅ are consistently below the maximum contaminant level (MCL) of 60 µg/L, while TTHM ranges from 70 to 110 µg/L, at times exceeding the MCL of 80 µg/L in the distribution system. Ozone alone removed total sulfide and reduced UV-254 by about 60% at the Aux Plant and 35% at the Main Plant. Producing an ozone residual of 0.50 mg/L prevented the formation of bromate while removing approximately 35 to 60% concentration of DBP precursors as measured by UV-254. Operating the GAC unit at an empty bed contact time (EBCT) of 10 minutes for the Aux Plant and 5.5 minutes for the Main Plant resulted in 75% and 53% of UV-254 reduction, respectively. The average 120 hour TTHM formation potential for the Aux and Main Plants were 66 µg/L and 52 µg/L, respectively, after treatment by ozone and GAC. GAC exhaustion was deemed to have occurred after seven weeks for the Aux Plant and eleven weeks for the Main Plant. The GAC columns operated in three phases: an adsorption phase, a transitional phase, and a biologically activated carbon (BAC) phase. The GAC adsorption phase was found to produce the lowest TTHMs; however, TTHMs remained less than 80 µg/L during the BAC stage at each plant. BAC exhaustion did not occur

during the course of this study. Ozone-GAC reduced chlorine demand by 73% for the Aux Plant and 10% for the Main Plant.

This thesis is dedicated to my grandparents, Jim and Joan Reiser, who have always supported
and believed in me.

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LIST OF ABBREVIATIONS

AC – Asbestos Cement

AOC – Assimilable Organic Carbon

AOP – Advanced Oxidation Process

Aux – Auxiliary

BAC – Biologically Active Carbon

BDOC – Biodegradable Dissolved Organic Carbon

CI – Cast Iron

DBP – Disinfection Byproduct Potential

DHAA – Dihaloacetic Acid

DI – Ductile Iron

DO – Dissolved Organic Carbon

DOC – Dissolve Organic Carbon

EBCT – Empty Bed Contact Time

GAC – Granular Activated Carbon

GLV – Galvanized

GWR – Ground Water Rule

HAA₅ – Haloacetic Acid

HDPE – High Density Polyethylene

IDC – Initial Demonstration of Capacity

IDSE – Initial Distribution System Evaluation

LRAA – Locational Running Annual Average

LFB – Laboratory Fortified Blanks

MCL – Maximum Contaminant Level

MDL – Minimum Detection Limit

MRDL – Maximum Residual Disinfectant Level

MRL – Minimum Reporting Limit

NOM – Natural Organic Matter

O&M – Operation and Maintenance

PAC – Powdered Activated Carbon

PT – Proficiency Testing

PVC – Polyvinyl Chloride

PWS – Public Water System

QAQC – Quality Control and Quality Assurance

RTCR – Revised Total Coliform Rule

SDWA – Safe Drinking Water Act

SSS – System Specific Study

SUVA – Specific Ultraviolet Absorbance

TCR – Total Coliform Rule

TOC – Total Organic Carbon

TTHM – Total Trihalomethane

USEPA – United States Environmental Protection Agency

UV – Ultraviolet

VSS – Very Small System

WTP – Water Treatment Plant

1. INTRODUCTION

The Floridan Aquifer is a major source of drinking water for Florida (Johnston & Bush, 1988). Two of the main aquifer quality characteristics of concern for Florida utilities are natural organic matter (NOM) and hydrogen sulfide. Whereas sulfide, an aesthetic contaminant, will react with disinfectants to form visible turbidity, NOM will react with disinfectants to form disinfection byproducts (DBPs). Many utilities are struggling with meeting the Environmental Protection Agency's (EPA's) Safe Drinking Water Act's (SDWA's) Stage 2 DBP Rule which sets a maximum contaminant level (MCL) of 80 µg/L for total trihalomethanes (TTHMs) and 60 µg/L for haloacetic acids (HAA₅) (Sudman, Hone, & Green, 2012; USEPA, 2006). The new rule requires utilities to meet the MCL using a locational running annual average (LRAA) calculation, unlike the Stage 1 DBP Rule which calculated the system running annual average to determine compliance. Both sulfides and organics (DBP precursors) can be removed by using a combination of aeration, oxidation processes, microbial filtration, membrane filtration, anion exchange, coagulation, activated carbon, or biotreatment (Duranceau & Trupiano, 2011; Bond, Goslan, Parsons, & Jefferson, 2011).

The City of Sanford located in Seminole County, Florida, is facing challenges with meeting the Stage 2 DBP Rule due to elevated TTHM concentrations detected throughout its distribution system. High DBP formations are likely resulting from combinations of high temperatures, organic concentrations, chlorine dosages, and water age. The City is implementing a program to lower system detention times through pipe rehabilitation and operational changes, and includes

studies aimed to identify those water treatment improvements needed for the City to maintain compliance with the SDWA.

A prior pilot-scale investigation was conducted by Robert and Dunkelberger (2011) that evaluated granular activated carbon (GAC) for treatment of post-aerated water at the City's Auxiliary (Aux) Water Treatment Plant (WTP). Although the process removed DBP precursors, the GAC media was exhausted after only seven weeks. It was also determined that the existing aerator treatment system employed by the City removed only 35 percent of the total sulfide from the water supply, a finding that appears to be in agreement with studies performed by Duranceau and Faborode (2012). Robert and Dunkelberger (2011) recommended piloting ozone prior to GAC to determine if the carbon media's bed-life could be extended.

The research presented in this thesis was conducted to evaluate alternative treatment processes to treat groundwater for sulfide and DBP precursors. Ozone oxidation prior to GAC filtration was piloted at the City of Sanford's Auxiliary and Main WTPs. The GAC component of the process was also studied for use as a biologically activated carbon (BAC) filter. Converting the media to BAC would significantly reduce the operations and maintenance (O&M) costs associated with replacing the GAC media.

This thesis presents the results from the ozone, GAC and BAC pilot study performed at both of the City of Sanford's water treatment facilities. If this treatment process is effective at removing hydrogen sulfide and DBP precursors from the City's raw water then the design and operational

parameters used to develop the pilot studies would be useful when designing the full scale systems.

2. LITERATURE REVIEW

Groundwater from the Floridan Aquifer

The Floridan Aquifer is one of the major groundwater sources in the United States. This aquifer has an area of about 100,000 square miles, located under Florida, parts of Georgia, Alabama, and South Carolina (Johnston & Bush, 1988). This aquifer is separated into two unconfined zones, the upper and lower aquifers, which are composed of a sequence of hydraulically connected carbonate rocks. The Floridan aquifer also contains a less permeable middle semi-confining unit that separates the two zones. Water chemistry in this aquifer is primarily related to flow, dissolution of rocks and proximity to the freshwater-saltwater interface.

Water quality in the Upper Floridan varies with proximity to recharge and discharge areas (Spechler & Halford, 2001). Northeast Seminole County contains an isolated recharge area surrounded by brackish water within the Floridan Aquifer (Phelps, Survey, Rohrer, & District, 1987). In this area, concentrations of contaminants, such as chloride, bromide, calcium, magnesium, potassium, sodium, specific conductance, strontium, and sulfate fluctuate, tending to increase with depth. Iron concentrations are typically low but other secondary parameters of concern include sulfate, hydrogen sulfide gas, and hardness.

Population growth in Seminole County has caused an increasing demand on the Floridan Aquifer. Water levels and spring flows have declined due to groundwater usage, which is primarily caused by increased pumping and below annual average rainfall (Spechler & Halford, 2001). Along with diminishing resources there is a concern for the potential degradation of fresh

groundwater resources near the major municipal wellfields for Sanford, Longwood, and Oviedo (Birdie & Blandford, 1994). The most immediate threat to water quality at these wells is not the regional movement of chloride concentrated water but the upconing of poor water quality from the middle semi-confining unit. If the water quality in these areas is significantly degraded, additional treatment may be required to protect public health and meet drinking water regulations.

Drinking Water Standards

The Safe Drinking Water Act (SDWA) was created by the Environmental Protection Agency (EPA) and adopted as a federal law in 1974 (USEPA, 2004). This law sets legal limits on certain contaminants present in America's drinking water and lists acceptable techniques for treating and measuring these contaminants. In 1996, amendments were added to the SDWA to recognize source water protection, operator training, funding for water system improvements, and public information as important components of providing safe drinking water to the public. Public Water Systems (PWSs) are required to abide by the SDWA as well as state laws which are equivalent to or more stringent than EPA's regulations (Florida Department of Environmental Protection, 2011).

The SDWA has established National Primary and Secondary Drinking Water Regulations. The National Primary Drinking Water Regulations are legally enforceable standards that protect public health by setting maximum contaminant levels (MCLs) for drinking water contaminants (USEPA, 2012). Contaminants are divided into the following categories: microorganisms,

disinfection byproducts, disinfectants, inorganic chemicals, organic chemicals, and radionuclides. For groundwater systems microorganisms are covered under the Groundwater and Total Coliform Rules (USEPA, 1989; USEPA, 2006). Disinfection byproducts and disinfectants are regulated under Stage 1 and Stage 2 of the Disinfectants and Disinfection Byproduct Rule (USEPA, 2006; USEPA, 1998). Inorganic/organic chemicals and radionuclides are tested once every three years in systems unless one of these contaminants is detected in which case the particular contaminant is monitored more frequently. National Secondary Drinking Water Regulations are non-enforceable guidelines concerning contaminants that may cause aesthetic problems in drinking water (USEPA, 2012). Contaminants with secondary standards include aluminum, chloride, color, copper, corrosivity, fluoride, foaming agents, iron, manganese, odor, pH, silver, sulfate, total dissolved solids, and zinc. No adverse health effects are associated with these standards but at considerably high concentrations health implications may exist and aesthetic degradation of water quality can occur (Florida Department of Environmental Protection, 2011).

If a PWS's source water is primarily groundwater then they must abide by the Ground Water Rule (GWR). The GWR provides increased protection against microbial pathogens and establishes a risk targeted approach to target groundwater systems that are susceptible to fecal contamination, instead of requiring disinfection for groundwater systems (USEPA, 2006). High risk systems are required to meet 4-log (99.99%) removal of viruses. Low risk systems must monitor their groundwater source and take corrective action when fecal contamination is found according to the Total Coliform Rule (TCR). The TCR improves public health by reducing fecal pathogens to minimal levels through the control of total coliform bacteria (USEPA, 1989).

Public health benefits associated with this rule include the reduction in risk from disease causing organisms associated with sewage and animal wastes. Systems cannot have greater than 5% of their routine distribution sampling test positive for total coliform without violating the rule. If a violation occurs the public must be notified. Currently, EPA is working on the Revision to the Total Coliform Rule (RTCR). The RTCR will require PWSs that are vulnerable to microbial contamination to identify and fix problems. The revision also establishes criteria for systems to qualify for and remain on reduced monitoring (USEPA, 2013).

Many PWSs are struggling to meet the Disinfectant Byproduct Rule (Sudman, Hone, & Green, 2012). Stage 1 of the Disinfectant Byproduct Rule was created in 1998 and applies to systems that treat their water with a chemical disinfectant for either primary or secondary disinfection (USEPA, 1998). Disinfectants are effective in controlling many microorganisms however they react with natural organic and inorganic matter in source water and the distribution system to form disinfection byproducts (DBPs). Toxicology studies have shown that certain DBPs are carcinogenic, can cause adverse reproductive and developmental effects, and increase risk of cancer. This rule establishes a maximum residual disinfectant level (MRDL) of 4 mg/L for chlorine and chloramines. MCLs for DBPs were specified at 80 µg/L for total trihalomethanes (TTHMs), 60 µg/L for haloacetic acids (HAA₅), 1000 µg/L for chlorite, and 10 µg/L for bromate. The MCL's in Stage 1 are based on a distribution system's annual running average. Stage 2 of the DBP Rule will maintain the same MCLs but will be calculated based on a locational running annual average (LRAA) from monitoring locations across the system (USEPA, 2006). PWSs had to complete an Initial Distribution System Evaluation (IDSE) in order to determine sampling locations for the new rule. IDSE requirements could be met by

performing standard monitoring, a system specific study (SSS), 40/30 certification, or by applying for a very small system (VSS) waiver (USEPA, 2006). The procedure for standard monitoring includes determining additional sampling locations for the Stage 2 Rule based on the results of one year of increased monitoring for TTHMs and HAA₅ along with the routine Stage 1 DBP Rule data. Systems that have extensive DBP data or technical expertise to prepare a hydraulic model may choose to conduct a SSS to select the Stage 2 monitoring locations. 40/30 certification is available for systems with Stage 1 sites that have less than 40µg/L and 30µg/L for TTHMs and HAA₅, respectively. These systems do not need to increase the number of sampling sites for the Stage 2 Rule. The VSS waiver can also be used to remain on a reduced sampling schedule.

Parameters of Concern

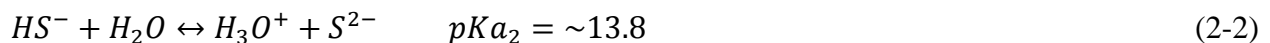
Florida groundwater parameters of concern include salinity, hydrogen sulfide, color, total organic carbon, and hardness (Duranceau & Trupiano, 2011). Many of these are aesthetic concerns and are regulated under the Secondary Drinking Water Standards. Total organic carbon does not have an MCL but its presence leads to the formation of DBPs which are regulated under the Primary Drinking Water Standards.

Sulfide

Sulfide is a federally non-regulated parameter that exists in dissolved and gaseous forms (Duranceau & Trupiano, 2011). Sulfide exists as hydrogen sulfide, bisulfide ions, and sulfide

ions, together making up total sulfide. Sulfides are commonly found in groundwater and other areas where anaerobic conditions exist.

Hydrogen sulfide is produced from the anaerobic decomposition of sulfur containing organic matter and from mineral sulfite/sulfate reduction (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2005). Hydrogen sulfide is known for its “rotten egg” smell and can impact water quality by causing corrosivity and increasing turbidity. If total sulfide exceeds 0.3mg/L then sulfide removal processes must be used in treatment (Duranceau & Trupiano, 2011). Treatment alternatives for sulfide in drinking water are based on sulfide-equilibrium including pH-dependent partitioning of hydrogen sulfide, conversion to sulfate, or formation of elemental sulfur. Hydrogen sulfide dissociation in water can be described by the equilibrium equations shown in Equation 2-1 and 2-2.



Only a portion of the total sulfide can be removed as hydrogen sulfide gas since many groundwaters are near a pH of 7 (Duranceau & Trupiano, 2011). Most groundwater treatment plants in the United States remove sulfide through the use of tray aeration followed by chlorination (Lyn & Taylor, 1992). Chlorination reacts with the remaining hydrogen sulfide concentration after aeration but produces turbidity. In this case, the precipitation of hydrogen sulfide to elemental sulfur can occur within the water distribution system producing black water. Alternative treatment technologies are recommended for systems with high sulfide

concentrations such as forced draft aeration, oxidation, microbiological filtration, oxidation followed by membrane filtration, membrane filtration, or anion exchange (Duranceau & Trupiano, 2011).

Natural Organic Matter Associated With Disinfected Byproducts

Natural organic matter (NOM) is found in dissolved, colloidal, and particulate forms throughout surface and groundwater (Karanfil, Schlautman, & Erdogan, 2002). The dissolved and colloidal forms of NOM provide food for microorganisms, which can lead to microbial growth in distribution systems. Furthermore, NOM can cause the formation of DBPs when mixed with disinfectants, consumption of coagulants, and clogging of filters and membranes making them problematic in drinking water treatment (Xie, 2004). Recently, organics have been closely examined due to more stringent DBP regulations. The composition of NOM can affect the concentration of DBPs formed. Hydrophobic and transphilic NOM exhibits the largest TTHM and HAA₅ formation potential along with organics containing high concentrations of aromatic compounds (Chae, 2002).

Measuring organics can help predict DBP formations. Organics in drinking water can be quantified by ultraviolet absorbance (UV-254), total organic carbon (TOC), dissolved organic carbon (DOC), specific ultraviolet absorbance (SUVA), biodegradable dissolved organic carbon (BDOC), or assimilable organic carbon (AOC) (Karanfil, Schlautman, & Erdogan, 2002; Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2005).

Measuring TOC involves converting the total organic carbon (sum of particulate and dissolved organic carbon) in the water to carbon dioxide which is then measured to indicate the concentration of organic carbon present. Measurement of DOC is similar to TOC except the water is run through a 0.45 μm filter prior to measurement. UV-254 measures ultraviolet light at a wavelength of 254 nm which is used as a surrogate concentration measurement tool for NOM (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2005). SUVA is calculated as the ratio of UV-254 absorbance to DOC which is correlated to the hydrophobic fraction of NOM. Both UV-254 and SUVA tend to correlate well with dissolved organic matter reactivity (Karanfil, Schlautman, & Erdogan, 2002).

BDOC and AOC are used to assess the potential for microbiological regrowth within distribution systems (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2005). BDOC is the total dissolved organic carbon that can be readily assimilated biologically while AOC is typically the most degradable fraction of TOC (Escobar & Randall, 2001). While BDOC and AOC provide complimentary information, AOC gives a more direct estimation of regrowth potential.

Disinfection Byproducts

DBP's are a group of organic and inorganic compounds that are formed from the reactions between disinfectants and NOM during drinking water treatment (Xie, 2004). Currently, EPA regulates four groups of DBPs: TTHMs, HAA₅, chlorite, and bromate, however many other groups also exist. There are four common types of TTHMs and nine common HAA₅ which are formed through different complex reactions between chlorine and NOM. Presence of even low

levels of bromide can significantly affect the DBP species formed during disinfection (Sketchell, Peterson, & Christofi, 1995). Bromide concentrations are considered to be high if they exceed 200 µg/L (Bond, Goslan, Parsons, & Jefferson, 2011; Rakness, 2005). High concentrations of bromide can lead to the formation of bromate if ozone is used within the water treatment process. Different types and dosages of disinfectants have an effect on the formation potentials of DBPs. Common disinfectants include chlorine, chloramine, ozone, and chlorine dioxide. Pre-ozonation tends to decrease the formation of TTHMs and HAA₅ for most waters after chlorination (Hua & Reckhow, 2007). The use of chloramines also decreases regulated DBP formation; however, chloramination produces a greater concentration of unknown and unregulated DBPs such as cyanogen chloride and N-nitrosodimethylamine (NDMA). If the DBPs formed are iodinated they may be more toxic than TTHMs and HAA₅ (Hua & Reckhow, 2007).

Contact time, temperature, and pH also have an effect on DBP formation potential. Longer contact times and high temperatures can lead to higher formation. Concentrations of TTHMs and dihaloacetic acids tend to increase substantially under alkaline pH conditions without chlorine residuals (Hua & Reckhow, 2012). Higher pH values can also result in a higher degradation of dihaloacetic acids (DHAA).

Treatment Alternatives

Formation of DBPs can be controlled by removing NOM prior to disinfection. Common treatment techniques used at municipalities for the removal of NOM from drinking water include coagulation, anion exchange, membranes, activated carbon, biotreatment, advanced oxidation

processes (AOPs), and ozone (Bond, Goslan, Parsons, & Jefferson, 2011). In order to comply with the Stage 2 DBP Rule, many municipalities have been switching from chlorine to chloramines or using a combination of membranes, granular activated carbon, and ozone to decrease DBP formation potential (Sudman, Hone, & Green, 2012).

Ozone

Ozone is a strong oxidant and a powerful disinfectant that has been used in drinking water treatment for approximately one hundred years (Rakness, 2005). Currently, nearly one third of the water treatment plants in the United States use ozone for disinfection, taste and odor control, or target compound destruction (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2005). Ozone can be used as a disinfectant, precipitant, coagulant, and can remove taste and odor, color, and toxins in drinking water (Rakness, 2005). Advantages of using ozone include oxidizing iron and manganese, and destroying and removing algae. Ozone reacts with and removes organic matter, requires a short reaction time, and produces no residual (Lahlou, 1999). Ozone treated drinking water can be expected to be cleaner, clearer, odorless, safer, and oxygenated. However, ozone does possess limitations such as producing little to no residual, and requiring an ozone-destruct unit for safety concerns in handling toxic off-gasses. In addition, ozone is costly in comparison to chlorination and requires a complex installation process. It is important to note that ozone will react with most parameters in the water not just the targeted contaminant (Rakness, 2005).

Ozone readily oxidizes sulfide and color which are both non-regulated secondary standards that are aesthetic concerns. The oxidation of hydrogen sulfide occurs in two steps: first converting hydrogen sulfide to elemental sulfur and second, oxidizing the elemental sulfur into sulfate (Rakness, 2005). Ozone also oxidizes many color-causing contaminants therefore effectively removing color in water.

Ozone can easily be used as a primary disinfectant within a water treatment system. However, a secondary disinfectant such as chlorine would be necessary in order to maintain a disinfectant residual within the distribution system because ozone does not provide a residual. Design of an ozone system for disinfection is based on ozone contact concentrations, competing ozone demands, and a minimum contact time (Lahlou, 1999). Ozone dose can be calculated using Equation 2-3 (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2005).

$$\text{Ozone dose } \left(\frac{\text{mg}}{\text{L}} \right) = \frac{Q_g}{Q_l} \times (C_{g,in} - C_{g,out}) \quad (2-3)$$

Where: $Q_g = \text{Gas Flow Rate (L/min)}$

$Q_l = \text{Water Flow Rate (L/min)}$

$C_{g,in} = \text{Concentration of Ozone in Feed Gas (mg/L)}$

$C_{g,out} = \text{Concentration of Ozone in Off-Gas (mg/L)}$

Ozone oxidation breaks down large long chain molecules into short chained organics such as aldehydes, ketoacids, and carboxylic acids which are more easily biodegradable (Rakness, 2005). Significant increases in AOC levels are usually seen in waters after ozonation (Escobar &

Randall, 2001). These organics can lead to TTHM formation during chlorination or biological regrowth within the distribution system. However, ozone avoids the formation of halogenated DBPs which are inherent in chlorine treatment (Lahlou, 1999). When using ozone, bromate formation must also be considered. If bromide is absent or present in low concentrations in the raw water then low bromate formations will occur. On the other hand, if bromide is present in moderate concentrations then ozone dosage may have to be adjusted (Rakness, 2005).

Ozone can be produced by electrical discharge, electrolytically, photochemically and radiochemically (Rakness, 2005). Since ozone is an unstable gas it must be manufactured on site which is usually done by passing air or oxygen through two electrodes with high alternating potential differences (Lahlou, 1999). In order to use the appropriate ozone dosage, ozone demand of the water to be treated must be determined. It is also recommended that finished water quality goals be established prior to determining a treatment design method.

The ozone treatment process consists of an ozone generator, feed-gas supply, ozone contactor, and an ozone destruct system (Rakness, 2005). The core component is the ozone generator which consists of a power supply unit, and generation vessel containing dielectrics and a cooling system. These components are often unique to each manufacturer and continue to improve over time. Using “Ozone-On-Demand” technology that precisely matches ozone production to real time demand, excess dosing can be minimized and the technology can deliver high ozone concentrations while minimizing the generator’s footprint (Neibauer, Roberts, Smith, Francis, & Honner, 2012). Oxygen-rich air streams such as liquid oxygen (LOX) must be used for the feed-gas supply in these advanced technologies (Lahlou, 1999). The ozone contactor can consist of

bubble diffusers, side-stream injection, or a venturi system. An ozone destruct or exhaust system is necessary to remove ozone from the spent-gas streams. This technology requires monitoring for leaks as ozone gas by itself could pose a potential health hazard.

Granular Activated Carbon

Activated carbon is a porous carbonaceous adsorbent that can remove a variety of organic solutes (Cecen & Aktas, 2012). This technology was first used to remove contaminants from drinking water in the 1920s (Cecen & Aktas, 2012). There are two common types of activated carbon: powdered activated carbon (PAC) and granular activated carbon (GAC). PAC is composed of crushed or ground carbon particles. It can be added at various locations in the water treatment process, and then removed through sedimentation or filtration (Crittenden, Trussell, Hand, Howe, & Tchobanoglous, 2005). GAC is typically in the form of crushed granules of coal or shell and is housed within contactors in which the water is filtered. GAC contactor options include gravity fed, pressure, and upflow/fluidized-bed. Activated carbon is used in water treatment mainly for the removal of NOM but is also known to remove tastes and odors, synthetic compounds, and radon.

Activated carbon is composed of microcrystallites consisting of carbon atoms and relies on adsorption to remove contaminants from drinking water (Cecen & Aktas, 2012). Adsorption generally takes place in the micropores which are the spaces between the microcrystallites, and involves the accumulation of substances at a surface or interface. In GAC, adsorption usually occurs between the liquid to solid phase where the activated carbon is the adsorbent and the

contaminants are the adsorbates. In GAC filtration, physical adsorption takes place by Van der Waals forces, when intermolecular reactions take place between favorable energy sites.

Factors influencing adsorption in GAC include the surface area, porosity, and chemical surface characteristics of the adsorbent; physical and chemical characteristics of the adsorbate; and the pH and temperature of the water medium. (Cecen & Aktas, 2012). These factors should be taken into consideration when determining a GAC media for the removal of DBP precursors. The properties that should be examined when selecting a GAC media are specific surface area, pore-size distribution, surface functional groups, the Iodine number, and the Tannin number (Rodriguez-Fuentes, Hilts, & Dvorak, 2005). GACs with the best DBP precursor removal efficiency generally have a relatively low surface basicity. Surface areas in a 5-50 Å pore width range and tannin adsorption are also useful indicators of DBP precursor adsorption potential.

The empty bed contact time (EBCT) also has an effect on the concentration of contaminants that are adsorbed onto the GAC. EBCT represents the theoretical residence time in the absence of packing media from the filter (Cecen & Aktas, 2012). EBCT is affected by hydraulic loading rate, bed area, length of the reactor bed, contact time, influent adsorbate concentration, adsorbent capacity as a function of the adsorbate, hydraulic gradient, backwash rate, and the mode of operation. System configuration and EBCT have a direct effect on the carbon usage rate. An EBCT of 10 to 15 minutes is recommended for DBP precursor removal but depends on the raw water characteristics (Bond, Goslan, Parsons, & Jefferson, 2011). The EBCT can be calculated by Equation 2-4 (Cecen & Aktas, 2012).

$$EBCT = \frac{V_B}{Q} \quad (2-4)$$

Where: $V_B = \text{Volume of the GAC Bed (L}^3\text{)}$

$Q = \text{Flow Rate (L}^3\text{/T)}$

After a certain amount of time, the carbon media will reach exhaustion (reach its adsorption capacity), which depends on several factors including the EBCT, adsorbate, and adsorbent. Once the media is “spent,” it can be regenerated through thermal reactivation in order to restore the adsorption capacity of the media. From an operator’s standpoint there are very few differences in adsorption among regenerated and virgin carbons for TOC and DBP precursor removal (Metz, DeMarco, Pohlman, Cannon, & Moore, 2004). Reactivated media tends to show a greater DBP precursor adsorption at the beginning of runs while the virgin media performed better in the latter part of the runs. Overall, according to Metz and colleagues (2004), the reactivation process has not proven to greatly affect the adsorption of DBP precursors.

Biologically Active Carbon Filters

Biologically active carbon (BAC) filters have been used for decades in North America and Europe for drinking water treatment but have only recently received more interest due to more stringent regulations (Zhu, Getting, & Bruce, 2010). BACs are used in drinking water to remove NOM, nitrate, trace organic compounds, perchlorate, sulfate, iron, and manganese. Biological processes can effectively remove biodegradable organics, synthetic organic compounds, and some inorganic substances that are ineffectively treated by conventional water treatment (Joo & Foldenyi, 2012). Biooxidation of organic matter (removal of AOC) will decrease the

concentration of available food for microorganisms in the distribution system; therefore, decreasing the chances of biofilm regrowth from occurring (Joo & Foldenyi, 2012).

Biological treatment processes are based on the growth of microbial communities capable of metabolizing contaminants through biologically-mediated oxidation-reduction reactions (Zhu, Getting, & Bruce, 2010). Biofilms develop as a fixed film on media such as sand, anthracite, GAC, or membranes. The microorganisms must first become acclimated to their surrounding environment and to the food provided (Peavy, Rowe, & Tchobanoglous, 1985). This acclimation period is called the lag phase which varies significantly depending on the environment, organisms, and available food. Eventually the stationary phase is reached which is when the production of microorganisms is offset by death. Growth rate, a hyperbolic function of the food concentration, is also affected by temperature, pH, toxins, influent dissolved oxygen, and concentrations of disinfectants present in backwash water.

Little is known about the genetic identities of biofilms since vast numbers of microorganisms exist in drinking water making BAC filters a “black box” technology (Zhu, Getting, & Bruce, 2010). General acceptance of this technology has been an issue, according to Zhu and coworkers (2010), due to the concern of possible microbiological breakthrough and sloughing even though coliform bacteria are rarely seen in BAC filtered water.

Combined Use of Ozone and Granular/Biological Active Carbon

The combination of ozone and GAC is being used more frequently in drinking water for the removal of organics and DBP precursors due to more stringent regulations (Sudman, Hone, & Green, 2012). Ozonation leads to lower molecular weight NOM which is more readily adsorbed to activated carbon (Kim, Yu, Koo, & Lee, 2006). Five to ten minutes should be allowed for the ozone residual to dissipate before entering the GAC depending on the initial residual. Ozone concentrations greater than 0.5 mg/L can reduce the lifespan and adsorptive capacity of the media. Pre-ozonation can vary adsorption velocities, increase biodegradability, prolong GAC filter service times, and decrease the equilibrium adsorption on GAC (Boere, 1992).

Microbiological organisms can naturally begin to grow on exhausted GAC media, forming biologically active carbon (BAC) filters. By allowing the GAC to convert to BAC, operational and maintenance (O&M) costs can be dramatically decreased since BAC has a long life-span (van Der Hoek, Hofman, & Graveland, 1999). A relationship between biofilm thickness and the remaining adsorptive capacity of the carbon has not yet been determined. Use of ozone prior to BAC can result in a lower organic matter concentration in the finished water and lower DBP formations. Increasing the EBCT or water temperature in BAC columns can increase the removal of halogenated organics and DBPs (Wu & Xie, 2005). Using the combination of ozone, GAC, and BAC may reduce the carbon reactivation frequency to every three years depending on the source water quality (van der Hoek, Bonne, & Hofman, 2002).

3. DESCRIPTION OF RAW WATER, EXISTING FACILITIES, AND PRIOR PILOT STUDIES

This chapter provides a brief overview of the City of Sanford's potable water system including groundwater quality, current treatment facilities, and distribution system. The Utilities Department, responsible for maintaining the potable water system, provided the historical water quality data that served as the background data for this study. The granular activated carbon pilot study performed by Reiss Engineering (2011) prior to this study is also presented. Reiss's (2011) reports on the granular activated carbon pilot study and previous water quality modeling conducted for the City were used as background data and for comparison throughout this study.

Potable Water System Overview

The City of Sanford is located in Seminole County, Florida and was founded in 1877. Sanford, one of Florida's oldest cities, has an aging potable water system. The potable water system supplies water to 57,022 people within the City, some areas of Seminole County, and pockets of unincorporated areas. The City's potable water system layout can be seen on Figure 3-1.

The City of Sanford has four wellfields with a total of nineteen wells located in the Upper Floridan Aquifer: Mayfair Golf Course, Oregon, Twin Lakes, and the Hidden Lakes Wellfields. These wellfields supply water to the two water treatment plants: Main Plant (Water Plant 1) and Auxiliary Plant (Water Plant 2). The Main Plant's water comes from the six Golf Course Wells, the five Oregon Wells, and the two Twin Lake Wells. The Aux Plant receives its water from the six Hidden Lakes Wells. The Main and Aux Plant water blends within the distribution system

which consists of over 324 miles of pipeline. The distribution system also contains two elevated storage tanks, one ground storage tank, and three emergency interconnections with other potable water systems. The capacity of the wells, ground storage tanks, and high service pumps can be seen on Figure 3-2.

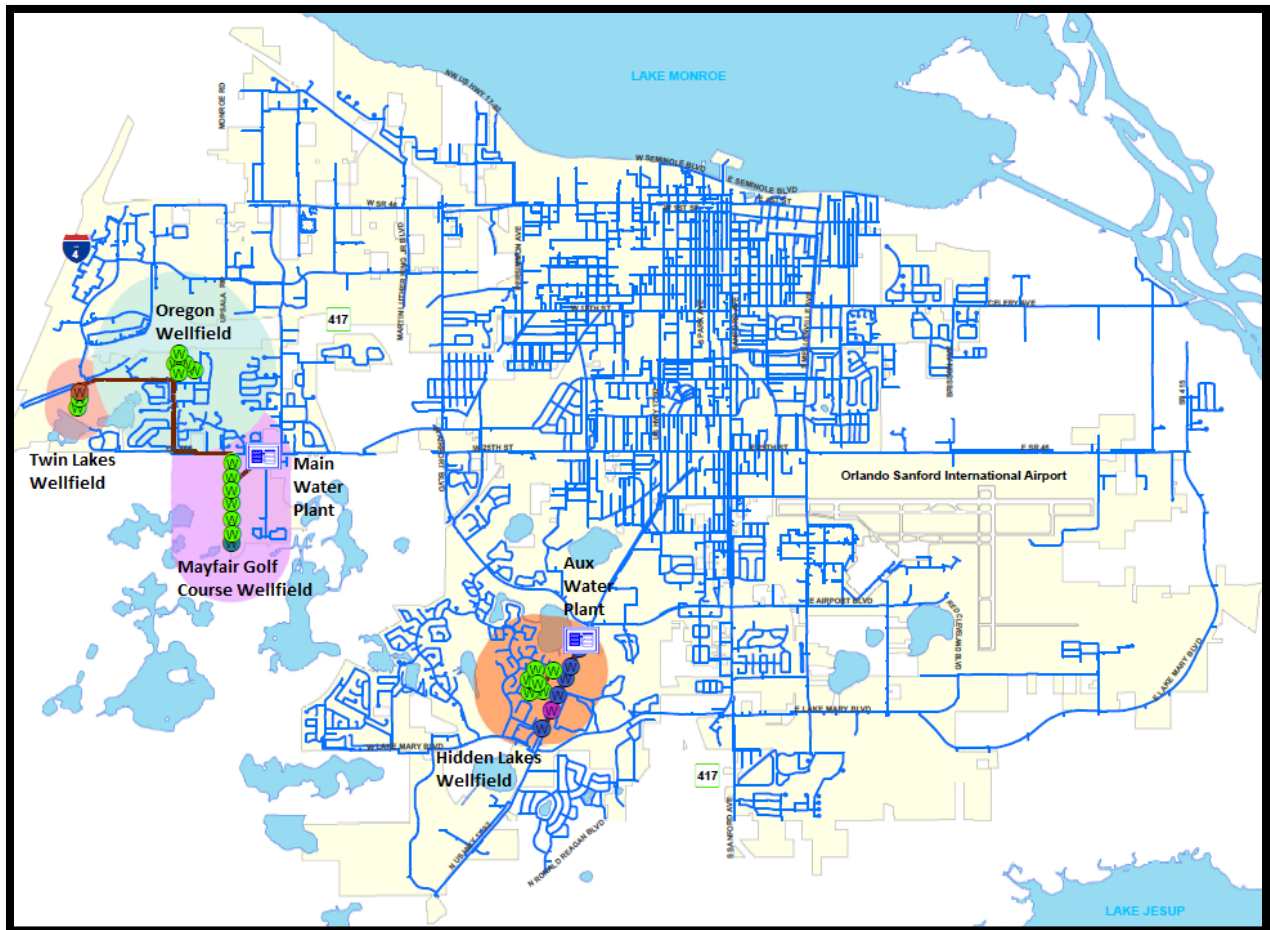


Figure 3-1: City of Sanford's Potable Water System

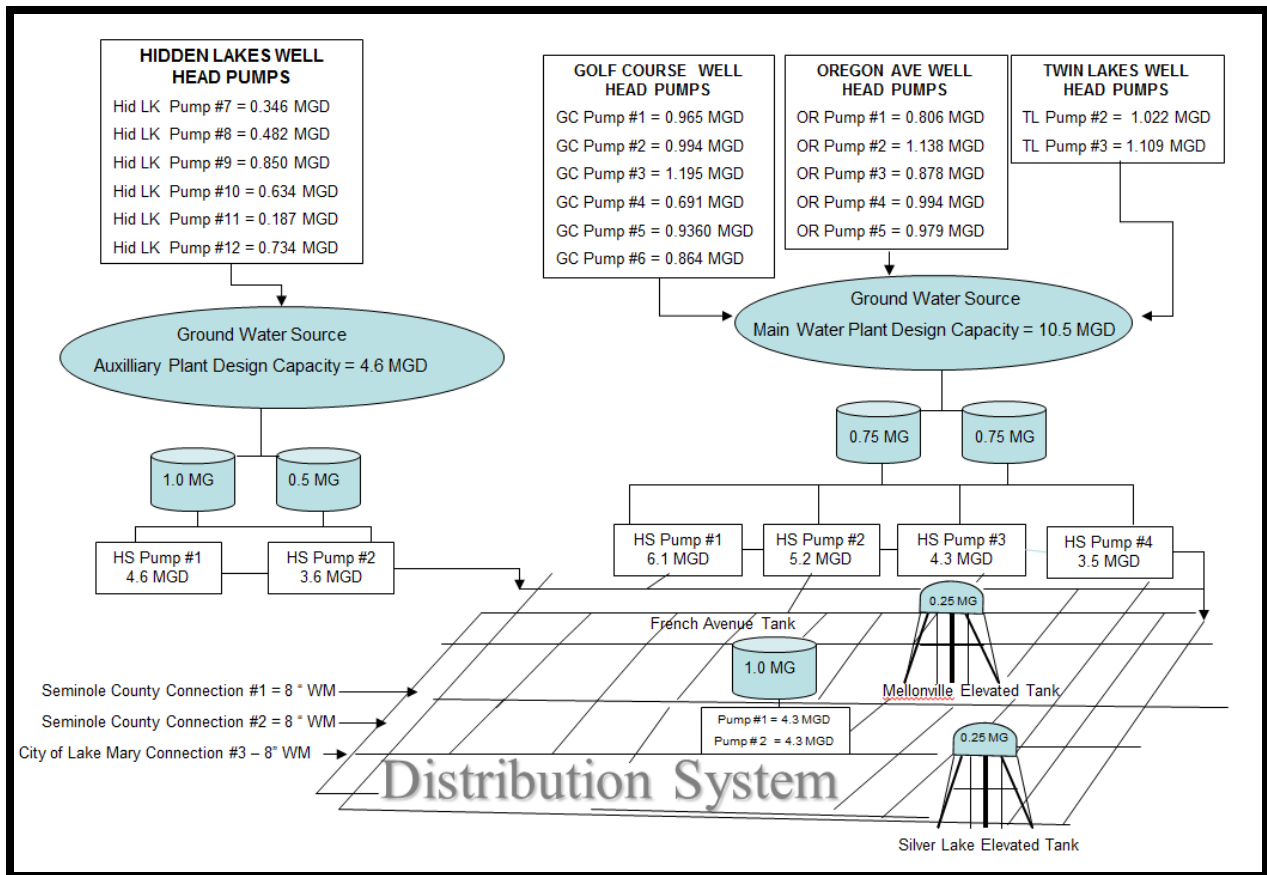


Figure 3-2: City of Sanford Potable Water System Capacity

Source Water and Quality

The City’s only water source is groundwater from the upper Floridan Aquifer. The St. John’s River Water Management District (SJRWMD) provided the City with a Consumptive Use Permit (CUP) which allocates a withdrawal of about 9.58 MGD from the aquifer (St. Johns River Water Management District, 2006). If the City continues to expand alternative water sources may be needed to meet water demand. Water could be drawn from the St. John’s River but it would be a costly option (St. Johns River Water Management Distirct, 2009). Currently the City is focusing on conservation in order to preserve their limited groundwater resources.

Sulfide concentrations ranging from 0.02 to 2.35 mg/L and TOC concentrations ranging from 0.61 to 2.20 mg/L are present in this area, which are common water quality characteristics of the Upper Floridan Aquifer. Some of the wells also have chloride concentrations averaging 100 mg/L which could be a sign of salt water intrusion caused by excess pumping.

Table 3-1 gives the hydraulic characteristics and general water quality for each of the City’s nineteen wells. Table 3-1 shows the wells vary in depth, with the shallowest well at 162 ft and the deepest at 700 ft. Water quality tends to vary by wellfield and depth. These wellfields are also slightly alkaline with an average pH of 7.9 and moderately hard with an average alkalinity of 139 mg/L as CaCO₃. Figure 3-3 shows that the hydrogen sulfide and TOC concentrations are higher in the Hidden Lakes Wellfield than the Main Plant’s wellfields.

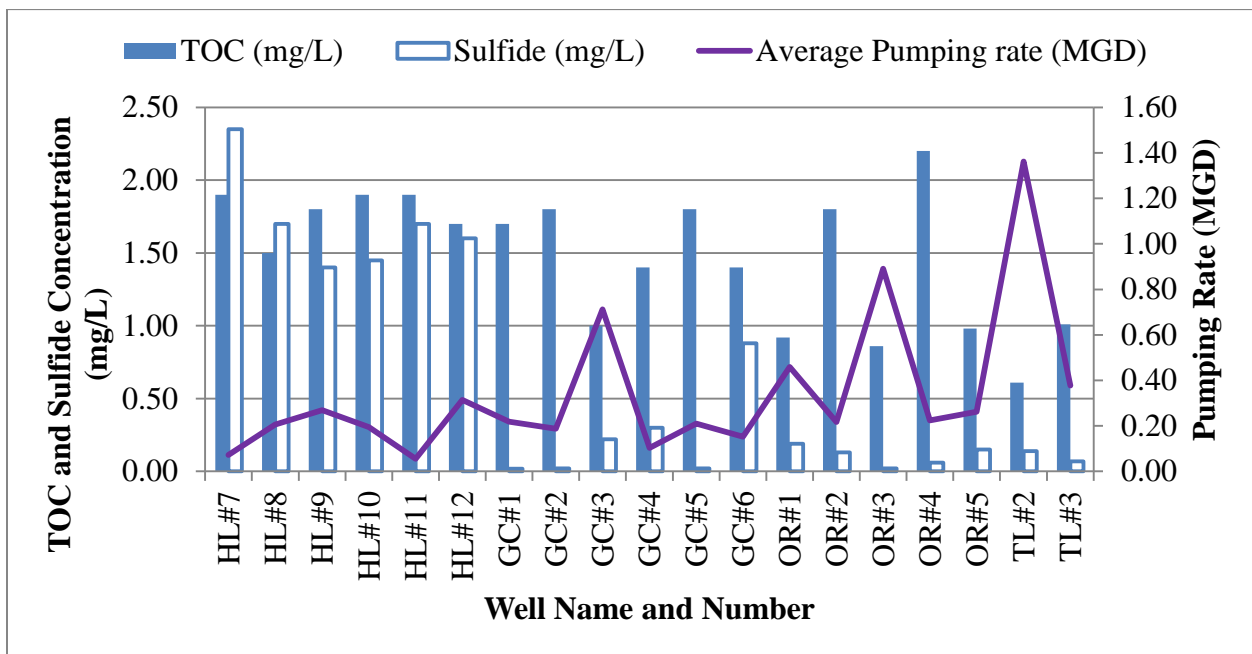


Figure 3-3: TOC, Hydrogen Sulfide, and Pumping Rate Comparison for Sanford’s Wells

Table 3-1: Sanford Well Characteristics

Well Name	Year Drilled	Depth (ft)		Pumping Rate (MGD)	pH	Fluoride (mg/L)	Iron (mg/L)	Alkalinity (mg/L as CaCO ₃)	Dissolved Oxygen (mg/L)	Turbidity (NTU)	TOC (mg/L)	Total Sulfide (mg/L)	Chloride (mg/L)	Hardness (mg/L as CaCO ₃)
		Well	Casing											
HL#7	N/A	162	0	0.07	7.86	0.15	0.022	129	2.41	0.0	1.90	2.35	50.4	189
HL#8	1961	350	350	0.21	7.92	0.15	0.020	147	2.14	0.0	1.50	1.70	26.5	171
HL#9	1984	303	125	0.27	7.88	0.15	0.025	136	2.11	0.0	1.80	1.40	40.6	182
HL#10	1984	302	125	0.20	7.90	0.15	0.022	139	2.42	0.0	1.90	1.45	33.4	182
HL#11	1984	328	140	0.06	7.93	0.14	0.025	137	2.93	0.0	1.90	1.70	29.5	179
HL#12	1984	303	107	0.31	7.89	0.14	0.022	140	2.96	0.1	1.70	1.60	24.5	181
HL Average		291	141	0.19	7.89	0.15	0.023	138	2.50	0.0	1.78	1.70	34.1	181
GC#1	1961	545	356	0.22	7.79	0.11	0.029	148	2.35	1.5	1.70	0.02	22.9	194
GC#2	1961	540	392	0.19	7.76	0.10	0.028	152	1.85	1.4	1.80	0.02	21.6	191
GC#3	1964	525	437	0.71	8.02	0.12	0.020	131	1.65	0.0	1.00	0.22	17.9	186
GC#4	1964	536	116	0.10	7.92	0.13	0.021	138	3.55	0.0	1.40	0.30	17.5	180
GC#5	1975	550	402	0.21	7.80	0.10	0.028	179	2.01	0.9	1.80	0.02	17.2	182
GC#6	1975	565	125	0.15	7.92	0.13	0.024	128	3.21	0.1	1.40	0.88	19.6	173
GC Average		544	305	0.26	7.87	0.11	0.025	146	2.44	0.6	1.52	0.24	19.5	184
OR#1	1985	700	400	0.46	8.01	0.16	0.021	123	2.42	0.9	0.92	0.19	66.0	196
OR#2	1985	607	350	0.22	7.87	0.14	0.021	143	3.80	0.0	1.80	0.13	70.8	212
OR#3	1985	650	350	0.89	7.77	0.11	0.022	145	2.45	0.1	0.86	0.02	22.5	191
OR#4	1985	650	350	0.22	7.87	0.12	0.029	152	2.83	0.0	2.20	0.06	51.3	209
OR#5	1985	575	350	0.26	7.91	0.15	0.020	123	2.55	0.6	0.98	0.15	100.3	201
OR Average		636	360	0.41	7.89	0.14	0.022	137	2.81	0.3	1.35	0.11	62.2	202
TL#2	1989	500	150	1.36	7.97	0.13	0.020	124	1.80	0.0	0.61	0.14	23.7	176
TL#3	2002	500	125	0.38	7.97	0.11	0.029	132	1.62	0.5	1.01	0.07	12.7	167
TL Average		500	138	0.87	7.97	0.12	0.024	128	1.71	0.2	0.81	0.11	18.2	171
Average		484	250	0.34	7.89	0.13	0.024	139	2.48	0.3	1.48	0.65	35.2	186

In order to improve the customer’s water quality, the City began using the wells with lower hydrogen sulfide and TOC concentrations more frequently in late 2008. Using these wells resulted in lower DBP formations within the distribution system. The average pumping rates for each of the wells are also shown in Figure 3-3. Since GC#3, OR#1, OR #3, and TL#2 are pumped more often, they must be closely monitored to be sure that water quality degradation is not occurring. Initially increasing the pumping rate at certain wells had an impact on chloride concentrations particularly at the Oregon Wellfield as shown in Figure 3-4.

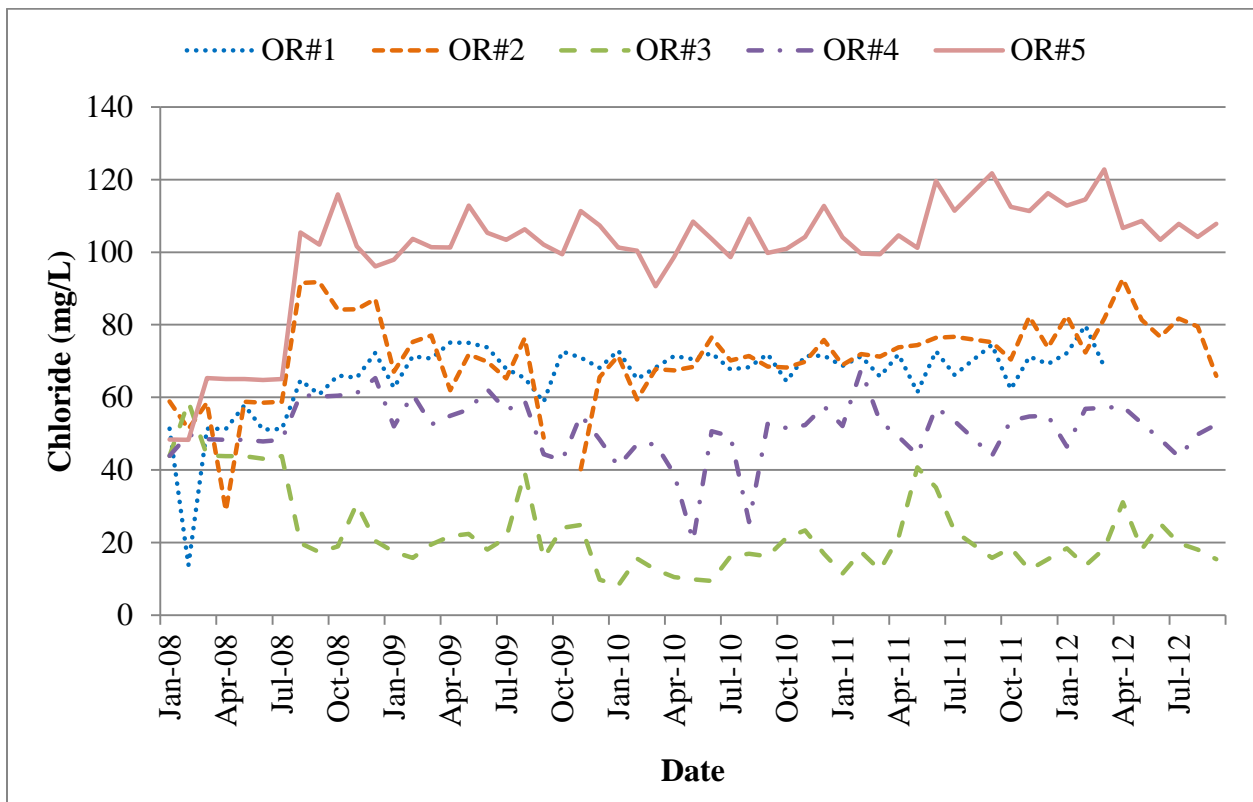


Figure 3-4: Oregon Wellfield Chloride Concentrations

Changing the pumping frequency of the Oregon Wellfield showed a significant increase in chloride concentrations particularly at OR#5. This could be the result of salt water intrusion or upconing of poorer water quality from the middle semi-confining unit. A significant change in chloride concentrations has not been observed again since the operational changes that occurred in late 2008. Improving treatment would give the City the opportunity to alternate well usage, not be continuously reliant on four particular wells, and provide better water quality to its customers.

Current Treatment Facilities

The City's two water treatment plants are both over 60 years old. Both the Main and Auxiliary Water Plants consist of two cascade aerators and two ground storage tanks. At the Main Plant, the aerators are mounted atop of the ground storage tanks. One of the aerators at the Aux Plant is mounted to the top of a ground storage tank and the other is free standing. The treatment plants finished water is disinfected using sodium hypochlorite to obtain a specified residual, 1.8 and 2.0 mg/L for the Main and Aux Plant respectively. Small dosages of sodium hypochlorite are also applied to the Aux Plants ground storage tanks in order to prevent algae growth; however, no residual is formed. Currently, neither plant meets 4-log virus removal; therefore, the City is responsible for monitoring their wells monthly according to the GWR and TCR. The facilities also add poly-orthophosphate (corrosion inhibitor) and fluoride to the treated water before sending it to the distribution system. High service pumps, four at the Main Plant and two at the Aux Plant, then pump the finished water into the pressurized distribution system.

Even though the CUP limits the quantity of water that the City can withdraw from the aquifer, the wellfields, treatment plants, and high service pumps have been designed for a higher capacity as shown in Table 3-2.

Table 3-2: Capacity of Sanford’s Water Treatment Plants

Capacity	Aux Plant (MGD)	Main Plant (MGD)	Total (MGD)
Source Water	3.2	12.7	15.9
Treatment Plants	4.6	10.5	15.1
High Service Pumps	8.2	19.1	27.3

Having higher treatment plant capacities allows for the capability of producing more water during drought or emergency situations. The historical monthly maximum flow rates produced for the entire system can be seen on Figure 3-5.

The quantity of water produced fluctuates seasonally with higher quantities of water being produced in the summer months. Figure 3-5 also shows that in the past five years, overall plant flow rates have decreased. This downward trend is due to the City’s water conservation plan, which includes frequently calibrating the treatment plant’s metering system, replacing customer’s meters with new AMR meters to improve accuracy and detect leaks, and replacing reactive flushing with a proactive unidirectional flushing (UDF) program. Figure 3-6 shows that the Main Plant produces the majority, about 80%, of the water supplied to the distribution system.

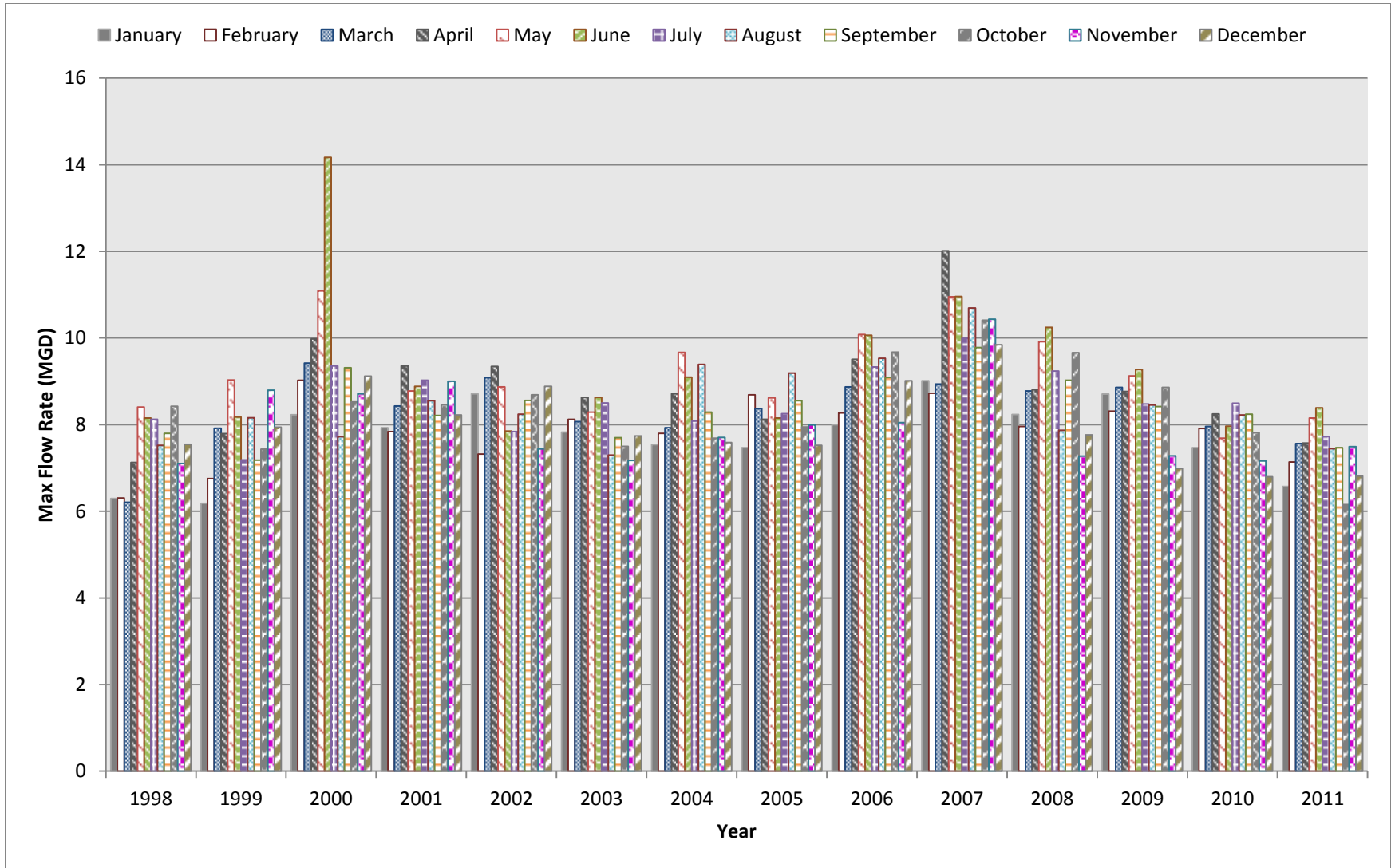


Figure 3-5: Historical Maximum Flow Rate for Water Treatment Plants

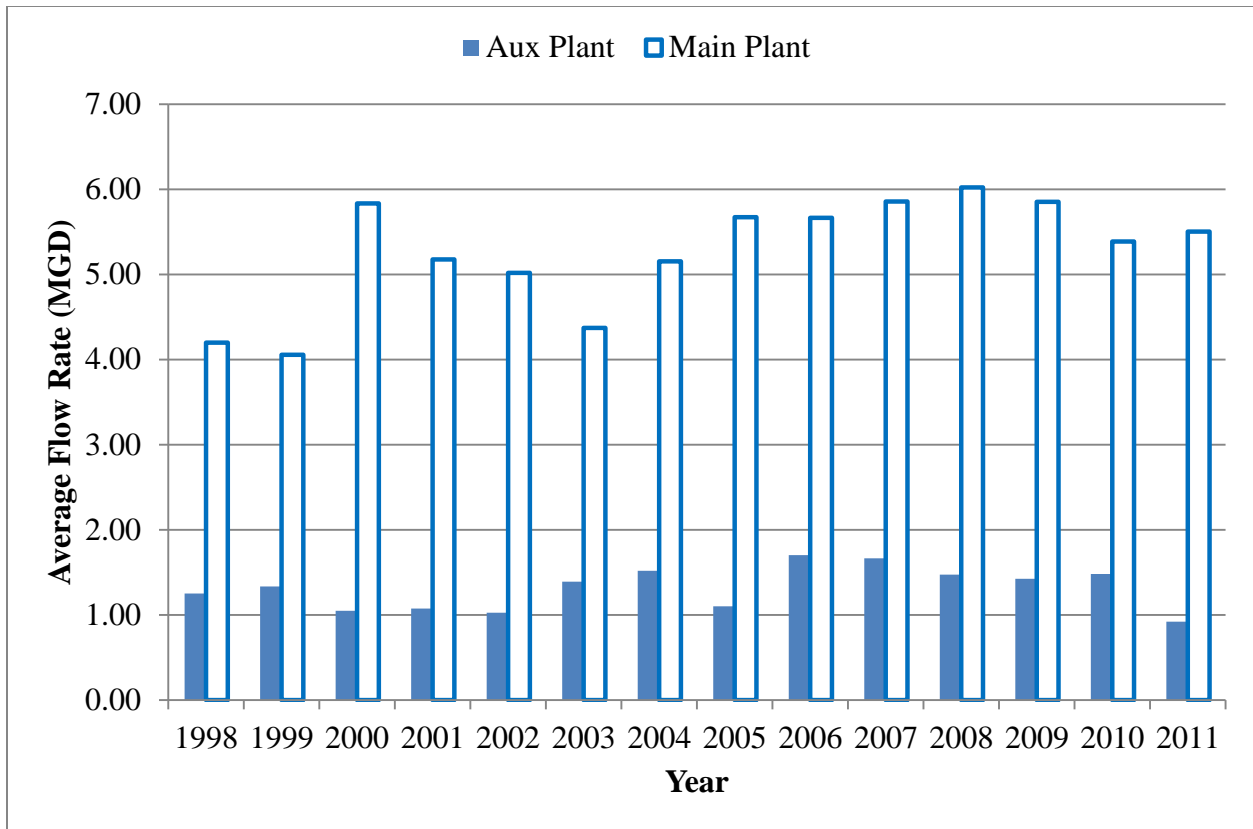


Figure 3-6: Average Production of Main and Aux Water Treatment Plants

Currently, the Aux Plant is only run for a few hours a day due to its poorer water quality. Treatment at the Aux Plant must be updated in order to increase usage and give the City the opportunity to be less reliant on the Main Plant and its wellfields.

Water quality historical data is not available for treatment plants finished water since regulations do not require many parameters to be measured. However, a bench study was performed at both plants to determine chlorine demand and the TTHM formation potential for the wells with lower concentrations of TOC and hydrogen sulfide (OR#1, OR#2, TL#2, GC#3, HL#8, HL#10, and

HL#12). These particular wells were chosen to show DBP formation potential for the best case scenario. Figure 3-7 shows the results of this bench study.

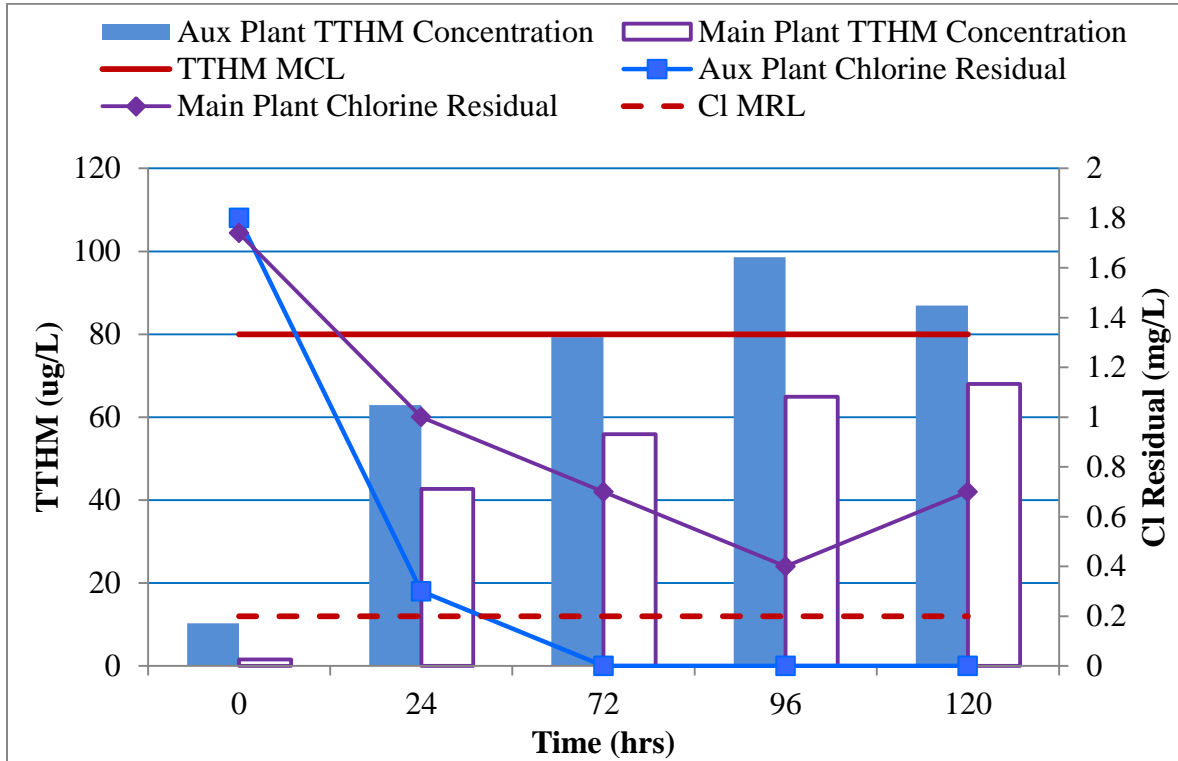


Figure 3-7: Main and Aux Plant TTHM Formation Potential and Chlorine Demand

After 24 hours the Aux Plant is close to the minimum detectable disinfectant residual of 0.2 mg/L for chlorine. Higher chlorine dosages would have shown a greater TTHM formation potential. Previously, chlorine was dosed based on the oxidation reduction potential (ORP), which caused inconsistency in the finished waters' chlorine residuals. Recently, control equipment was added to both plants' chlorine dosage systems to stabilize the chlorine residual. This bench study was performed while the chlorine dosages were based on the ORP causing the fluctuations in TTHM and chlorine concentrations shown on Figure 3-7.

Distribution System

Most of the City’s distribution system was created in the 1950’s; making the majority of the system’s piping over 60 years old. The system is made up of many different pipe materials including cast iron (CI), ductile iron (DI), galvanized (GLV), polyvinyl chloride (PVC), asbestos cement (AC), and high density polyethylene (HDPE) pipe. Table 3-3 shows the percentage of each material found in the distribution. Currently, the City is working on replacing the oldest sections of CI, DI, and GLV pipe with HDPE through the process of pipe bursting. This process is a less invasive way of replacing pipe and provides customers with water in a shorter timeframe. The City currently doesn’t have the funds to replace the entire distribution system. Therefore, when installing a new treatment process that will change the water quality being fed into the system, the old pipe conditions, including corrosion and biofilm, must be taken into consideration.

Table 3-3: Percentage of Pipe Material in Distribution System

Material	Percentage of Pipe Material in Distribution System
AC	2%
CI	17%
DI	5%
GLV	8%
HDPE	4%
PE	1%
PVC	61%
Unknown	2%

The City's potable water system has a detention time of over 5 days (120 hours) and quite a few dead ends containing stagnant water, which causes water quality degradation. Reiss Engineering has proposed looping certain areas of the system in order to decrease detention time and provide better water quality to the City's customers (Reiss Engineering, 2011). However, looping certain areas could increase detention time due to the system's configuration shown in Figure 3-1. The City's hydraulic model can be used to determine if closing and opening specific valves could be used to limit detention times and potential DBP formations.

Reiss Engineering (2011) also used the hydraulic model to conduct a SSS to determine the IDSE locations for the Stage 2 DBP Rule. Seven sites were chosen based on the locations with the highest TTHM and HAA₅ concentrations (SO_LO1, SO_LO2, SO2_LO2, SO2_LO3, SO2_LO4, SO2_LO5, and SO2_LO6). Over the past year, samples have been collected monthly at these seven locations to analyze the water quality and determine the treatment required to reduce DBP formation. Since the City did not have historical TTHM data prior to this analysis, these monthly sampling events helped to identify trends, which could be used to determine the best technique—treatment, pipe replacement, looping, or flushing, to improve water quality in these areas. The average water quality at these sites is shown in Table 3-4. These results will be used to make comparisons once new treatment is installed to show improvements in water quality and any positive or negative effects it may have on the current distribution system. These sites have high TTHM concentrations and/or low chlorine residuals. Monthly chlorine residuals for these sites are shown on Figure 3-8.

Table 3-4: Average Water Quality for IDSE Sites

Site #	pH	Turbidity (NTU)	Conductivity	Temp (°C)	DO (mg/L)	Chlorine (mg/L)	TTHM (µg/L)	HAA ₅ (µg/L)
SO1_LO1	7.65	0.60	478	26.7	7.78	0.45	68.7	25.8
SO1_LO2	7.67	7.31	468	25.2	8.26	1.16	48.3	17.9
SO2_LO2	7.54	2.05	494	25.0	8.22	1.15	45.3	17.2
SO2_LO3	7.56	1.20	467	25.9	8.12	0.72	74.5	32.9
SO2_LO4	7.59	2.22	485	26.0	6.32	0.24	82.7	5.16
SO2_LO5	7.52	1.54	469	26.3	7.77	0.64	72.7	29.4
SO2_LO6	7.57	2.04	456	26.1	7.49	0.34	91.3	36.8
System Average	7.58	2.42	474	25.9	7.71	0.67	69.1	23.6

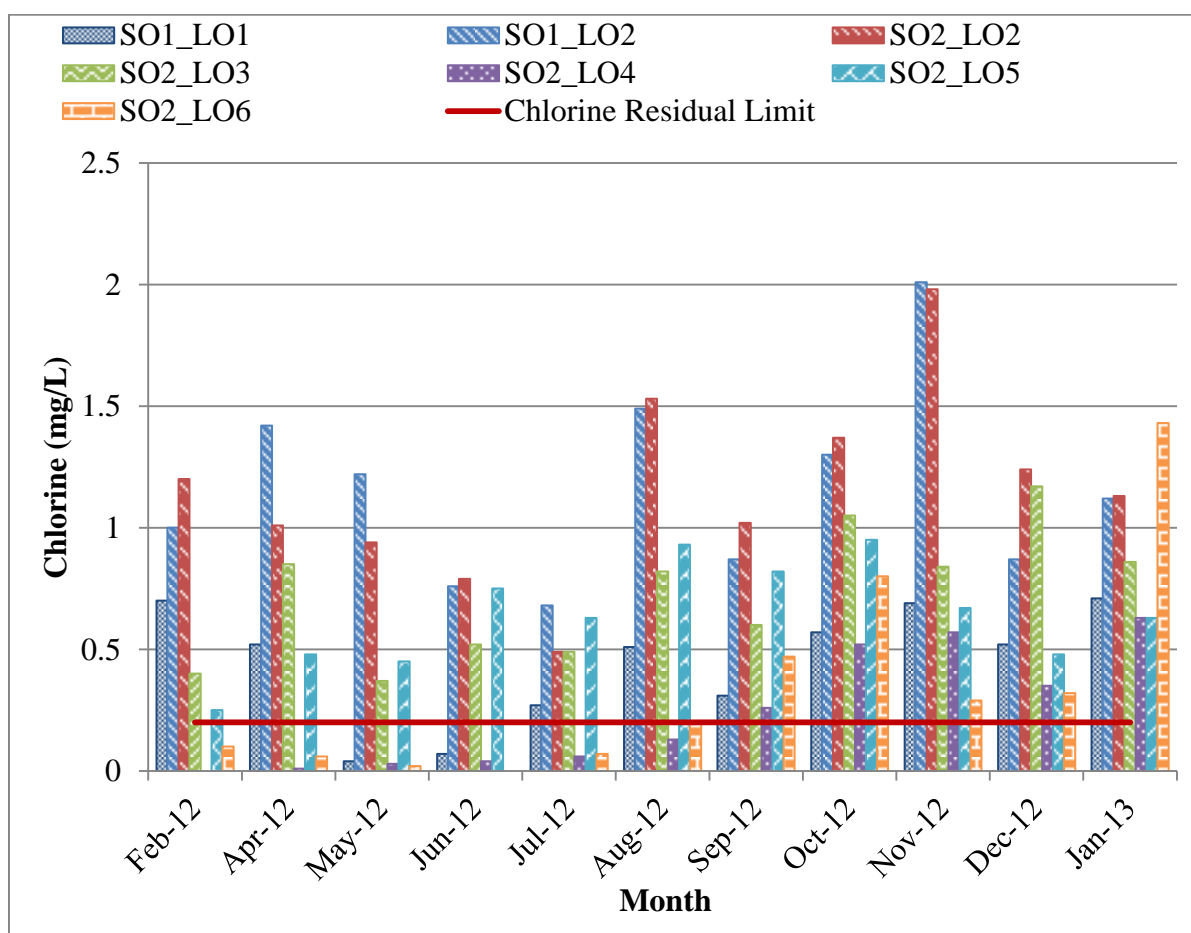


Figure 3-8: IDSE Sites Monthly Chlorine Residuals

When sample collection began in early 2012 three sampling sites (SO1_LO1, SO2_LO4, and SO2_LO6) showed consistently low chlorine residuals. Chlorine residuals are also consistently low when water demand is low and temperatures are high. In an attempt to increase chlorine residuals at these points prior to implementing new treatment, the City added an automatic flushing device near the SO1_LO1 location and began turning over the elevated tanks more frequently. These changes did not affect the TTHM concentrations drastically as shown in Figure 3-9.

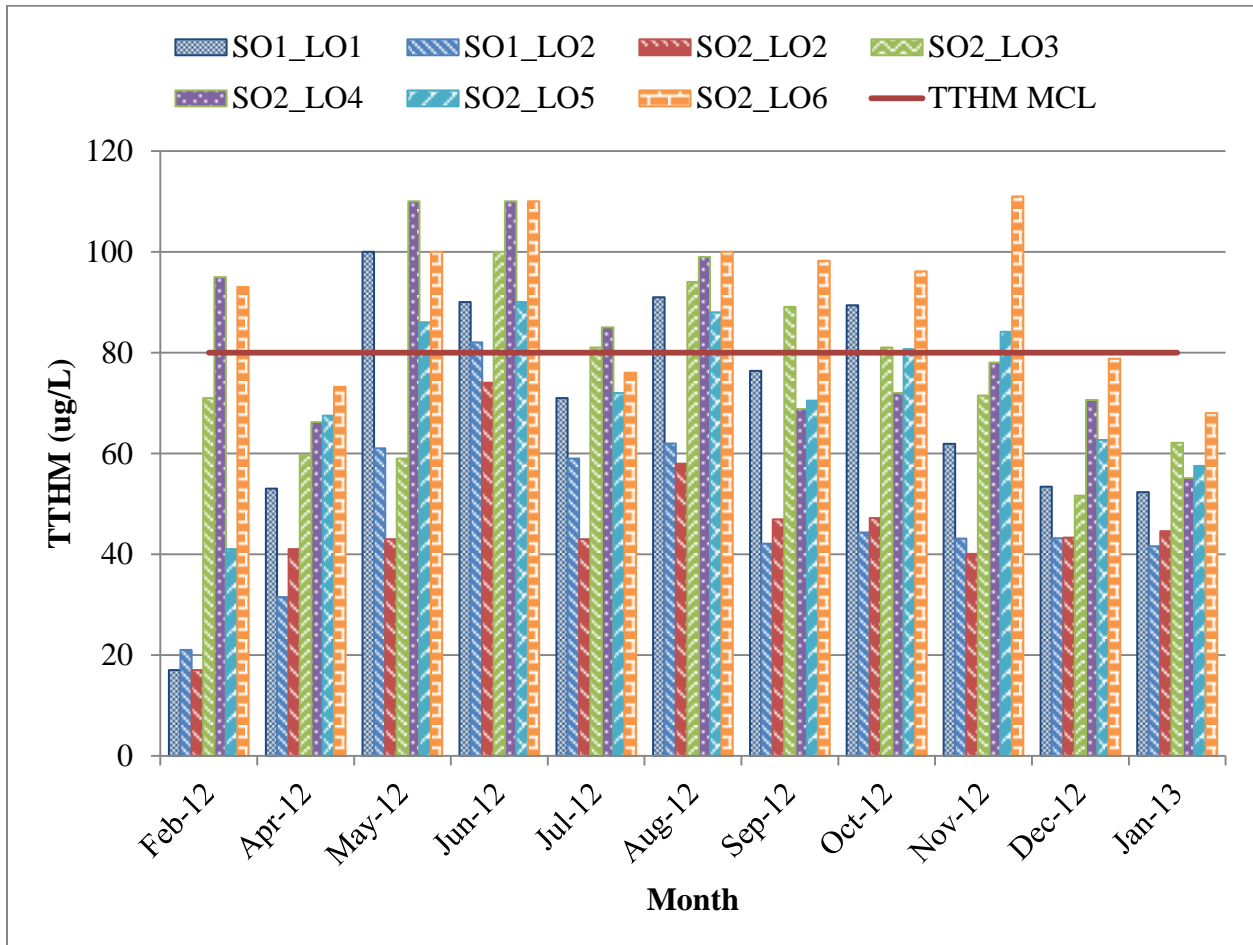


Figure 3-9: IDSE Sites Monthly TTHM Concentrations

TTHM concentrations are higher than the MCL at several locations particularly in the summer months when water temperature is higher. In the past, the City has not violated the DBP Rule since Stage 1 was based on a system average. In April 2012 the wells with the lowest TOC and hydrogen sulfide concentrations were run to determine if an impact was made on TTHM concentrations throughout the system. Running the wells with the better water quality did lower TTHMs but is not a long term solution. Figure 3-9 shows that treatment will need to be implemented in order to significantly decrease TTHM concentrations throughout the distribution system.

Initial Granular Activated Carbon Pilot Study Performed in 2011

Prior to the ozone and GAC pilot study that is discussed in this paper, Reiss Engineering (2011) conducted a pilot study consisting of only GAC at the Aux Plant. The objective of the study was to remove organics which would result in a DBP reduction throughout the distribution system (Robert & Dunkelberger, 2011). A bench study was also conducted prior to the pilot study by Reiss Engineering (2011). The bench study was used to test the TOC adsorption capacity of different GAC medias that could be used in the pilot testing.

Bench Study

Three different GAC media types were chosen to be tested during the prior study: Calgon WPH, Calgon WPH 1000, and Norit Hydrodarco 300 (Robert & Dunkelberger, 2011). These medias are commonly used for removing DBP precursors from groundwater supplies. During the bench study, the TOC and UV-254 removal was evaluated over time for the different types and dosages

of media. Disinfection byproduct formation was also evaluated after the chlorination of the treated water. The data showed that a 90% UV-254 removal corresponded to a TOC removal of 50%. Results also showed that most of the DBPs were formed in the first 24hrs after chlorination. The three types of media were able to remove up to 75% of the TOC from the raw water; however, the Calgon WPH 1000 media produced the smallest concentration of TTHMs at the lowest dosage. Reiss Engineering recommended conducting a 4 inch column pilot study in order to evaluate whether this would be an effective treatment process to use at the full-scale treatment facility.

2011 GAC Pilot Study

The GAC pilot treatment process consisted of two parallel treatment trains, each containing two columns running in series (Robert & Dunkelberger, 2011). This configuration allowed Reiss Engineering to evaluate a 10 or 20 minute EBCT and to compare the efficiency of both virgin (Virgin F300 GAC) and regenerated (Regenerated F300 GAC) media at removing organics. The GAC influent had already been pretreated with sodium hypochlorite and ran through the cascade tray aerators for hydrogen sulfide removal. The system was run continuously to evaluate organic breakthrough and determine media replacement frequency. DBP formation potentials were also performed on the pilot finished water and analyzed.

The organic removal efficiency of each of the columns was examined through the course of the pilot study by measuring TOC, UV-254, and SUVA (Robert & Dunkelberger, 2011). TOC and UV-254 results for the feed water and each of the columns are shown in Table 3-5.

Table 3-5: GAC Pilot Study Organic Results

Location	TOC (mg/L)			UV-254 (cm ⁻¹)		
	Min.	Max.	Ave.	Min.	Max.	Ave.
Feed Water	1.6	2.4	2	0.048	0.072	0.061
Virgin F300 GAC 10-min EBCT	0.5	1.7	1.14	0.001	0.043	0.017
Virgin F300 GAC 20-min EBCT	<0.4	0.7	0.47	0.000	0.008	0.002
Regenerated F300 GAC 10-min EBCT	0.6	1.8	1.23	0.002	0.073	0.023
Regenerated F300 GAC 20-min EBCT	<0.4	0.7	0.52	0.000	0.014	0.005

Results showed that the 20 minute EBCT performed slightly better than the 10 minute EBCT; however, this would require more media and columns, increasing both capital and operational costs. Furthermore, the virgin media removed, on average, 10% more UV-254 than the regenerated media. The 10-min EBCT columns consistently removed at least 50% of the organics present in the feed water until breakthrough occurred at 7 weeks.

DBP formation potential was performed on the feed water, treated GAC filtered water, and blends of the GAC filtered water and feed water. The TTHM and HAA₅ results for the fifth day of these formation potentials can be found in Table 3-6. The GAC with the 20-min EBCT had a lower DBP formation potential than the 10-min EBCT. The 10-min EBCT GAC did produce an average of 47% less TTHMs than the feed water. The blended water still produced high TTHMs meaning the entire flow at the Aux Plant needs to be treated in order to stay under the 80 µg/L MCL.

Table 3-6: GAC Pilot Study DBP Formation Potential Results for 120 hrs

Location	TTHM (µg/L)			HAA ₅ (µg/L)		
	Min.	Max.	Ave.	Min.	Max.	Ave.
Feed Water	86	222	148	33	51	41
Regenerated F300 GAC 10-min EBCT	70	87	79	9	26	19
Regenerated F300 GAC 20-min EBCT	11	35	20	3	10	6
25% Feed Water & 75% Regenerated F300 GAC 20-min EBCT	55	115	88	16	29	21
25% Feed Water & 75% Regenerated F300 GAC 20-min EBCT	82	209	133	38	43	41

The GAC pilot study performed by Reiss Engineering (2011) proved that GAC alone can remove a percentage of the organics and therefore limit DBP formation potential. Hydrogen sulfide was also assumed to be completely removed by the cascade aerators when this study was conducted, which was not the case. Hydrogen sulfide could have been using up some of the adsorption capacity of the GAC that could have been used for removing organics. Reiss Engineering (2011) suggested conducting a pilot study consisting of ozone followed by GAC to see if the run time of the GAC media could be increased.

4. MATERIALS AND METHODS

This chapter describes the materials and methods used to conduct this research study. The purpose and objectives of this research are briefly described in the experimental plan portion of this chapter. Water quality parameters tested are also listed in the experimental plan component of this chapter. The pilot setup and equipment used for the pilot study are described within the pilot equipment and set-up section of this chapter. The methods and materials used to conduct water quality sampling and operational activities are also discussed in this chapter. Laboratory quality control procedures are briefly discussed as well within this chapter.

Experimental Plan

The primary goal of this research was to determine the effectiveness of ozone and GAC treatment at removing sulfide and DBP precursors from the source water. The same pilot treatment processes were used at both of the City's water treatment facilities. Effectiveness was determined through monitoring UV-254 and sulfide removal efficiencies as well as by performing DBP formation potential. A 5 day (120 hr) detention time was used while performing TTHM formation potential to replicate the water age seen in the City's distribution system. TTHM concentrations were monitored, graphed, and analyzed at 120 hours to determine effectiveness of the ozone and GAC treatment process.

GAC exhaustion occurred when the UV-254 and TOC concentrations peaked. The pilot study was continued after the GAC media had been exhausted. Water quality parameters continued to

be monitored to see if the GAC columns could be turned into BAC. TTHM formation potential was monitored to see if running the unit as BAC is a feasible option.

Water Quality Parameters

Field parameters that were monitored on a daily basis included pH, temperature, conductivity, total sulfide, turbidity, dissolved oxygen, and UV-254. TTHM formation potential was performed biweekly by testing the chlorine and TTHMs at particular water ages. Other parameters tested throughout the course of the study included bromide, bromate, HAA₅, TOC, DOC, and AOC.

Pilot Equipment and Set-Up

A schematic depicting the pilot set-up is shown in Figure 4-1. Raw water was fed into the ozone unit where ozone was injected using a side stream injection process. The ozone pilot unit produced 7 gallons of ozonated water per operating minute. The ozonated water then flowed to a 250 gallon equalization tank where the water entered through the bottom and exited through the top. At a feed rate of 7 gpm the tank had a 36 minute contact time which was more than sufficient time for the ozone residual to dissipate before entering the GAC unit. The GAC pilot configuration consisted of two treatment trains each containing two columns that were run in series with one another. Each of the four columns was designed to exhibit an EBCT of 7 minutes. Since the first and last two columns are in series the total EBCT for columns 2 and 4 was designed to be approximately 14 minutes. Operating in this configuration allowed for the entire GAC unit to produce 0.84 gpm of treated water with each train producing 0.42 gpm.

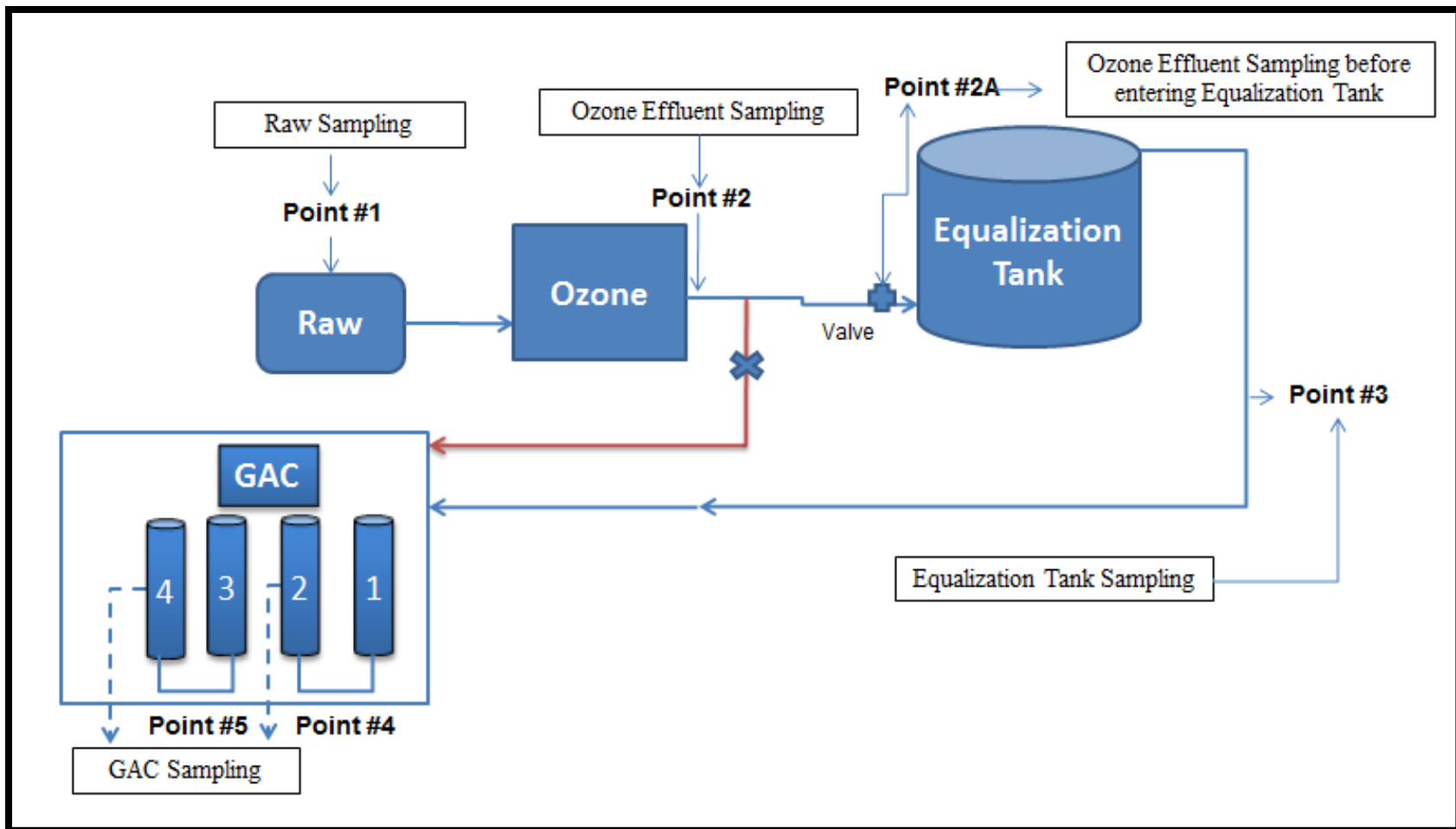


Figure 4-1: Ozone/GAC Pilot Set-Up

The pilot set-up shown in Figure 4-1 was used at both the Aux and Main Plant pilot for consistency and comparison purposes. The utilization factor for the ozone and GAC pilot units at each of the plants was calculated by dividing the operational time by the total duration of the pilot study. Finished water was not fed into the City's distribution system since it was not chlorinated and would have required permitting.

Ozone Pilot Equipment

The ozone equipment is shown in Figure 4-2. The pilot ozone system consisted of a Plasma Block technology which allows for a smaller footprint than other ozone generators and a more concentrated system (Guardian Manufacturing, 2008). The pilot ozone equipment consists of an oxygen concentrator, the Plasma Block ozone generator, and gas injection.



Figure 4-2: Ozone Pilot Equipment

The oxygen concentrator utilizes a Pressure Swing Adsorption (PSA) technology which concentrates the oxygen gas from the ambient air (Guardian Manufacturing, 2008). The surrounding air becomes pressurized within the compressor and is sent into the PSA. The PSA consists of cylinders containing molecular sieves designed to adsorb nitrogen from the pressurized air and allow oxygen to pass through. Once the cylinder is completely saturated with nitrogen the unit switches pressurized air flow into another cylinder. The previous cylinder's pressure is reduced and nitrogen is desorbed. The PSA provides approximately 94% pure oxygen gas to the ozone generator.

The ozone generator consists of a specially designed corona discharge or plasma cell called the Plasma Block (Guardian Manufacturing, 2008). Within the Plasma Block is two flat metal electrode plates separated by a dielectric sheet. The oxygen gas produced by the PSA flows into the Plasma Block under slight pressure. Electricity at 22-24 kHz is applied to the electrodes which creates a field of plasma between the plates. The plasma splits the oxygen into single oxygen atoms which will recombine with the remaining molecular oxygen to create ozone (O_3). The concentration of the ozone in the gas stream exiting the Plasma Block is between 5-10% by weight. The ozone created from the Plasma Block is then injected into the raw water using a venturi.

The venturi creates a vacuum due to high pressure drop that is caused by the reduction in the pipe diameter. As the ozone enters the water stream it creates a chaotic mix of gas bubbles and water which produces dissolved ozone in the water. This unit works on an ozone percentage feed basis which is adjusted using a rheostat. The feed percentage directly affects the ozone

dosage being applied and the ozone residual produced. This pilot unit does not automatically adjust the ozone dosage as influent water quality changes. The ozone percentage feed necessary to remove hydrogen sulfide and decrease DBP's was found through initial staged testing to determine the feed percentage necessary to run the ozone pilot unit through the course of the pilot study at each of the treatment plants.

GAC Pilot Equipment

The carbon used in the GAC columns for this study was virgin and regenerated Calgon Filtrasorb 300M. This carbon was the same type of carbon used in the prior study conducted by Reiss Engineering (2011) to allow for study comparisons. Filtrasorb 300M is manufactured from bituminous coals, and has a high internal service area with optimum pore size for effective adsorption of a broad range of high and low molecular weight organic contaminants (Calgon Carbon Corporation, 2012). The specifications for the Filtrasorb 300M media are shown in Table 4-1. The regenerated carbon was created through thermal reactivation of exhausted virgin Filtrasorb 300M. Since some of the original media is lost during transporting and the reactivation process, 15% of the regenerated carbon was made up of virgin media. The regenerated media used for the Aux Plant Pilot came from a pilot conducted at a WTP in Tallahassee, FL with similar source water. The regenerated media for the Main Plant Pilot was reactivated from the virgin media used in the Aux Plant Pilot.

Table 4-1: Carbon Media Filtrasorb 300-M Specifications

Specifications	Filtrasorb 300-M
Iodine Number	900 mg/g
Moisture by Weight	2%
Effective Size	0.8 - 1.0 mm
Uniformity Coefficient	2.1
Abrasion Number	78
Trace Capacity Number	10 mg/cc
Apparent Density	0.58 g/cc

Before the columns could be placed into service the carbon must be properly wetted (Calgon Carbon Corporation, 2011). A minimum wetting period of 24 hours is required; a period of up to 72 hours is recommended for complete wetting. If media is not properly wetted air within the pores can cause high pressure drop and premature breakthrough of contaminants. The unit must be backwashed before being placed in service.

Backwashing is a procedure that involves running clean water upflow through the adsorber (Calgon Carbon Corporation, 2011). For both pilot studies backwash water was ozonated ground water which originated from the Equalization Tank. Backwashing was conducted before placing fresh media online in order to size segregate the media so that subsequent backwashing will return the media to the same relative position in the bed, remove any remaining air from the bed as well as remove media fines which could lead to pressure drop and flow restriction. When pressure in the columns reached over 40 psi the columns were backwashed. Only one column was backwashed at a time. Each column was backwashed long enough for 30% bed expansion to occur using a low flow rate that was increased every 2 minutes. Once the desired expansion was achieved the flow was ramped down every 2 minutes until backwash flow rate was completely reduced. Backwashing was also conducted as needed during operation to remove

sediment from the top of the bed, media fines that may be plugging the underdrain nozzles, and air that is binding the bed.

The GAC pilot unit consists of 4 columns that can be operated in a number of configurations. For the purposes of this study the process consisted of two parallel treatment trains, each containing two columns in series. Having two parallel treatment trains allowed for the testing of two different types of media: virgin and regenerated carbon. Columns were covered with tin foil during both pilot studies to prevent algae growth from occurring and interfering with results.

The parallel configuration resulted in an EBCT of about 7 and 14 minutes for the two columns in series. In order to obtain these EBCTs a flow rate of 0.42 gpm was used for each of the four columns. Flow rate measurements were read for each column daily. Pressure readings were also taken daily to determine when backwashing the unit was necessary.

Methods and Materials

The methods and materials for water quality analysis employed in the field and in the laboratory are presented in Table 4-2 (Eaton, Clesceri, Rice, & Greenberg, 2005). This table also indicates whether analysis was performed in the field, utilities lab (Sanford Lab), or if a certified laboratory conducted the analysis. The laboratories used for this study included Harbor Branch Environmental Laboratory (HBEL, 4155 St. Johns Parkway Suite 1300, Sanford, FL 32771), Flowers Chemical Laboratories Incorporated (Flowers, 481 Newburyport Ave., Altamonte Springs, FL 32701), and Montgomery Watson Harza Laboratories (MWH, 750 Royal Oaks Drive Suite 100, Monrovia, CA 91016).

Table 4-2: List of Methods Used for Water Quality Analysis

Test	Location Tested	Method and Reference Number	Method Detection Level
AOC	MWH Lab	Weinreich et. al. AOC-AWWSC Bioluminescent Method	1 µg/L
Bromate	HBEL Lab	EPA 300.0 A. Determination of Inorganic Anions By Ion Chromatography	7 µg/L
Bromate	MWH Lab	EPA 317.0 Determination of Inorganic Oxyhalide Disinfection By-Products in Drinking Water Using Ion Chromatography with the Addition of a Post-column Reagent for Trace Bromate Analysis	1 µg/L
Bromide	HBEL Lab	EPA 300.0 B. Determination of Inorganic Anions By Ion Chromatography	0.009 mg/L
Chlorine, Free	Field	SM 4500-Cl G. DPD Colorimetric Method	0 - 2.2 mg/L
Conductivity	Field	SM 2510 B. Laboratory Method	0.01 µS/cm
Dissolved Oxygen	Field	SM 4500-O G. Membrane Electrode Method	0-22 mg/L
Flavor Profile Analysis	Utilities Department	SM 2170 B. Flavor Profile Analysis	NA
HAA ₅	HBEL/ Flowers Lab	EPA Method 552.1 Determination of Haloacetic Acids and Dalapon in Drinking Water by Ion-Exchange Liquid-Solid Extraction and Gas Chromatography with an Electron Capture Detector	0.18 µg/L
HPC	HBEL	SM 9215 B. Heterotrophic Plate Count Pour Plate Method	1 CFU/1mL
Ozone	Field	SM 4500-O ₃ B. Indigo Method	0 - 1.50 mg/L
pH	Field	SM 4500-H ⁺ B. Electrometric Method	0.01 pH units
Temperature	Field	SM 2550 B. Laboratory and Field Methods	0.1°C
TOC and DOC	HBEL Lab	SM 5310 B. Total Organic Carbon or Dissolve Organic Carbon High-Temperature Combustion Method	1.0 mg/L
TOC and DOC	Flowers Lab	SM 5310 C. Persulfate-Ultraviolet or Heated-Persulfate Oxidation Method	1.0 mg/L
Total Sulfide	Field	SM 4500-S ²⁻ D. Methylene Blue Method	0 - 0.70 mg/L
TTHM	HBEL/ Flowers Lab	EPA Method 524.2 Measurement of Purgeable Organic Compounds in Water by Capillary Column Gas Chromatography/Mass Spectrometry	0.15 µg/L
Turbidity	Field	SM 2130 B. Nephelometric Method	0 NTU
UV-254	Sanford Lab	SM 5910 B. Ultraviolet Absorption Method	0.00 cm ⁻¹

Sampling Procedures

Samples were collected throughout the course of the pilot study at the raw water, ozone, ozone pipe, equalization tank, and GAC column 1, 2, 3, and 4 sites as shown in Figure 4-1. Parameters were analyzed in the field, in the utilities lab, or by one of the certified laboratories.

Field Sampling

Field sampling was conducted on average 5 days a week for the majority of the Aux Plant Pilot and 2-3 days a week for the Main Plant Pilot. Temperature, pH, conductivity, total sulfide, turbidity, and dissolved oxygen were sampled throughout the course of the studies. Ozone residual was also tested frequently. Table 4-3 shows the equipment, calibration, and zeroing procedures used for sampling these parameters (Eaton, Clesceri, Rice, & Greenberg, 2005).

UV-254 was sampled at the same frequency as the other field parameters but was analyzed at Sanford's South Water Reclamation Facility where the DR 5000 was located. UV-254 samples were collected in glass containers and analyzed as soon as possible according to SM 5910 B. Ultraviolet Absorption Method using 0.45 micron filters (Eaton, Clesceri, Rice, & Greenberg, 2005).

Table 4-3: Field Sampling Matrix

Test	Equipment	Calibration or Zeroing with Blank
Chlorine, Free	HACH DR850 Portable Colorimeter	Fill a sample cell with 25 mL of sample, place sample in unit and zero.
Conductivity	Fisher Scientific Accumet AP85 meter	Rinse probe 3 times with DI, use traceable calibration standard to read 999-1001 $\mu\text{S}/\text{cm}$ if reading is more than +/- 5% replace probe
Dissolved Oxygen	HACH HQ40d multi meter	Rinse probe with DI, prepare a tap water sample by shaking sample, place probe in sample for 10 minutes, calibrate, if slope is out of range replace membrane
Ozone	HACH DR850 Portable Colorimeter	Pour DI water in beaker, fill one Indigo Ozone Reagent AccuVac Ampule and one with the sample, use sample to zero equipment then read the concentration using the DI blank
pH	Fisher Scientific Accumet AP85 meter	Calibrated prior to analyzing samples using 3 point calibration with standard buffers (pH 4, 7, and 10)
Temperature	Fisher Scientific Accumet AP85 meter	Calibrated against NIST-certified thermometer
Total Sulfide	HACH DR 850 Portable Colorimeter	Create blank by filling a sample cell with 25 mL of DI water, add 1.0 mL of Sulfide 1 Reagent and mix, add 1.0 mL of Sulfide 2 Reagent and mix, wait 5 minutes, insert sample cell into meter and zero
Turbidity	4aMotte 220 Turbidimeter	Calibrated prior to analyzing samples using 3 point calibration with standard NTUs
UV-254	HACH DR5000 UV-Vis Spectrophotometer	Prepare blank by rinsing sampling cell with DI 3 times, fill cell with DI, align clear windows with light path when inserting the cell into the equipment, and zero the equipment

DBP Formation Potential

DBP formation potential was created by dosing 1L amber bottles of pilot finished water with a premade chlorine solution until the desired residual had been obtained. A 1000 ppm chlorine solution was developed using 10 mL of 12% chlorine and 990 mL of DI water. The DBP formation potential was performed in accordance with SM 5710 B., Trihalomethane Formation Potential (Eaton, Clesceri, Rice, & Greenberg, 2005). A five day (120 hr) formation potential was used throughout the course of this study.

Flavor Profile Analysis

Since customer complaints with regards to taste and odor are common in the City of Sanford, a flavor profile analysis was performed on the Aux Plant Pilot water. Customers and City staff members conducted an olfactory test then rated and compared current tap water to the pilot water. Samples were prepared and rated as described in SM 2170 B. of *Standard Methods for the Examination of Water & Wastewater* (Eaton, Clesceri, Rice, & Greenberg, 2005). Table 4-4 shows the rating scale that was used when conducting the Flavor Profile analysis.

Table 4-4: Flavor Profile Analysis Odor Ratings

Odor Rating	Description of Intensity
-	odor-free
T	threshold
2	very weak
4	weak
6	weak to moderate
8	moderate
10	moderate to strong
12	strong

Certified Laboratory Analysis

EPA Certified labs were used to analyze the parameters shown in Table 4-5. This table also shows the type of sampling container, preservative method, and maximum holding time for each particular parameter.

Table 4-5: Lab Analyzed Samples and Preservatives Used

Test	Preservation Technique	Maximum Holding Time
AOC	Collect sample in a 250mL amber glass container, add 0.25mL thio (8%), refrigerate at 4°C	48 hrs
Bromate (HBEL)	Collect sample in a glass or polyethylene container, no preservative required, refrigerate at 4°C	28 days
Bromate (MWH)	Collect sample in a 60mL polyethylene container, add 0.6mL of 1% EDA solution, refrigerate at 4°C	28 days
Bromide	Collect sample in a glass or polyethylene container, no preservative required, refrigerate at 4°C	28 days
DOC	Filter sample through 0.45µm-pore-diameter filter, collect in glass bottle, add hydrochloric acid, refrigerate at 4°C	28 days
HAA ₅	Collect sample in an amber glass bottle, add 1.0 mL of a 10 mg/mL aqueous solution of NH ₄ Cl to the sample bottle for each 100mL, refrigerate at 4°C	28 days
HPC	Collect sample in sterilized nonreactive borosilicate glass or plastic bottles, add 0.1mL of a 3% solution of sodium thiosulfate in a 120mL bottle, refrigerate at 4°C	8 hrs
TOC	Collect sample in glass bottle, add hydrochloric acid, refrigerate at 4°C	28 days
TTHM	Collect sample in a glass vial, add 25mg of sodium thiosulfate for every 40mL of sample, be sure no air bubbles are present, refrigerate at 4°C	14 days

For the beginning of the pilot study HBEL was used to conduct analysis. Halfway through the study quality control became a concern which is when Flowers was contracted to conduct the remainder of the pilot study lab analysis. MWH performed the AOC analysis throughout the study until they were bought out by Eurofins who analyzed the last AOC sampling set. Both HBEL and MWH conducted bromate analysis. HBEL's bromate analysis was used to verify that concentrations were not exceeding the 10 µg/L MCL. MWH's bromate analysis was used to get a more realistic idea of the actual bromate concentrations being produced.

Field and Laboratory Quality Control

Field and laboratory quality control measures were implemented as needed throughout the course of this study. Duplicate field measurements were taken for pH, temperature, conductivity, turbidity, total sulfide, UV-254, and chlorine residual. The three labs performed quality control procedures in accordance with EPA protocol and the *Standard Methods for the Examination of Water & Wastewater* (Eaton, Clesceri, Rice, & Greenberg, 2005). Each laboratory was required to have a Laboratory Quality Assurance Plan, which requires the QC be performed for the specific method being used (USEPA, 2005).

In order to become certified to analyze a particular analyte, each lab is required to perform different types of analysis (USEPA, 2005). Proficiency testing (PT) samples are required at least once every 12 months for each analyte. Results from the PT testing must be within acceptable limits listed in the "MCL and Proficiency Testing Sample Acceptance Criteria in the CFR, Primary and Secondary Drinking Water Regulations." Quality control samples are analyzed

according to the particular method being used. Daily calibration curves for target analytes should be generated with at least three points that include the sample concentration range. If performing a daily calibration curve is impractical, then a calibration check should be performed by analyzing at least one standard for each of the target analytes at the expected concentration range. A laboratory blank should be carried through the full analysis with every batch of samples. Blanks should not exceed the lab's MRL. Laboratory fortified blanks (LFBs) should be analyzed for a known quantity of analytes to a percentage of the routine samples in order to develop a LFB matrix. LFB control charts for accuracy and precision should be generated from the mean percent recovery and the standard deviation of the percent recovery. Equations 4-1 and 4-2 are used to establish upper and lower control limits.

$$\text{upper control limit} = \bar{x} + 3S \text{ (upper warning limit} + 2S) \quad (4-1)$$

$$\text{lower control limit} = \bar{x} - 3S \text{ (lower warning limit} - 2S) \quad (4-2)$$

Each lab is also required to perform an initial demonstration of capability (IDC) which includes a demonstration of the ability to achieve a low background, the precision and accuracy required by the method, and determination of the MDL (USEPA, 2005). Quantitation of multicomponent organic analytes is required due to the complex nature of chromatography, sample weathering, degradation and interferences that may be present in samples. Quantitation involves analyzing sampling pattern peaks and comparing them to the standard. Equation 4-3 should be used to calculate the MDL for each analyte initially and when any changes are made.

$$MDL = t \times S \quad (4-3)$$

Where: t = student's value for a 99% confidence level and a standard deviation estimate with $n-1$ degrees of freedom

S = standard deviation of the replicates analyzed

Minimum reporting limits (MRLs) are required to be reported to clients along with data (USEPA, 2005). Laboratories should run a LFB at their MRL every day. If the method requires it, percent recovery should also be calculated for analytes using Equation 4-4.

$$R = \frac{C_s - C}{s} \times 100 \quad (4-4)$$

Where: R = percent recovery

C_s = fortified sample concentration

C = sample background concentration

s = concentration equivalent of analyte added to sample

Different percent recovery ranges are required for different methods. The laboratory is required to be within a specific percent recovery for each analyte. If the lab falls out of this range the sample must be resampled and the labs QAQC methods may need to be revisited.

5. RESULTS AND DISCUSSIONS

This chapter will present the findings of the study and discuss the data collected throughout the course of the pilot study. Data will be presented and compared from both the Main and Aux Plants. Since both plants contain different raw water quality varying results were observed at each plant even though the same treatment process was tested. Results were also compared to current plant finished water quality and the original GAC Pilot Study results performed by Reiss Engineering (2011).

Auxiliary Plant Pilot Performance

The ozone and GAC pilot study was conducted at the Aux Plant for 35 weeks (September 14, 2011 – May 10, 2012). The utilization factor for the ozone and GAC pilots were 99% and 98%, respectively. The average daily field results collected throughout the course of the study are shown in Table 5-1.

Table 5-1: Aux Plant Pilot Average Field Results

Sampling Point	pH	Temp (°C)	DO (mg/L)	Turbidity (NTU)
Raw	7.49	24.0	1.95	2.15
Ozone	7.35	24.2	15.70	1.47
Ozone Pipe	7.37	24.2	16.43	1.70
Ozone Tank	7.36	24.2	16.44	1.23
GAC 1 (Virgin)	7.25	26.3	14.91	1.70
GAC 2 (Virgin)	7.25	26.3	13.60	1.92
GAC 3 (Regenerated)	7.27	26.4	15.39	2.59
GAC 4 (Regenerated)	7.28	26.3	13.49	2.12

Temperature increased on average by 2°C throughout the treatment process while pH gradually declined by about 3%. Turbidity was fairly consistent throughout the course of the study. Turbidity spikes were typically seen directly before and after backwashing the GAC columns. When running the GAC columns in biological mode turbidities up to 8 NTU were observed when biological sloughing was occurring. Using ozone did increase DO levels in the finished water to an average of 16 mg/L. DO was reduced by 17% after the water was filtered through the GAC columns. Producing finished water with significantly different water quality characteristics such as higher DO concentrations could cause problems in an old distribution system such as Sanford's.

Equipment Settings and Maintenance

The ozone and GAC units had to be closely monitored throughout the course of the study in order to determine optimal settings and usage for both units. The ozone feed percentage was changed once a week for the first four weeks of the study to determine the desired ozone residual used to decrease DBP precursors. The GAC columns pressures and flow rates were monitored to determine the EBCT and when backwashing was necessary.

Ozone

An ozone demand study was performed by the ozone pilot equipment manufacturer (Guardian Manufacturing, 2750 Dillard Road Suite 12, Eustis, FL 32726) to determine the actual ozone dosage at different ozone feed percentages for the City's groundwater. The ozone demand study was performed by measuring the ozone residual produced at different ozone feed percentages.

The ozone dose is based on the actual ozone output of the generator, the mass transfer efficiency, and the flow rate of the water stream being treated. The ozone demand study results are shown in Table 5-2.

Table 5-2: Ozone Demand Study

% Output	O₃ Gas Conc. (g/NM³)	Oxygen Flow (mL/min)	Gas Flow (Nm³/hr)	Gas to Liquid Ratio	O₃ Mass Rate (g/hour)	O₃ MTE (%)	Applied O₃ Dose (mg/L)	HACH O₃ Conc. (mg/L)
40%	99.5	2.05	0.136	0.085	13.5	95%	7.83	0.00
44%	104	2.05	0.135	0.085	14.1	95%	8.16	0.05
46%	106	2.05	0.135	0.085	14.4	95%	8.35	0.15
48%	108	2.05	0.135	0.085	14.6	95%	8.51	0.28
50%	110	2.05	0.135	0.085	14.8	95%	8.62	0.31
50%	110	2.05	0.135	0.085	14.9	95%	8.66	0.36
60%	119	2.05	0.135	0.085	16.1	95%	9.32	0.76

Through preliminary ozone testing it was determined that running the unit at 30% ozone feed did not completely remove sulfide from the water. Using 40% ozone feed would remove sulfide and some UV-254. Increasing the ozone feed percentage increases the ozone residual present in the ozonated water. The relationship between ozone residual and UV-254 is shown in Figure 5-1.

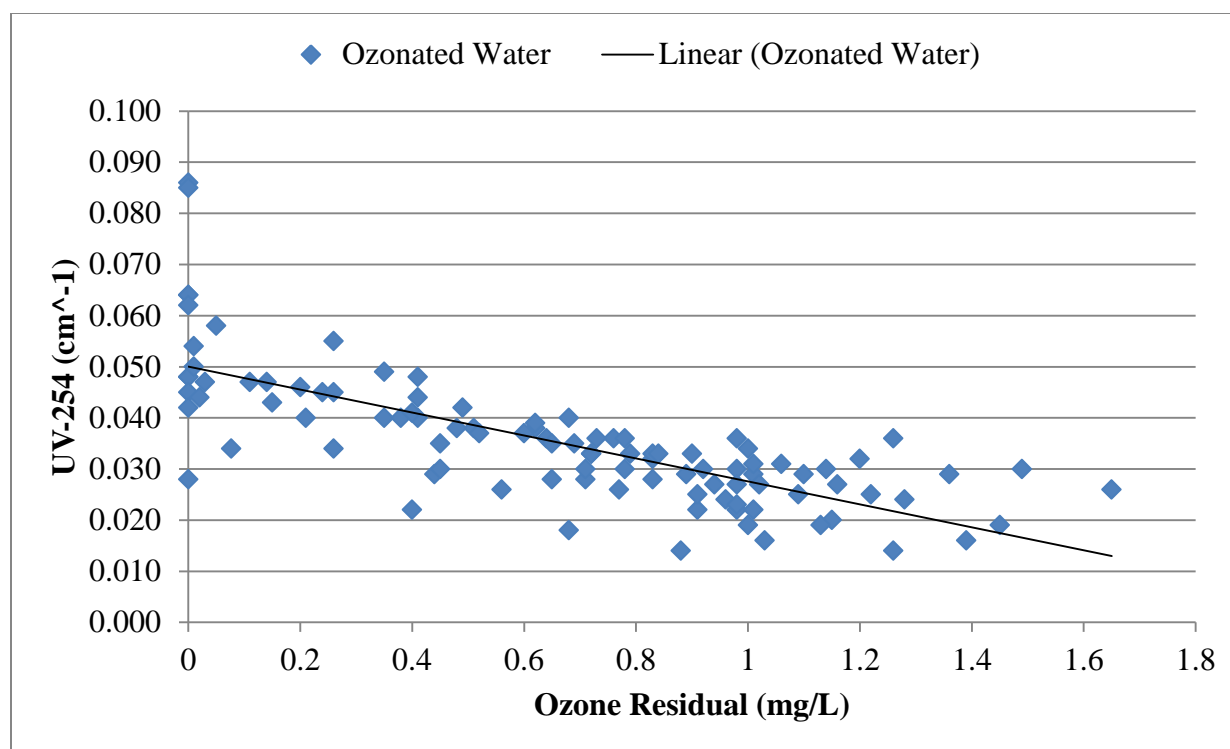


Figure 5-1: Ozone Residual Compared to UV-254 for Aux Plant Pilot

As the ozone residual increased from 0 to 1.0 mg/L, the UV-254 concentration decreased from about 0.050 to 0.020 cm⁻¹. This relationship shows that ozone can help to remove DBP precursors particularly when higher residuals are present. Using 60% ozone feed removed a large concentration of organics; however, producing ozone at this rate would increase capital and O&M costs. Using the applied ozone dose associated with 60% ozone feed may also require additional contact time (more than 5 minutes) in order to allow ozone residual depletion before entering the GAC columns. The ozone unit was run at 40% ozone feed for the first half of the study and 50% for the second half. According to Table 5-2, an ozone dosage of 7.83 and 8.62 mg/L is required for running the unit at 40% and 50%, respectively. Running the ozone unit between 40-50% would allow for the removal of sulfides and a percentage of UV-254.

GAC

The GAC columns were monitored daily for pressure and flow data. Pressure data for each of the four columns recorded throughout the course of the pilot study is shown on Figure 5-2. GAC 1 and 3 should both be experiencing rising pressure due to clogging and air binding that commonly occurs in the first column of a train. However, only GAC 3 experienced increased pressures throughout the course of the study. It is normal for GAC 2 and 4 to not experience significant pressure increases since they are the second columns running in series for Trains 1 and 2 respectively.

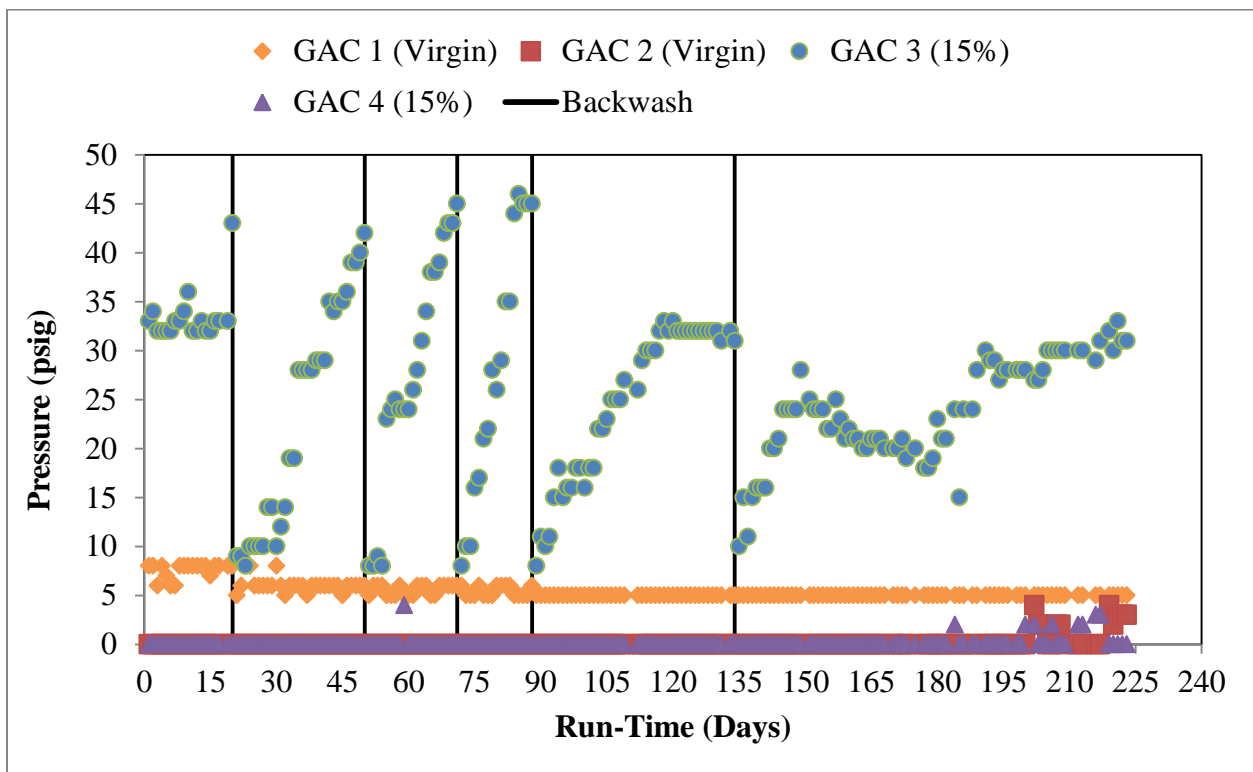


Figure 5-2: Pressure of GAC Columns for the Duration of the Aux Plant Pilot

The GAC pilot column manufacturer suggested performing a backwash on a column when the pressure rose above 40 psig (Calgon Carbon Corporation, 2011). Per this suggestion Column 3 was backwashed for the first time on October 10, 2011. After backwashing the column according to procedures outlined in the Pilot Column Operations Manual, it was noted that pressure did not decrease as it should of. Subsequently, GAC 1, 2, and 4 were backwashed, which decreased the pressure in GAC 3. For the remainder of the study, the four columns were backwashed whenever the pressure in GAC 3 reached 40 psig. The columns were backwashed 5 times over the course of the study on Week 5 (October 10, 2011), Week 10 (November 18, 2011), Week 13 (December 12, 2011), Week 16 (December 26, 2011), and Week 22 (February 10, 2012). Backwashing was frequently needed while the GAC was transitioning to BAC. After Week 16, backwashing was performed less frequently and pressures stabilized which could mean backwashing is needed less frequently for BAC.

The designed EBCT for each of the columns was 7 minutes each resulting in an EBCT of 14 minutes for each train. The actual EBCT was then calculated using the average flow rate, the media height, and the column diameter. The actual EBCTs for each of the columns and trains are show in Table 5-3. The actual EBCTs were about a minute and a half less than the criteria established in the design. The full-scale GAC process should be designed for EBCTs similar to the ones produced during this study. The bed volumes were calculated using the EBCT and the number of weeks each stage was in operation. The treatment bed volume is a dimensionless number representing the volume of the GAC column that is occupied by GAC media. The bed volumes used during the GAC, transitional, and BAC stages are shown in Table 5-4.

Table 5-3: Actual EBCTs for Aux Plant Pilot GAC Columns

Column	Media Height (ft)	Column Diameter (ft)	Volume (gal)	Average Flow Rate (gpm)	EBCT (min)
GAC 1	3.33	0.33	2.18	0.38	5.69
GAC 2	3.17	0.33	2.07	0.37	5.52
Train 1: GAC 1 & 2 in Series					11.2
GAC 3	3.29	0.33	2.15	0.40	5.39
GAC 4	3.25	0.33	2.12	0.37	5.81
Train 2: GAC 3 & 4 in Series					11.2

Table 5-4: Bed Volumes for Aux Plant GAC Pilot

Column	GAC Stage (Weeks 1-6)	Transitional Stage (Weeks 6-13)	BAC Stage (Weeks 13-35)	Total (Weeks 1-35)
GAC 1	10600	12400	39000	62100
GAC 2	11000	12800	40200	64000
GAC 1 & 2 in Series	5400	6300	19800	31500
GAC 3	11200	13100	41200	65500
GAC 4	10400	12100	38200	60700
GAC 3 & 4 in Series	5400	6300	19800	31500

DBP Precursors Removal

TOC was measured when formation potential was performed in an attempt to develop a correlation between the concentrations of TOC and TTHMs formed. A correlation between TOC concentrations and TTHM formation was not determined in this study since most of the TOC concentrations were below the laboratory MDL of 1.0 mg/L. At the beginning of the study, it was assumed that 90% of the TOC was DOC which was later shown to not be the case. A DOC correlation between TTHM formation and DOC was also not determined in this study since the

DOC concentrations were below the laboratory MDL of 1.0 mg/L. TOC and UV-254 concentrations were compared on Figure 5-3.

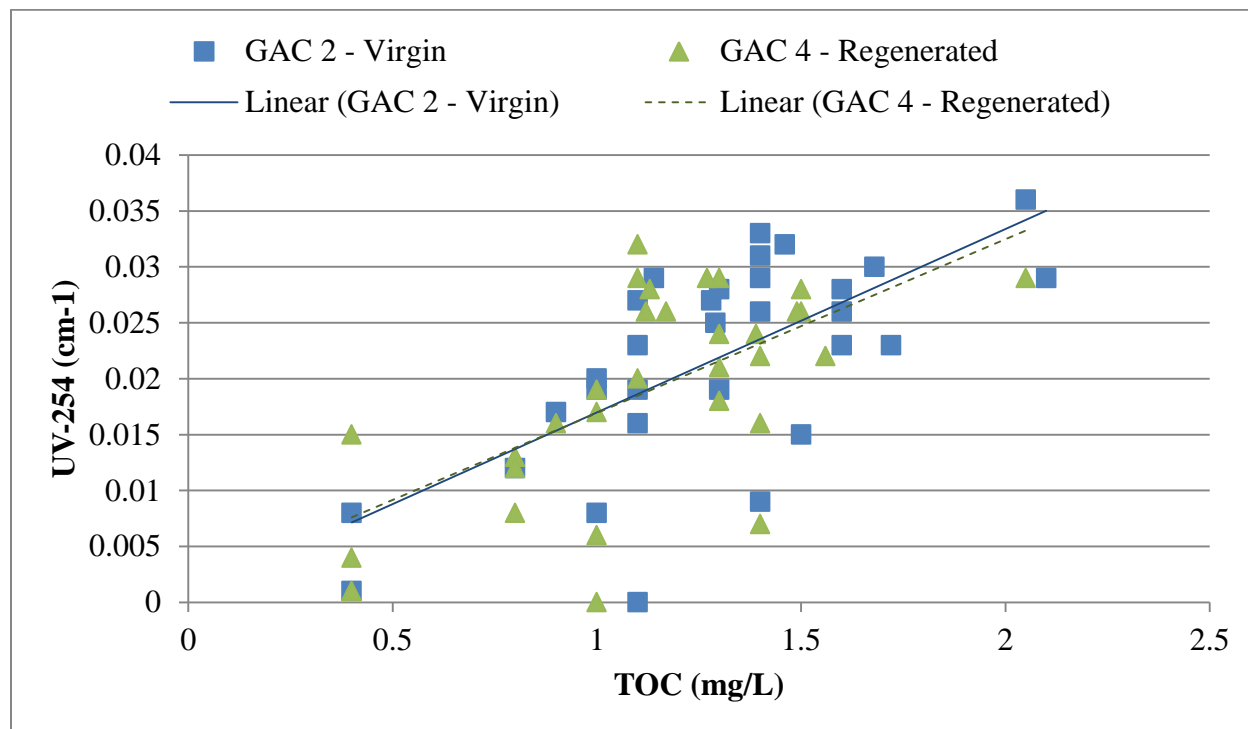


Figure 5-3: Aux Plant Pilot UV-254 Compared to TOC Results

A linear correlation between TOC and UV-254 was observed during the GAC stage of the study. TOC concentrations ranging from 1.0 to 1.5 mg/L resulted in UV-254 concentrations ranging from 0.015 to 0.030 cm^{-1} . DBP precursor patterns were overall more difficult to decipher and compare to DBP formation potential during the BAC stage of the study. The average TOC, DOC, and UV-254 concentrations collected throughout the study are shown in Table 5-5.

Table 5-5: TOC, DOC, and UV-254 Results for Aux Plant Pilot

Location	TOC (mg/L)	DOC (mg/L)	UV-254 (cm ⁻¹)	Percent Removal of UV-254 (%)
Raw	2.0	1.2	0.087	-
Ozone Tank	2.0	1.0U	0.035	59.3
GAC 2 (Virgin)	1.3	1.0U	0.021	75.7
GAC 4 (Regenerated)	1.3	1.0U	0.019	78.2

As expected, UV-254 removal improved throughout the treatment process. The ozone tank does not show a change in the concentration of TOC but does reduce UV-254. Ozonation shows an average reduction in UV-254 absorbing constituents by 59%. The columns containing virgin media removed slightly less UV-254 than the regenerated columns. The UV-254 concentrations for the raw water, ozone tank, and each of the four GAC columns are shown on Figure 5-4.

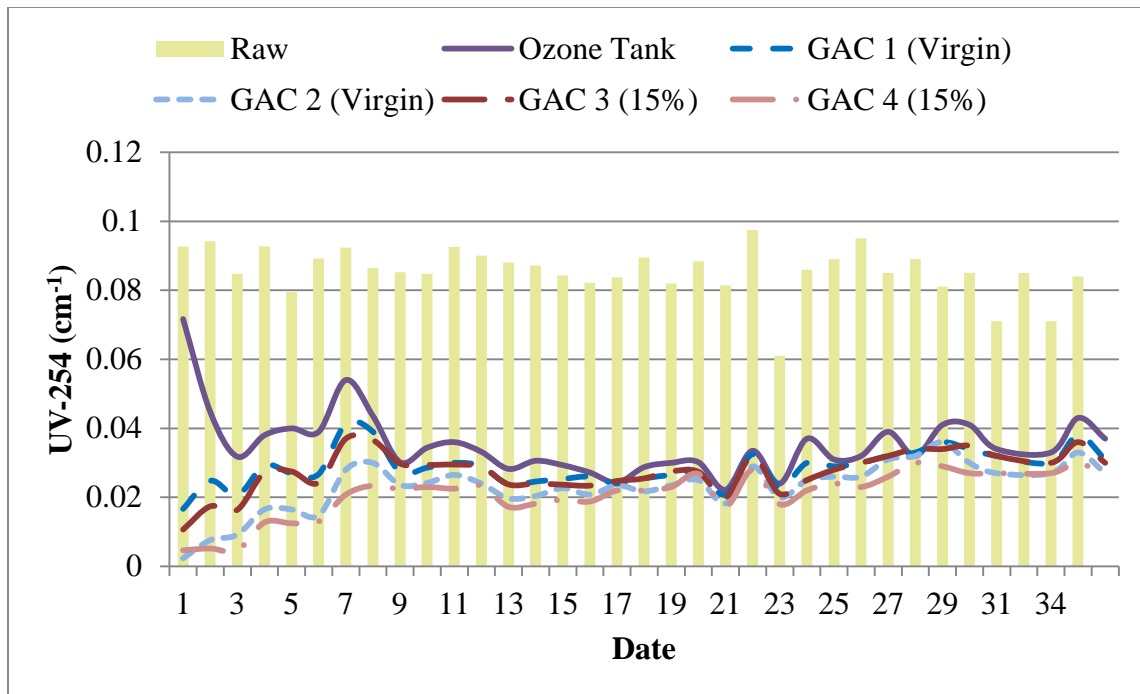


Figure 5-4: Aux Plant Pilot Daily UV-254 Results

The UV-254 concentration in the raw water fluctuated throughout the study due to varying water quality within the wellfield that supplies water to the Aux Plant. Ozone tank UV-254 concentrations changed depending on the ozone feed percentage and ozone residual produced by the pilot unit. As seen on Figure 5-4, the columns with the shorter EBCTs (GAC 1 and 3) consistently removed less UV-254 than the columns with the longer EBCTs (GAC 2 and 4). Over the course of the study, UV-254 gradually trended upward until about Week 11 (November 1-8) when it decreased slightly. UV-254 remained fairly stable between Weeks 12-25 (November 10 – March 1) and then trended upward slightly until the end of the study. The decline and stabilizing of results occurred in the transitional and BAC stages, respectively. The average percent removal of UV-254 for the GAC, transitional, and BAC are shown in Table 5-6. Running the columns using GAC adsorption does remove a greater percentage of UV-254 than running the unit as a biological treatment process. BAC removes at least 68% of the UV-254.

Table 5-6: Percent Removal of UV-254 for Aux Plant GAC Stages

Stage	GAC 1	GAC 2	GAC 3	GAC 4
GAC	74.6	88.8	78.5	91.7
Transitional	64.2	72.2	65.2	75.9
BAC	68.5	72.3	69.2	74.0

Even though bromide is not an organic compound it can still be considered a DBP precursor since its presence leads to the formation of bromate particularly after water has been ozonated (Rakness, 2005). The average bromide concentrations found throughout the pilot treatment process at the Aux Plant are shown in Table 5-7. The Aux Plant's water contains moderate bromide concentrations since bromides are considered to be high if the concentration exceeds 0.20 mg/L (Bond, Goslan, Parsons, & Jefferson, 2011).

Table 5-7: Aux Plant Pilot Bromide Results

Date	Raw (mg/L)	Ozone Tank (mg/L)	GAC 2 (mg/L)	GAC 4 (mg/L)
10/20/2011	0.14	0.11	0.12	0.12
10/21/2011	0.18	0.17	0.16	0.18
10/24/2011	0.14	0.12	0.12	0.13

DBP Formation Potential

Twenty six DBP formation potentials were performed over the course of this pilot study. The average chlorine dosages and residuals used when performing formation potential are shown in Table 5-8.

Table 5-8: Aux Plant Disinfectant and DBP Formation Potential Comparison

Location	Cl₂ Dose (mg/L)	Initial Cl₂ Residual (mg/L)	% Cl₂ Demand	120 hr Cl₂ Residual (mg/L)	% Cl₂ Reduction at 120 hr	TTHMs at 120 hr (µg/L)	HAA₅ at 120 hr (µg/L)
Current Aux Plant	12.0	2.0	83.3	0.0	100.0	98.0	27.0
Ozone	5.4	2.2	59.3	0.0	100.0	98.0	30.0
GAC 2 (Virgin)	3.3	1.9	43.1	0.6	69.2	67.2	14.1
GAC 4 (Regenerated)	3.4	1.9	43.9	0.8	59.3	60.6	11.2

The ozone and GAC treatment process would considerably lower the chlorine dosage required to develop and maintain a chlorine residual for the City's distribution system. Currently the Aux Plant is dosed with 12mg/L of chlorine product to produce a chlorine residual of 2.0 mg/L which is completely diminished before 120 hours. Using the combination of ozone and GAC lowers

the chlorine dose by 72% while providing the same initial chlorine residual and a 0.6 mg/L residual after 120 hours. Ozone alone will reduce the chlorine dosage but not the DBPs.

HAA₅ produced from the Aux Plant was significantly below the MCL of 60 µg/L within the City. However, HAA₅ was still evaluated in this study to determine if the advanced treatment process would not adversely impact exiting HAA₅ levels. The results of the HAA₅ formation potential for the ozone, GAC Virgin (GAC 2), and GAC 15% Regenerated (GAC 4) are shown in Figure 5-5.

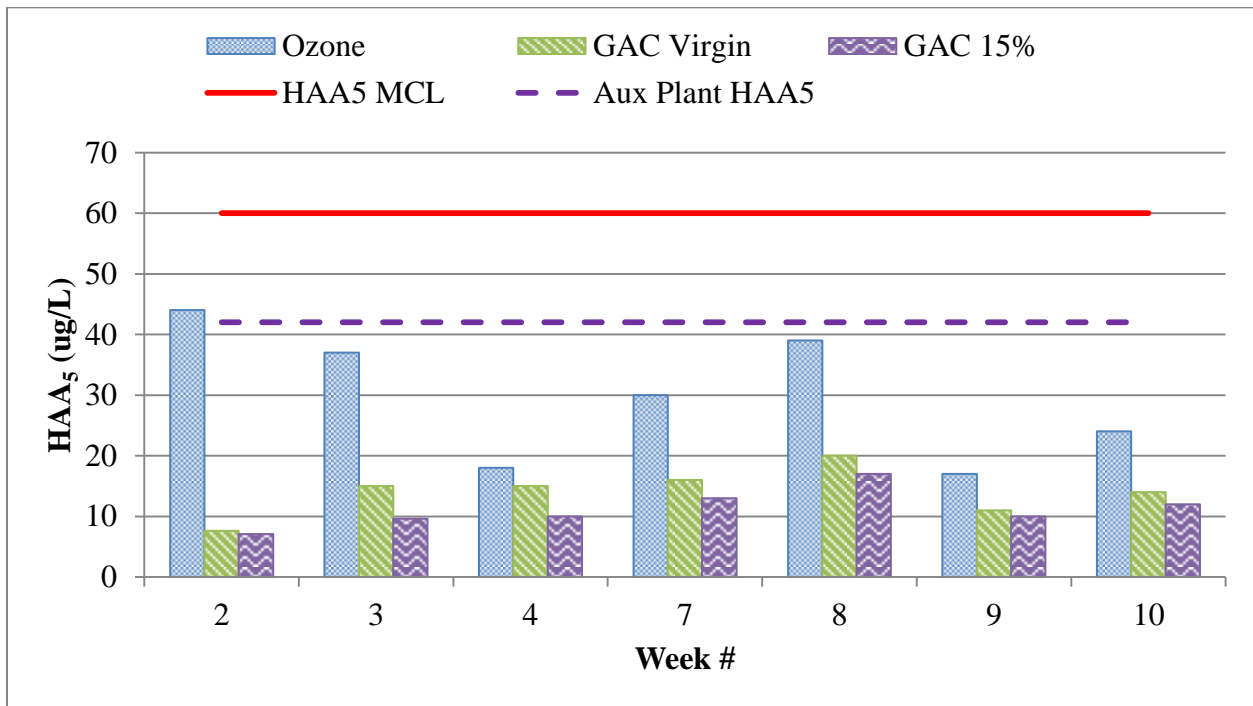


Figure 5-5: Aux Plant Pilot HAA₅ Results from 120 hr Formation Potential

HAA₅ concentrations were significantly below the MCL at 120 hrs after both the ozone and GAC treatment processes as was expected. HAA₅ were no longer performed after Week 10 in order to devote more funds toward performing TTHM formation potential. TTHM formation potential was performed on 26 out of the 35 weeks of the pilot study. The TTHM concentrations for 120 hour contact time were performed after GAC 2 and 4 and are shown in Figure 5-6.

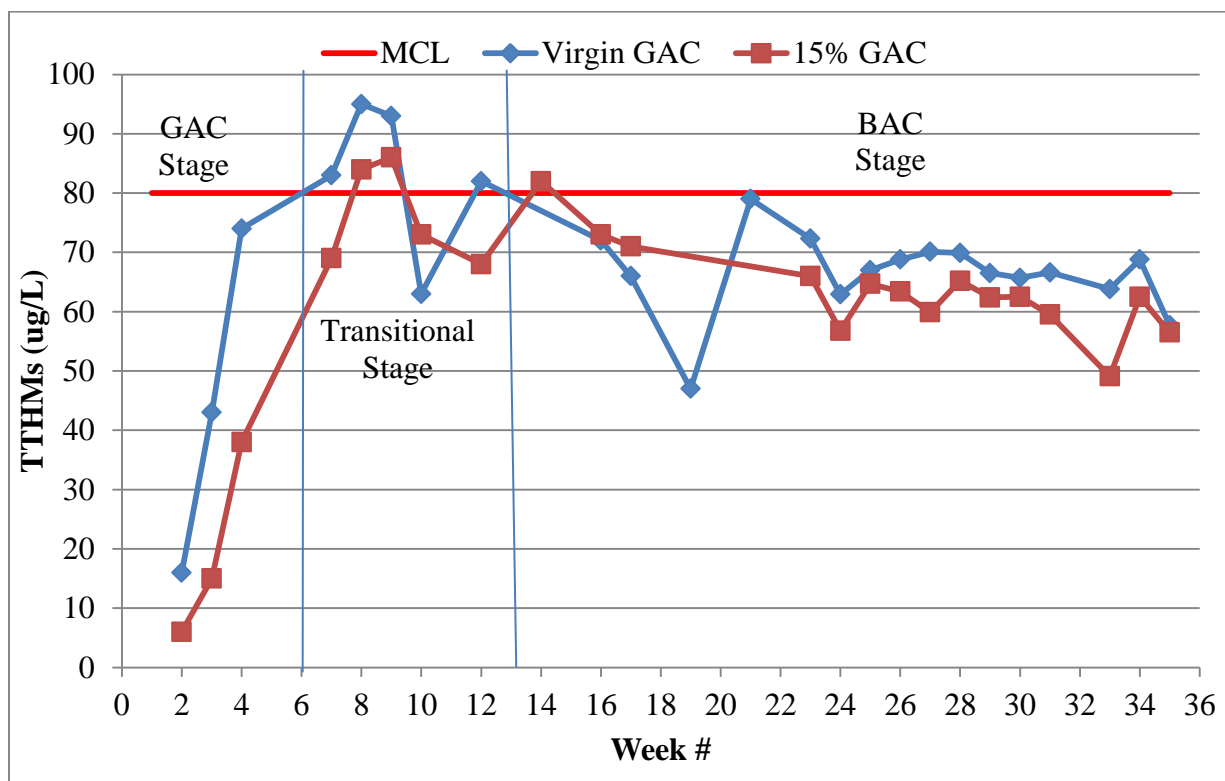


Figure 5-6: Aux Plant Pilot TTHM Results for 120 hr Formation Potential

When UV-254 concentrations peaked the virgin and regenerated GAC trains were exhausted which happened between Week 7 and 8 as shown on Figure 5-4. TTHM concentrations also peaked between Weeks 7 and 8 as shown on Figure 5-6. TTHM concentrations then fluctuated between Weeks 6-13 which is considered the transitional phase. During the transitional phase,

the microorganisms were adjusting to the environment. TTHMs then decreased and stabilized around 70 and 65 µg/L for the virgin and regenerated columns, respectively. Once the UV-254 concentration stabilized the TTHM concentrations also stabilized suggesting the GAC had become fully converted to a biological treatment process once stabilization occurred. It was not determined during this study when exhaustion of the BAC would occur since the pilot ended after 35 weeks due to time restraints.

Another DBP that was examined before deeming ozone, GAC, and BAC an effective treatment process for the City of Sanford was bromate. The MCL for bromate is 0.010 mg/L. The bromate results for different ozone feed percentages and residuals are shown in Table 5-9.

Table 5-9: Aux Plant Pilot Bromate Results

Ozone Feed (%)	Ozone Residual (mg/L)	Bromate (mg/L)
0	0.00	<0.007
40	0.03	<0.007
40	0.05	<0.007
40	0.72	0.005
40	1.00	<0.007
50	1.01	<0.007
50	1.10	0.009

Bromate concentrations were consistently less than 0.007 mg/L as long as the ozone residual was less than 1 mg/L. Since HBEL Laboratories used a method that could not detect bromate concentrations below 0.007 mg/L, two sample sets were sent to MWH Laboratories who used a method with a detection limit of 0.001 mg/L. One sample was produced using an ozone feed

percentage of 40% and the other with 50%. The 40% ozone feed sample had an ozone residual of 0.72 mg/L and a bromate concentration of 0.005 mg/L. The 50% ozone feed sample had an ozone residual of 1.1 mg/L and a bromate concentration of 0.009 mg/L. It appears that as long as an ozone residual less than 1.0 mg/L is used, the City should not exceed the bromate MCL based on the conditions experienced in this study.

AOC

AOC sampling sets were collected six times throughout the course of the pilot study for the raw water, ozone tank, and for GAC 2 and 4. The AOC results are shown in Table 5-10.

Table 5-10: Aux Plant Pilot AOC Results

Date	Raw (µg/L)	Ozone Tank (µg/L)	GAC 2 (µg/L)	Percent Reduction for GAC 2 (%)	GAC 4 (µg/L)	Percent Reduction for GAC 4 (%)
9/21/2011	260	460	280	39.1	320	30.4
9/29/2011	170	410	130	68.3	110	73.2
10/31/2011	180	310	89	71.3	140	54.8
11/28/2011	180	440	210	52.3	210	52.3
1/19/2012	160	460	180	60.9	230	50.0
5/10/2012	240	330	<10	97.0	<10	97.0

During each of the six sampling sets ozone significantly increased the concentration of AOC from the raw water. The GAC columns did reduce the AOC to about the concentration seen in the raw water. However, at AOC concentrations over 100 µg/L, biological regrowth within the distribution system can still occur (USEPA, 1999). The last sampling set, when the unit was in

biological mode, showed AOC concentrations were reduced by 97% proving that BAC can effectively remove 300 µg/L of AOC. The high concentrations of AOC being fed into the GAC columns by the ozone may have helped the GAC convert to BAC by providing food for the microorganisms and converting the organic precursors to a form that was more readily reduced by the BAC.

Flavor Profile

The results of four flavor profiles performed throughout the course of the study are shown in Table 5-11. Participants conducted olfactory tests and rated five different types of water: raw, ozone, GAC virgin, GAC recharge, and tap water. Most participants considered the raw water to have a strong odor which was due to the high hydrogen sulfide concentrations present in the raw water. Tap water ratings ranged from weak to moderate. It was unanimous that there was significant improvement in the pilot finished water scent compared to the current tap water scent. Many of the participants found the pilot water to be odor-free (-).

Table 5-11: Aux Plant Pilot Flavor Profile Analysis

Date	Number of Participants	Raw Water	Ozone	GAC Virgin	GAC Recharge	Tap Water
10/26/2011	5	12	-	-	-	8
11/2/2011	5	12	-	-	-	4
12/14/2011	4	12	2	T	T	8
5/9/2012	8	10	-	-	-	2

Blending Study

A blending study was performed between the pilot water and the Main Plant water. This blending study was conducted in order to see if adding treatment at the Aux Plant would be sufficient enough to lower TTHM concentrations throughout the mixed distribution system. The formation potential was performed on Week 25 of the pilot study which was considered to be part of the BAC stage. Since the BAC stage will be the longest stage; performing the blending study within this time frame gave a more realistic result as to the TTHM concentrations that will be seen at 120 hours within the distribution system. Formation potential was performed on the current Aux and Main Plant treated water for comparison purposes. The main plant water and pilot water were blended for both the virgin and regenerated columns. Blending included 25% and 50% pilot water with Main Plant water; the Aux Plant is not large enough to produce more than 50% of the systems water.

Figure 5-7 shows that the TTHM results were similar between the Main Plant Current Treatment, the pilot treatment, and the mixed water. However, the chlorine demand for each water type did show differences. A higher chlorine dosage may be necessary to keep at least a 0.2 mg/L chlorine residual within the City's distribution system which could result in higher TTHM formation than were present during the mixing study. TTHM results were about 70 µg/L for the blended water at 120 hrs which is under the MCL of 80 µg/L. It may be necessary to increase treatment at the Main Plant in order to lower TTHMs to a lower level if this treatment process is used.

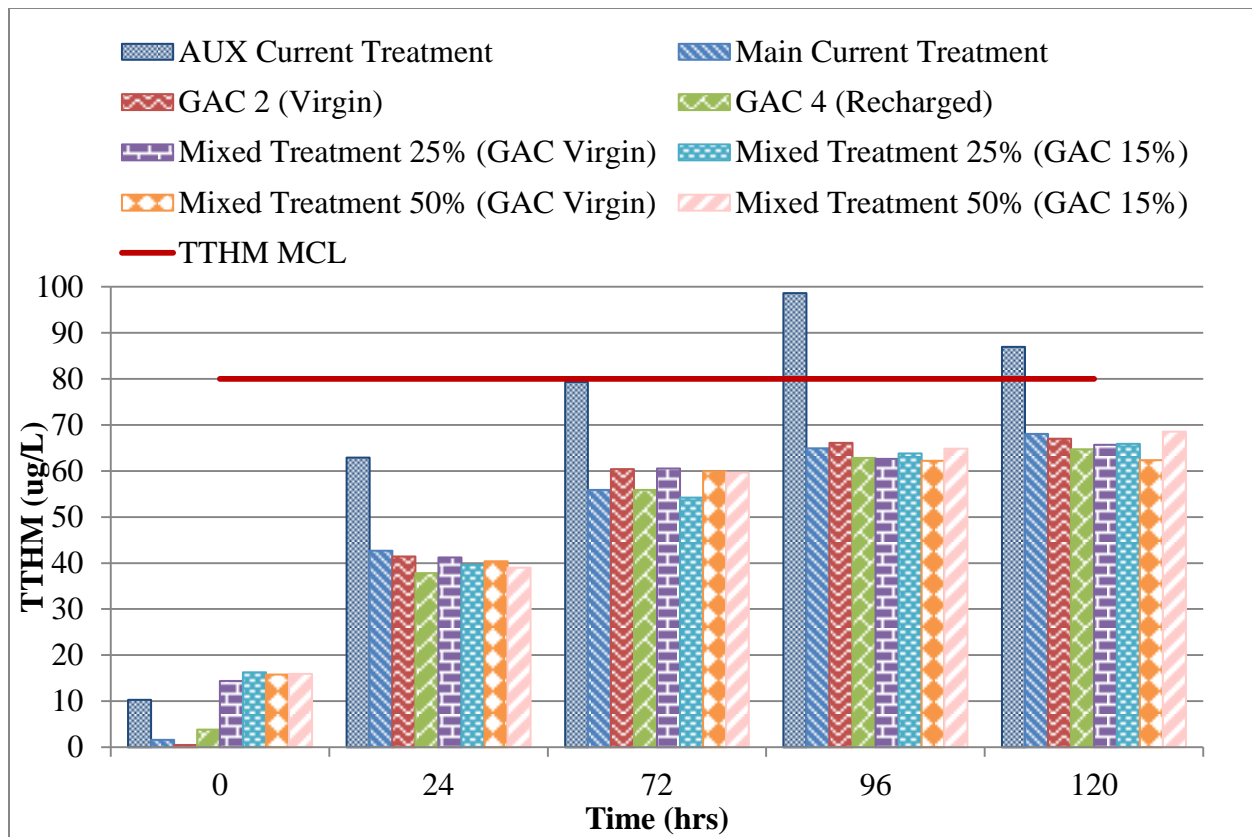


Figure 5-7: TTHM Formation Potential Results for Aux Plant Pilot Blending Study

Main Plant Pilot Performance

The ozone and GAC pilot was conducted at the Main Plant for 30 weeks (July 9, 2012 – January 28, 2013). The utilization factor for the ozone and GAC pilots were 85% and 98%, respectively. Extensive testing was not performed on the Main Plant Pilot since the raw water quality is considered better than the Aux Plant’s. The average daily field results collected during the duration of the study are shown in Table 5-12.

Table 5-12: Main Plant Pilot Average Field Results

Sampling Point	pH	Temp (°C)	Conductivity (µS/cm)	DO (mg/L)	Turbidity (NTU)
Raw	7.39	24.1	473	2.79	1.59
Ozone	7.44	24.3	449	14.0	1.76
Ozone Pipe	7.45	24.4	447	14.6	1.68
Ozone Tank	7.47	24.4	447	14.3	1.46
GAC 1 (Virgin)	7.40	25.9	448	12.6	0.52
GAC 2 (Virgin)	7.56	26.2	446	10.2	0.05
GAC 3 (Regenerated)	7.43	26.2	447	13.0	0.35
GAC 4 (Regenerated)	7.63	26.2	448	9.77	0.03

Temperature and pH increased less than 10% throughout the treatment process. Conductivity was lowered 5% through ozonation but remained fairly stable through the GAC columns. Turbidity increased by about 10% after ozonation but was removed through the GAC filtration process. Turbidity spikes up to 8 NTU were common in the GAC finished water directly before and after backwashing and when biological sloughing was occurring. DO concentrations after ozonation ranged from 10 – 20 mg/L which was reduced by 10 to 30% after the GAC columns.

Equipment Settings and Maintenance

The same pilot equipment and setup was used for the Main Plant Pilot that was used for the Aux Plant Pilot. Ozone settings were determined at the beginning of the study and adjusted if ozone residuals were produced greater than 1.0 mg/L. The GAC was also monitored daily for pressure and flow to determine EBCT and when backwashing was necessary.

Ozone

An ozone demand study was not performed at the Main Plant since the source water at both plants is groundwater from the Upper Floridan Aquifer. However, ozone unit settings still needed to be determined through preliminary testing due to differing contaminant concentrations.

The preliminary ozone results are shown in Table 5-13.

Table 5-13: Main Plant Pilot Ozone Settings

Ozone Feed (%)	Ozone Residual (mg/L)	pH	Temp. (°C)	Turbidity (NTU)	Ozone Sulfide (mg/L)	UV-254 (cm⁻¹)	Conductivity (µS/cm)	DO (mg/L)
0	0	7.45	25.6	1.2	0.28	0.046	439	3.07
5	0	7.34	25.5	1.6	0	0.044	430	15.3
10	0.38	7.29	25.8	1.1	0	0.033	432	15.1
13	0.5	7.4	24.8	1.5	0	0.035	470	15.3
15	0.6	7.35	25.4	1.6	0	0.025	433	16.0
20	0.87	7.36	25.5	1.5	0	0.024	435	15.4
22	1.01	7.37	25.6	1.6	0	0.026	469	16.1

Preliminary ozone testing was conducted while running the wells with the highest concentrations of TOC and sulfide. Running 5% ozone feed removed sulfide but did not provide an ozone residual necessary for the removal of UV-254. A 10% ozone feed was found to remove hydrogen sulfide while removing some UV-254. During the first week of the study, it was noticed that an ozone residual greater than 1.0 mg/L was produced while using 10% ozone feed. At 10% ozone feed the applied ozone dose was 2.0 mg/L. Consistently running at high ozone residuals would be costly and inefficient. The wells with lower sulfide and TOC concentrations do not require this high of an ozone dosage. Since the wells with the better water quality are run more frequently at the Main Plant the ozone feed percentage was set between 4-5% for the

remainder of the study. A full-scale ozone unit at the Main Plant would need to be designed to account for the wells that require 10% ozone feed.

GAC

When the GAC pilot unit was being utilized at the Main Plant the same pressure problem occurred as it did when it was at the Aux Plant. When the pressure in GAC 3 rose above 40 psig, each of the four columns were backwashed in order to decrease the pressure in GAC 3. The daily pressure recordings for each of the four columns are shown in Figure 5-8.

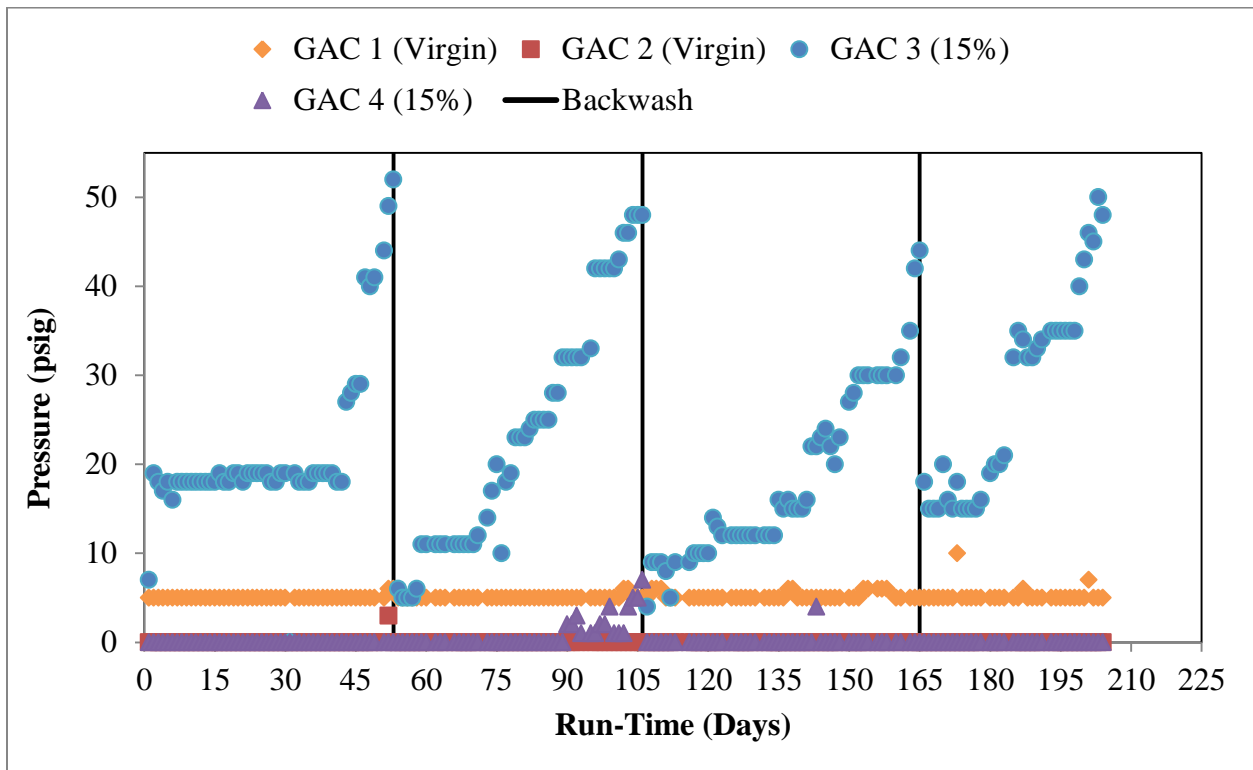


Figure 5-8: Pressure of GAC Columns for the Duration of the Main Plant Pilot

The columns were backwashed 3 times over the course of the study on Week 8 (August 30, 2012), Week 16 (October 22, 2012), and Week 24 (December 20, 2012). A half backwash was performed on Week 24 due to time constraints, explaining the higher pressure at the end of the backwash. Another backwash was necessary on Week 28, but wasn't performed since the pilot operation was coming to an end. If a full backwash was performed on Week 24, a backwash may not have been necessary on Week 28. The designed EBCT for each of the columns was the same as it was for the Aux Plant Pilot; 7 minutes for each of the columns and 14 minutes for each train. Table 5-14 shows the actual EBCTs for the Main Plant Pilot GAC columns.

Table 5-14: Actual EBCT for Main Plant Pilot GAC Columns

Column	Media Height (ft)	Column Diameter (ft)	Volume (gal)	Average Flow Rate (gpm)	EBCT (min)
GAC 1	3.00	0.33	1.96	0.38	5.11
GAC 2	3.08	0.33	2.01	0.38	5.27
GAC 1 & 2 in Series					10.4
GAC 3	3.17	0.33	2.07	0.37	5.61
GAC 4	3.17	0.33	2.07	0.36	5.70
GAC 3 & 4 in Series					11.3

The actual EBCTs were about a minute and a half less than the criteria established in the design. GAC 1 and GAC 3 were examined throughout the study to determine if a shorter EBCT was sufficient enough to remove UV-254. Using a shorter EBCT would result in fewer columns being needed for treatment at the Main Plant. The bed volumes used throughout the course of the study were calculated and are presented in Table 5-15.

Table 5-15: Bed Volumes for Main Plant GAC Pilot

Column	GAC Stage (Weeks 1-11)	Transitional Stage (Weeks 11-13)	BAC Stage (Weeks 13-30)	Total (Weeks 1-30)
GAC 1	21700	3940	33500	59200
GAC 2	21000	3830	32500	57400
GAC 1 & 2 in Series	10700	1940	16500	29100
GAC 3	19800	3590	30500	53900
GAC 4	19400	3540	30100	53000
GAC 3 & 4 in Series	9800	1780	15100	26700

DBP Precursors Removal

Three sets of TOC and DOC samples were analyzed during the beginning of the study. Table 5-16 shows that for each of the four columns TOC and DOC results were under the lab detection limit of 1.0 mg/L; therefore, a correlation was not able to be made between the UV-254, DOC, and TOC concentrations.

Table 5-16: TOC, DOC, UV-254 Results for Main Plant Pilot

Location	TOC (mg/L)	DOC (mg/L)	UV-254 (cm⁻¹)	Percent Removal of UV-254 (%)
Raw	1.26	1.2	0.034	-
GAC 1	1.0U	1.0U	0.016	53
GAC 2	1.0U	1.0U	0.012	65
GAC 3	1.0U	1.0U	0.015	56
GAC 4	1.0U	1.0U	0.011	68

UV-254 was examined weekly throughout the course of the study. On average, the columns with shorter EBCTs (GAC 1 and 3) removed 50% of the raw water's UV-254 and the columns with longer EBCTs (GAC 2 and 4) removed 65%. Figure 5-9 shows the average weekly UV-254 concentrations recorded throughout the pilot treatment process.

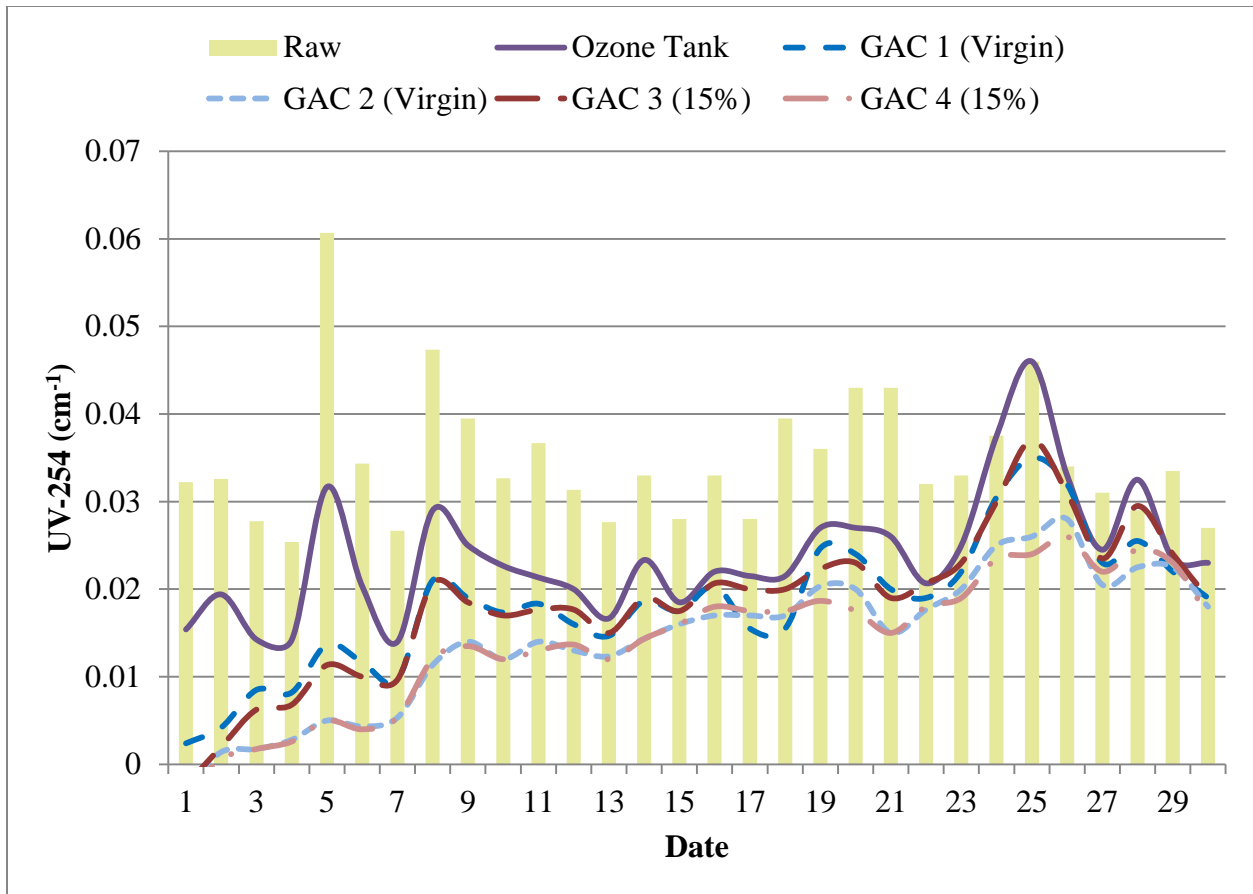


Figure 5-9: Main Plant Pilot UV-254 Results

On average, the ozone removed 34% of the UV-254. The ozone unit was down during Weeks 24-28 which is why the UV-254 concentrations after ozonation are similar to the raw water. The virgin and recharged columns removed similar concentrations of UV-254 throughout the course of the pilot. UV-254 concentrations increased until Week 11 when GAC exhaustion occurred. UV-254 remained stable after Week 11. When the ozone unit was out of service between Weeks 24 and 28, UV-254 concentrations increased to about 0.030 cm⁻¹. Table 5-17 shows the percent removal of UV-254 for the GAC, transitional, and BAC phases.

Table 5-17: Percent Removal of UV-254 for Main Plant GAC Stages

Stage	GAC 1	GAC 2	GAC 3	GAC 4
GAC	70.8	87.3	75.7	88.0
Transitional	46.7	56.7	44.8	56.9
BAC	35.3	44.1	33.6	44.4

Since the concentration of UV-254 in the GAC column finished water increased throughout the duration of the study, the GAC stage has the highest percent removal followed by the transitional and BAC stages. The BAC stage removed about 34% of the UV-254 for GAC 1 and 3 and about 44% for GAC 2 and 4.

DBP Formation Potential

TTHM formation potential was performed seven times over the course of the pilot study. Table 5-18 shows the average chlorine dosages and residuals used when performing formation potential. Using a 5 or 10 minute EBCT lowers chlorine dosages by about 12%. Utilizing the ozone and GAC process would result in chlorine residuals being 20% higher after a 120 hour contact time.

Table 5-18: Main Plant Disinfectant and DBP Formation Potential Comparison

Location	Cl ₂ Dose (mg/L)	Initial Cl ₂ Residual (mg/L)	% Cl ₂ Demand	120hr Cl ₂ Residual (mg/L)	% Cl ₂ Reduction at 120hr	TTHMs at 120hr (µg/L)
Current Main Plant	5.0	1.8	64.0	0.7	61.1	68.0
GAC 1 (Virgin)	4.6	1.8	60.3	0.9	50.7	52.1
GAC 2 (Virgin)	4.3	1.8	57.4	1.2	35.4	35.9
GAC 3 (Regenerated)	4.4	1.8	59.1	0.9	48.7	49.0
GAC 4 (Regenerated)	4.2	1.8	57.2	1.2	31.7	32.4

HAA₅ was only analyzed once during this study since the Main Plant currently forms HAA₅ at 120 hrs below the MCL of 60 µg/L. The HAA₅ concentrations formed from the GAC pilot water shown in Table 5-19 are also below the MCL.

Table 5-19: Main Plant Pilot HAA Results from 120 hr Formation Potential

Location	HAA ₅ (µg/L)
Main Plant (Current)	40
GAC 1 (Virgin)	8.4
GAC 2 (Virgin)	13.1
GAC 3 (Regenerated)	16.9
GAC 4 (Regenerated)	20.9

Figure 5-10 shows the TTHM formation potential results at 120hrs during the study. TTHM concentrations were below the MCL of 80 µg/L after the GAC treatment process. TTHM concentrations did gradually increase until Week 11 when UV-254 concentration peaked and GAC exhaustion occurred as shown in Figure 5-9. The transitional stage occurred between

Weeks 11-13 when the TTHM concentrations began to decrease as shown in Figure 5-10. After Week 16, TTHM concentrations stabilized at about 50 µg/L.

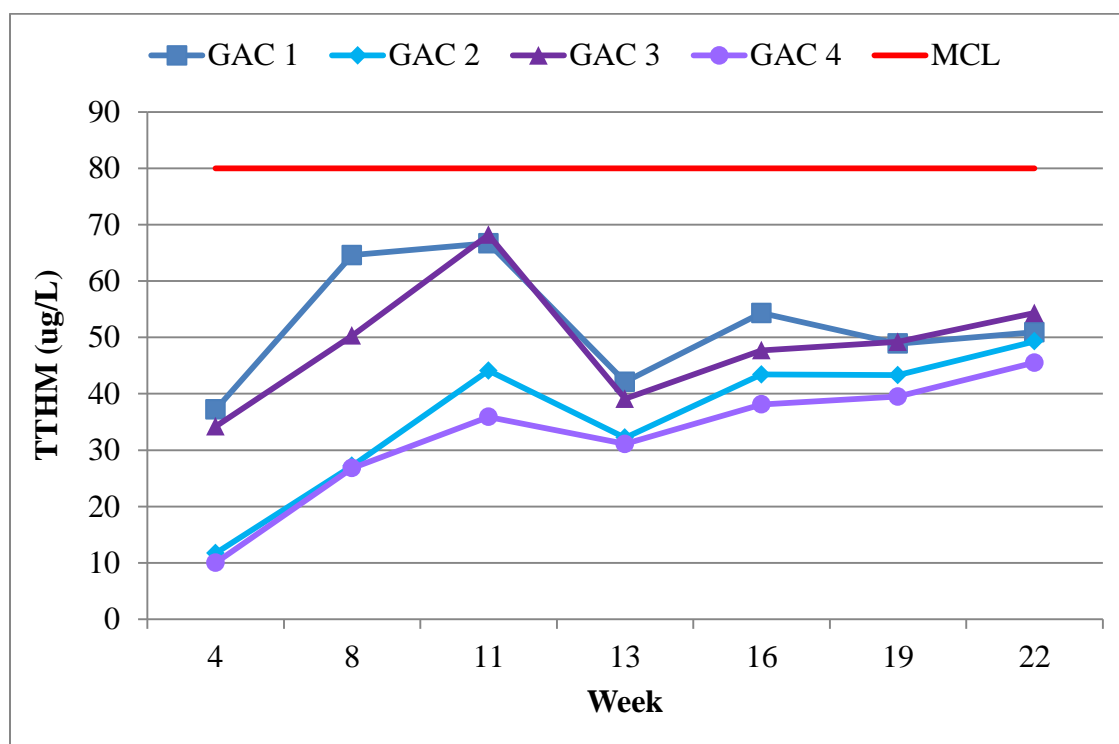


Figure 5-10: Main Plant Pilot TTHM Results for 120 hr Formation Potential

TTHMs for GAC 2 and 4 were lower than the concentrations produced by GAC 1 and 3 during the GAC stage. As the BAC stage progressed, TTHM concentrations were similar for the four columns. A TTHM formation potential was also performed when the ozone unit was out of service during Week 26. The TTHMs were about 65µg/L at 120 hrs.

Bromate sampling was conducted during preliminary ozone testing to confirm that ozone could be used without exceeding the bromate MCL (0.001 mg/L). Table 5-20 shows the bromate

results for samples collected at 0, 5, 13, and 22% ozone feed. Bromate was below the laboratories detection limit of 0.007 mg/L, making ozone a viable treatment option for the Main Plant.

Table 5-20: Bromate Results for Main Plant Pilot

Ozone Feed (%)	Ozone Residual	Bromate (mg/L)
0	0	<0.007
5	0	<0.007
10	0.38	NA
13	0.5	<0.007
15	0.6	NA
20	0.87	NA
22	1.01	<0.007
25	1.22	NA

Blending Study

Current Main Plant finished water and treated pilot water were blended to see if the entirety of the Main Plant feed water needs to be treated using ozone, GAC, and BAC in order to lower DBPs. The mixing study was performed during the BAC stage (Week 22) of the pilot. Figure 5-11 shows the 120 hour TTHM concentrations and chlorine residuals for the Main Plant's current finished water, each of the GAC columns, and 25%, 50%, and 75% blended water. Blending would only result in TTHM concentrations at 120 hours under the MCL if 75% of the water was treated using ozone and GAC while 25% is treated using the current treatment (aeration). Chlorine residual after 120 hrs was at least 40% higher for the pilot samples than the Main Plant current finished water or any of the blended water combinations.

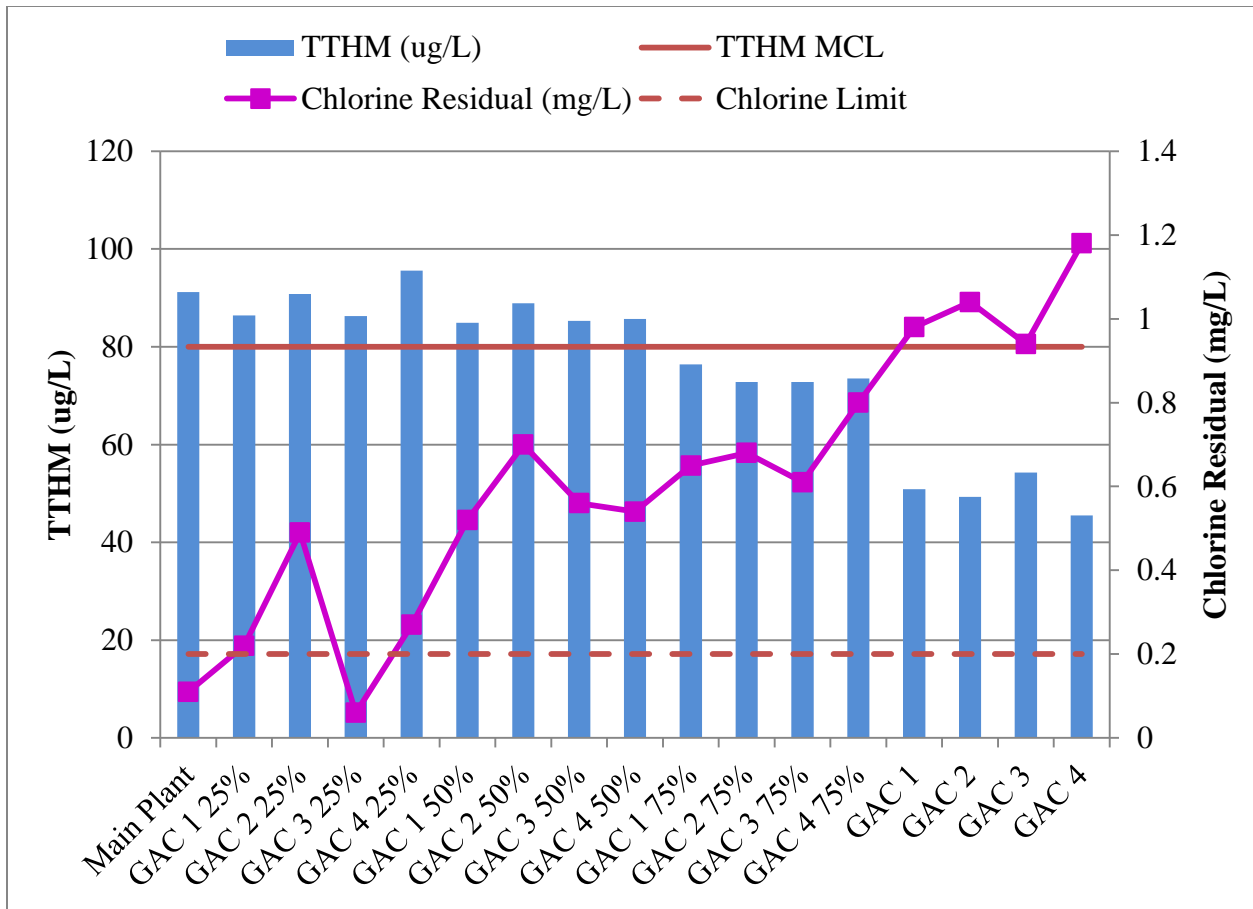


Figure 5-11: 120 hr TTHM Formation Potential Mixing Results for Main Plant Pilot

Auxiliary and Main Plant Pilot Comparison

Results from the Aux and Main Plant pilot studies were compared in order to determine if ozone, GAC, and BAC should be used at both of the City’s plants. The City also desired clarification that installing the treatment at the Aux Plant first and not at the Main Plant would be the best option for meeting the Stage 2 DBP Rule when considering the City’s goals for the project.

Ozone Performance

The same ozone generator was used for each of the pilot studies. However, different applied ozone dosages were necessary at each of the plants due to the different water qualities present in each of the wellfields. The ozone dosages along with the average ozone residual and UV-254 percent removal seen over the course of the studies are shown in Table 5-21.

Table 5-21: Ozone Treatment Comparison for Aux and Main Plant Pilots

Treatment Plant	Ozone Feed Percentage	Ozone Dosage (mg/L)	Ozone Residual (mg/L)	Raw UV-254 (cm⁻¹)	Ozone UV-254 (cm⁻¹)	Percent Removal of UV-254	Percent Sulfide Removal
Aux	50%	8	0.66	0.087	0.035	60%	100%
Main	10%	2	0.58	0.034	0.022	35%	100%

The Aux Plant required 75% more ozone than the Main Plant, due to the higher TOC and sulfide concentrations in the source water. Table 5-21 also shows UV-254 concentrations in the raw water are an average of 60% higher for the Aux Plant. The average ozone residuals produced at each of the pilots were similar although different ozone dosages were being applied. Even with similar residuals, ozone removed an average of 60% of the UV-254 at the Aux Plant while only 35% was removed at the Main Plant.

Granular Activated Carbon Performance

The GAC pilot unit was set up in the same configuration at both the Aux and Main Plant. The designed EBCT was also consistent between the two pilot studies. As was the case with ozone, it was expected that the GAC lifespan and performance would be different when the pilot was conducted at each of the plants due to the differences in raw water contaminant concentrations. Table 5-22 shows the average bed volumes that were used by the GAC columns for an EBCT of about 10 minutes.

Table 5-22: GAC Pilot Bed Volume Comparison

Pilot	GAC Stage	Transitional Stage	BAC Stage	Total
Aux Plant (Reiss Engineering)	4300	NA	NA	4300
Aux Plant (Ozone & GAC)	5400	6300	19800	31500
Main Plant (Ozone & GAC)	10200	1940	16500	28700

Reiss Engineering's pilot which consisted of only the GAC process used 4,300 bed volumes before GAC exhaustion occurred (Robert & Dunkelberger, 2011). The Aux Plant pilot, consisting of ozone and GAC, reached 5,400 bed volumes before media exhaustion occurred. Ozone and GAC can be deemed the more effective process since it produced about 1,000 more bed volumes at the Aux Plant as compared to prior studies.

DBP Precursor Comparison

A UV-254 comparison was made for the effectiveness of the ozone, GAC, and BAC treatment process at both the Aux and Main Plants which is shown on the graphs in Appendix A. Each of the treatment plants contains significantly different raw water UV-254 concentrations. The regenerated media did a better job at removing UV-254 than the virgin media for both studies. The columns with the longer EBCTs (GAC 2 and 4) also removed more UV-254 in both studies. Similar percent removals were seen when the pilot unit was running as an adsorption process (GAC stage). UV-254 reduction is higher for the Aux Plant Pilot than the Main Plant Pilot during the BAC stage of the study. Looking at the percent removal of UV-254 after the ozone tank allowed for the GAC removal efficiencies to be examined without taking into account removal that took place due to the ozone process. Both studies showed that ozone had a large effect on DBP precursor removal particularly while running the process biologically.

TTHM Comparison

TTHMs were used over the course of the pilot for determining when GAC adsorption capacity was reached and when the media was operating as a biological treatment process. Both pilots produced average TTHM concentrations below the MCL after 120 hours of disinfectant contact. Figure 5-12 shows the TTHM results at 120 hours for the duration of the pilot studies. The ozone and GAC process will reduce TTHM formation at 120 hrs from 100 to 70 $\mu\text{g/L}$ for the Aux Plant and from 70 to 50 $\mu\text{g/L}$ for the Main Plant. Chlorine residuals at 120 hour contact time will increase from 0 to 0.6 mg/L for the Aux Plant and from 0.4 to 0.9 mg/L for the Main Plant.

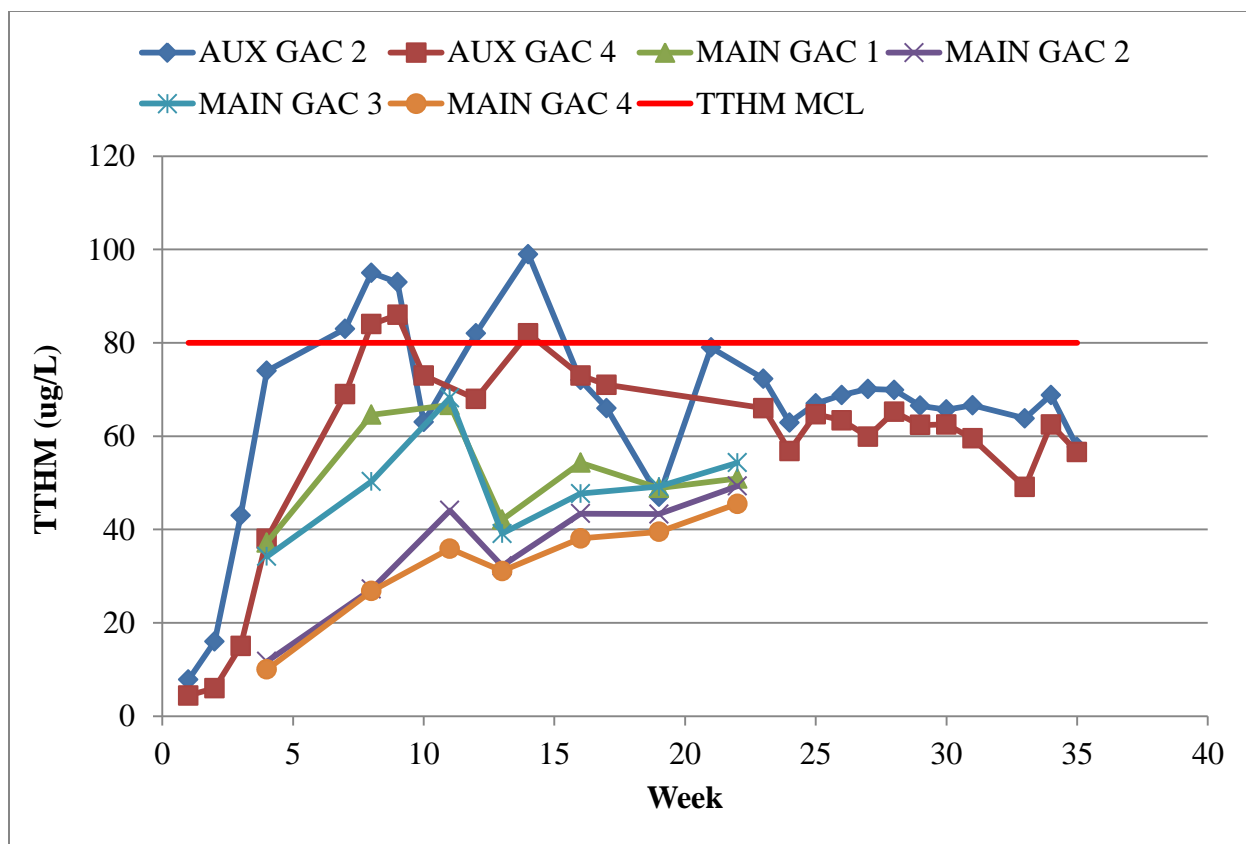


Figure 5-12: Aux and Main Plant Pilot TTHM Comparison at 120 hr Formation Potential

Each of the GAC pilots were broken into three stages; the GAC, transitional, and BAC stages. GAC exhaustion occurred after 7 weeks for the Aux Pilot when the TTHMs exceeded the MCL. GAC exhaustion was deemed at 11 weeks for the Main Pilot even though TTHMs were still significantly below the MCL. Since both pilots were ended due to time constraints, BAC exhaustion was never seen. Running on biological mode may mean that the carbon media could go at least 8 months without needing to be replaced. Treatment should first be added to the Aux Plant since it is currently more of a problem for the City.

6. CONCLUSIONS

The City of Sanford contains groundwater with sulfide concentrations ranging from 0.02 to 2.35 mg/L and TOC concentrations ranging from 0.61 to 2.20 mg/L which are not removed by the City's current treatment, cascade aeration. In order to remove hydrogen sulfide and DBP precursors from the City of Sanford's drinking water, an ozone and GAC process was evaluated at the Main and Aux Plants. Once GAC exhaustion occurred, after 7 weeks for the Aux Pilot and 11 weeks for the Main Pilot, the GAC media was converted into a biological treatment process in order to extend the life of the carbon media. BAC extended carbon life another 28 weeks for the Aux Pilot and 19 weeks for the Main Pilot. However, both pilots were ended due to time constraints; BAC exhaustion never occurred.

Ozone effectively removed sulfide at a dosage of 8 and 2 mg/L for the Aux and Main Plant's, respectively. Sulfide was reduced from an average of 1.7 mg/L to 0 mg/L at the Aux Plant and 0.15 mg/L to 0 mg/L at the Main Plant. At this dosage bromate was under 0.07 mg/L which is below the MCL of 0.10 mg/L. As the applied ozone dosage was raised, the ozone residual increased. Ozone residual appeared to have a direct effect on the removal of UV-254. On average, ozone removed 60% of the UV-254 at the Aux Plant and 35% of UV-254 at the Main Plant. These results could be due to the higher concentrations of UV-254 present in the Aux Plant's source water. Ozone also played a part in converting the GAC to BAC by converting organics to AOC, which acts as a food source for microorganisms.

Two GAC trains were run in parallel, each containing 2 columns in series with one another. GAC 1 and 2 contained virgin media, while GAC 3 and 4 contained regenerated carbon media. Actual GAC EBCT's ranged from about 5-6 minutes for GAC 1 and 3 and 10-11 minutes for GAC 2 and 4 for the pilots at both plants. During the course of this study, the GAC transitioned through three stages: an adsorption phase, transitional and bio-acclimation phase, and a BAC phase. The duration of these phases were based on UV-254 removal. The GAC phase lasted 7 weeks for the Aux Plant and 11 weeks for the Main Plant. The transitional phase lasted about 7 weeks for the Aux Plant and 2 weeks for the Main Plant. The BAC phase lasted 22 and 17 weeks for the Aux and Main Plant Pilots, respectively.

A distinct correlation between TOC, UV-254 and TTHMs was not found. As a whole, the treatment process did reduce UV-254 concentrations, TTHM concentrations, and chlorine dosages for the Aux Plant by an average of 68%, 38%, and 72%, respectively. UV-254, TTHM and chlorine dosages for the Main Plant were reduced by an average of 48%, 28%, and 14%.

Blending studies were conducted during the BAC stage of each study. Aux Plant Pilot water was blended with different percentages of Main Plant water to better represent the distribution system. The 120 hour formation potential for the blended water indicated that TTHMs would be present at about 70 µg/L. Main Plant pilot water was also blended with different percentages of the current finished water to see if the entirety of the Main Plant needs additional DBP precursor treatment. The 25% and 50% pilot blends were above the MCL while 75% was slightly below the MCL.

7. RECOMMENDATIONS

It is recommended that the City's water treatment upgrades should be added to the Aux Plant first due to higher sulfide and TOC concentrations present in the raw water. Adding treatment to the Main Plant should be considered in order to further reduce DBP concentrations within the distribution system.

An ozone system should be chosen that automatically adjusts the ozone residual for changes in feed water quality. An ozone residual of 0.5 mg/L should be used at both plants because it will remove sulfides and a portion of the DBP precursors. Using the ozone system to obtain disinfection credit should also be evaluated in order to reduce chlorine dosages.

The GAC unit should be designed with an EBCT of about 10 minutes for the Aux Plant and 5-6 minutes for the Main Plant. Converting the GAC system into BAC is also recommended. This will reduce the frequency of media replacement, therefore reducing O&M costs. When the media is replaced, regenerating the media should be considered. A method for quantifying the number of bacteria present such as Adenosine triphosphate (ATP) testing should be considered to determine when the media has reached biological mode. A backwashing program for both the GAC and BAC stages should be developed.

Prior to installing and implementing the ozone, GAC, and BAC treatment process the effects on the City's aged distribution system should be considered. Adding this treatment process will change the chemistry of the water being fed into the system. Changing the system's water

quality can disrupt the existing pipe-wall equilibrium, which may loosen and dislodge biofilm and metal/precipitate deposits. Increasing the DO through ozonation may result in aesthetic concerns, such as red water throughout the system. In order to avoid this, procedures that gradually introduce the better water quality can be used such as slowly blending the Aux Plant water into the system and slowly increasing ozone dosage. System flushing should also be implemented prior to starting up the new treatment process. A public notification and consumer confidence program should be developed prior to implementation of the improvements so that the public is involved and aware of the water quality changes that will be taking place.

The City should continue to replace aged pipe and promote looping within the distribution system. The unidirectional flushing program should continue in order to properly move water throughout the system. Conducting these tasks and improving treatment at both plants should improve customer's water quality.

APPENDIX A: UV-254 DATA

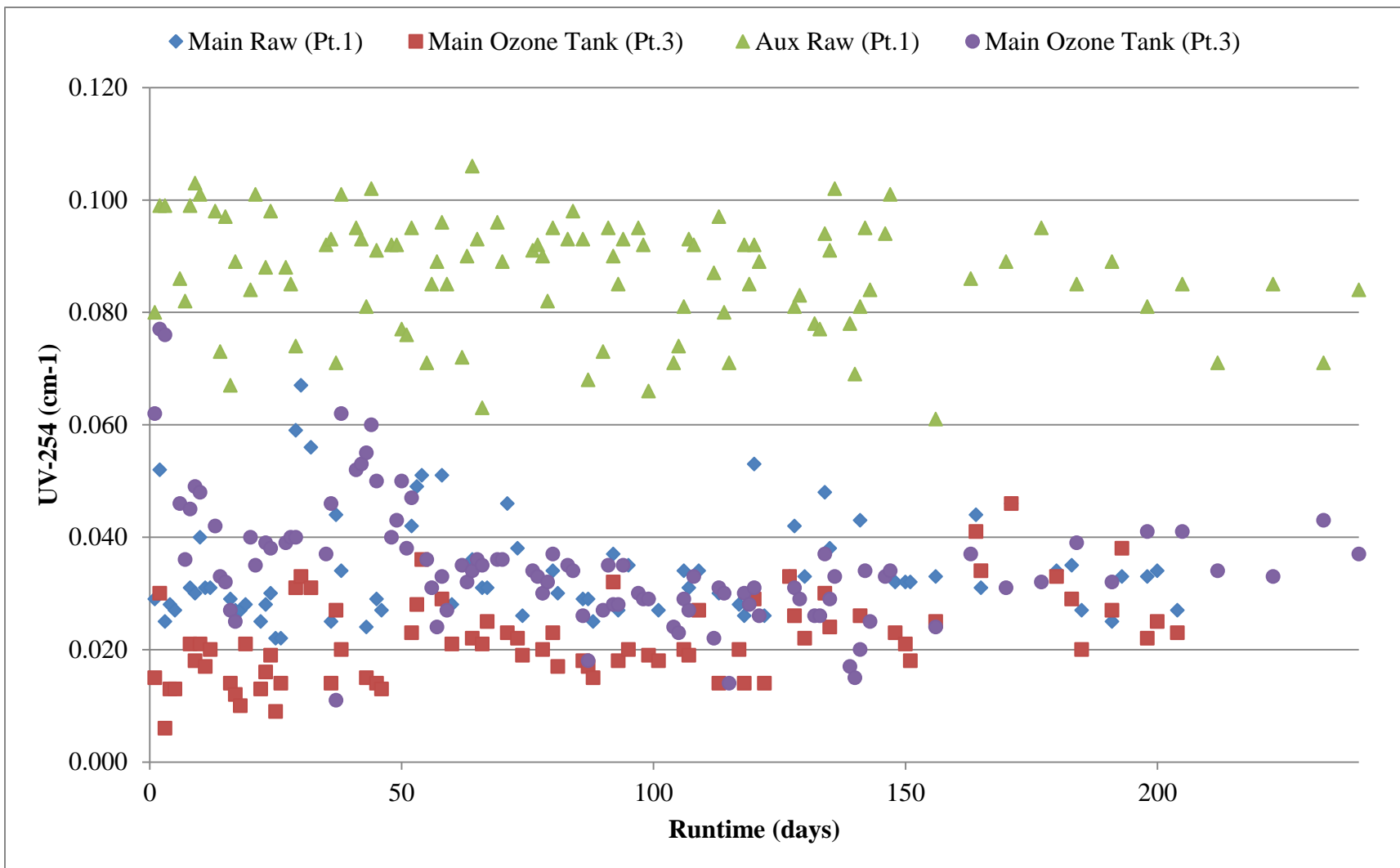


Figure A-1: UV-254 Results after Ozone

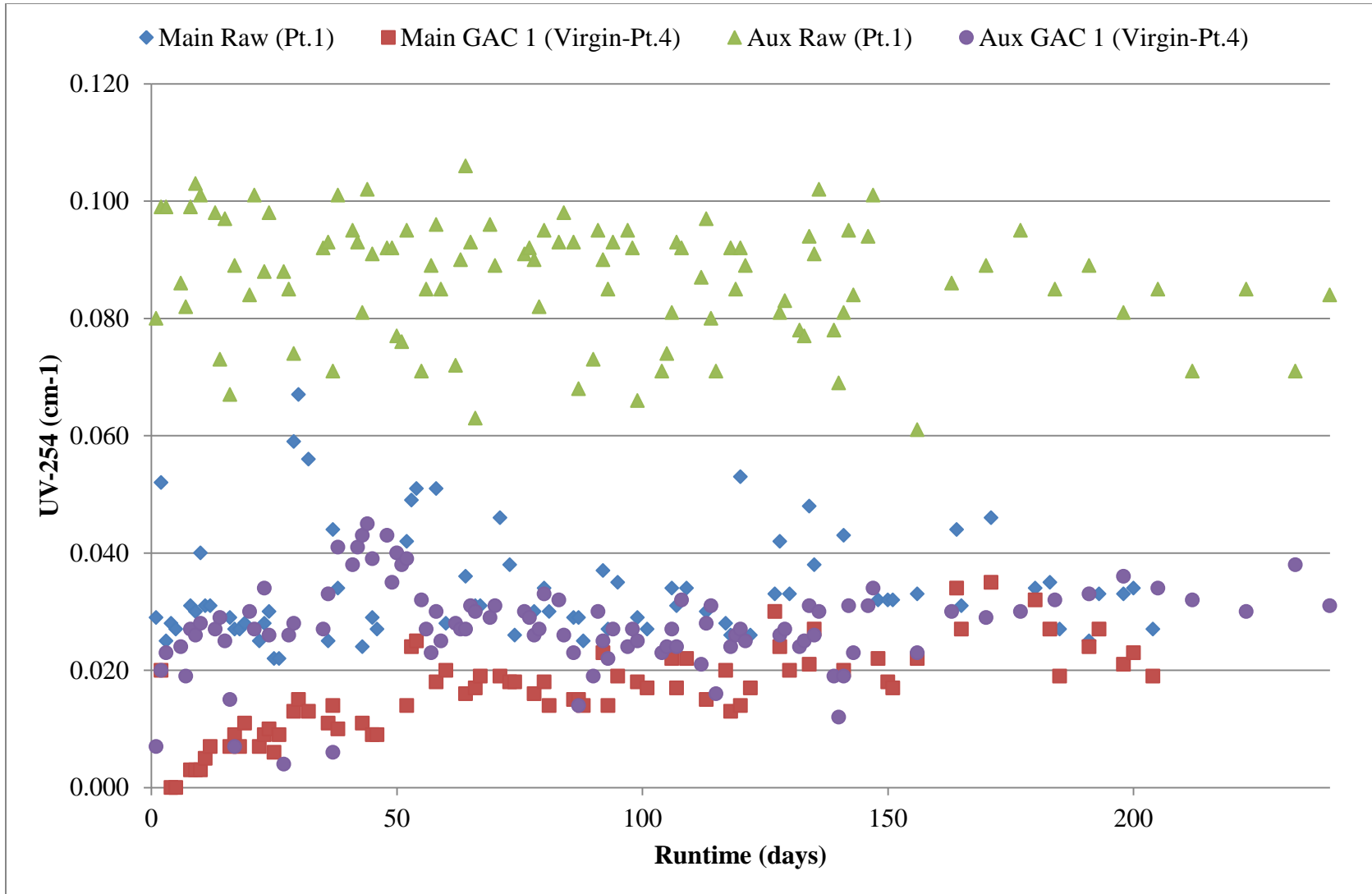


Figure A-2: UV-254 Results after GAC Virgin Media and an EBCT of 7 min

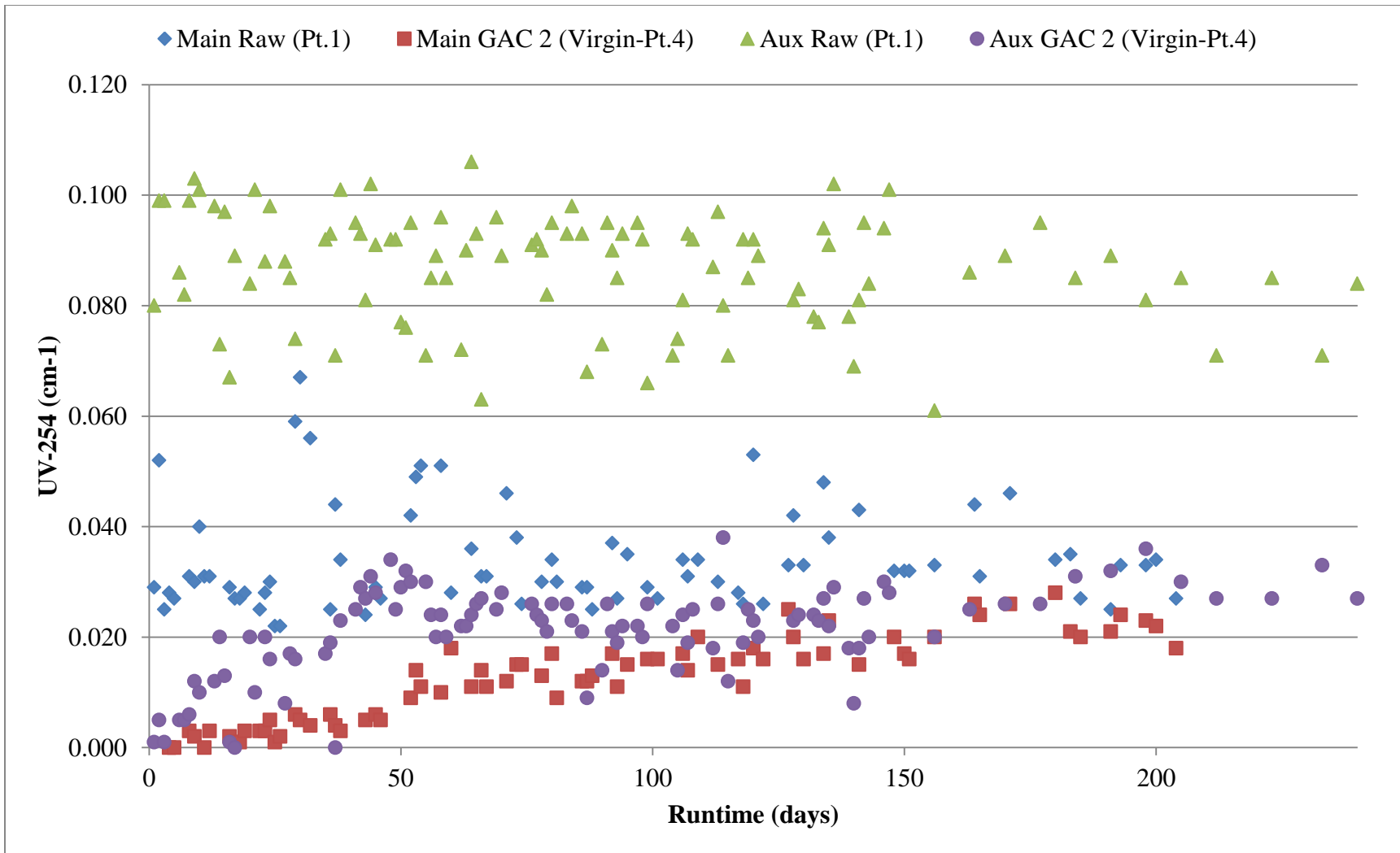


Figure A-3: UV-254 Results after GAC Virgin Media and an EBCT of 14 min

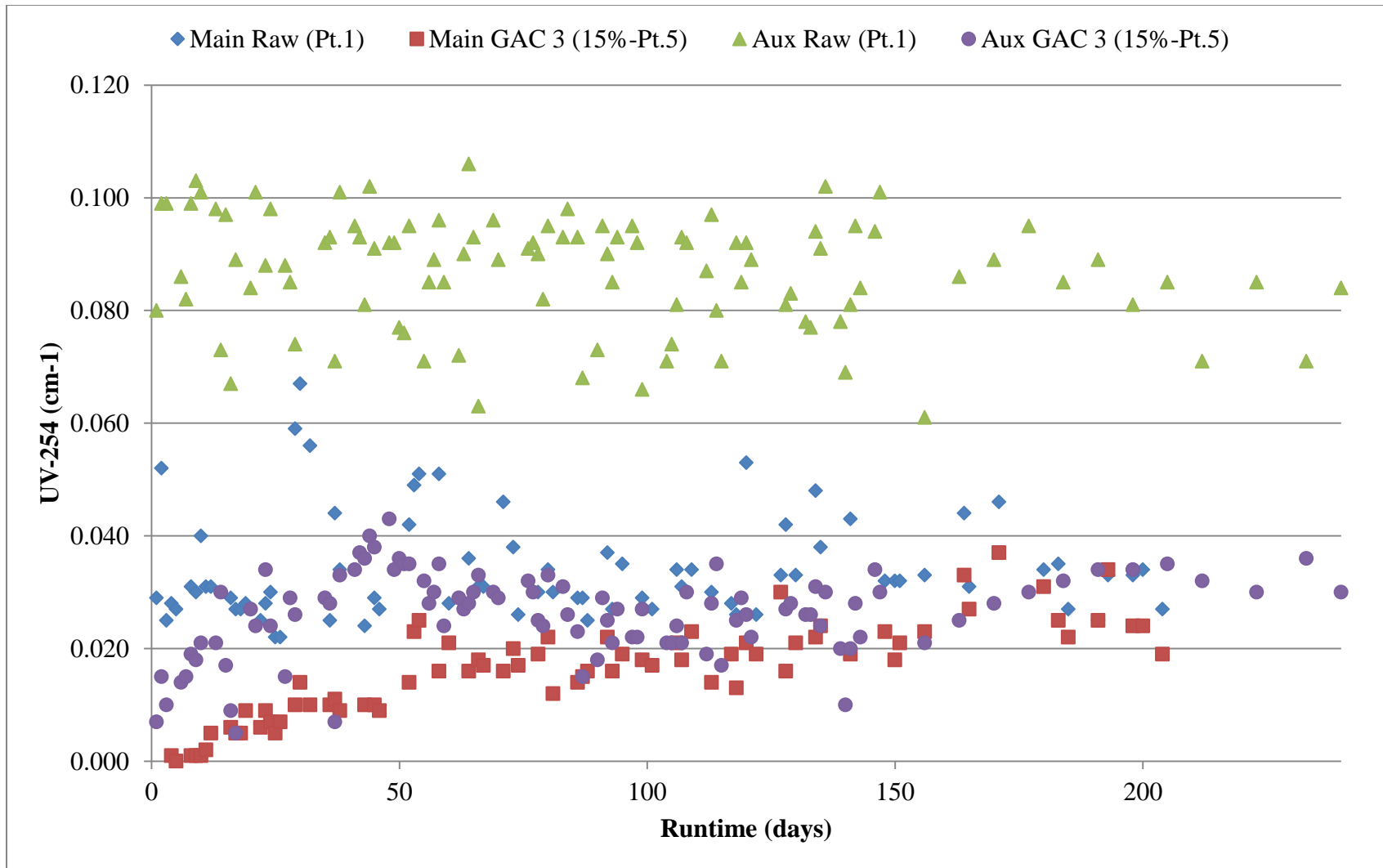


Figure A-4: UV-254 Results after GAC Regenerated Media and an EBCT of 7 min

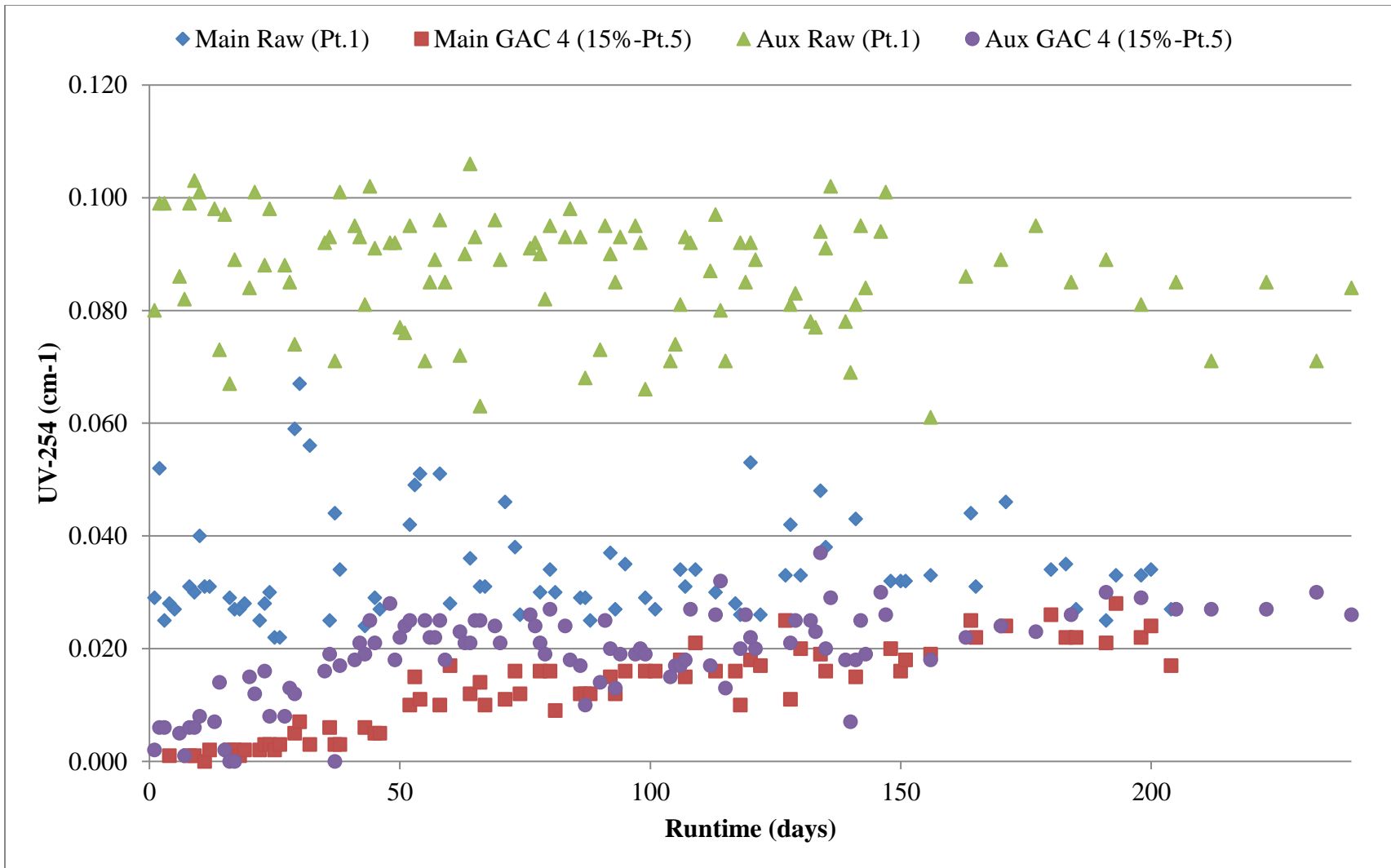


Figure A-5: UV-254 Results after GAC Regenerated Media and an EBCT of 14 min

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