COMPARITIVE ANALYSIS OF TURBIDITY AND ORGANICS REMOVAL IN BIOLOGICAL ACTIVATED CARBON AND ANTHRACITE-SAND FILTERS IN THE MOORHEAD WATER TREATMENT PLANT

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Title

Comparative Analysis of Turbidity and Organics Removal in Biological Activated Carbon and Anthracite-Sand Filters in the Moorhead Water Treatment Plant

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MASTER OF SCIENCE

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ABSTRACT

The source water for the Moorhead Water Treatment Plant (MWTP) exhibits high concentrations of total organic carbon (TOC) throughout the year and seasonal taste and odor (T&O) events. To prevent biological regrowth in the distribution system there is a need to improve organics removal in the existing biological anthracite-sand filters, especially during cold water conditions when a significant decrease in removal efficiencies are observed. Three types of granular activated carbon (GAC) were selected for a pilot study to evaluate the potential of enhanced organics and T&O removal in biological activated carbon (BAC) filters compared to anthracite-sand. Turbidity removal was also evaluated to ensure regulatory requirements could be met with BAC filters. The overall performance of the BAC filters demonstrated a significant improvement over anthracite-sand. The bituminous coal-based GACs outperformed the coconut-based GAC and exhibited surface characteristics which may have a significant impact on the removal of organics, T&O, and turbidity.

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First, I would like to thank my advisor Dr. Wei Lin. Your advice will continue to guide me in my future endeavors. Thank you for pushing me out of my comfort zone to become a better engineer. I would also like to thank my supervisory committee members Dr. Achintya Bezbaruah, Mr. Troy Hall, and Dr. Stephanie Day.

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Last, but not least, I would like to thank my family, friends, and loved ones. I would like to extend my deepest gratitude to my Mom and my brother Mike for always being there for me and for putting a smile on my face. I am so fortunate to have you all in my lives. I could not have completed this without your love and encouragement.

DEDICATION

To my brother Mike.

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LIST OF ABBREVIATIONS

BAC .....Biological Activated Carbon

BOM .....Biodegradable Organic Matter

CT .....Concentration × Time

DOC .....Dissolved Organic Carbon

D/DBP.....Disinfectants/Disinfection By-products

EBCT .....Empty Bed Contact Time

ES.....Effective Size

GAC .....Granular Activated Carbon

HRT.....Hydraulic Retention Time

MDH .....Minnesota Department of Health

mgd .....million gallons per day

MPS.....Moorhead Public Service

MWTP.....Moorhead Water Treatment Plant

NOM .....Natural Organic Matter

NTU .....Nephelometric Turbidity Units

OTC.....Odor Threshold Concentration

SCADA.....Supervisory Control and Data Acquisition

SEM .....Scanning Electron Microscope

SUVA.....Specific Ultraviolet Absorbance

SWTR .....Surface Water Treatment Rule

TOC.....Total Organic Carbon

T&O .....Taste and Odor

UC.....Uniformity Coefficient

USEPA.....United States Environmental Protection Agency

UV254...Ultraviolet Absorbance at 254 nanometers

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CHAPTER 1. INTRODUCTION

Moorhead Public Service (MPS) owns and operates a surface water treatment plant that serves municipal and industrial customers in the cities of Moorhead and Dilworth, as well as the Oakport Township in Minnesota. The Moorhead Water Treatment Plant (MWTP) obtains a majority of its source water from the Red River of the North (Red River), and the remainder from groundwater sources.

Red River water quality varies significantly throughout the seasons. High concentrations of natural organic matter (NOM), measured as total organic carbon (TOC), are observed throughout the year. In addition, the Red River often experiences taste and odor (T&O) events during spring runoff. Currently, odor is listed as a Secondary Drinking Water Standard, which are non-enforceable guidelines set by the Environmental Protection Agency (EPA). Contaminants that are listed as secondary standards are generally of aesthetic concern and do not pose any health risks. However, consumers often associate the quality of their drinking water with aesthetics, such as T&O. As a result, it is not uncommon for the MWTP to receive numerous customer complaint calls related to T&O during spring runoff.

The MWTP is a conventional treatment plant with the addition of ozone prior to dual-media biological filtration (biofiltration) with anthracite and sand. The ozone chambers are designed to oxidize organics and T&O compounds. During ozonation, organics are partially oxidized into biodegradable organic matter (BOM). BOM can be utilized as a substrate for microbial regrowth in the distribution system if left untreated. Therefore, biofiltration is operated after ozonation to enhance the biological stability of the finished water (Water Supply Committee of the Great Lakes, 2012).

The removal of organics is less effective in the biofilters during cold water temperatures, which drop to near 32°F for several months during the winter. In addition, ozonation is not always effective in the oxidation of T&O compounds. The oxidation of T&O compounds requires a high ozone dose and pH. High organic loadings often occur simultaneously during T&O events, which increases the ozone demand and makes the oxidation of T&O compounds more difficult. Furthermore, T&O events are often unpredictable, and T&O compounds may reach the distribution system before operational changes can be made.

The MWTP has been in operation since 1995, and the existing filters need replacement. Therefore, MPS is considering media replacement with granular activated carbon (GAC) to enhance the removal of organics and T&O compounds, and to produce biologically stable water. Once a natural biofilm forms on the GAC media, it is commonly referred to as biological activated carbon (BAC).

A pilot study is required by the Minnesota Department of Health (MDH) before BAC can be considered for filtration. The MDH has concerns that BAC filters can meet effluent turbidity requirements. Therefore, a biological filtration pilot study was initiated at the MWTP to: 1) ensure that BAC filters could meet regulatory requirements, 2) select the GAC type and filter bed configuration that is able to best meet the treatment objectives for the MWTP, 3) design the full-scale replacement, and 4) establish operational strategies. The study was carried out for a period of one year to allow for a sufficient duration to treat all expected water quality conditions and to ensure establishment of full biological activity.

1.1. Research Objectives

The main goal of this study is to determine if BAC filters can achieve better removals of organics and T&O compounds, especially during the sustained cold water conditions experienced at the MWTP. The specific objectives of this study are as follows:

1) Determine if BAC filters provide better removals of organics under both high and low temperature conditions;
2) Determine if BAC filters provide enhanced removal of T&O compounds;
3) Determine the effectiveness of turbidity removal in BAC filters versus anthracite-sand filters; and,
4) Recommend a specific type of GAC to implement in the full-scale system based on a comprehensive analysis of different GAC media performances.

1.2. Scope of Work

The specific tasks that were carried out to achieve the objectives of this study were as follows: literature review, historical data analysis of MWTP, and water sample collection and analysis during the pilot study.

The literature review was carried out to gain a better understanding of the following subjects: physical aspects of granular media filtration, fundamentals of adsorption and biological processes, and the effect of filter media type and temperature on biofilter performance. The literature review provided the framework necessary for developing the tasks that followed.

The purpose of the historical data analysis of the MWTP was to consider data found in the literature review to have a significant impact on the removal of organics. The historical data analysis spanned five years to gain a better understanding of seasonal variations in raw water characteristics and the impact of seasonal temperature variations on the transformation and/or

removal of organics throughout each treatment process. This analysis provided the information needed to better understand and analyze the data that would be obtained during water sample collection.

Finally, the collection and analysis of water samples from the pilot filtration system was done to compare the removal of organics, T&O compounds, and turbidity through the BAC and anthracite-sand filters. Water samples were collected for the analysis of TOC, dissolved organic carbon (DOC), and ultraviolet absorbance at 254 nm (UV254) on a weekly basis from September 2017 to August 2018. Water samples were collected for the analysis of turbidity on a daily basis from October 2017 to August 2018. Turbidity was also measured online in the pilot filtration system from August 2017 to August 2018. Finally, three T&O challenge tests were carried out under high and low temperature conditions. The knowledge gained from the literature review and the historical data analysis of the MWTP was used to put the data obtained during this study into perspective and to determine the relationships between them.

CHAPTER 2. MOORHEAD WATER TREATMENT PLANT

Moorhead Public Service (MPS) owns and operates a drinking water treatment plant that serves the cities of Moorhead and Dilworth as well as the Oakport Township in Minnesota. Currently, over 12,000 metered service connections serve an estimated population of over 48,000 people (MWTP, 2018). The plant was constructed in 1995 and has a design capacity of 10 million gallons per day (mgd). The plant utilizes lime-soda ash softening, primary disinfection with ozone, dual-media biological filtration (anthracite-sand) and secondary disinfection with chloramines to treat surface water or a mixture of surface and groundwater.

The average monthly water demand at the Moorhead Water Treatment Plant (MWTP) from 2013 to 2017 are shown in Figure 1. Over the past five years, water demands have averaged at approximately 4.0 mgd in the winter and above 4.5 mgd in the summer. Between 2013 and 2017, the average monthly demand was 4.42 mgd. The peak monthly demand during that period was 7.05 mgd in June 2017, and the minimum monthly demand was 2.24 mgd in January 2016.

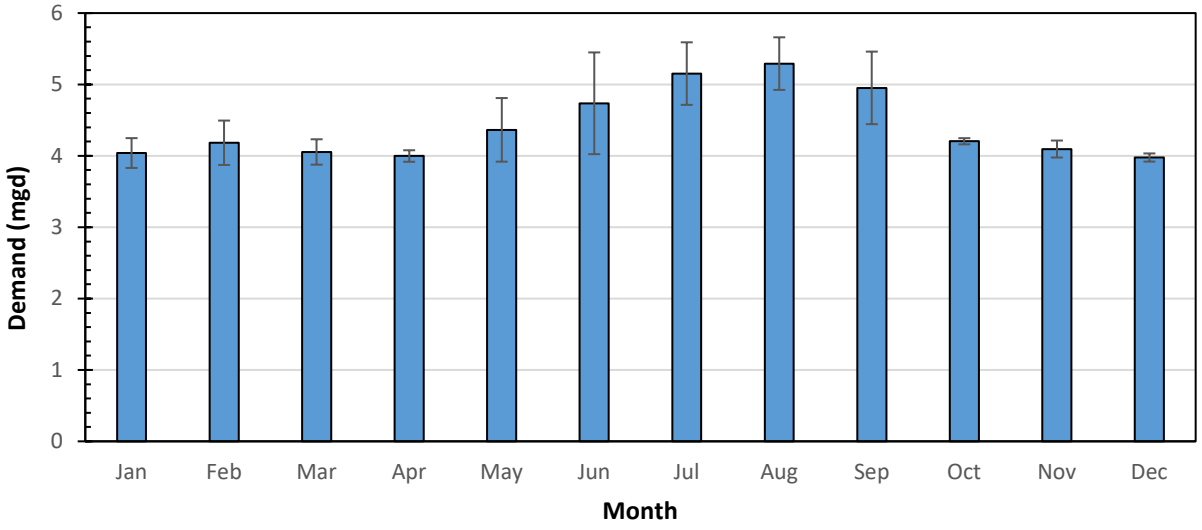

Figure 1. MWTP Average Monthly Water Demands (2013-2017)

2.1. Water Sources and Uses

The MWTP treats water from both surface and groundwater sources. The primary water source is the Red River of the North (Red River); while, groundwater from two aquifers, the Moorhead and Buffalo aquifers, is used as a supplementary and backup source. Historically, the MWTP obtains approximately 80 percent of its source water from the Red River. Groundwater sources are used conservatively in case of drought or contamination of the Red River that would require groundwater to be the primary water source. Groundwater is typically utilized in the summer to improve water quality and to reduce water temperature.

2.1.1. Red River Water Characteristics

The Red River originates at the confluence of the Bois de Sioux and Otter Tail rivers near the cities of Wahpeton, North Dakota and Breckenridge, Minnesota. The Red River forms most of the border between the states of North Dakota and Minnesota, where it flows north and discharges into Lake Winnipeg in Manitoba, Canada. The Red River can experience large variations in water quality in terms of temperature, hardness, turbidity, and organics content throughout the seasons, which makes it challenging to treat.

2.1.1.1. Temperature in the Red River

Water temperature in the Red River varies from near freezing during the cold months to as high as 80°F during the warm months. Daily variations of temperature in the Red River from 2013 to 2017 are shown in Figure 2, and average monthly temperatures in the Red River from 2013 to 2017 are shown in Figure 3. Water temperatures in the Red River are generally the coldest during the months of November through March each year, with temperatures typically peaking in the months of July or August. These variations in water temperature can have a significant impact on treatment processes and operational parameters at the MWTP.

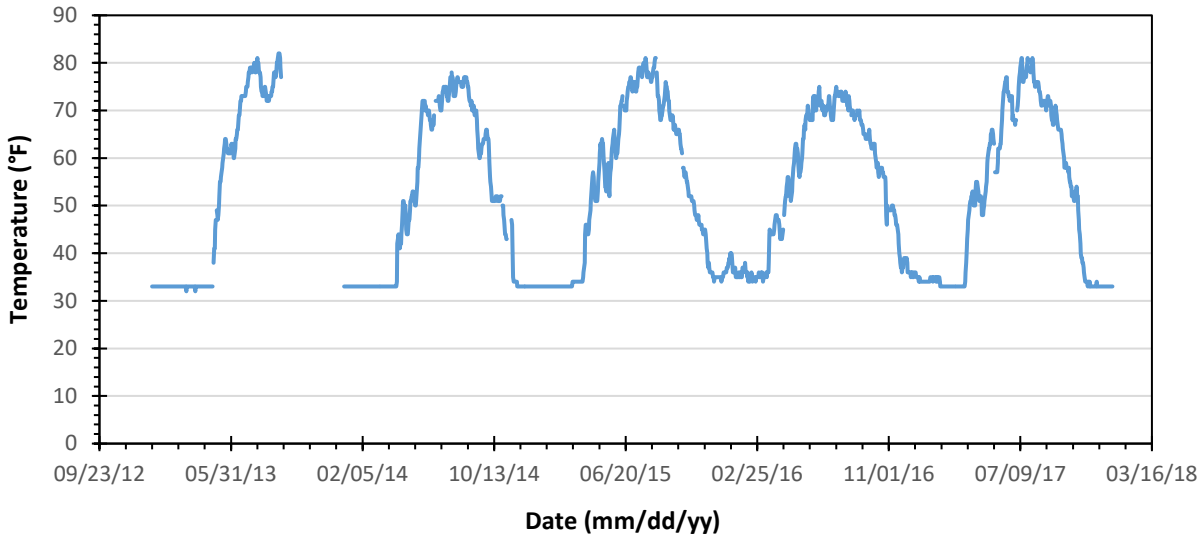

Figure 2. Red River Temperature (2013-2017)

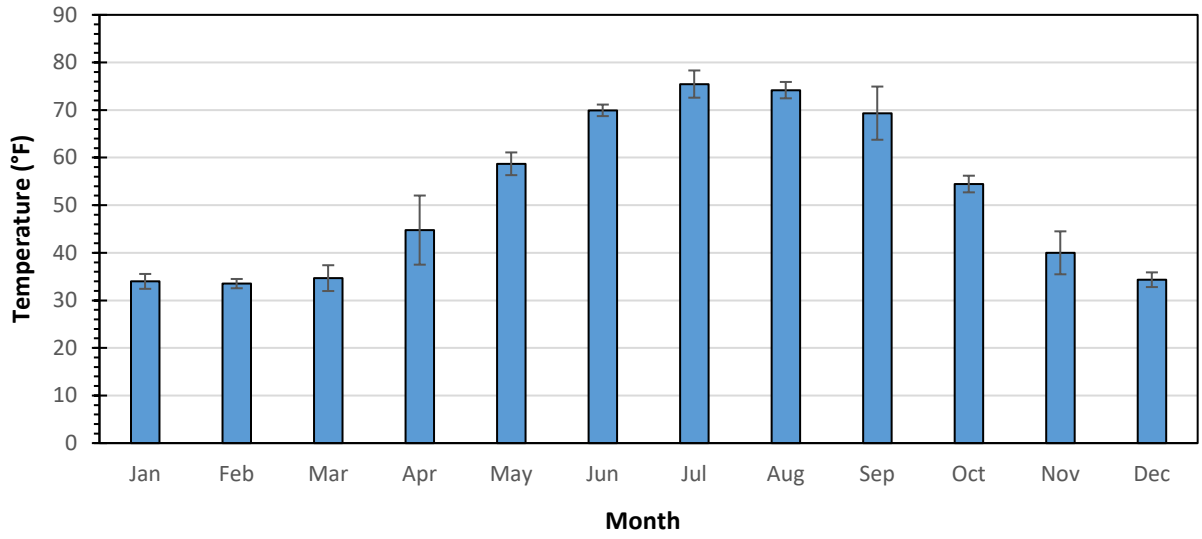

Figure 3. Average Monthly Red River Temperature (2013-2017)

2.1.1.2. Total Hardness in the Red River

Hardness of the Red River water ranges from hard to very hard. Total hardness varies throughout the seasons, with increases often observed during spring runoff, rainfall and upstream activity (discharges from lakes, wastewater and industrial facilities). Total hardness in the Red River between 2013 and 2017 is shown in Figure 4, and average monthly total hardness in the Red River from 2013 to 2017 is shown in Figure 5. During this period, total hardness ranged

from 140 to 876 milligrams per liter as calcium carbonate (mg/L as $CaCO_3$). The average monthly total hardness during that period was 368 mg/L as $CaCO_3$.

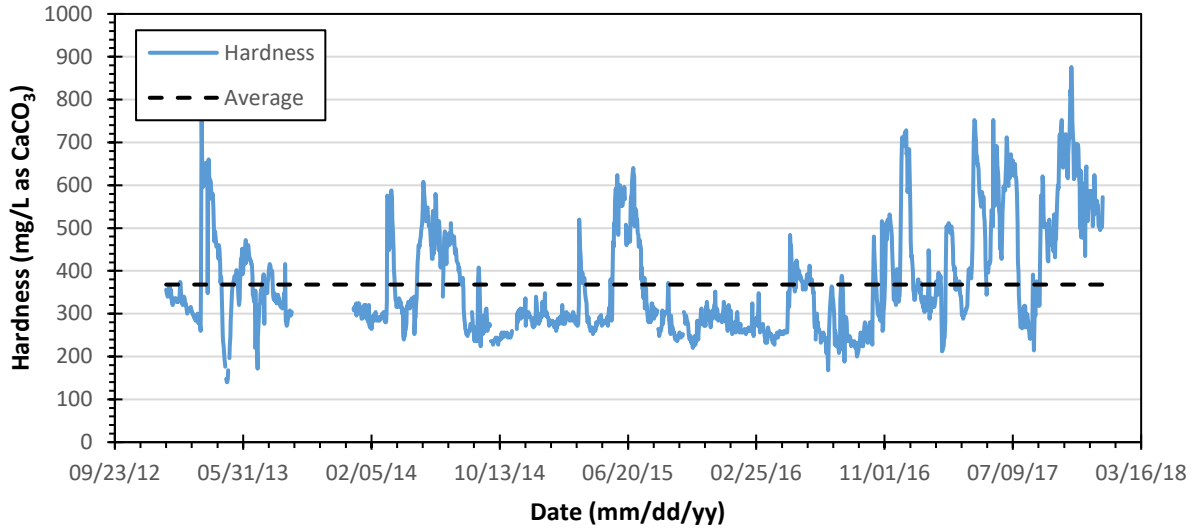

Figure 4. Red River Total Hardness (2013-2017)

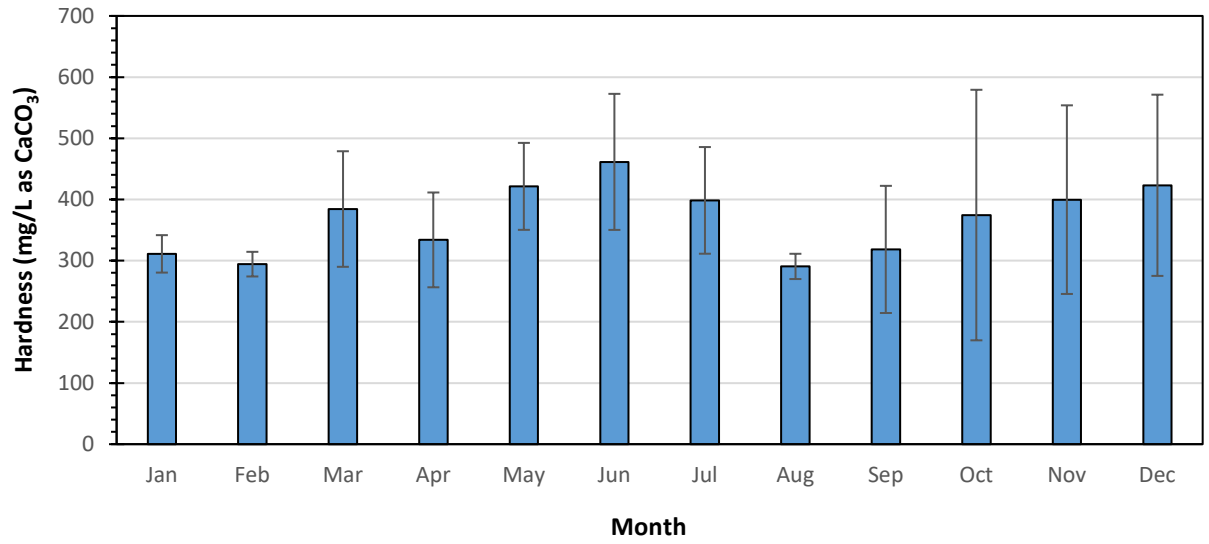

Figure 5. Average Monthly Red River Total Hardness (2013-2017)

2.1.1.3. Turbidity in the Red River

Turbidity remains relatively constant throughout the cold months when the river is covered with ice. However, once the river thaws and snow melts in the spring, rapid changes in turbidity begin to occur. Turbidity in the Red River between 2013 and 2017 is shown in Figure 6,

and average monthly turbidities in the Red River from 2013 to 2017 are shown in Figure 7. Low turbidity, typically less than 10 nephelometric turbidity units (NTUs) is observed during the colder months. However, large variations in turbidity are observed during the warmer months, due to spring runoff and rain events, especially during low flow periods in the Red River. Turbidity values typically peak in May or June from spring runoff and rainfall, as shown in Figure 7. Turbidity in the Red River between 2013 and 2017 ranged from 1.8 to 670 NTU, with a monthly average of 36.9 NTU.

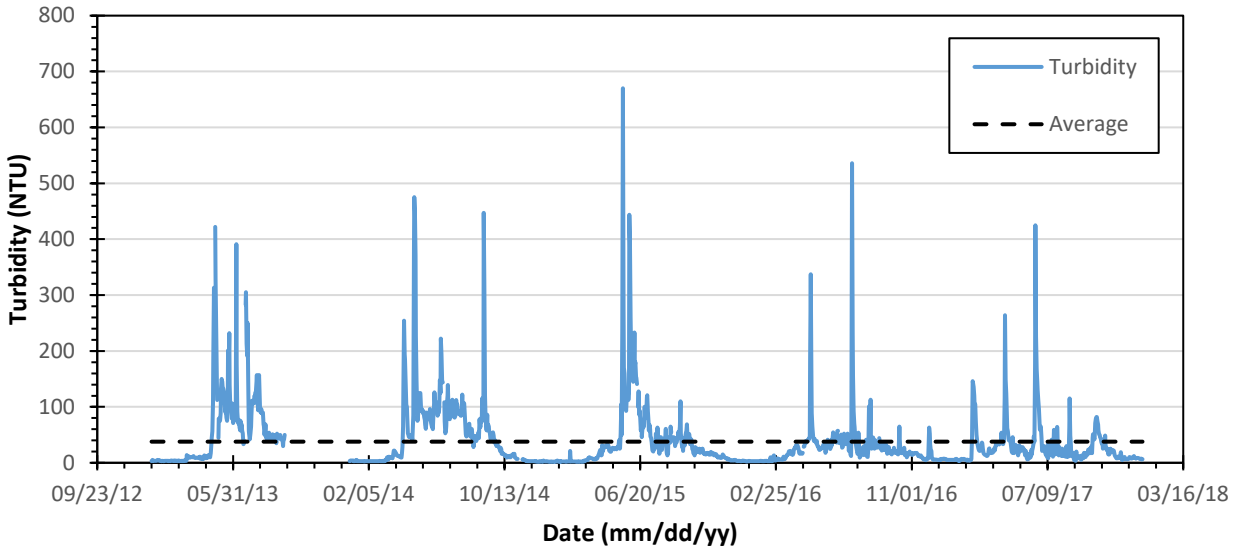

Figure 6. Red River Turbidity (2013-2017)

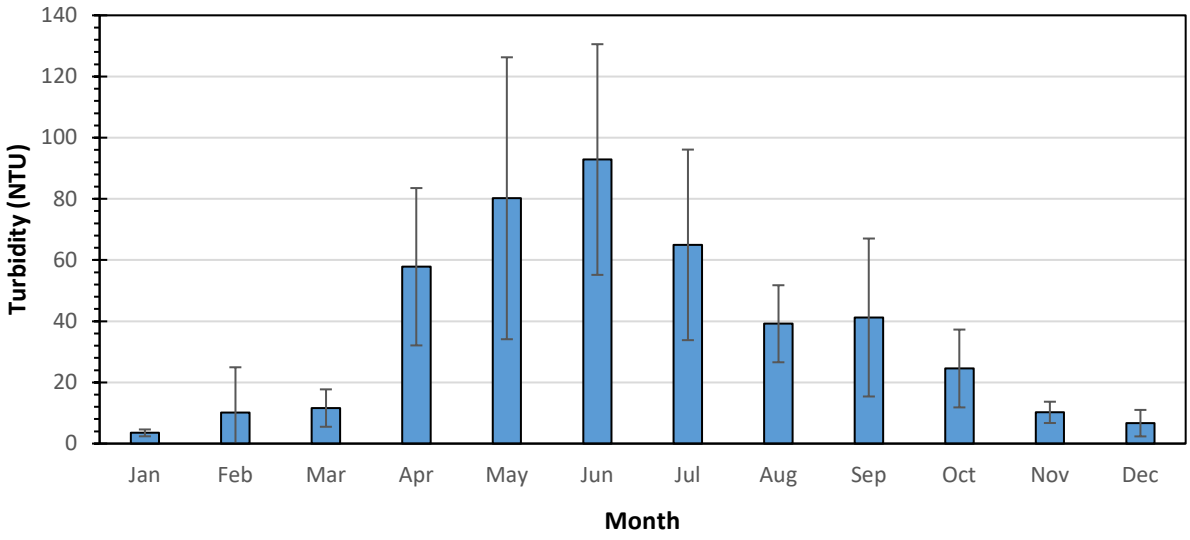

Figure 7. Average Monthly Red River Turbidity (2013-2017)

2.1.1.4. TOC in the Red River

The Red River has relatively high concentrations of natural organic matter (NOM). Organic content in the Red River is measured as total organic carbon (TOC). TOC is a nonspecific indicator of the organics content and general quality of the water. TOC in the Red River between 2013 and 2017 is shown in Figure 8, and average monthly TOC in the Red River from 2013 to 2017 is shown in Figure 9. Between 2013 and 2017, the average TOC was 8.8 mg/L. The maximum TOC observed during that period was 16.5 mg/L in January 2016 and the minimum was 4.5 mg/L in September 2016. Variations of TOC in the Red River can occur for several reasons, including spring runoff, rain events and upstream activity.

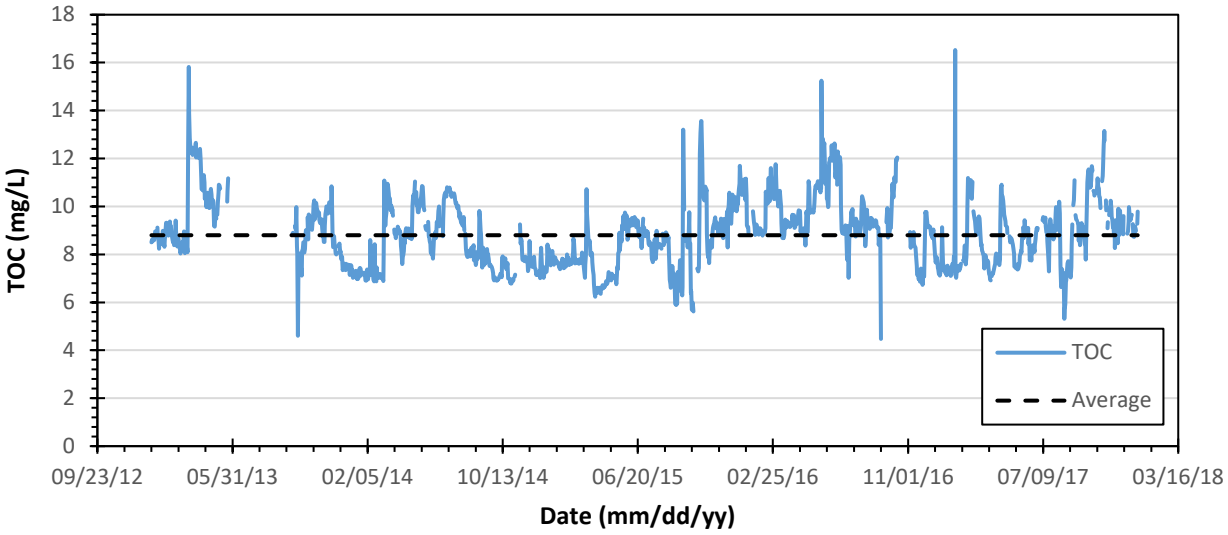

Figure 8. Red River TOC (2013-2017)

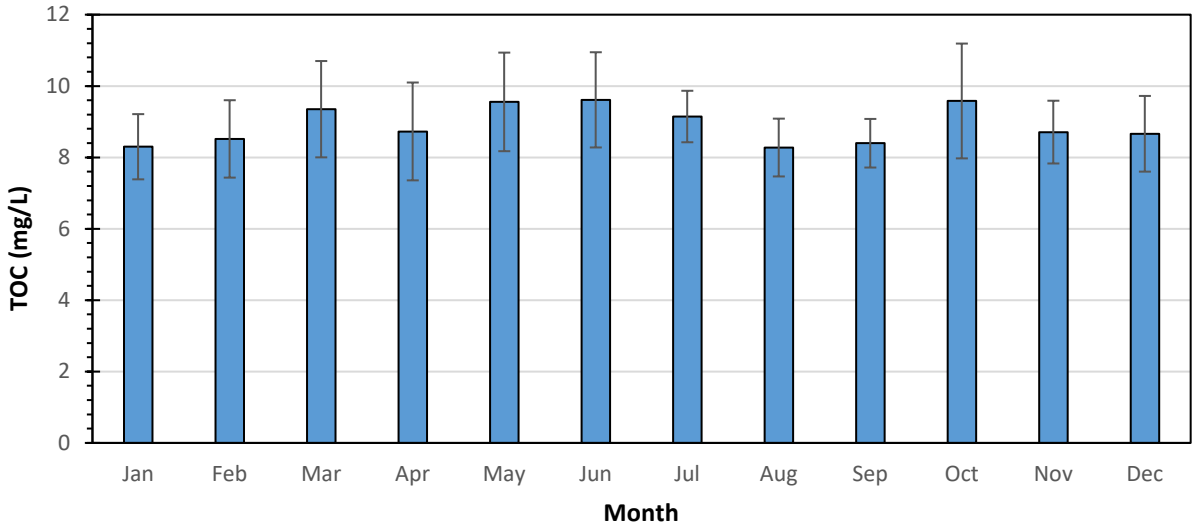

Figure 9. Average Monthly Red River TOC (2013-2017)

2.1.2. Groundwater Characteristics

The MWTP pumps groundwater from seven municipal wells located in the Moorhead and Buffalo aquifers. The Moorhead aquifer, a confined aquifer, contains two wells, 6 and 6B, which are located across the street from the MWTP. The Buffalo aquifer is an unconfined aquifer about four miles east of the City of Moorhead. There are two well fields, namely the North and South Buffalo wells, in the Buffalo aquifer. Wells 1 and 2 are located in the south well field,

while wells 8, 9 and 10 are in the north well field. Locations of the Moorhead and Buffalo aquifers with respect to the MWTP are shown in Figure 10.

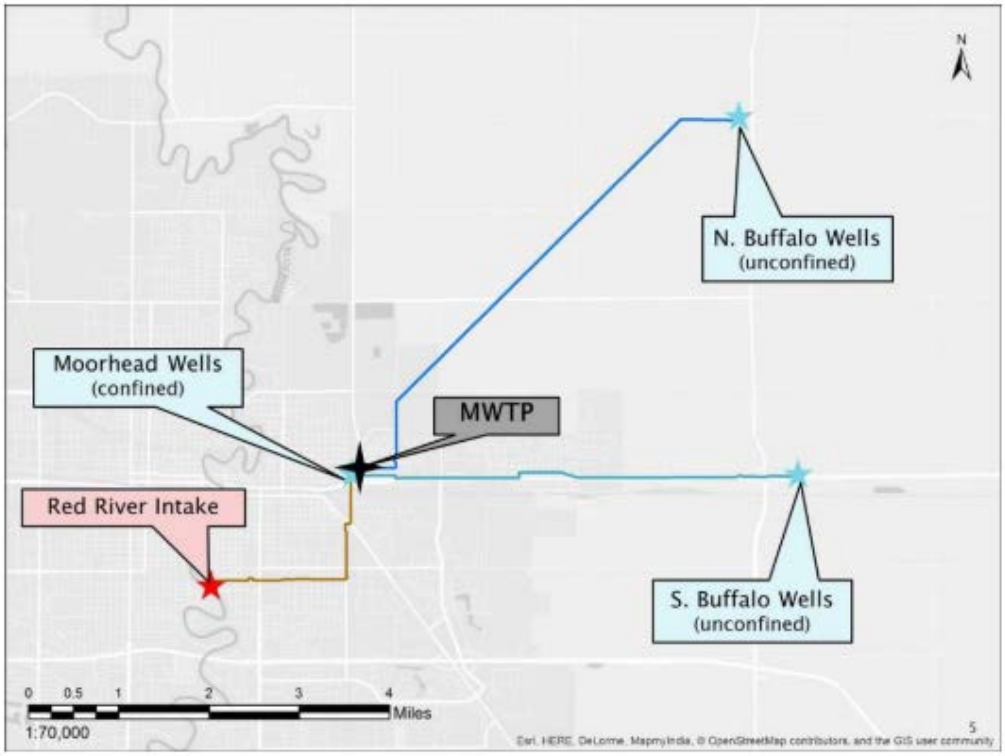

Figure 10. MWTP Source Water Locations (Young, 2014)

Groundwater sources are used to supplement river water to improve influent water quality, such as temperature, hardness, turbidity, and TOC. Water quality characteristics of each well are described in Table 1. Well water has a relatively constant temperature of approximately 52°F and is used to reduce the overall temperature of the treated water to below 70°F, as requested by MPS' largest industrial customer. The hardness of each well ranges from 152 mg/L to 360 mg/L as $CaCO_3$, with the lowest hardness observed in wells 6 and 6B. Typically, wells 6 and 6B are used to lower overall hardness of the finished water when river hardness levels exceed 500 mg/L as $CaCO_3$.

Table 1. Groundwater Characteristics (MWTP, 2018)

Aquifer	Well No.	Hardness (mg/L $CaCO_3$)	Calcium Hardness (mg/L $CaCO_3$)	TOC (mg/L)	Average Temperature (°F)
Moorhead	6	180	152	2.00	52
	6B	180	152	1.81	
North Buffalo	1	550	346	1.47	
	2	550	346	1.67	
South Buffalo	8	547	360	1.66	
	9	475	310	1.67	
	10	475	310	NA	

NA – not available

The MWTP also uses groundwater to reduce overall TOC levels, since high TOC can make it difficult to maintain the required CT (disinfectant concentration × contact time) in the ozonation chambers to meet disinfection requirements. This is due to ozone that would otherwise be available for disinfection being used to oxidize additional organics. TOC in each well is generally less than 2.0 mg/L, which is significantly lower than the average TOC between 2013 and 2017 of 8.8 mg/L in the river.

2.2. Treatment Processes

Treatment processes at the MWTP consist of lime-soda ash softening, primary disinfection with ozone, dual-media biological filtration, and the addition of chloramines for secondary disinfection. The MWTP treatment process and chemical additions are illustrated in Figure 11. Prior to softening, ferric sulfate ($Fe_2(SO_4)_3$) is added to the river water to aid in the coagulation process and is mixed with a flash mix pump. River water and groundwater enter the treatment plant through the inlet structure, where they are combined in an influent channel. It is also at this point that water wasted from filter backwashes, as well as decant from the lime-sludge ponds are added.

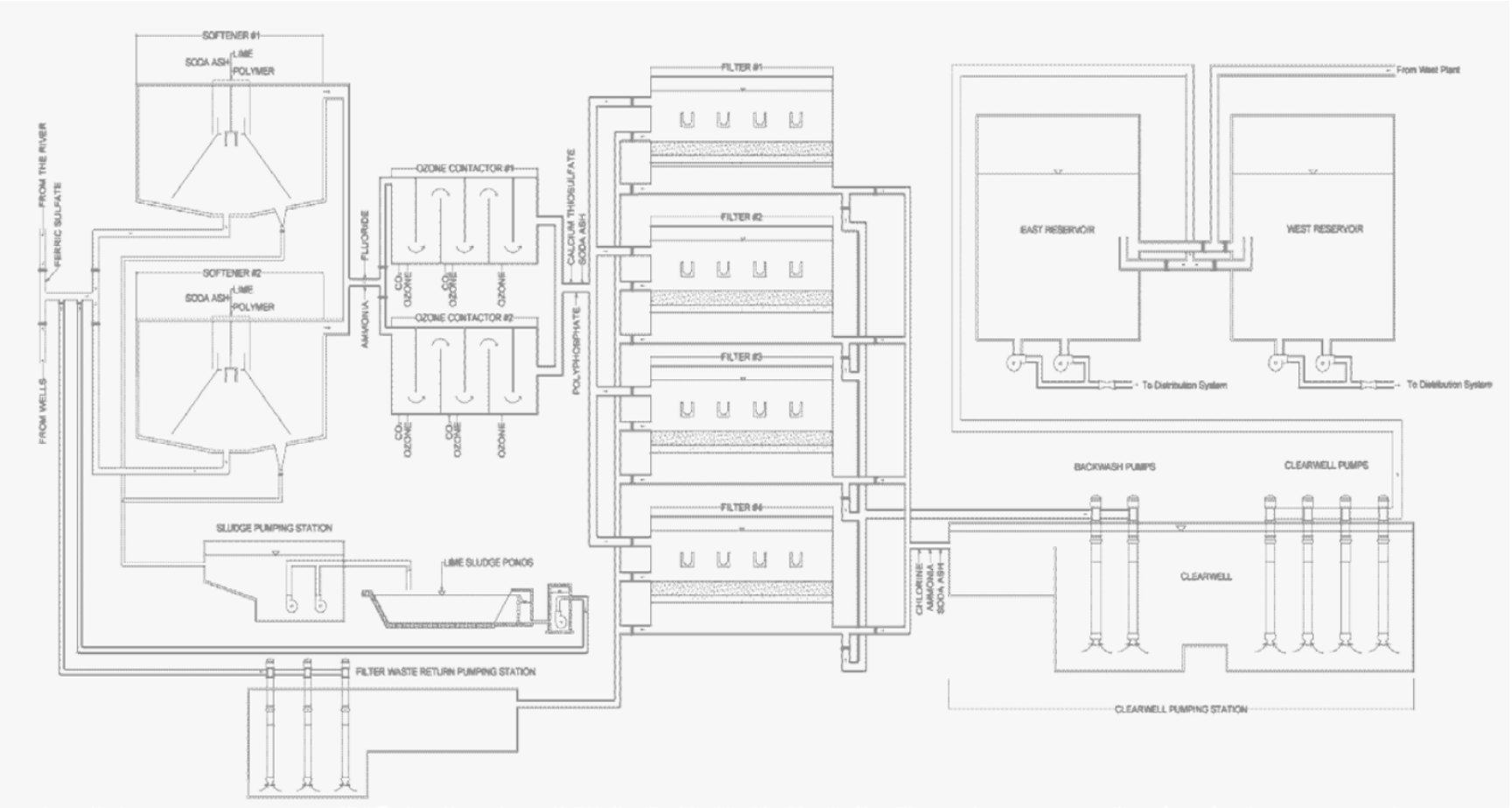

Figure 11. MWTP Treatment Process and Chemical Additions (Storlie, 2013)

2.2.1. Lime-Soda Ash Softening

The lime-soda ash softening process at the MWTP removes hardness-causing minerals, mainly calcium and magnesium. The single-stage softening process (rapid mix, flocculation and sedimentation) takes place in two softening basins that are operated in parallel. Each basin was designed with a capacity of 5 mgd. During low demand periods only one basin is used; however, if demands exceed 5 mgd, both basins will be utilized. Each basin is equipped with a center mixer and perimeter rake to aid in chemical reactions and to move the sludge to pits, where it is slowly pumped out and sent to sludge ponds. During this process, lime ($Ca(OH)_2$) and soda ash (Na_2CO_3) are added to remove carbonate and non-carbonate hardness, respectively, from the source water. A polymer is also added in the softening basin to aid in floc settlement and to thicken the sludge blanket. The pH in the softening basins is maintained above 10.6 to precipitate calcium carbonate and magnesium hydroxide out of solution. The total hardness is reduced to a level of approximately 100 mg/L as $CaCO_3$. The softened water is collected in effluent launders prior to being directed into the ozonation chambers. Fluoride is added at this point to improve the dental health of consumers.

2.2.2. Ozonation and Recarbonation

After softening, water flows into the ozonation chambers for the oxidation of organics and T&O compounds, recarbonation, and primary disinfection. The MWTP is equipped with two ozonation chambers that are operated in parallel. Like the softening basins, one ozone chamber is utilized during low flows, and two chambers are used when flows exceed 5 mgd. Each ozone chamber is split by baffles into six cells (A-F). Ozone and carbon dioxide (CO_2) can be applied to water in cells A, C and E through fine bubble diffusers located at the bottom of each cell. Each ozone chamber can be divided into three sections based on the over-under flow pattern, as

illustrated in Figure 12. The volume and hydraulic retention time (HRT) of each section are shown in Table 2.

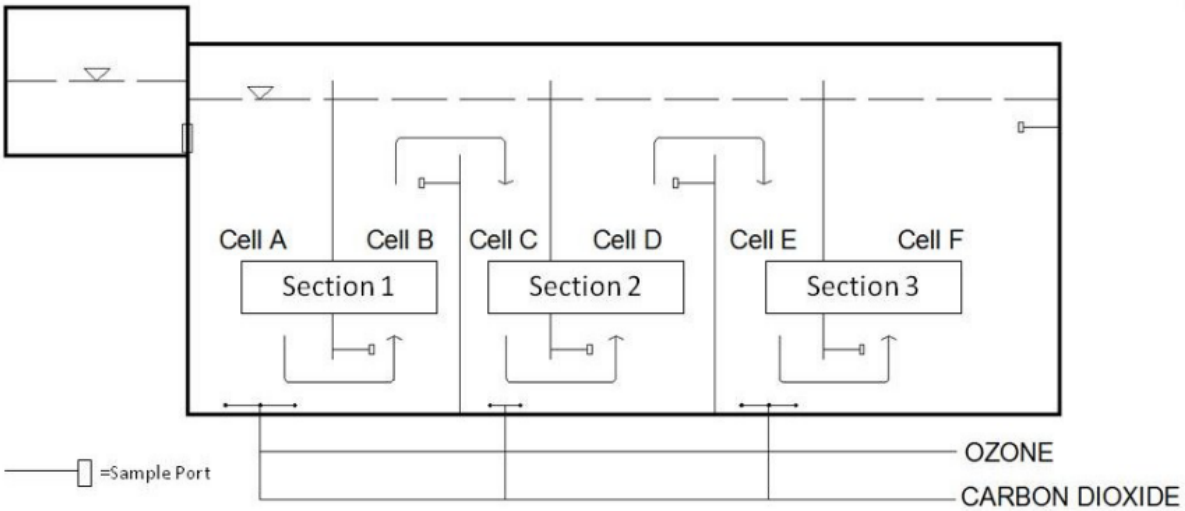

Figure 12. MWTP Ozone Chamber Schematic (Storlie, 2013)

Table 2. Ozone Chamber Volume and HRT (JMM Consulting Engineers, Inc., 1992)

Section	Volume (gal)	Design HRT at 5 mgd (min)
1	28,700	8.3
2	26,800	7.7
3	36,300	10.5

Each section of the ozone chamber serves a specific purpose. Section 1 (cells A and B) was designed to employ an advanced oxidation process (AOP) to oxidize organics and T&O compounds by applying ozone to water at a high pH (above 10.6 from the softening process). At a high pH, ozone will decompose to form hydroxyl radicals ($HO^{\bullet}$). The formation of $HO^{\bullet}$ is beneficial for the removal of organics and T&O compounds since they are a strong and non-selective oxidant.

Section 2 (cells C and D) is utilized for recarbonation to drop the pH from above 10.6 to a finished water level of approximately 9.30. The pH must be reduced to maintain a proper ozone

residual to meet disinfection requirements in subsequent cells. Originally, the ozonation chambers were designed for CO_2 to only be applied in cells C or E. However, the process was modified to include a CO_2 feed in cell A to reduce the pH earlier in the process, as will be explained further. CO_2 is typically applied in cells A or C, depending on the season. In the winter, CO_2 is applied to cell C to maintain a high pH in cells A and B for the oxidation of organics and T&O compounds. However, during the summer, CO_2 must be applied to cell A to lower the pH earlier in the process. During the summer, when water temperatures are warmer, the reaction rate and demand of ozone increases. Consequently, higher ozone doses must be applied to maintain the proper ozone residual in subsequent cells. Therefore, a decrease in pH earlier in the process reduces the necessary ozone dose. This not only aids in the facilities ability to maintain an ozone dose within the operating range of equipment, but also reduces bromate formation. If the summer recarbonation method results in an undesirably low pH, the pH must be increased again. In this case, soda ash is added to the clearwell to raise the finished water pH back up to 9.30.

The main purpose of the ozonation process is for primary disinfection, which occurs in Section 2, as well as Section 3 (cells E and F). The MWTP is required to inactivate 3-log (99.9%) Giardia and 4-log (99.99%) virus by the U.S. Environmental Protection Agency (USEPA) Surface Water Treatment Rule (SWTR). The MDH monitors the MWTP for compliance and has granted the MWTP with 2.5-log Giardia credit and 2-log virus credit for the inactivation achieved through the softening process. Therefore, a required inactivation of 0.5-log Giardia and 2-log virus remains for the ozone disinfection process.

The USEPA has developed a required CT (disinfectant concentration × contact time) based on water temperature for ozone inactivation of Giardia and viruses, as described in Table

3. With ozone disinfection, 2-log virus inactivation requires a higher CT than 0.5-log Giardia inactivation. Therefore, 2-log virus inactivation is the controlling factor for disinfection. A plot of the USEPA required CT against temperature is shown in Figure 13. By connecting the first and last points of the required CT for 2-log virus inactivation, a linear equation was developed to use as a conservative benchmark for required CT. This linear equation was then programmed into the MWTP Supervisory Control and Data Acquisition (SCADA) system to calculate the required CT in real time.

Table 3. CT Values for Ozone Inactivation of Giardia and Viruses (USEPA, 1999a)

Temperature (°C)	1	5	10	15	20	25
0.5-log Giardia	0.48	0.32	0.23	0.16	0.12	0.08
2.0-log Viruses	0.9	0.6	0.5	0.3	0.25	0.15

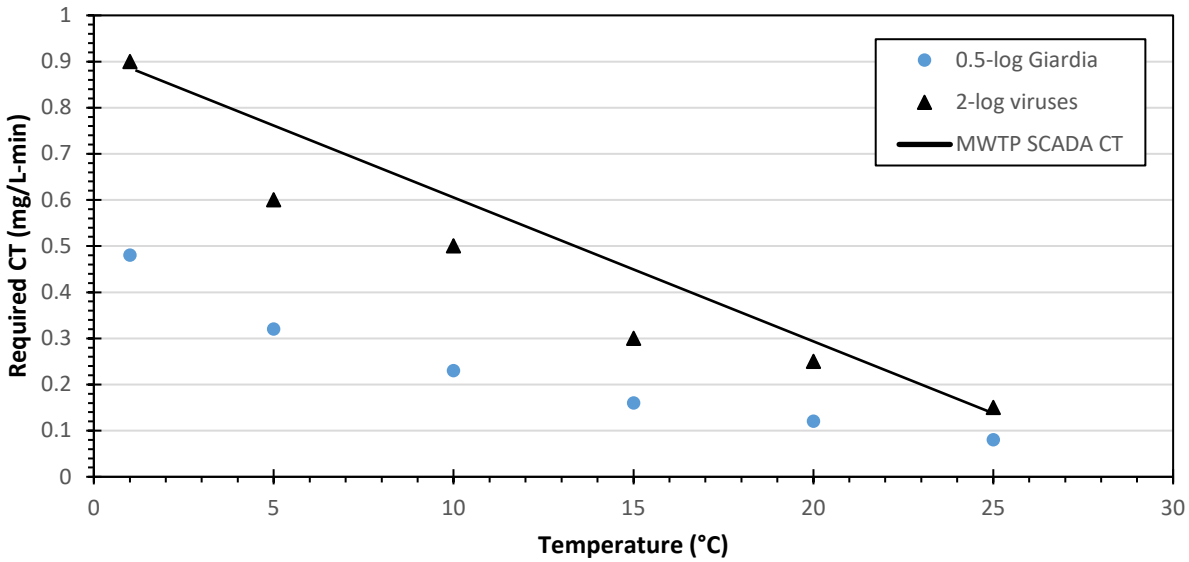

Figure 13. USEPA Required CT and MWTP SCADA CT (MWTP, 2018)

The actual CT achieved in the ozonation chamber is also calculated in real time by SCADA, so it can be compared against the required CT. The actual CT in the ozonation chamber is calculated by multiplying the ozone residual by the HRT in sections 2 and 3. Section 1 is not

included in this calculation, since it was designed for the oxidation of organics and T&O compounds. The equation used to calculate the actual CT in the ozonation chambers is shown below in Equation 1. A baffling factor of 0.7, which assumes superior mixing and very little short-circuiting in the chamber, was determined by the MDH when the ozone chambers were designed.

$$Actual\ CT\ \left(\frac{mg}{L} \times min\right) = 0.7\left[C_2\left(\frac{V_2}{Q}\right) + C_3\left(\frac{V_3}{Q}\right)\right] \quad (1)$$

$Where,$

$C\ =\ ozone\ residual\ in\ the\ effluent\ of\ sections\ 2\ and\ 3, mg/L$

$V\ =\ volume\ of\ each\ section, gal$

$Q\ =\ flow\ rate\ through\ the\ ozone\ chambers, gpm$

$0.7\ =\ baffling\ factor$

The CT ratio (actual CT/required CT) is monitored by SCADA to ensure that disinfection requirements are being met. When the CT ratio is one or above, disinfection requirements are being met. However, when the CT ratio drops below one, the ozone dose needs to be increased or the pH needs to be dropped to regain compliance.

After ozonation, calcium thiosulfate (CaO_3S_2) may be added to quench any residual ozone. High ozone residuals generally occur during the winter due to the slower ozone decomposition rate. Sodium polyphosphate $(NaPO_3)_6$) is also added at this point to prevent the scaling or lead/copper leaching of pipes in the distribution system. Sodium polyphosphate prevents scaling by sequestering soluble metals (calcium and magnesium) to maintain their solubility in water. Sodium phosphate also forms a protective coating of insoluble mineral scale (phosphate salts) on the inside of pipes to keep lead/copper materials contained in the pipes from leaching into the water.

2.2.3. Filtration

After ozonation, water flows into the filters, which are used primarily for particle removal to prevent adverse health effects from exposure to pathogens. Pathogenic microorganisms can attach themselves to suspended particles, which may shield them from disinfection. Turbidity is commonly used to measure the concentration of suspended particles in the filtered water. Turbidity removal must meet criteria set forth by the USEPA SWTR and its provisions (USEPA, 1999b). Compliance with the SWTR is determined by filtered water turbidity, with regulatory limits described in Table 4.

Table 4. SWTR Requirements for Turbidity Removal (USEPA, 1999b)

Regulation	Compliance Indicator	Requirements
IESWTR(1)(3) LT1SWTR(2)(3)	CFWT(4)	<0.3 NTU 95% of the time <1.0 NTU any time
	IFWT(5)	<0.5 NTU(6) <1.0 NTU(7)

(1) Interim Enhanced Surface Water Treatment Rule

(2) Long Term 1 Enhanced Surface Water Treatment Rule

(3) These requirements apply to utilities using surface water or groundwater under the direct influence of surface water

(4) Combined filtered water turbidity

(5) Individual filtered water turbidity

(6) In any two consecutive measurements taken 15 minutes apart at the end of the first 4 hours of continuous filter operation after backwash

(7) In any two consecutive measurements taken 15 minutes apart

The MWTP utilizes dual-media filters with larger grain size anthracite on top of smaller grain size sand. The configuration of dual-media filters, with larger grain size media on top of smaller grain size media, encourages better penetration of solids into the filter bed and reduces

the rate of head loss development. Larger particles are removed by the anthracite and the smaller particles are strained out by the sand.

The MWTP utilizes four dual-media gravity filters, each 26 feet long by 13 feet wide, with a filtering area of 338 square feet. The filters were designed with 24 inches of anthracite coal with an effective size of 0.95-1.05 mm and 12 inches of silica sand with an effective size of 0.45-0.55 mm. The media is supported by five inches of torpedo sand with an effective size of 0.90-1.20 mm. The filters were designed to have a maximum hydraulic loading rate (HLR) of 5.1 gallons per minute per foot squared (gpm/ft^2), which corresponds to an empty bed contact time (EBCT) of 4.4 minutes. The average HLR to each filter between 2013 and 2017 was 2.6 gpm/ft^2 (EBCT of 9.8 minutes). The peak HLR during that period was 3.9 gpm/ft^2 (EBCT of 6.5 minutes) in September of 2014, and the minimum HLR was 1.1 gpm/ft^2 (EBCT of 23 minutes) in February of 2016. The filters are backwashed at regular time intervals based on past experience. The filters are generally operated for approximately 70 to 96 hours before they are backwashed.

Filter backwash sequences begin with an air scour to break up and dislodge particulate matter from the filter bed. The filters are then washed by reversing the flow of water upward through the filter at a rate that adequately fluidizes or expands the media. Backwash water is collected in troughs and is sent to a backwash water reclaim pit before being pumped back to the head of the plant. When the backwash is complete, the media is allowed to settle, with media of a lower density (anthracite) settling on top of media of a higher density (sand). Water is then filtered-to-waste for approximately one hour, or until filter effluent turbidity drops to below 0.1 NTU.

Filter effluent turbidities are very stable throughout the year. The average effluent turbidity for the filters from 2013 to 2017 ranged from 0.03 to 0.04 NTU. In addition to turbidity

removal, the filters are operated as biofilters and have the added benefit of removing easily biodegradable organic compounds generated during the ozonation process, as will be discussed in more detail in the next section.

2.3. Organics Removal Analysis in MWTP Processes

The MWTP is required to monitor the removal of TOC between the raw water and finished water sampling points per the USEPA Stage 1 Disinfectants and Disinfection By-Product (D/DBP) Rule to prevent the formation of disinfection by-products (DBPs), with removal requirements provided in Table 5. The percent removal requirements range from 15 to 50 percent and were developed with recognition of the tendency of TOC removal to become more difficult as alkalinity increases and TOC decreases (USEPA, 1999c). The average raw water alkalinity and TOC between 2013 and 2017 was 316 mg/L as $CaCO_3$, and 8.8 mg/L, respectively. Therefore, according to typical source water characteristics, the MWTP is required to remove approximately 25 to 30 percent of TOC in the raw water.

Table 5. Stage 1 D/DBP Rule TOC Removal Requirements (USEPA, 1999c)

Source Water TOC (mg/L)	Source Water Alkalinity (mg/L as $CaCO_3$)		
	0-60	>60-120	>120
>2.0 to 4.0	35.0%	25.0%	15.0%
>4.0 to 8.0	45.0%	35.0%	25.0%
>8.0	50.0%	40.0%	30.0%

As part of monitoring daily operations at the MWTP, TOC is measured at the following locations: raw water, well water, softening basin effluent, ozone chamber effluent, combined filter effluent, clearwell, and reservoirs. The following sections provide an analysis of available data on organics removal throughout each treatment process between 2013 and 2017. Organics removal is represented as concentration or percent removed from the previous process.

2.3.1. Organics Removal in the Softening Basins

Most TOC removal occurs in the softening basins at the MWTP. TOC removal in the softening basins between 2013 and 2017 is shown in Figure 14. During this period, TOC removals ranged between 2.2 mg/L (29%) and 11 mg/L (90%) with an average removal of 5.2 mg/L (58%). No significant seasonal variations in effluent TOC concentrations were observed.

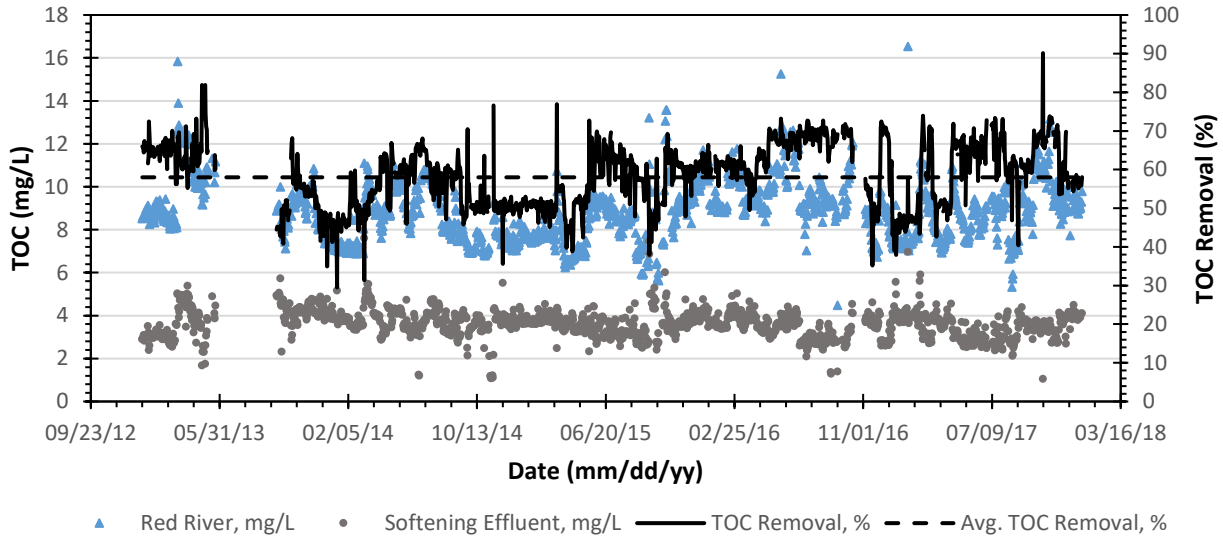

Figure 14. TOC Removal in MWTP Softening Basins (2013-2017)

2.3.2. Organics Removal in the Ozone Chambers

While significant TOC removal is achieved in softening basins, TOC removal in the ozonation chambers is typically less than 10 percent. A decrease in TOC is associated with the complete oxidation of organics into CO_2 and water, which does not occur to a significant extent during the ozonation process. Rather, the composition of organic compounds changes, as complex organic molecules are partially oxidized into smaller, more easily biodegradable compounds. TOC removals during the ozonation process at the MWTP between 2013 and 2017 are shown in Figure 15. During this period, the average TOC removal was 0.19 mg/L (5.3%), with higher TOC removals typically observed during the summer. TOC removals in the ozonation chamber were found to increase by approximately 10% from the cold to warm periods,

as shown in Figure 16. This is due to a combination of decreased ozone effectiveness at lower temperatures and the higher ozone doses utilized at the MWTP during the summer (Hurley, 2001).

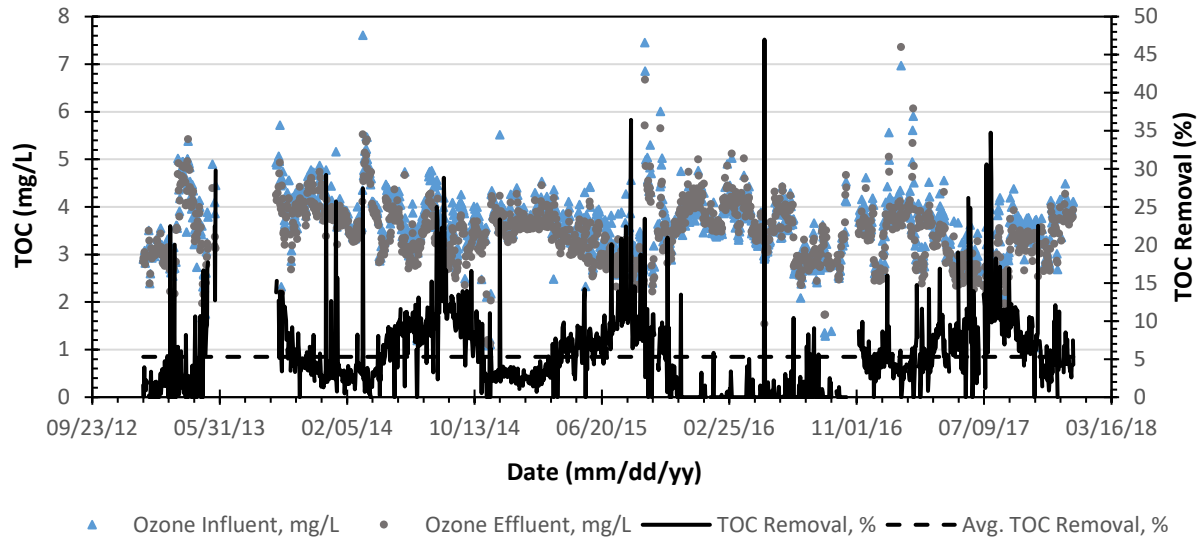

Figure 15. TOC Removal in MWTP Ozonation Chambers (2013-2017)

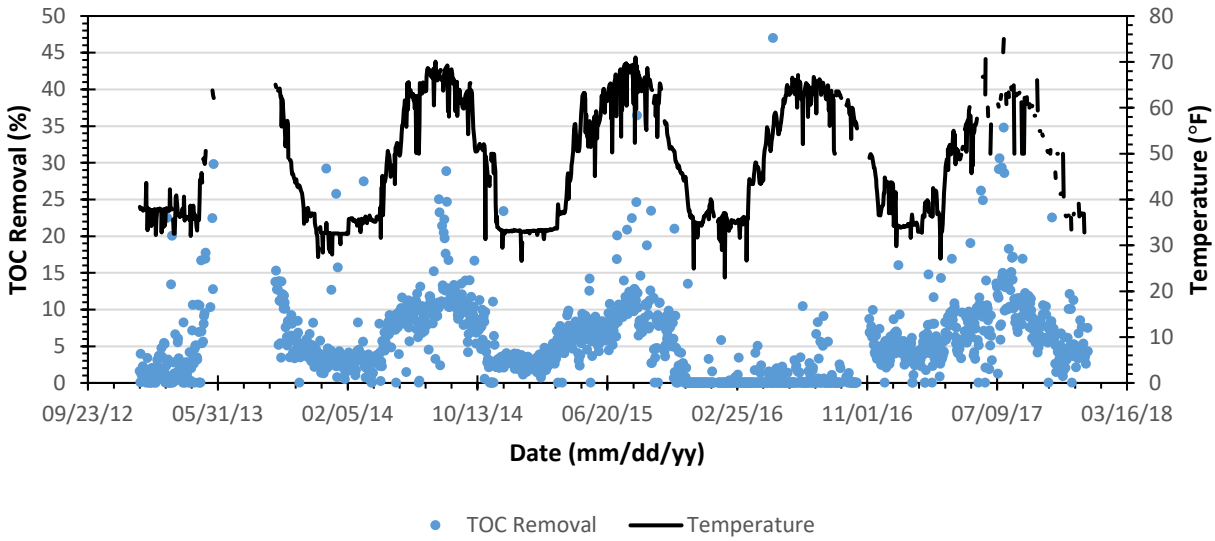

Figure 16. TOC Removal and Temperature in MWTP Ozonation Chambers (2013-2017)

UV absorbance at 254 nanometers (UV254) is an indicator of organic materials in a water sample containing aromatic rings or unsaturated bonds (double or triple), which have a strong absorbance of UV light at a wavelength of 254 nm. High UV254 in source water indicates

contamination with NOM that may not be biodegradable. However, limited data is available on UV254 reduction during the ozonation process at the MWTP, since in the past it has only been collected for research purposes. Previous work at the MWTP found that an average of 54 percent UV254 reduction occurred during the period studied (August 2012 to January 2013), as shown in Figure 17 (Storlie, 2013). This is due the oxidation of aromatic organic matter containing aromatic rings or unsaturated bonds.

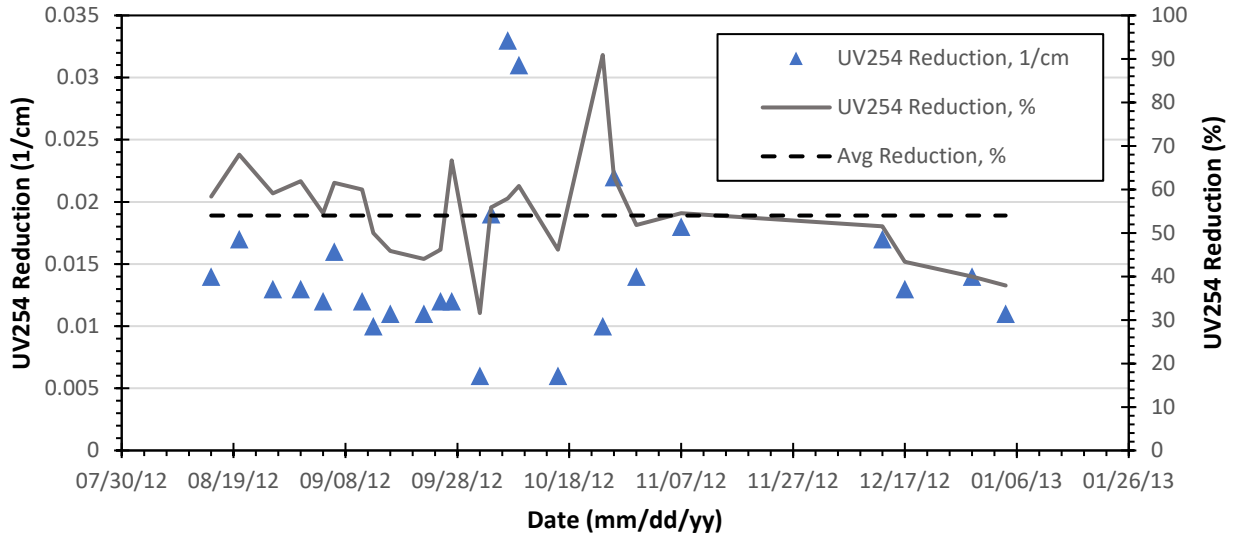

Figure 17. UV254 Reduction in MWTP Ozonation Process (Storlie, 2013)

Specific UV absorbance (SUVA) is a measure of the ratio of unsaturated bonds and/or aromaticity within the NOM. SUVA is defined as the UV absorbance (UV254) of a water sample normalized with respect to the dissolved organic carbon (DOC) concentration, as shown in Equation 2 below.

$$SUVA\ \left(\frac{L}{mg \times m}\right) = \frac{UV254}{DOC} \times 100 \qquad (2)$$

$Where,$

$UV254\ =\ 1/cm$

$DOC\ =\ mg/L$

$A\ conversion\ factor\ of\ 100\ cm/m\ is\ used\ to\ express\ SUVA\ as\ L/(mg \times m)$

SUVA > 4 indicates mainly hydrophobic and aromatic material, whereas a SUVA < 2 is mainly low molecular weight, hydrophilic material. SUVA values between 2 and 4 indicate the NOM consists of a mixture of aquatic humics and other NOM (Edzwald and Tobiason, 1999). Therefore, a decrease in SUVA generally reflects lower aromaticity and hydrophobicity of NOM, and hence, higher biodegradability.

Since UV254 is not analyzed regularly in the MWTP process, SUVA values cannot be calculated, and limited historical data is available. Previous research at the MWTP has found that SUVA values continually decrease throughout the ozone chamber, which demonstrates that partial oxidation is taking place. SUVA values and reductions that occurred throughout the ozone chamber between August 2000 and December 2000 are shown in Figure 18 and Figure 19, respectively. The greatest reduction in SUVA occurs in Section 1 (Zone 1), on average 0.38 L/mg-m, due to the initial application of ozone (Hurley, 2001). The very low ozone chamber effluent SUVA values, typically less than 1 L/mg-m, indicate that the filter influent water is mainly composed of easily biodegradable organic compounds, which must be effectively removed by subsequent biological filtration processes to prevent biological regrowth in the distribution system.

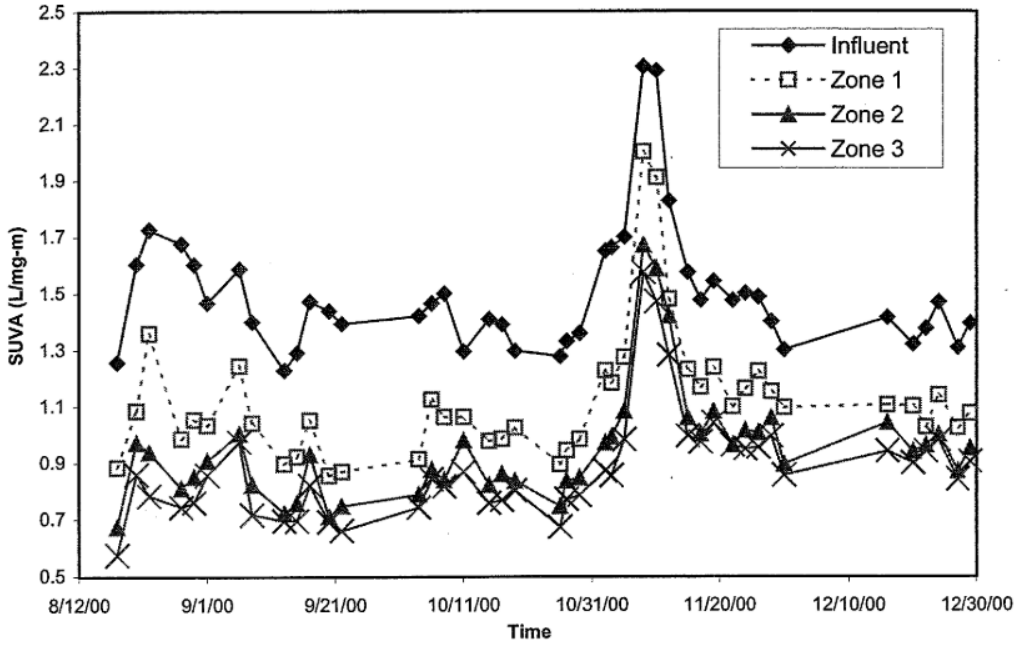

Figure 18. SUVA Values in MWTP Ozone Chamber (Hurley, 2001)

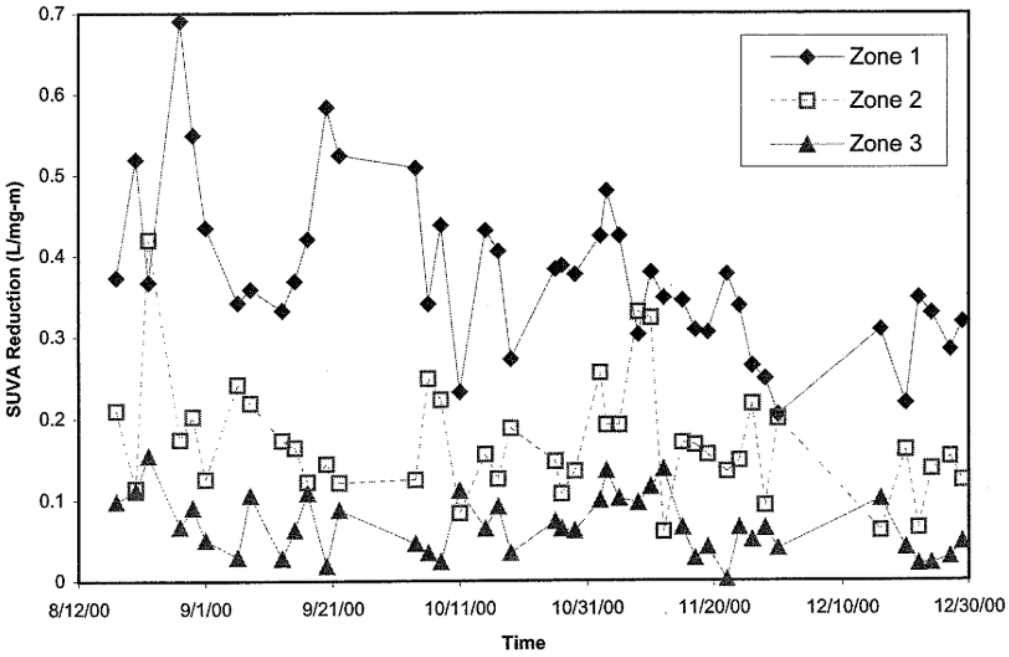

Figure 19. SUVA Reduction in MWTP Ozonation Process (Hurley, 2001)

2.3.3. Organics Removal in the Filters

TOC removal in the MWTP filters varies significantly throughout the year. TOC removal in the MWTP filters between 2013 and 2017 is shown in Figure 20. During this period, TOC removals ranged from no removal up to 1.7 mg/L (36%) with an average removal of 0.19 mg/L (5.8%). It was also observed that TOC removal in the filters is significantly impacted by temperature, as presented in Figure 21. While up to 20 percent TOC removal is achieved during the warmer months, typically less than five percent removal occurs during the colder months. This is due to less biological activity in the filters under cold conditions.

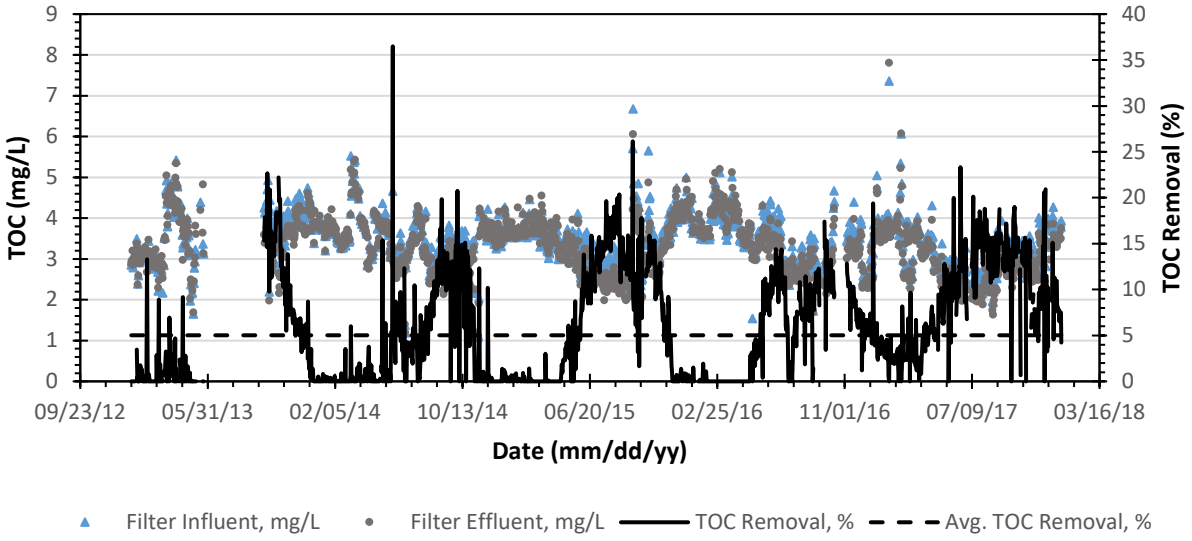

Figure 20. TOC Removal in MWTP Filters (2013-2017)

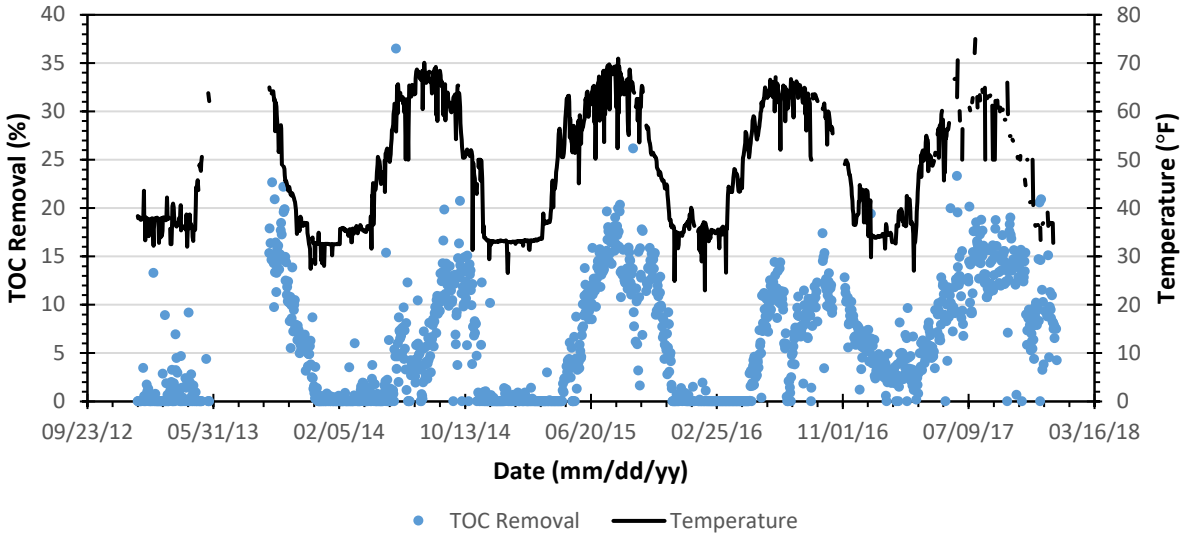

Figure 21. TOC Removal and Temperature in MWTP Filters (2013-2017)

2.3.4. Summary of Organics Removal in MWTP Process

TOC removals between the raw and finished water sampling points in the MWTP between 2013 and 2017 averaged 5.6 mg/L (62%), as shown in Figure 22. A summary of TOC removal throughout the MWTP process is given in Table 6. Although USEPA removal requirements of 25 to 30 percent are exceeded during treatment at the MWTP, effluent TOC concentrations in the finished water are still relatively high. Finished water effluent TOC concentrations ranged between 1.2 and 6.9 mg/L with an average of 3.3 mg/L between 2013 and 2017. A decrease in finished water TOC levels would also inherently reduce levels of easily biodegradable organics. Ultimately, this would lead to the production of more biologically stable water and reduce the potential for biological regrowth in the Moorhead distribution system.

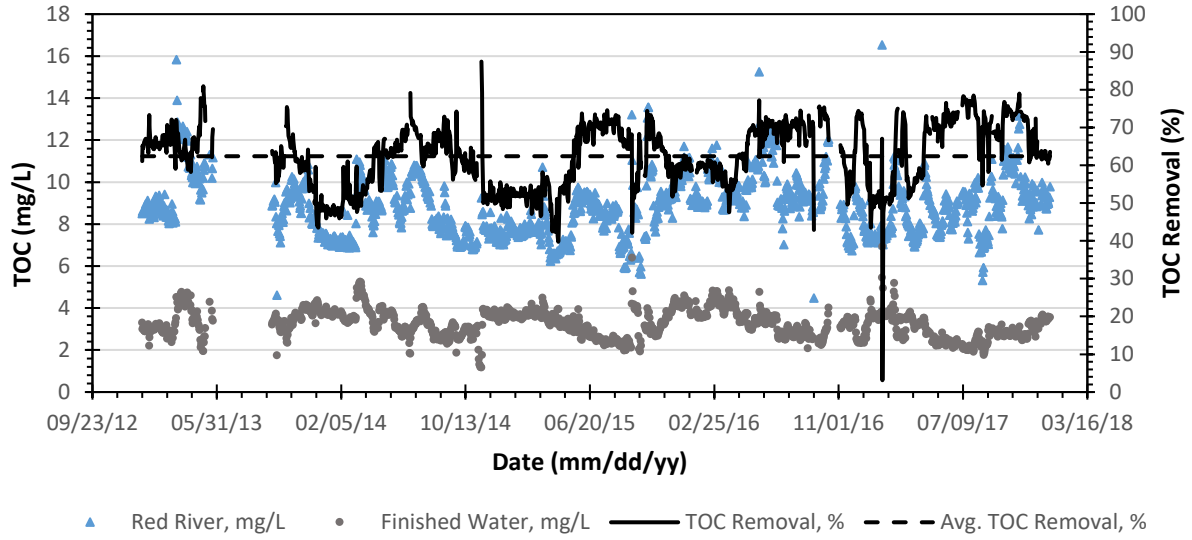

Figure 22. Total TOC Removal in MWTP Process (2013-2017)

Table 6. TOC Removal Summary in MWTP Processes (2013-2017)

	Min. TOC Removal		Avg. TOC Removal		Max. TOC Removal	
Treatment Process	mg/L	%	mg/L	%	mg/L	%
Softening	2.2	29	5.2	58	11	90
Ozonation	0.0	0.0	0.19	5.3	2.1	47
Filtration	0.0	0.0	0.19	5.8	1.7	36
Total	0.22	3.1	5.6	62	11.8	87

TOC removal expressed in concentration or percent of previous process

CHAPTER 3. LITERATURE REVIEW

The purpose of this chapter is to provide a review of previous literature related to biofiltration in drinking water treatment. The main focus of this review is to obtain a comprehensive understanding of the removal mechanisms in biofilters, which are physical, chemical, and biological in nature. The effects of filter media type (specifically, sand, anthracite, and GAC) and temperature on biofilter performance will be considered. First, the physical aspects of granular media filtration need to be understood, which are covered in section 3.1. Then, the biological aspects of filtration are reviewed in section 3.2.

3.1. Granular Media Filtration

Filtration is a process that follows coagulation, flocculation, and sedimentation in conventional drinking water treatment. Filtration provides the final barrier to protect from the release of particles and microbes into the distribution system.

The USEPA SWTR was developed primarily to prevent the introduction of pathogens into distribution systems. The SWTR requires drinking water treatment facilities to filter and disinfect surface water sources. However, surface water sources that meet criteria for water quality and watershed protection only require disinfection (USEPA, 1999b).

The mechanisms by which particles are removed in granular media filters are complex and are influenced by the chemical characteristics of the water being treated, the physical and chemical characteristics of the suspended particles and the filter media, and the method of operation of the filter (Weber Jr., 1972). In this section, the influence of the physical characteristics of the filter media on particle removal will be discussed.

3.1.1. Overview of Granular Media Filtration Process

During conventional granular media filtration, water that contains suspended particles flows downward through a packed bed of porous media in which the particles are captured. This process continues until the filter needs to be cleaned, or backwashed. The period between backwashes is commonly referred to as a filter run.

The behavior of filters throughout each run is dynamic and is often measured by head loss and filter effluent turbidity. Head (or pressure) loss is the head required to produce a given flow through a bed of filter media. The accumulation of particles in the filter bed results in an increase in head loss from the initial, or clean bed head loss.

Filter effluent turbidity generally follows three stages: ripening, effective filtration, and breakthrough. During ripening, the effluent quality begins to improve as captured particles serve as additional particle collectors (Darby and Lawler, 1990; Moran et al., 1993a). Different layers of the filter bed can be at different stages simultaneously. For example, breakthrough may occur in the top of the filter bed while the bottom is still ripening (Benjamin and Lawler, 2013).

Breakthrough is a term commonly used to refer to the rapid increase of turbidity in the effluent. Breakthrough is caused either by a lack of particle attachment or the detachment of previously captured particles (Moran et al., 1993b). As particles accumulate in the filter bed, the fluid velocities within the pores of the filter bed increase, along with the hydrodynamic shear on the captured particles (Hunt et al., 1993). The retention of particles in a filter bed requires that the adhesion force between the filter grain (or previously deposited particles) and the particle is greater than or equal to the hydrodynamic shear. When the hydrodynamic shear exceeds the adhesive force, particles will be sheared away and pushed deeper into the filter bed

(Amirtharajah, 1988; Bai and Tien, 1997; Bergendahl and Grasso, 2000). A generic plot of head loss and effluent turbidity throughout a typical filter run is shown in Figure 23.

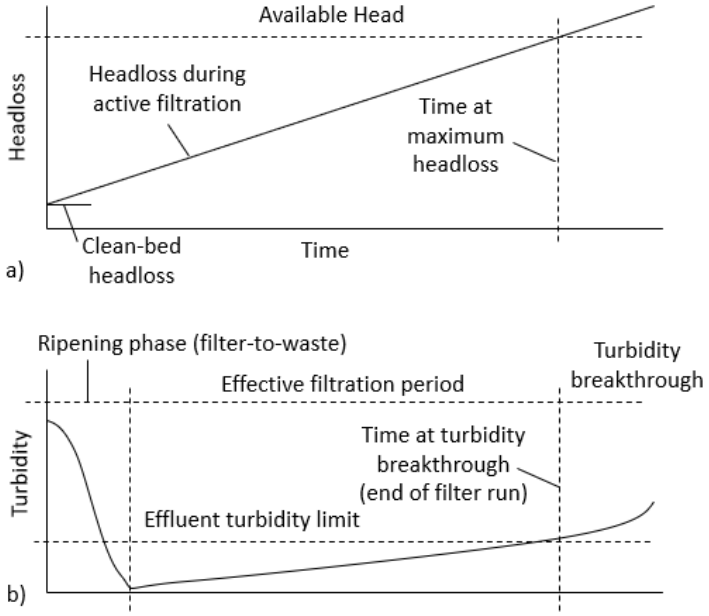

Figure 23. Typical Filter Performance in Single Run

After a period of operation, the head loss or effluent turbidity reaches a predetermined value, and the filter must be cleaned. Filters are usually designed such that the maximum head loss governs the end of the filter run to avoid turbidity breakthrough. In some cases, filters are backwashed at a regular time interval based on experience with the above two criteria. Backwashing is accomplished by reversing the flow through the filter and is often assisted with an air scour system to break up and dislodge particulates.

3.1.2. Filter Media Type and Properties

Granular media filtration is influenced by the properties of the filter media and the filter bed configuration (selection of single, dual, or multi-media filters). Important filter media properties include grain size and uniformity, filter bed depth, grain shape and filter bed porosity, and grain roughness.

3.1.2.1. Size, Uniformity, and Depth

Grain size is a property that is well known to affect filter performance. Grain size is commonly defined by the effective size (ES), which is determined by sieve analysis. The ES is the diameter at which 10 percent of the grains are smaller by weight (EPA, 1995).

Grain size must be selected to achieve effective particle removal without excessive head loss. A decrease in grain size results in filter beds with smaller pore spaces (Amirtharajah, 1988) and a higher initial head loss (Crittenden et al., 2012). Smaller pore spaces confine the effective zone of removal to the upper portion of the filter bed. As a result, removal efficiency improves but head loss development increases. Higher rates of head loss development are undesirable since they shorten the length of the filter run. On the other hand, an increase in grain size results in filter beds with larger pore spaces. This facilitates the passage of particles deeper into the filter bed. Consequently, head loss development decreases but removal efficiency also decreases (Goldgrabe et al., 1993; Kau and Lawler, 1995; Moran et al., 1993a).

Filter bed depth is also known to significantly influence filter performance (Amini, 1996; Tchio et al., 2003). The lower removal efficiencies obtained with larger grain size media can be offset with an increase in filter bed depth due to more surface area available for particle attachment (Kau and Lawler, 1995; Moran et al., 1993a; Trussell et al., 1980). In addition, filter bed depth affects head loss. For example, an increase in filter bed depth results in an increase in initial head loss (Crittenden et al., 2012).

The uniformity of the filter media also affects filter performance; however, to a lesser extent than grain size or filter bed depth (Tchio et al., 2003). The uniformity of the filter media is defined by the uniformity coefficient (UC). The UC represents the grain size distribution of the media, as determined by sieve analysis. The UC is defined as the ratio of the diameter at which

60 percent of the grains are smaller by weight to the ES (EPA, 1995). A lower UC represents more uniformly distributed grain sizes. Filter media tends to stratify during backwash, where fine grains collect at the top of the filter bed and large grains settle to the bottom. This results in more particle removal at the surface of the filter bed and shorter filter run times. A lower UC increases particle removal throughout the depth the filter bed and minimizes this effect (Edzwald, 2011).

3.1.2.2. Grain Shape and Filter Bed Porosity

Grain shape has a significant influence filter performance. Grain shape is commonly characterized as rounded (spherical) or angular. Grain shape mainly influences the porosity of the filter bed (Baylis, 1937). The porosity is defined as the ratio of the void volume to the total bed volume. The porosity depends on how well the grains pack together in a filter bed. For example, as filter grains become more spherical, the porosity of the filter bed decreases (Crittenden et al., 2012). The porosity of the filter bed is known to significantly influence head loss. For example, filter beds with a higher porosity will have a lower initial head loss (Crittenden et al., 2012). In addition, longer filter run times have been attributed to the higher porosity of angular materials (Hazen, 1950; Trussell et al., 1980).

Limited studies have also shown that grain shape affects particle removal efficiency. Angular materials have been shown to demonstrate better particle removal than spherical materials in drinking water filtration (Suthaker et al., 1995; Trussell et al., 1980). However, these studies did not explain why grain shape affected particle removal. Other studies found that angular materials more efficiently capture particles through straining at grain to grain contacts (Barton and Buchberger, 2007; Tufenkji et al., 2004).

3.1.2.3. Grain Roughness

Grain roughness has been recognized to be an important factor in particle removal. Roughness is a term used to describe the texture of the filter grain surface and should not be confused with grain shape. Asperities that are large enough to impact grain shape are better defined by angularity. Currently, there is no standard method to quantitatively describe surface roughness. However, scanning electron microscope (SEM) analysis has been used in several studies to observe the surface morphology of granular filter media (Bai and Zhang, 2001; Wang et al., 2007; Weber et al., 1978).

Most studies on the subject of media surface roughness have been in the form of modelling and bench-scale experiments. Modelling studies have used surface roughness to explain discrepancies between theoretical predictions and experimental observations of particle and surface interactions (Bhattacharjee et al., 1998; Elimelech and O'Melia, 1990; Huang et al., 2009). Several bench-scale studies have found that surface roughness can enhance particle removal. Kau and Lawler (1995) compared spherical glass beads to sand for turbidity removal in a bench-scale column study. It was found that the sand media demonstrated higher initial turbidity removal and faster filter ripening (Kau and Lawler, 1995). Similarly, Shellenberger and Logan (2002) observed 50% higher latex microsphere removal on rough glass beads as compared to smooth beads (Shellenberger and Logan, 2002).

Researchers have observed that surface roughness can reduce the occurrence of particle detachment. As previously mentioned, an increase in hydrodynamic shear has been recognized as a significant factor in particle detachment. It is thought that surface asperities provide areas with reduced hydrodynamic shear (Bergendahl and Grasso, 2003). This suggests that particles captured between surface asperities are protected from hydrodynamic shear. Batra et al. (2001)

theoretically investigated the detachment of particles from a surface when subjected to hydrodynamic shear. It was observed that the hydrodynamic shear force required for detachment increased along with an increase in asperity height (Batra et al., 2001).

While several studies have found surface roughness to enhance particle removal, other studies have found that surface roughness does not necessarily result in better particle removal. Morales et al. (2009) reported that a rough surface resulted in a 20% increase in particle removal when relatively small media (effective size of 0.3-0.4 mm) was used. However, no differences in particle removal were observed between rough and smooth media when relatively larger media (0.8-1.2 mm) was used (Morales et al., 2009). Jin et al. found that media surface roughness can either increase or decrease particle removal due to the existence of a critical roughness size (Jin et al., 2017). For example, it was found that the critical roughness size for minimum particle removal depends on the relationship between particle and filter grain size.

Some studies have reported that rough surfaces result in less particle removal relative to smooth surfaces. Tabor (1977) found that rough surfaces decreased particle removal. It was suggested that larger particles cannot fit between surface asperities to be sheltered from hydrodynamic shear and also do not achieve direct contact over the entire surface area (Tabor, 1977). Ko and Elimelech (2000) found that particle removal was substantially reduced due to the creation of shadow zones downstream of surface asperities (Ko and Elimelech, 2000).

3.1.2.4. Filter Bed Configuration

Filter media may be used alone (single-media) or in combination with other media (dual- or tri-media). In single-media filters, which typically consist of sand, most of the particle removal occurs in the top layer of the filter. This can increase the rate of head loss development and decrease filter run times. Consequently, single-media filters are seldomly used in modern

filters in the United States (Monk, 1987). A dual-media filter that consists of a coarse layer of anthracite coal on top of a finer layer of silica sand is more commonly used. The dual-media configuration allows for the penetration of particles deeper into the filter bed, which decreases the rate of head loss development and increases filter run times (Mohanka, 1969; Zouboulis et al., 2007).

3.1.3. Particle Removal Mechanisms

In general, particle removal in granular media filters occurs by the mechanisms of surface straining and depth filtration. Straining involves the exclusion of particles larger than the pore spaces in the filter. As previously described, surface straining causes a layer to form at the surface of the filter bed. This results in rapid increases in head loss and shorter filter run times. Although a majority of the particles that enter the filters are smaller than the pore spaces of the filter (with adequate pretreatment), surface straining cannot be completely avoided. Consequently, filters are often designed to minimize straining and to encourage removal within the filter bed, which is referred to as depth filtration (Crittenden et al., 2012).

In depth filtration, particles are smaller than the pore spaces in the filter and must be removed in two distinct steps: transport and attachment (O'Melia and Stumm, 1967). In the first step, the particles must be transported from the fluid streamlines within the pore spaces of the filter to the vicinity of the filter grain surface or previously deposited particles. Second, as the particle approaches the surface of the filter grain, an attachment mechanism is required to retain the particle. Particle transport is a physical process. However, particle attachment is mainly a chemical process (O'Melia and Stumm, 1967).

The mechanisms involved in depth filtration include interception, sedimentation, flocculation, and straining, as shown in Figure 24. The relative importance of each mechanism

depends on several factors such as flow conditions (HLR, water temperature), filter bed geometry, and particle characteristics (size, shape, density) (Jegatheesan and Vigneswaran, 2005). These mechanisms are also influenced by other factors such as biological growth within the pore spaces of the filter bed (Metcalf & Eddy, 2014).

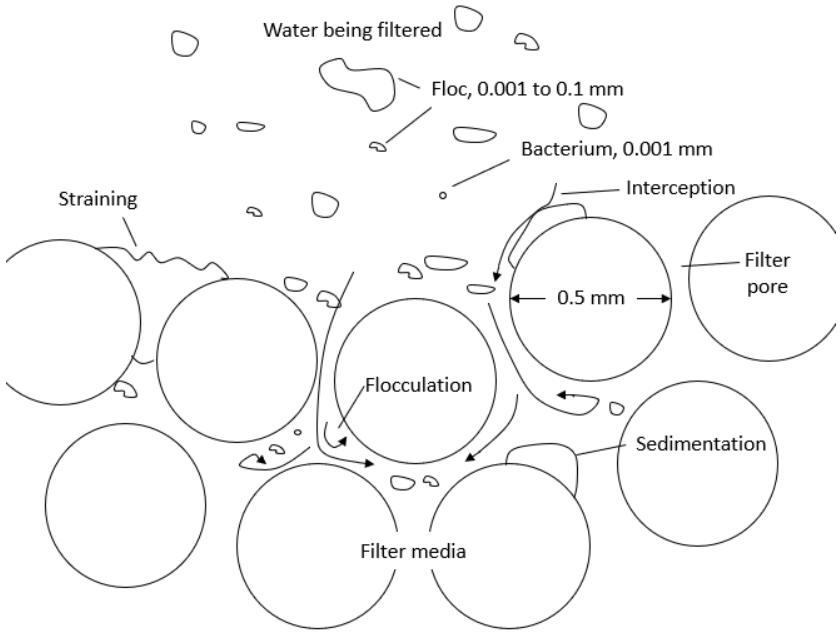

Figure 24. Particle Removal Mechanisms

3.1.3.1. Transport Mechanisms

Mechanisms which transport the particle to the vicinity of the filter grain surface for attachment include interception and sedimentation. The mechanism of interception occurs when the particle remains in the center of the fluid streamline and approaches the filter grain surface to within the particle radius (Jegatheesan and Vigneswaran, 2005). Interception is significantly influenced by grain size. Stevenson (1997) conducted modelling experiments and found that particle removal efficiency varied with the inverse cube of grain size when interception was considered as a transport mechanism (Stevenson, 1997).

The mechanism of sedimentation occurs due to gravitational forces and the associated settling velocity of the particle, which cause it to migrate across the fluid streamlines and contact the filter grain surface (Zamani and Maini, 2009). For this mechanism to occur, the particles must have a density significantly greater than that of water. Sedimentation is also influenced by grain size; however, to a lesser extent than interception. Stevenson (1997) found that particle removal efficiency varied with the inverse of grain size when sedimentation was considered as a transport mechanism (Stevenson, 1997).

3.1.3.2. Hydrodynamic Action

Hydrodynamic action within the pores of the filter bed influences the transport of particles to the filter grain surface. A velocity gradient exists in the pores of the filter bed with zero velocity at the boundary of the filter grain surface and a maximum velocity at the pore center. The velocity gradient creates a shear field in each pore. The shear field causes particles to cross the fluid streamlines, which may cause them to reach the filter grain surface (Jegatheesan and Vigneswaran, 2005). The shear field in each pore is influenced by the pore geometry of the filter bed. However, the effect of hydrodynamics on particle motion in depth filtration is difficult to define due to the complexity of the pore geometry (Zamani and Maini, 2009).

3.1.3.3. Flocculation

Flocculation has been suggested to influence particle removal during granular media filtration (Metcalf & Eddy, 2014). Flocculation is influenced by the shear field in the filter bed pores. The shear field in the filter pores causes mixing, which causes smaller particles to contact one another and aggregate (flocculate) (Jegatheesan and Vigneswaran, 2005). Flocculation is not a direct removal mechanism, rather it contributes to removal. The larger, aggregated particles can

deviate from the streamlines more easily and may be removed by other mechanisms such as interstitial straining or sedimentation (Metalf & Eddy, 2014).

3.1.3.4. Biological Growth

Some studies suggest that biological growth can influence particle removal. First, biological growth within the filter will reduce the pore volume and may enhance removal by other mechanisms such as straining (Metcalf & Eddy, 2014). For example, Cunningham et al. investigated the influence of biofilm accumulation on porous media hydrodynamics in a bench-scale biofilm reactor study. It was observed that the accumulation of a biofilm resulted in a decrease in media porosity and permeability, and an increase in the friction factor of the media (Cunningham et al., 1991). However, the effects on particle removal were not evaluated. Second, it has been proposed by some researchers that the sticky extracellular polymers produced by the microorganisms can enhance particle removal (Bellamy et al., 1985).

3.1.3.5. Effect of Temperature

Water temperature has been recognized as an important factor that affects particle removal. As temperatures decrease, the water becomes more viscous and the settling velocity of the particles also decrease (Cole, 1976). As a result, the probability of removal decreases. For example, water temperature plays an important role in sedimentation since the effectiveness of this mechanism depends on the viscosity of the water (Amirtharajah, 1988).

3.2. Biofiltration in Drinking Water Treatment

Biofiltration has become increasingly popular in North America since the 1980s due to more stringent water quality regulations and the more prevalent use of ozone (Uhl, 2000; Urfer et al., 1997). Biofiltration refers to the process in which a filter is used not only for particle removal, but also for the microbial degradation of organics (Basu et al., 2016).

Biofiltration is usually applied after ozonation, since ozone partially oxidizes large recalcitrant humic acid molecules into smaller, more easily biodegradable organic matter (BOM) (Owen et al., 1995). This increase in BOM upon ozonation often promotes biological regrowth in the distribution system if left untreated (Prest et al., 2016). During biofiltration, BOM is utilized by bacteria attached to the surface of the filter media as an energy supply and carbon source (Chaudhary et al., 2003). As a result, BOM is reduced along with the potential for biological regrowth in the distribution system.

3.2.1. Effect of Filter Media

Several types of granular media can be used for biofiltration including sand, anthracite, and GAC. However, GAC provides several benefits. Due to its adsorptive capacity, GAC can attenuate high influent contaminant concentrations, which can then be gradually desorbed (Herzberg et al., 2005). Traditionally, once the adsorptive capacity of the GAC is exhausted it is either regenerated or replaced. However, it can also be maintained in the filter bed and allowed to develop a biofilm. Once the GAC develops a natural biofilm, it is commonly referred to as biological activated carbon (BAC).

In past years, several studies have compared adsorptive (GAC) and non-adsorptive (sand and anthracite) media for biological BOM removal (Urfer et al., 1997). Some of these studies suggest that each type of media performs similarly (Krasner et al., 1993). However, other studies suggest that GAC can be more effective as a biofiltration media (Lechevallier et al., 1992; Wang et al., 1995). The advantage of GAC may be that it provides a better surface for microbial attachment and growth. Bacteria cannot enter the GAC micropores due to their relatively small pore diameter of less than 2 nm as compared to the diameter of bacteria, which is generally greater than 200 nm (Urfer et al., 1997). However, the macroporous structure and rough surface

of the GAC provides recesses which may shelter the biofilm from hydrodynamic shear stresses (Chang and Rittmann, 1987). Furthermore, GAC can adsorb slowly biodegradable constituents that can be subsequently biodegraded by the attached biomass leading to regeneration of the GAC (Chaudhary et al., 2003).

3.2.2. Effect of Temperature

Most research related to biofiltration in drinking water treatment has demonstrated that a decrease in water temperature results in lower organics removal. For example, at lower operating temperatures, there is less biological activity, which leads to lower organics removal efficiencies (Moll et al., 1999). Some studies have observed that BAC filters are less affected by cold water temperatures than anthracite or sand filters (Emelko et al., 2006; Liu et al., 2001). This suggests that GAC may mitigate the effect of cold water temperatures; however, the reason for this is not well understood. On the other hand, some studies have demonstrated a minimal impact of temperature on organics removal during biofiltration (Melin and Ødegaard, 2000; Nishijima et al., 1998; Persson et al., 2006).

3.2.3. T&O Removal

The removal of taste and odor (T&O) compounds is another important benefit of GAC utilization. Geosmin (trans-1, 10-dimethyl-trans-9-decalol) and MIB (2-methylisoborneol) have been identified as major contributors to T&O in drinking water obtained from surface water (Srinivasan and Sorial, 2011). Geosmin and MIB are produced during the metabolic processes of bacteria (actinomycetes, cyanobacteria) and impart an earthy-musty odor to water. Currently, there are no regulations in place for geosmin and MIB, as they are not associated with any health risks. However, T&O is a common source of customer complaints, since consumers often

associate the safety of their drinking water with T&O. As a result, water utilities spend an average of between 5 and 9% of their total budget on T&O control (Suffet et al., 1996).

Geosmin and MIB are challenging to water utilities since they have odor threshold concentrations (OTCs) (concentration at which they can be detected by human senses) in the low ng/L range (Salemi et al., 2006; Zhang et al., 2005). In addition, geosmin and MIB cannot be effectively removed by conventional treatment processes (Nerenberg et al., 2000). Treatment methods that have been shown to be successful in removing geosmin and MIB from drinking water are activated carbon adsorption, advanced oxidation processes, and biological treatment (Elhadi et al., 2004; Ho and Newcombe, 2010; Westerhoff et al., 2006).

3.2.3.1. T&O Removal with GAC/BAC

GAC has been used successfully for the adsorption of T&O compounds in drinking water (Srinivasan and Sorial, 2011). Adsorption is a process in which contaminants partition from the liquid phase (water) onto the surface of a solid phase (GAC). The substance to be adsorbed is called the adsorbate, and the surface onto which it absorbs is referred to as the adsorbent.

Physical adsorption is the dominant adsorption mechanism in drinking water treatment (Crittenden et al., 2012). Adsorbates are considered to be physically adsorbed if the forces of attraction involve only physical forces, such as van der Waals forces. Physical adsorption is nonspecific for which components adsorb to surface sites. Physical adsorption is also reversible. That is, if the adsorbate concentration decreases or the adsorbate is displaced by a more strongly adsorbed species, desorption will occur (Crittenden et al., 2012).

The surface area and pore size distribution are important factors that affect adsorption. GAC is an effective adsorbent due to its high internal surface area ranging between 400 to 1500 m^2/g (Crittenden et al., 2012). The pore structure of the GAC consists of micropores, mesopores,

and macropores. Micropores are very small, with a pore diameter of less than 2 nm. Mesopores have pore diameters that range from 2 to 50 nm. While, macropores have pore diameters that exceed 50 nm (IUPAC, 1994). The micropores are where a majority of the adsorption occurs. However, the meso- and macropores are essential for internal transport to the micropore surface area (Chowdhury et al., 2013). The adsorption of NOM and T&O compounds occurs primarily in the pores that match the dimensions of the targeted contaminant. Therefore, most T&O compounds adsorb in the small micropores (Yu et al., 2007).

Competitive adsorption is an important factor to consider since T&O compounds compete for adsorption sites with background NOM (Herzing et al., 1977). Background NOM adsorbs onto the surface of the GAC and reduces the number of adsorption sites available for T&O compounds either by direct competition or by pore blockage (Li et al., 2003). The extent of competition depends on a variety of factors such as strength of adsorption of the competing adsorbates, the concentrations of these adsorbates, and the type of GAC (Edzwald, 2011). However, the pore size distribution of the GAC relative to the molecular weight of the adsorbates (T&O compounds and NOM) may be the dominant factor influencing competitive adsorption (Pelekani and Snoeyink, 1999).

GAC has a finite adsorption capacity. Studies have reported varying lengths of use with respect to T&O compound removal in GAC filters before the media needs to be regenerated or replaced. Some studies have suggested that the bed life of GAC filters for T&O removal can be extended to an order of years due to biological degradation (Scharf et al., 2010). Adsorption and biodegradation are known to be the removal mechanisms that contribute to T&O removal in BAC filters. However, it is difficult to identify the relative importance of the two mechanisms at different operational stages of the GAC filters. Some studies have suggested that adsorption still

played a significant role in the removal of micropollutants after the media had been exhausted with organics (Ho and Newcombe, 2010; Persson et al., 2007; Wang et al., 2007).

CHAPTER 4. MATERIALS AND METHODS

Materials and methods used to achieve the goals and objectives of this research are presented in this chapter. A description of the pilot filtration system design and operation, experimental methodologies, sampling procedures, sample analytical methods, and statistical analysis methods is provided.

4.1. Pilot Filtration System

The pilot filtration system utilized in the study is comprised of five 97.5-inch tall, 8-inch nominal diameter (7.942-inch inner-diameter) clear PVC columns that are operated independently from one another. Feed water was drawn from full-scale ozone chamber effluent after chemical addition (calcium thiosulfate, polyphosphate) to ensure that the pilot filters were treating the same water as the full-scale filters. Feed water was pumped to the top of each column via individual variable frequency drive pumps.

4.1.1. Pilot Filtration System Media

Adsorption capacities of the GAC media utilized in the study were exhausted with raw water for a period of six months prior to being placed into each column. Three types of GAC were evaluated. The GAC with the best overall performance throughout the study would be selected for full-scale media replacement. Calgon Filtrasorb 300 (F300) GAC is a reagglomerated carbon produced from a pulverized blend of bituminous coal. Jacobi AquaSorb CX (Jacobi) GAC is a coconut-based carbon. Cabot Norit 300 GAC (Norit 300) is a bituminous coal-based carbon (non-reagglomerated). The Jacobi GAC contains a large volume of micropores suitable for the removal of low molecular weight organics. The F300 and Norit 300 GACs contain a larger volume of meso- and macropores for general purpose organics reduction. The specifications for each type of media used in the study are described in Table 7.

Table 7. Pilot Filter Media Specifications

Media Characteristic	F300	Jacobi	Norit 300	Anthracite	Sand
Raw material	Bituminous coal (reagg.)	Coconut shell	Bituminous coal	Anthracite coal	Silica sand
Uniformity coefficient	2.1 (max)	<1.6	2.1 (max)	<1.5	<1.5
Effective size (mm)	0.8-1.0	1.0	0.8-1.0	0.95-1.05	0.45-0.55
Iodine number (mg/g)	900 (min)	1,100 (min)	900 (min)	NA	NA
Apparent Density (g/cc)	0.56	0.52	0.52	0.80	1.6

NA - Not applicable

Each column was filled with 36-inches of media, the same depth of the full-scale filters. The filter media and depth contained in each pilot column is shown in Figure 25. Columns 1 through 3 contained three different types of GAC, respectively. In Column 4, the purpose of the sand layer in addition to the GAC layer, was to determine if it was necessary to meet effluent turbidity requirements set forth by the USEPA. Finally, Column 5 served as the control column (mimic full-scale filter) and was filled with 24 inches of anthracite and 12 inches of silica sand obtained from the full-scale filters. Each column contained both media and water sampling ports at media depths of 8-, 14-, 26-, 32-inches. Each column contained an effluent sample port. A common influent sampling port was also available, as illustrated in Figure 26.

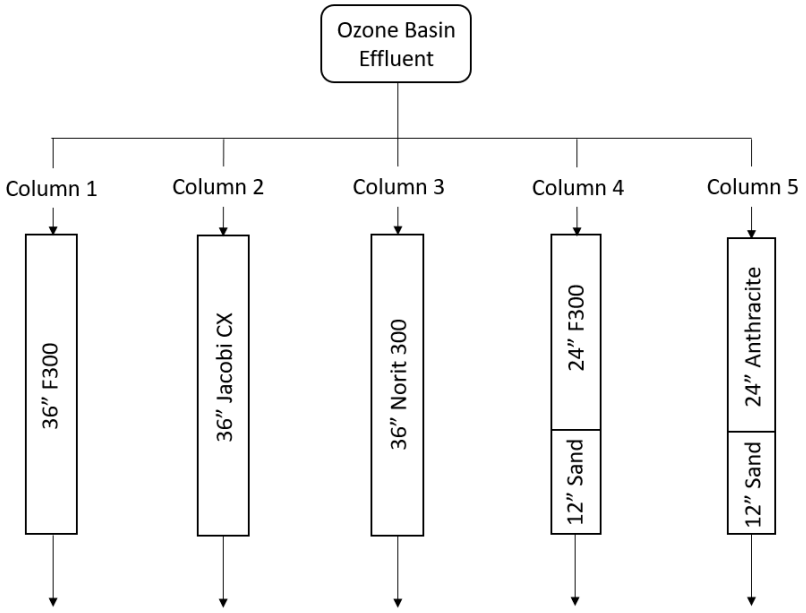

Figure 25. Pilot Column Filter Media and Depth Schematic

4.1.2. Online Data and Instrumentation

The pilot filter skid included online data logging every hour of flow rate, head loss, influent turbidity and dissolved oxygen (DO), as well as effluent pH, temperature, DO and turbidity. All online data generated was transmitted to a programmable logic controller, and skid controls were accessed through a digital display screen on the side panel of the skid. Historical data generated by the skid was then transmitted to the SCADA system for viewing in real-time and stored for future use on the historical data server.

Each column was outfitted with its own flow meter, differential pressure (DP) meter, turbidimeter, DO meter, and pH meter. Influent flow for each column was measured via a magnetic flow meter. Each column contained a DP meter to measure head loss. The turbidimeters have a functioning range of 0-1,000 NTU and utilize ultrasonic cleaning to achieve accurate online data. As part of the pilot study quality control, all instrumentation was calibrated and cleaned according to the manufacturer's recommendations or per standard method.

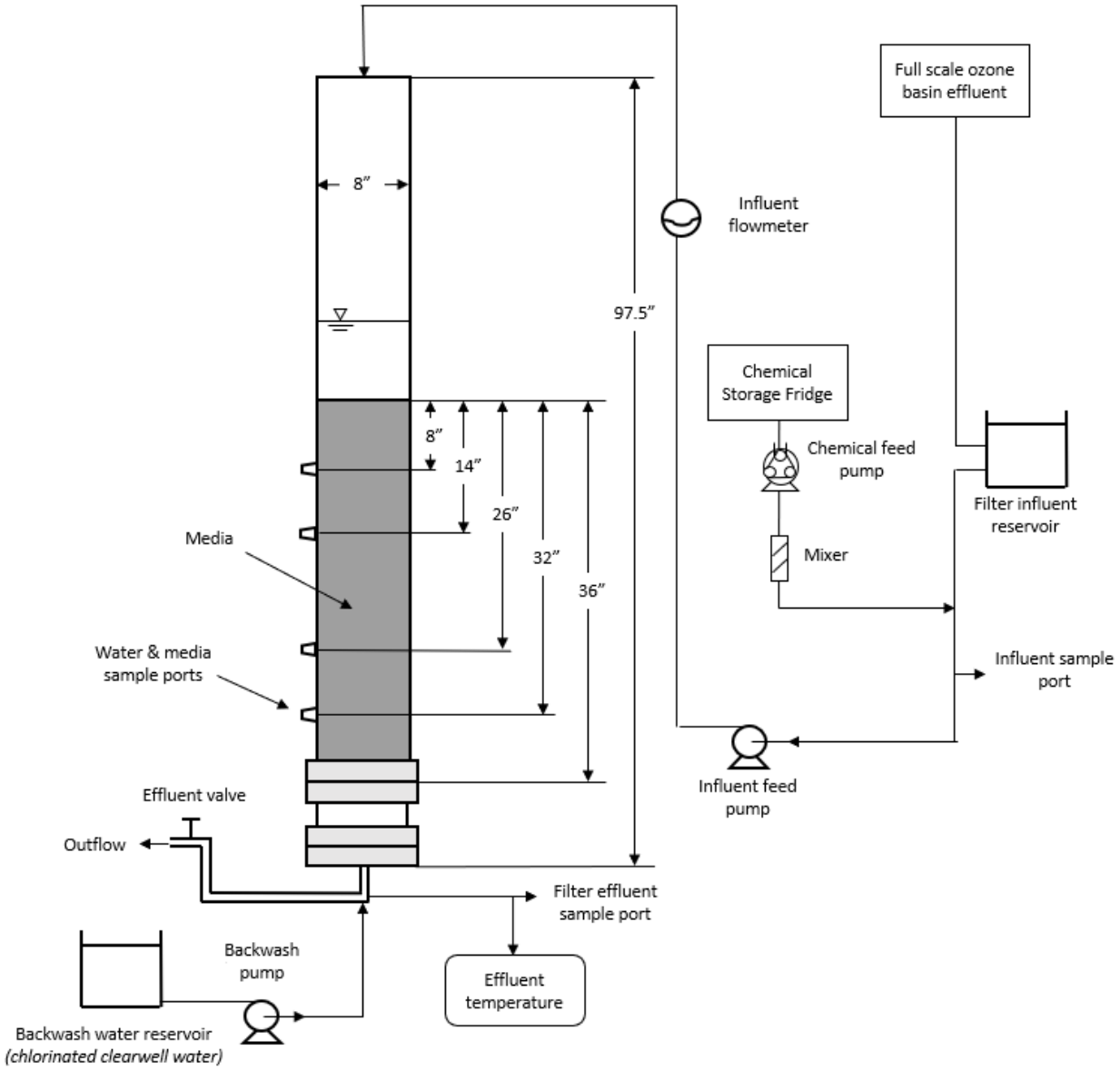

Figure 26. Pilot Filter Column Schematic

4.1.3. Pilot Filtration System Operation

The pilot study was carried out for approximately one year to subject the pilot filters to a complete cycle of seasonal variations in water quality and to ensure establishment of full biological activity. Operation of the pilot system began in August 2017 and data collection continued until August 2018.

4.1.3.1. Pilot Filter Loading Rate

The loading rate to each filter was maintained at 2.8 gpm/ft^2 (EBCT of 8.0 minutes) for a majority of the study, which was slightly higher than the average loading rate to each filter in the full-scale system between 2013 and 2017 (2.6 gpm/ft^2). To minimize study variables, it was desirable to maintain a consistent loading rate for most of the study period. However, low and high loading rates were also applied to the filters to observe the impact on performance, during the periods shown in Table 8.

The pilot filters were operated under a low loading rate of 2.0 gpm/ft^2 (EBCT of 11.2 minutes) and a high loading rate of 3.7 gpm/ft^2 (EBCT of 6.1 minutes) for a period of three weeks. The loading rate was returned to 2.8 gpm/ft^2 on January 31st, 2018. However, due to cold water temperatures during this period, significant air binding occurred in the pilot feed pumps. Water temperatures in the pilot filtration system increased by up to approximately 15°F during the winter months due to the ambient air temperature in the MWTP, which caused dissolved oxygen to come out of solution and the feed pumps to lose prime. To eliminate air binding, the loading rate was increased back to 3.7 gpm/ft^2 on February 7th, 2018 to allow the water to pass through the pilot filtration system more quickly so less warming could occur. Once air binding subsided, the flow rate was returned to 2.8 gpm/ft^2 for the remainder of the study.

Table 8. Pilot Filter Loading Rate Schedule

Period	Start Date	End Date	Duration (weeks)	Filtration Rate (gpm)	HLR (gpm/ft^2)	EBCT (minutes)
1	08/02/17	12/19/17	20	0.95	2.8	8.0
2	12/19/17	01/09/18	3	0.70	2.0	11.2
3	01/09/18	01/31/18	3	1.27	3.7	6.1
4	01/31/18	02/07/18	1	0.95	2.8	8.0
5	02/07/18	02/22/18	2	1.27	3.7	6.1
6	02/22/18	08/19/18	25	0.95	2.8	8.0

4.1.3.2. Pilot Filter Backwashing Procedure

Each pilot filter was backwashed approximately every five days with chloraminated clearwell water at a concentration of approximately 3.0 mg/L (same water used to backwash the full-scale filters). Backwash sequences began with an air scour for three minutes to break up filter media and dislodge particulates. The media was then backwashed at the appropriate flow rate for each media type (depending on specific weight) to achieve 50 percent bed expansion. When the backwash was complete, the media was allowed to settle, with the lower specific gravity of the GAC or anthracite (Columns 4 and 5, respectively) settling on top of the sand media.

4.2. Sampling Procedures

The following sections describe the sampling procedures utilized for the analysis of turbidity and organics in the pilot filtration system.

4.2.1. Turbidity

Water samples were collected daily from the effluent of all five pilot filters for turbidity analysis. Online turbidity measurements were used for quality control. Water samples were tested immediately after collection for turbidity in NTUs.

4.2.2. Organics

Water samples were collected from the pilot filtration system to evaluate organics removal capabilities of the four BAC filters in comparison to anthracite-sand filters. Samples were collected on a weekly basis for analysis of TOC, DOC and UV254. Water sample locations for organics analysis in the pilot filtration system included the common influent port and the effluent ports of each filter.

4.3. Experimental Methodologies

Methodologies for the T&O challenge tests, and turbidity and head loss studies are described in detail in this section.

4.3.1. T&O Challenge Tests

T&O challenge tests were conducted during cold and warm water periods to compare removal capabilities between the BAC and anthracite-sand filters. Three T&O challenge tests were carried out. In each test, the pilot filters were challenged with relatively high concentrations of geosmin, a common contributor to T&O in surface water. The purpose and methodology of each test is described in the following sections.

4.3.1.1. T&O Challenge Test 1

The purpose of T&O Challenge Test 1 was to determine which of the five pilot filters would achieve the highest removals of geosmin. The test was conducted from October 25th, 2017 to November 1st, 2017. The loading rate to each filter was maintained at 2.8 gpm/ft^2 throughout the study. Backwashing occurred for one filter each day.

Analytical grade geosmin was used for this study. A feed solution of geosmin at a concentration of 4.5 mg/L was prepared in reagent grade water. The feed solution was stored in an air-tight bag at 4°C throughout the duration of the experiment. A feed solution sample was

taken immediately after preparation each time to verify the concentration. The feed solution was pumped from the air-tight bag via a peristaltic pump at a feed rate set point of 1.5 mL/minute (it was previously determined that a pump rate of 0.4 mL/min was not adequate to reach the target influent concentration). The feed solution was pumped prior to a static mixer (Figure 26) to ensure proper mixing with a target influent concentration of 100 ng/L of geosmin. The effluent concentration goal was not to exceed 10 ng/L, which is the approximate OTC of geosmin.

Water samples were sent to Analytical Environmental Laboratories (AEL) in Tyler, Texas for analysis. AEL provided 40-mL amber glass vials containing sodium omadine (preservative) that were utilized for sampling throughout the challenge test. Samples were collected free of headspace and all samples received by AEL were analyzed within their holding time of 7 days. Samples were analyzed according to standard method 6040D using solid-phase micro-extraction (SPME) gas chromatography mass spectrometry (GC/MS). The method detection limit (MDL) of geosmin was 0.360 ng/L.

The geosmin feed was initiated 24 hours prior to sample collection. Sample collection began on October 26th, 2017. Water samples were collected from the common filter influent and all five filter effluent ports (Figure 26) and were immediately sent to AEL for analysis. The next day, an estimated concentration of 60 ng/L of geosmin for the influent was received from AEL. Since geosmin was below the targeted influent concentration value of 100 ng/L, the pump rate was increased from 1.5 to 2.5 mL/min to achieve an influent concentration of 100 ng/L. The real pump rate was determined to be 2.2 mL/min by pumping water into a bucket for a period of 24 hours at a set point of 2.5 mL/min and determining the volume pumped over time. Sample collection continued daily in the common filter influent and all five filter effluent ports for a total of six different sampling periods.

4.3.1.2. T&O Challenge Test 2

The purpose of T&O Challenge Test 2 was to compare geosmin removals in each pilot filter over a longer period of time during the spring, when T&O events typically occur at the MWTP. The test was carried out from March 6th, 2018 to April 4th, 2018. A geosmin-dosing period of two weeks was followed by a geosmin-free period of a week, then geosmin was re-introduced for another week. This was done to better simulate the intermittent nature of a real T&O event, and to determine to what extent desorption would occur in the BAC filters during the geosmin-free period. The loading rate to each filter was maintained at 2.8 gpm/ft^2 throughout the study. To keep operating conditions the same, each filter was backwashed at approximate five-day intervals.

A significantly more economic supply of geosmin was obtained from a perfume supply company for this study. The preparation procedure for the geosmin stock solution was modified. A 3,000 mg/L geosmin stock solution was prepared in reagent grade water. The geosmin stock solution was utilized to prepare a feed solution at a concentration of 1.3 mg/L. No changes were made to how the geosmin feed solution was stored and pumped to the pilot filters. In addition, water sample collection and analysis remained the same.

Geosmin was fed for an initial two-week period, beginning on March 6th, 2018 and ending on March 21st, 2018. During this time, the common filter influent and effluent of each pilot filter was monitored for geosmin on seven different sampling periods. Following the two-week period, the geosmin feed was stopped, and filter effluent geosmin concentrations were monitored on five sampling periods from March 22nd, 2018 to March 28th, 2018 to determine the extent of geosmin desorption in the BAC filters. After the geosmin-free period, the geosmin feed was resumed beginning on March 29th, 2018 and ending on April 4th, 2018. During this time,

water samples were collected from the common filter influent and effluent of each pilot filter on four sampling periods.

4.3.1.3. T&O Challenge Test 3

The purpose of T&O Challenge Test 3 was to evaluate geosmin removal in BAC and anthracite-sand filters during a warm period as compared to the cold period. Filter 3 was selected for this test due to its high performance in previous challenge tests to compare with Filter 5. The test was carried out from June 18th, 2018 to August 1st, 2018. The loading rate to each filter was maintained at 2.8 gpm/ft^2 throughout the study. Similar to Challenge Test 2, each filter was backwashed at approximate five-day intervals. No changes were made to the preparation and storage procedures for geosmin stock and feed solutions. Additionally, no changes were made to the method of water sample collection and analysis. Water samples were collected from the common filter influent as well as the filter effluents ports on thirteen different sample periods during the study.

4.3.2. Turbidity and Head Loss Studies

Turbidity and head loss studies were carried out to evaluate and compare the effect of filter media type on particle removal the in BAC and anthracite-sand filters and to explain possible differences in particle removal mechanisms operative in each filter. Filter 3 was selected for each study to compare with Filter 5. Two studies were conducted, with methodologies described in the following sections.

4.3.2.1. Turbidity Profile and Head Loss Buildup Study

Turbidity as a function of time and depth was compared in each filter to determine the effect of media type on particle removal. Head loss buildup was also measured in each filter. The study was carried out from February 19th, 2019 to March 2nd, 2019 with 10 different sampling

periods. The study was conducted for a period long enough to observe changes in turbidity removal throughout all stages of the filter run. The study was terminated under the following conditions: 1) water surface level reached the top of the column, 2) effluent turbidity exceeded 0.1 NTU, or 3) after a period of 10 days.

Water samples were collected for the analysis of turbidity at filter run times of 6, 24, 48, 72, 96, 120, 144, 168, 216, and 264 hours from the following locations in each filter: common filter influent, filter bed depths of 8-, 14-, 26-, 32-inches, and filter effluent. Each sample was collected at the same flow rate. Duplicate samples were collected at each location and each sample was measured in triplicate. Each time water samples were collected, the water surface level in each column was recorded to measure head loss buildup over time.

4.3.2.2. Turbidity and Head Loss Profile Study

To provide a more complete picture of particle removal in the BAC and anthracite-sand filters, the original study was amended to include the measurement of total head loss and head loss profiles in each filter. The previous set up of the pilot filtration system only allowed for the comparison of overall head loss buildup. Therefore, the pilot system was modified to allow for the measurement of head loss profiles and total head loss in each filter.

The pilot system was modified as follows. The elevation of the filter outflow point was raised to allow for a static water surface level in each column. The static water surface level was used as a reference point from which to measure the clean bed head loss and total head loss, as shown in Figure 27. Water surface level indicator tubes (clear PVC tubing) were installed on each water sample port available on the sidewall of each column to determine the head loss throughout the depth of each filter. Three-way vales were installed on each tube to sample for turbidity at various filter bed depths while maintaining the water level in the tubes.

The study was carried out from May 1st, 2019 to May 3rd, 2019. During this period, water samples were collected for the analysis of turbidity at filter run times of 30, 46, 51, 70, and 76 hours from the same locations in the filter as the previous study. Duplicate samples were collected at each location and each sample was measured in triplicate. Measurements of total head loss and head loss at filter bed depths of 8-, 14-, 26-, 32-inches were made on each filter at run times of 1, 6, 30, 46, 51, 70, and 76 hours. Water samples were also collected for the analysis of TOC and UV254 throughout the depth of each filter as an indirect method to compare potential differences in biomass. Water samples were collected from the following locations in each filter: common filter influent, filter bed depths of 8-, 14-, 26-, 32-inches, and the filter effluent at run times of 30 and 76 hours.

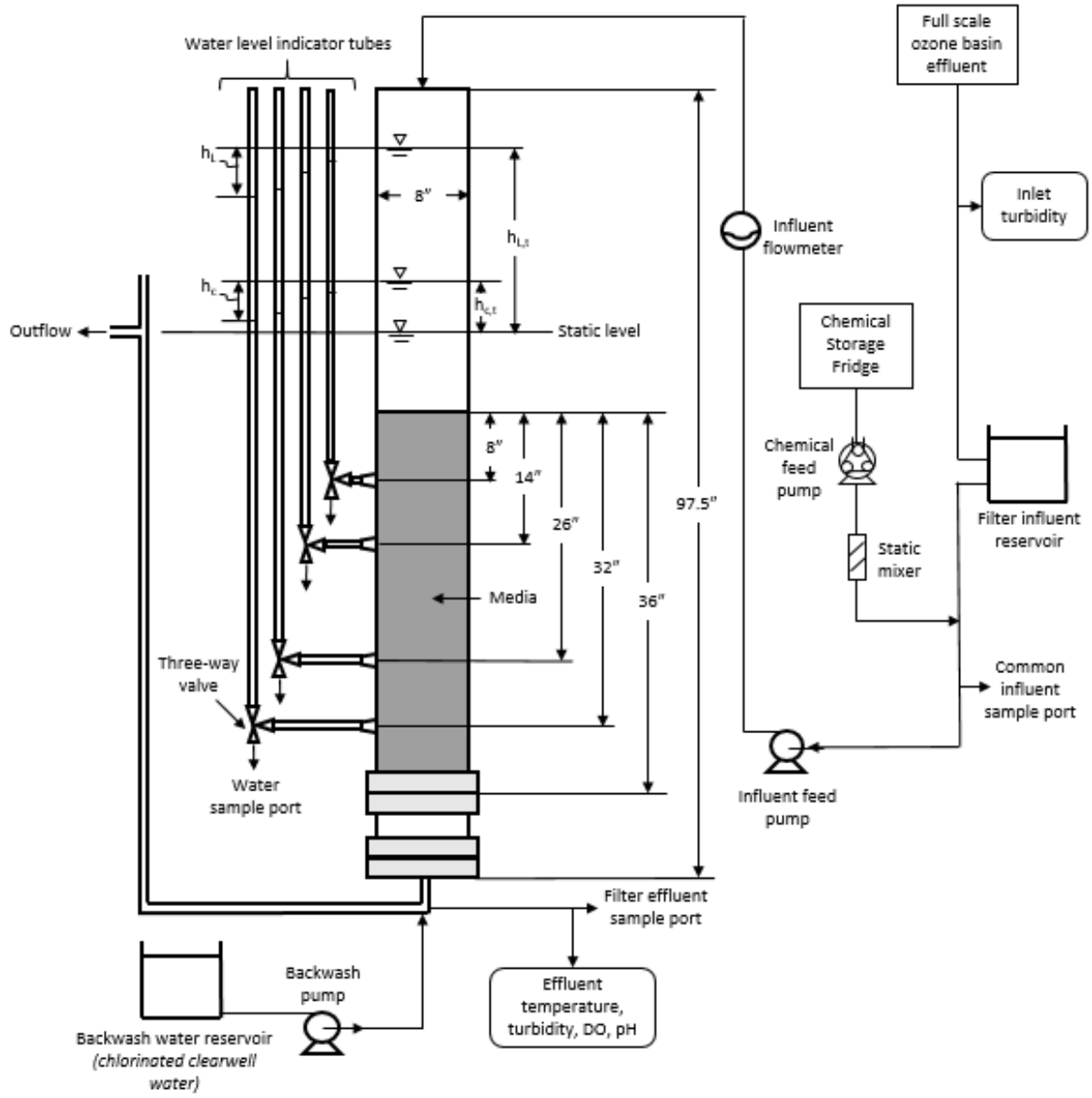

Figure 27. Modified Pilot Filter Column Schematic

4.4. Sample Analytical Methods

The following section describes the analytical methods used for the analysis of turbidity and organics for water samples collected from the pilot filtration system.

4.4.1. Turbidity

Turbidity grab samples were measured immediately after collection on a Hach 2100N turbidimeter in NTU under accordance with USEPA method 180.1. The MWTP purchased a new

Hach TU5200 turbidimeter in April 2019 to improve the sensitivity of turbidity analysis. It should be noted that the new model was utilized for the measurement of turbidity in water samples collected for the Turbidity and Head Loss Profile Study previously described.

4.4.2. Organics

Organics analysis was done in accordance with USEPA Method 415.3: Determination of Total Organic Carbon and Specific UV Absorbance at 254 nm in Source Water and Drinking Water (Potter and Wimsatt, 2009). Total and dissolved organic carbon was analyzed using O-I Analytical Aurora Model 1030 TOC Analyzer. DOC samples were filtered with a pre-washed 0.45 µm membrane filter prior to analysis. TOC and DOC samples were preserved with phosphoric acid and stored at 4 ± 2°C for less than the maximum holding period of 28 days prior to analysis. A portion of the filtered sample was utilized for UV254 analysis immediately after collection. UV254 was measured with a ThermoFisher Scientific Orion AquaMate 8000 UV-Vis Spectrophotometer and one-centimeter pass-through quartz cells.

4.5. Statistical Analyses

The student's *t*-test (two-sample assuming equal variances) was used to determine whether significant differences were observed between filtered-water data sets for a given parameter at the five percent significance level. The *t*-test was used to test the null hypothesis that the means of the two data sets were the same. Therefore, the means were not considered statistically significant for $p > 0.05$ and significantly different if $p < 0.05$. p values were developed using a software package. Plotted data that have error bars associated with them are shown as the mean ± one standard deviation.

CHAPTER 5. RESULTS AND DISCUSSION

Results of this study are presented and discussed in this chapter. First, results from the weekly collection of water samples for the analysis of organics removal are discussed. Then, results from the three T&O challenge tests are discussed. Finally, results from the daily collection of water samples for the analysis of effluent turbidity, and results from the turbidity and head loss studies are discussed.

5.1. Study Conditions

Water temperatures in the pilot filtration system varied significantly throughout the study, as shown in Figure 28. Water temperatures in the pilot filters dropped from 64°F in the beginning of September 2017 to a low of 43°F in mid-February 2017. Then, water temperatures steadily increased to a high of nearly 76°F in mid-August 2018. The pilot filtration system and water storage reservoirs were all stored in the same area of the MWTP and thus were exposed to the same ambient air temperatures. The significantly smaller volume of water contained in the pilot system resulted in more temperature variations than in the full-scale system, as shown in Figure 28. For example, in the colder months, water warmed over time in the pilot system because of the warmer ambient indoor temperature. The largest temperature difference between the pilot- and full-scale systems occurred during the winter at up to approximately 15°F.

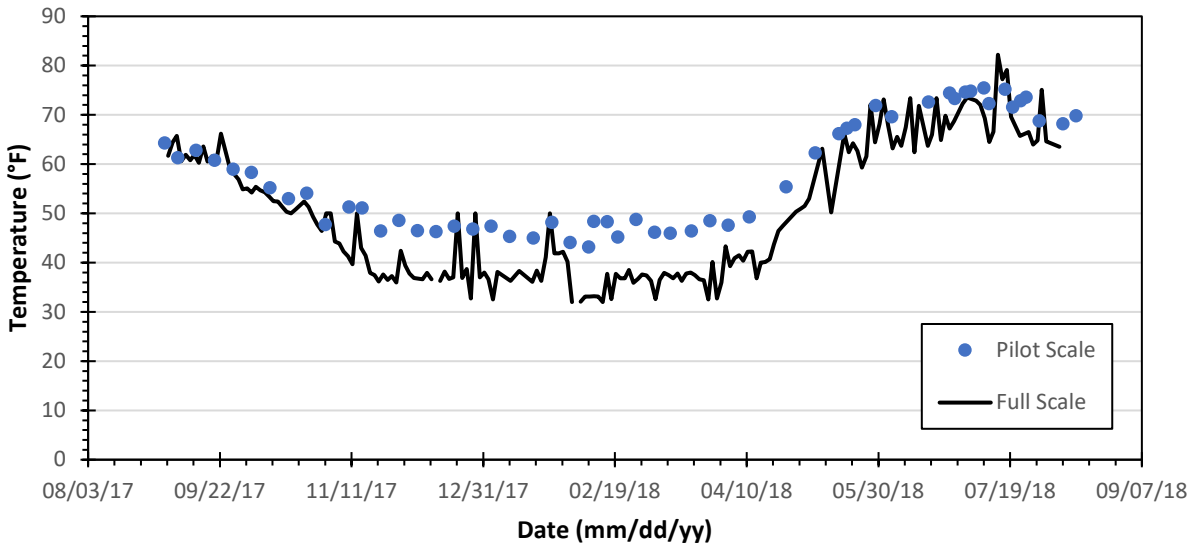

Figure 28. Temperature in Pilot and Full Scale System

5.2. Organics Data and Analysis

Results from the measurement of TOC and UV254 in water samples collected from the pilot filtration system are presented and discussed in this section. It should be noted that since TOC and DOC concentrations were very similar (maximum difference of ± 0.1 mg/L), only TOC data is presented in this section. The same parameters were also measured in the combined effluent of the full-scale filters to compare with Filter 5 (anthracite-sand) and to determine how well the pilot filters mimicked the full-scale filters in terms of organics removal. The impact of media type and temperature on organics removal was investigated in each filter. A summary of the data included in this section is located in Appendix A.

5.2.1. TOC in the Pilot Filtration System

Measurements of TOC were performed on the influent and effluent waters of each pilot filter, as well as the full-scale filter effluent. A summary of TOC concentrations is shown in Figure 29. Influent TOC concentrations to the pilot filters ranged between 2.5 and 5.7 mg/L with an average of 3.5 mg/L. As shown in Figure 29, influent TOC concentrations peaked during the winter months, which was likely due to upstream discharging. Influent TOC concentrations

spiked again during the spring months due to runoff from snowmelt and/or rainfall. This is common at the MWTP, although milder than previous years since no spring flooding occurred.

Effluent TOC concentrations were compared between Filter 5 and the full-scale filters. Overall, effluent TOC concentrations in the full-scale filters (average of 3.2 mg/L) were in close range to those observed in Filter 5 (average of 3.1 mg/L), which indicates that the pilot filters effectively mimicked the full-scale filters in terms of TOC removal.

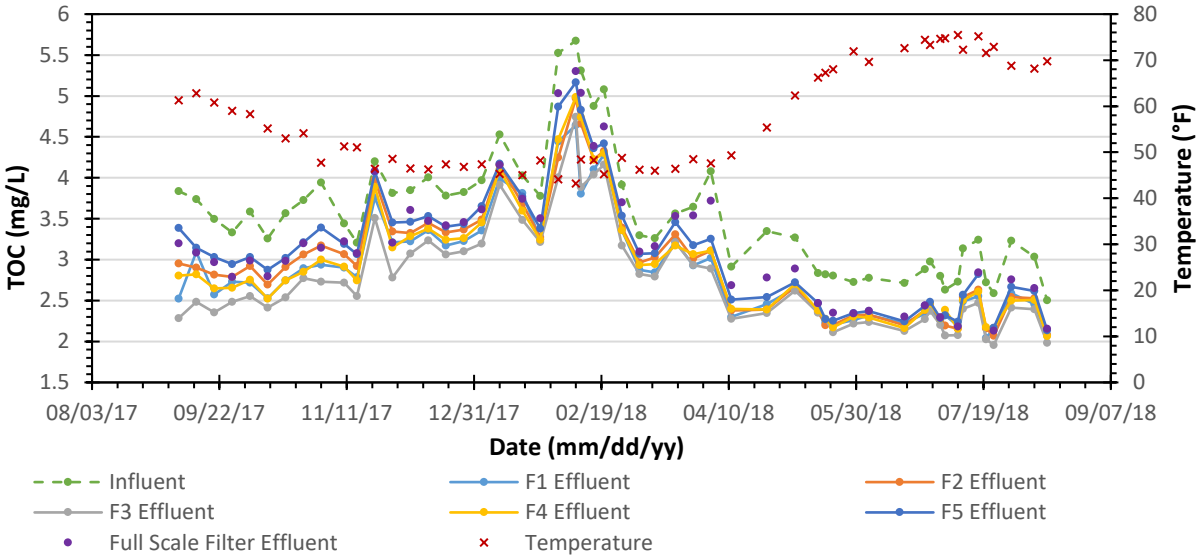

Figure 29. TOC (mg/L) and Temperature in Pilot- and Full-Scale Filters

5.2.1.1. Impact of Filter Media

TOC removal efficiencies were compared in the pilot filters, with data shown in Figure 30. TOC removal efficiency data in each pilot filter is also summarized in box and whisker plots, as shown in Figure 31. In the box and whisker plots, the middle of the box represents the median, and the top and bottom of the box represents the first and third quartiles, respectively. The x-mark in each box indicates average removal efficiency; while, the ends of the vertical lines represent the maximum and minimum removal efficiencies.

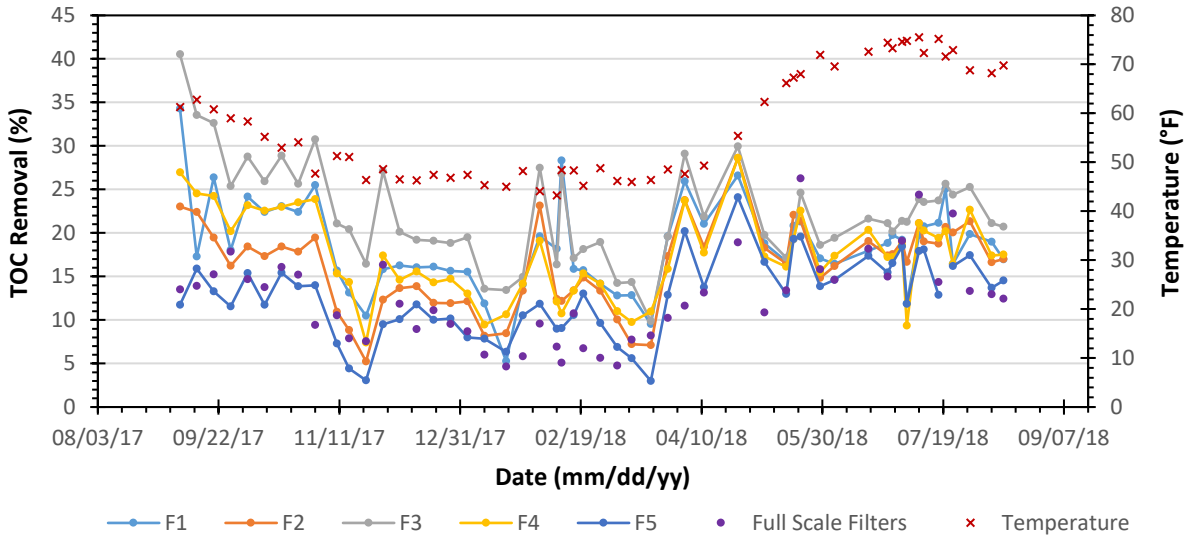

Figure 30. TOC Removal (%) and Temperature in Pilot- and Full-Scale Filters

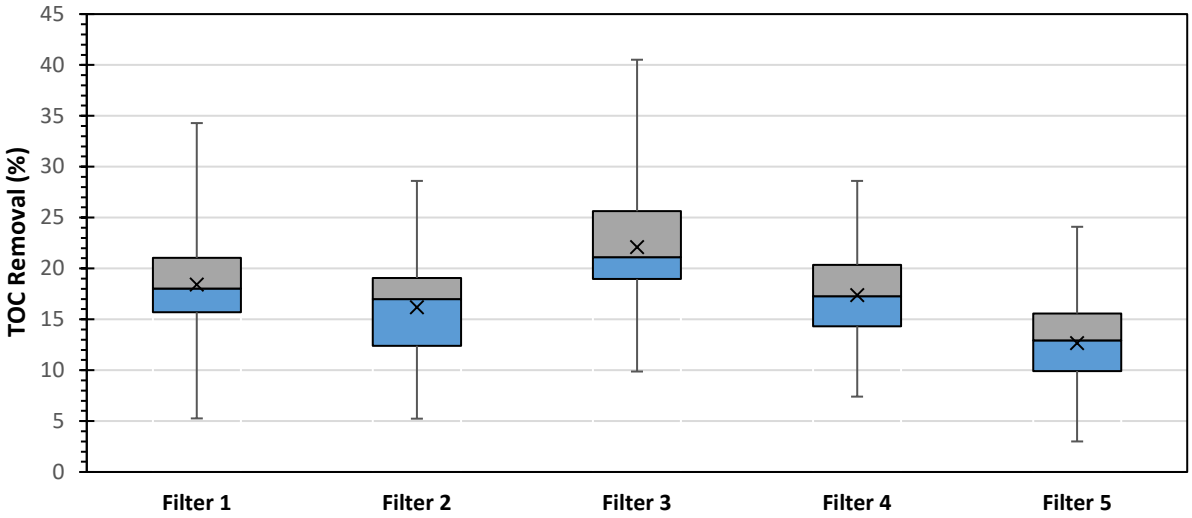

Figure 31. TOC Removal (%) in Pilot Filters – Box and Whisker Plots

It should be noted that at the beginning of the study, the difference in TOC removals between the BAC and anthracite-sand filters were more pronounced, and gradually decreased over time before eventually reaching a steady state, as shown in Figure 30. Although it was intended to exhaust the carbon with organics prior to the study, residual adsorption capacity may have remained in the BAC filters. This residual adsorption capacity would have become

exhausted over time, which explains why the difference in TOC removals between the BAC and anthracite-sand filters decreased during the first few months of the study.

TOC removal efficiencies were compared between the BAC and anthracite-sand filters. Filter 5 consistently had the lowest removal, which averaged 0.48 mg/L (12.7%). Since anthracite has negligible adsorption capacity, TOC removal in Filter 5 was due solely to biological degradation. Significantly higher TOC removals were observed in the BAC filters ($p < 0.05$), which ranged between 0.56 to 0.78 mg/L (16.2 to 22.1%). Although residual adsorption capacity could account for some of the differences in TOC removals observed between the BAC and anthracite-sand filters at the beginning of the study, once the BAC media was saturated with organics, it was mostly due to differences in biodegradation. The macroporous structure and rough surface of the GAC provides recesses which may shelter the biofilm from hydrodynamic shear stress. Therefore, GAC has the potential to maintain a larger amount of biomass than anthracite or sand, which would likely translate into the higher organic removals observed in the BAC filters during this study.

TOC removal efficiencies were also compared between each of the BAC filters. It should be noted that the layer of sand in Filter 4 (F300 GAC and sand) must be considered for this comparison due to major differences in media characteristics between the GAC and sand. Among the four BAC filters, Filter 3 (Norit 300 GAC) consistently removed the most TOC. Overall, Filter 2 (Jacobi GAC) removed the least TOC. However, it should be noted that over time, removals in Filter 2 became within closer range to removals in Filter 4, as shown in Figure 30. This could be due to differences in adsorption capacity at the beginning of the study before the carbon was exhausted.

Significant differences were observed between each BAC filter ($p < 0.05$), with the exception of Filter 1 (F300 GAC) compared to Filter 4, and Filter 2 compared to Filter 4. TOC removal efficiencies were likely not found to be significantly higher in Filter 1 as compared to Filter 4 since F300 GAC was used in both filters. This also suggests that the sand layer did not have a significant positive impact on the removal of TOC in Filter 4. TOC removal efficiencies in Filters 2 and 4 were similar during most of the study period.

In addition to the overall higher TOC removals achieved in the BAC filters, it was found that the BAC filters were able to attenuate high TOC loadings to the filters better than the anthracite-sand filter. For example, during the rapid increase in TOC concentrations to the filters that occurred in February 2018, Filter 3 removed up to 15% more TOC than Filter 5, as shown in Figure 32. Although the GAC was essentially exhausted during this time of the study, it can still attenuate high influent concentrations of organics. This is because adsorption is driven by the concentration gradient between the solid and liquid phases.

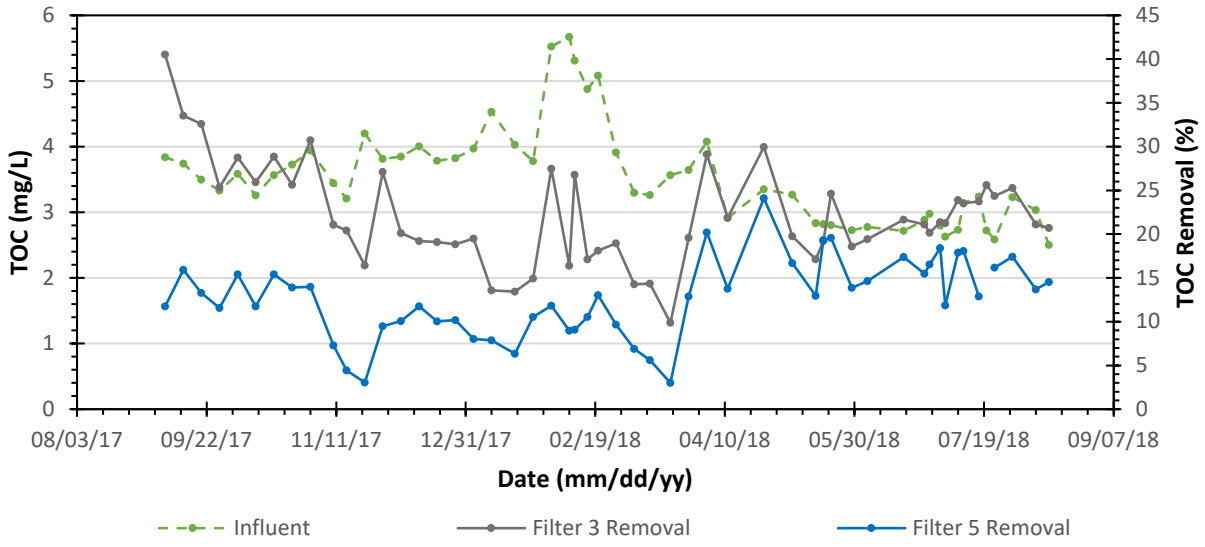

Figure 32. Influent TOC (mg/L) and TOC Removal (%) in Pilot Filters 3 and 5

5.2.1.2. Impact of Temperature

The impact of temperature on TOC removal in the pilot filters was investigated. First, the organics data was divided into four periods based on water temperature, as shown in Figure 33. Period 1 (09/06/17 to 11/10/18) and Period 3 (04/25/18 to 05/21/18) were cooling and warming periods, respectively. Period 2 (11/22/17 to 04/11/18) was a steady cold water period, with water temperatures below 50°F. Period 4 (05/29/18 to 08/13/18) was a steady warm water period, with water temperatures above 68°F.

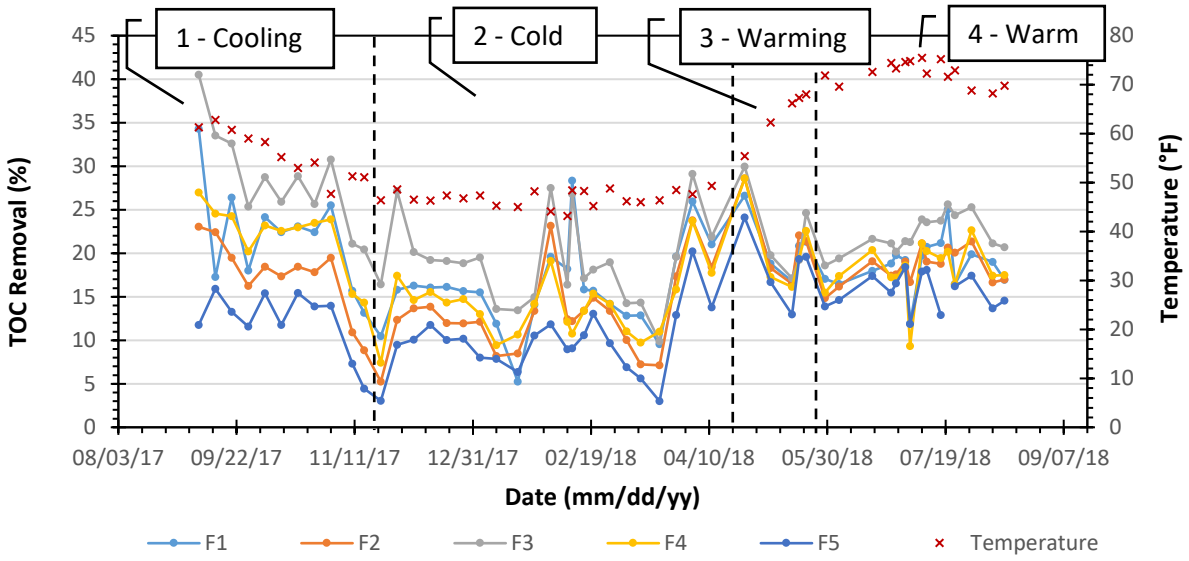

Figure 33. Temperature Periods

TOC removal efficiencies during the cold and warm water periods were used to make different comparisons between the pilot filters. First, TOC removal efficiencies were compared in each pilot filter individually between cold and warm water periods. This was done to determine if each filter was significantly impacted by a decrease in temperature. Then, TOC removal efficiencies were compared between BAC and anthracite-sand filters during both cold and warm water periods. This was done to determine if TOC removals in the BAC filters were significantly higher during both the cold and warm water periods.

TOC removal efficiencies were found to decrease from the warm to cold water periods in each filter. The decrease in TOC removal efficiencies from the warm to cold water period was found to be significant in each filter ($p < 0.05$), except Filter 1. This suggests that overall, temperature was a significant factor affecting TOC removal in the biofilters. However, cold temperatures had the largest negative impact on TOC removals in the anthracite-sand filter. TOC removal comparisons between cold and warm periods in the individual pilot filters are shown in Table 9.

Table 9. TOC Removal Comparison between Cold and Warm Periods in Pilot Filters

	Mean TOC Removal (%)			
Filter	Cold Period	Warm Period	Difference (%)	Significant difference?
1	15.9	18.7	2.8	No
2	12.9	18.4	5.5	Yes
3	18.9	22.1	3.2	Yes
4	13.9	18.0	4.1	Yes
5	9.67	15.6	5.9	Yes

Student's t-test at 5% significance level

TOC removal efficiencies were compared between the BAC and anthracite-sand filters during the warm and cold water periods, as shown in Table 10 and Table 11, respectively. Significant differences ($p < 0.05$) in TOC removal efficiencies were observed between the BAC and anthracite-sand filters during both warm and cold water periods. This suggests that the BAC filters can perform significantly better than the anthracite-sand filters not only during the warm water period, but also during the cold water period when there is less biological activity.

Table 10. TOC Removal Comparison between BAC and A-S Filters - Warm Period

Filter	Mean TOC Removal (%)	Significant Difference between BAC and A-S Filters?
1	18.7	Yes
2	18.4	Yes
3	22.1	Yes
4	18.0	Yes
5	15.6	-

Student's t-test at 5% significance level

Table 11. TOC Removal Comparison between BAC and A-S Filters - Cold Period

Filter	Mean TOC Removal (%)	Significant Difference between BAC and A-S Filters?
1	15.9	Yes
2	12.9	Yes
3	18.9	Yes
4	13.9	Yes
5	9.67	-

Student's t-test at 5% significance level

5.2.2. UV254 in the Pilot Filtration System

UV254 measurements were made in the pilot filtration system and full-scale filter effluent, with data shown in Figure 34. UV254 values to the pilot filters followed a similar trend as TOC, with peaks observed during the winter and spring runoff. This means that the character of the organic matter, such as aromatic compounds that strongly absorb UV light, is representative of the TOC present. Since a majority of UV254 reduction occurs during softening and ozonation, very low influent UV254 values were observed throughout the study. Influent UV254 values ranged between 0.010 and 0.044 cm^{-1} with an average of 0.024 cm^{-1}.

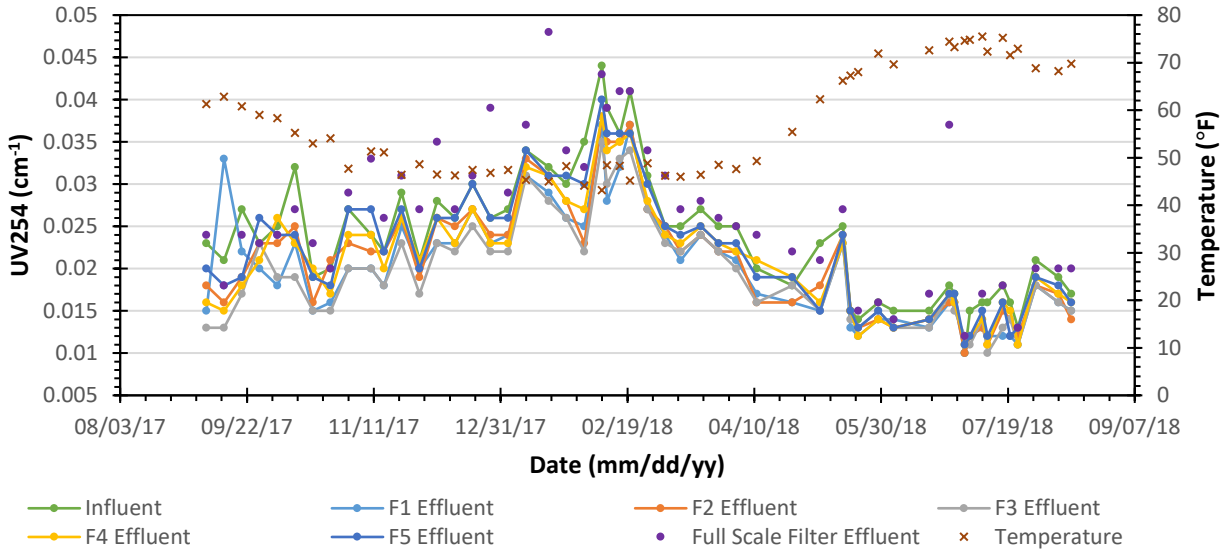

Figure 34. UV254 Values (cm-1) and Temperature in Pilot Filters

Effluent UV254 values were compared between Filter 5 and the full-scale filters. Effluent UV254 values were observed to be significantly higher in the full-scale filters, with an average of 0.027 cm^{-1} (12.3% removal), as compared to Filter 5, which had an average of 0.022 cm^{-1} (1.73% removal). This could have been due to the relatively warmer water temperatures observed in the pilot filters during the winter months, which would enhance biological activity and result in higher UV254 reduction efficiencies.

5.2.2.1. Impact of Filter Media

UV254 reduction efficiencies were compared in the BAC and anthracite-sand filters. UV254 reduction was observed in all five filters, with data shown in Figure 35. UV254 reduction is also summarized in box and whisker plots in Figure 36. Similar to TOC data, a larger difference in UV254 reduction was noted that at the beginning of the study between the BAC and anthracite-sand filters, which was likely due to residual adsorption capacity.

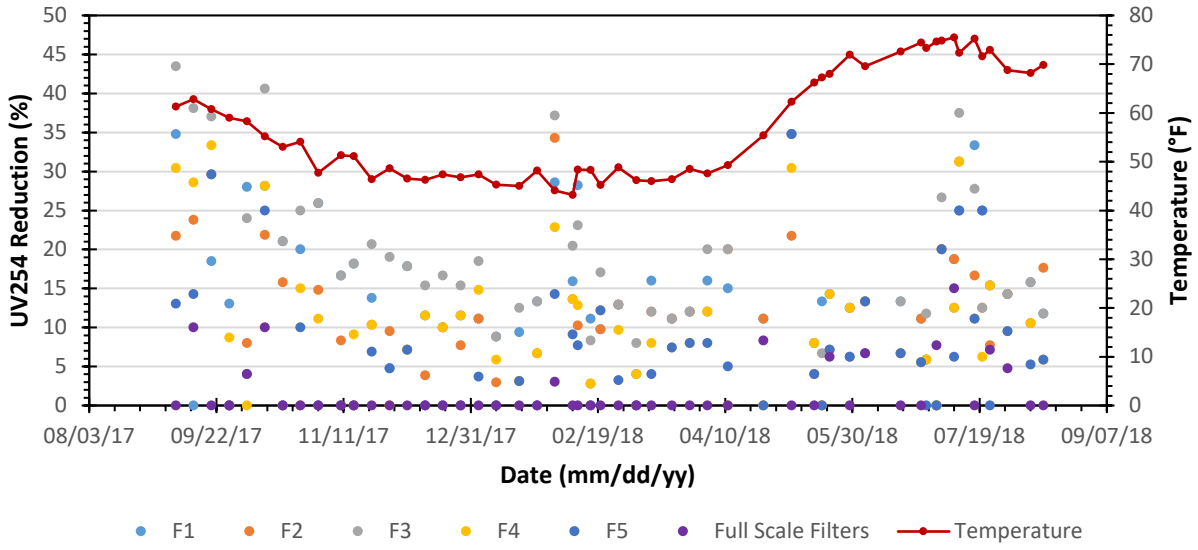

Figure 35. UV254 Reduction (%) and Temperature in Pilot Filters

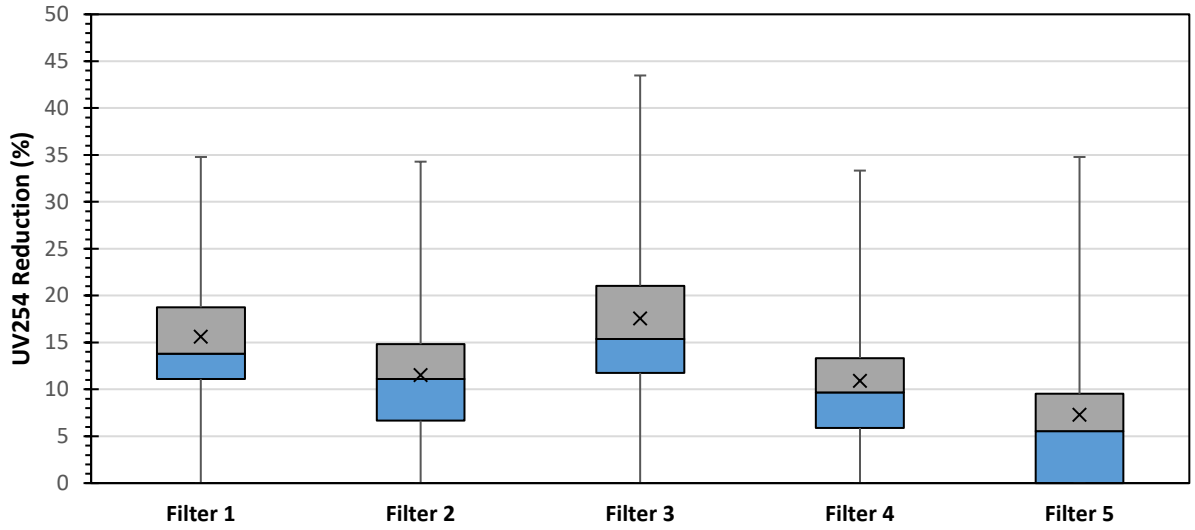

Figure 36. UV254 Reduction (%) in Pilot Filters – Box and Whisker Plots

Significantly higher UV254 reductions were achieved in the BAC filters ($p < 0.05$), on average 0.0026 to 0.0043 cm^{-1} (10.9 to 17.6%), as compared to the anthracite-sand filter, which averaged reductions of only 0.0017 cm^{-1} (7.3%). As previously mentioned, UV254 reduction in the anthracite-sand filter would be due solely to biodegradation since anthracite has a negligible adsorption capacity. In the BAC filters, a majority of UV254 reduction would have been due to biodegradation after the residual adsorption capacity was exhausted at the beginning of the study.

However, UV254 reductions in the BAC filters may have also been partly due to adsorption. Lower molecular weight organic compounds, as measured by TOC in this study, are selectively biodegraded in the BAC filters. On the other hand, recalcitrant organic compounds (not easily biodegraded), as measured by UV254 in this study, may have first been adsorbed onto the BAC media and then slowly biodegraded by the attached microbial mass.

UV254 reduction efficiencies were compared between the BAC filters. The highest UV254 reductions were consistently achieved in Filter 3, with reductions between 0.0 and 0.013 cm^{-1} (0 to 43.5%) and an average of 0.0043 cm^{-1} (17.6%). The lowest UV254 reduction efficiencies occurred in Filter 4, with reductions between 0.0 and 0.009 cm^{-1} (0 to 33.3%) and an average of 0.0026 cm^{-1} (10.9%). This was closely followed by Filter 2, with reductions between 0.0 and 0.012 cm^{-1} (0 to 34.3%) and an average of 0.0027 cm^{-1} (11.5%).

Significant differences were observed between each BAC filter ($p < 0.05$), with the exception of Filter 1 compared to Filter 3, and Filter 2 compared to Filter 4. Unlike with TOC removal data, UV254 reduction efficiencies were found to be significantly different between Filters 1 and 4. This suggests that the sand layer had a significant negative impact on the reduction of UV254 in Filter 4. This could have been due to the additional 12 inches of GAC in Filter 1, which provided more surface area to adsorb refractory organics. In addition, the significantly larger difference in UV254 reductions than TOC removals between Filters 1 and 4 further supports the theory that adsorption played a significant role in UV254 reduction in the BAC filters. Similar to TOC removal efficiency data, UV254 reduction efficiencies in Filters 2 and 4 were similar during most of the study period.

5.2.2.2. Impact of Temperature

UV254 reduction efficiencies were found to decrease from the warm to cold water periods in each filter, with the exception of Filter 3, where mean UV254 reductions increased slightly (1.4%). The decrease in UV254 reduction efficiencies from the warm to cold water period was only found to be significant in Filter 5 ($p < 0.05$). UV254 reduction comparisons between cold and warm periods in the individual pilot filters are shown in Table 12.

Table 12. UV254 Reduction Comparison between Cold and Warm Periods in Pilot Filters

	Mean UV254 Reduction (%)			
Filter	Cold Period	Warm Period	Difference (%)	Significant difference?
1	13.3	15.3	1.9	No
2	10.1	13.3	3.1	No
3	16.4	15.0	-1.4	No
4	8.8	11.1	2.3	No
5	4.8	9.3	4.6	Yes

Student's t-test at 5% significance level

UV254 reduction efficiencies were also compared between the BAC and anthracite-sand filters during the warm and cold water periods, as shown in Table 13 and Table 14, respectively. Significant differences ($p < 0.05$) in TOC removal efficiencies were observed between the BAC and anthracite-sand filters during the cold water period; however, no significant differences were observed during the warm water period. Overall, these data suggest that the BAC filters may mitigate the effects of cold water temperatures in terms of organics removal efficiencies.

Table 13. UV254 Reduction Comparison between BAC and A-S Filters - Warm Period

Filter	Mean UV254 Reduction (%)	Significant Difference between BAC and A-S Filters?
1	15.3	No
2	13.3	No
3	15.0	No
4	11.1	No
5	9.3	-

Student's t-test at 5% significance level

Table 14. UV254 Reduction Comparison between BAC and A-S Filters - Cold Period

Filter	Mean UV254 Reduction (%)	Significant Difference between BAC and A-S Filters?
1	13.3	Yes
2	10.1	Yes
3	16.4	Yes
4	8.8	Yes
5	4.8	-

Student's t-test at 5% significance level

Overall, the bituminous coal-based GACs (F300 and Norit 300) provided better removals of organics (TOC and UV254) than the coconut-based GAC (Jacobi). This was likely due to differences in surface characteristics (pore structure and surface roughness). For example, Jacobi is a microporous GAC and microorganisms are unable to enter the small pores for attachment. Whereas, the F300 and Norit 300 GACs have a larger volume of macropores. It was also postulated that the surfaces of the F300 and Norit 300 GACs provided a better surface for biofilm attachment due to a potentially higher surface roughness. Furthermore, the microporous structure of the Jacobi GAC is not well-suited for the adsorption of larger molecular weight organics. This may be evident by the significantly lower UV254 reduction efficiencies observed in Filter 2 (Jacobi GAC) as compared to Filters 1 (F300 GAC) and 3 (Norit 300 GAC).

Knutson (2019) conducted SEM analysis on the pilot filter media used in the current study (Knutson, unpublished manuscript, 2019). SEM analysis was carried out on the virgin GAC media to observe the surface morphology and assess its potential impact on biofilm formation. SEM analysis was also carried out on BAC and anthracite media sampled at depths of 8- and 26-inches after a period of 10 months of operation to observe and compare the biofilm on each media type and to evaluate the impacts of filter bed depth on biofilm formation.

SEM images of virgin pilot filter media at 30x magnification are shown in Figure 37. The surface of the F300 and Norit 300 GAC were observed to be considerably rougher than the surface of Jacobi GAC and anthracite, which appear to be relatively smooth. As noted previously, average TOC removal was the highest in Filter 3 (Norit 300 GAC), followed by Filter 1 (F300 GAC). Filter 2 (Jacobi GAC) had the lowest average TOC removal of the filters containing GAC, while Filter 5 (anthracite) had the lowest average TOC removal of all five pilot filters. The rougher surface of the F300 and Norit 300 GAC likely made it more amenable to biofilm attachment and growth than the Jacobi GAC or anthracite. Potentially higher biomass levels in filters containing F300 and Norit 300 GAC would help to explain why correspondingly higher removals of TOC were observed in these filters. Overall, both bituminous coal-based GACs were observed to have a rougher surface than the coconut-based GAC and the anthracite.

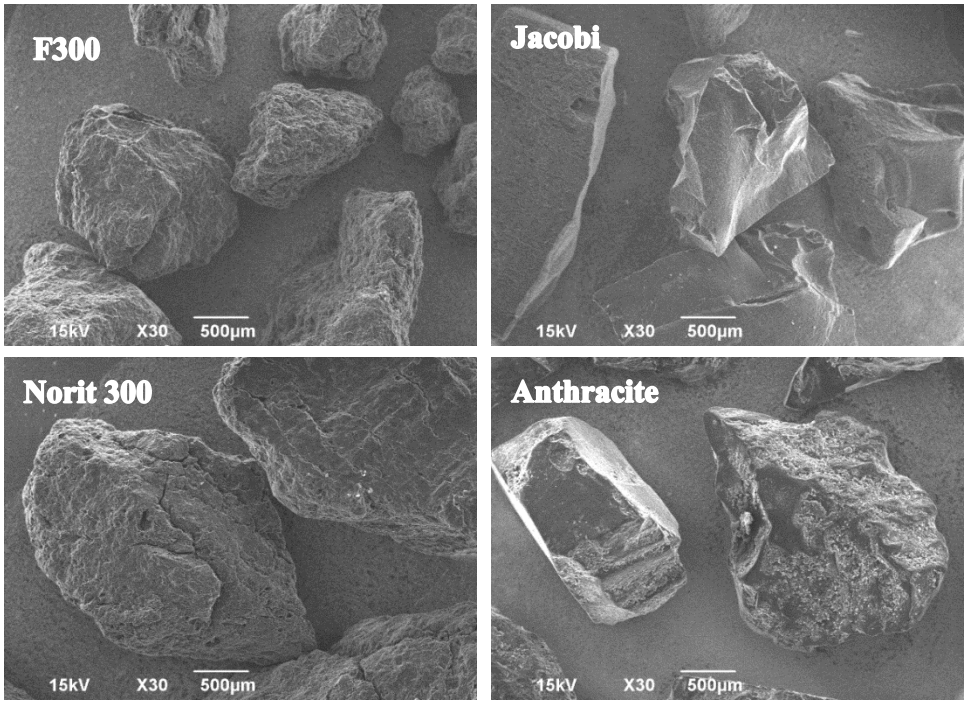

Figure 37. SEM Images of Virgin Pilot Filter Media at 30x Magnification (Knutson, unpublished manuscript, 2019) (Note: anthracite shown was sampled at 8-inch bed depth after 10 months since virgin media was not collected)

SEM images of pilot filter media sampled at 8- and 26-inch depths after 10 months of operation at 1500x magnification are provided in Figure 38 and Figure 39, respectively. Significantly more biomass was observed at a depth of 8-inches than at a depth of 26-inches for each media type. This finding agrees with previous studies, where higher levels of biomass were observed at the top of the biofilter (Pharand et al., 2014; Wang et al., 1995) and implies that most organics removal would occur in this location. An investigation into microbial community structures was out of the scope of this project; however, several types of microorganisms were found to be present on the surface of the pilot filter media.

Biofilm formations were compared between each filter. It appears a relatively high amount of biomass formation occurred on the F300 GAC. The reagglomerated nature of the F300 GAC likely provides more protection to the biomass from fluid shear stresses due to a

rougher surface. There also appears to be a relatively high amount of biofilm attachment on Norit 300 GAC and anthracite; however, there appears to be a lack of biofilm coverage on the Jacobi GAC. Since the Jacobi GAC was found to have a relatively smooth surface, it is likely that it was less amenable to biofilm growth and attachment. It should be noted that caution must be exercised when observing biofilm attachment in SEM images, since biomass coverage is not homogenous, and cannot be quantified with SEM analysis. In addition, it is difficult to discern between the presence of microorganisms and solids attached to the surface of the media. Biomass quantification is currently in progress for this study.

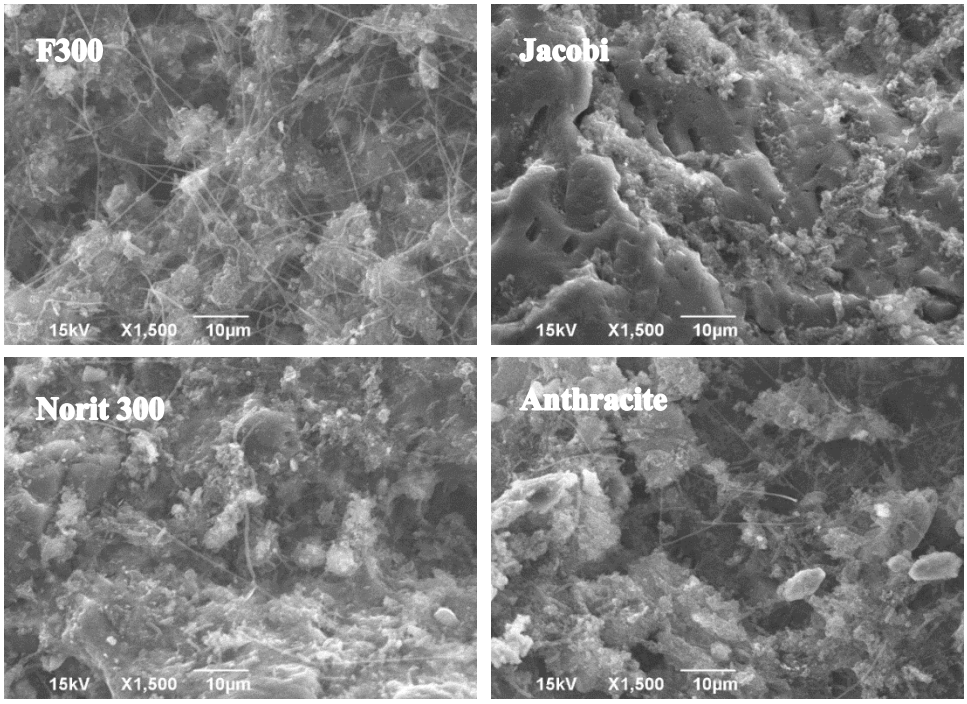

Figure 38. SEM Images of Colonized Pilot Filter Media Sampled at 8-inch bed depths at 1,500x Magnification (Knutson, unpublished manuscript, 2019)

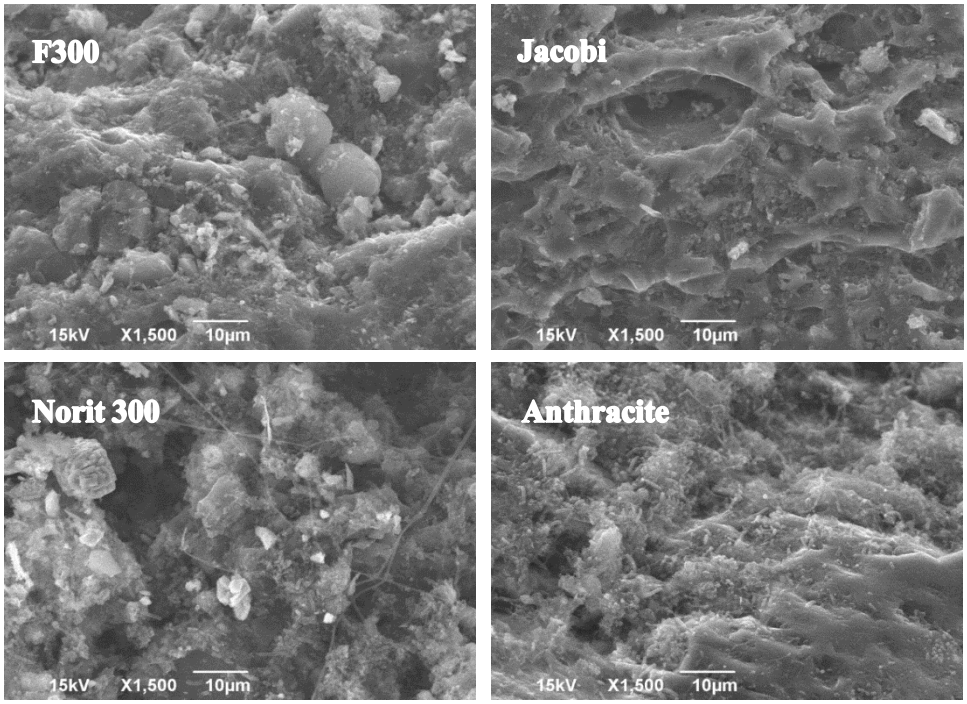

Figure 39. SEM Images of Colonized Pilot Filter Media Sampled at 26-inch bed depths at 1,500x Magnification (Knutson, unpublished manuscript, 2019)

5.2.3. SUVA in Pilot Filtration System

UV254 and DOC was measured in the pilot filtration system, therefore SUVA values could be calculated to evaluate the changes in the relative amounts of aromatic constituents through each filter. Influent and effluent SUVA values in the pilot filters are shown in Figure 40. Influent SUVA to the filters is very low, on average 0.65 L/mg-m, since a significant portion is reduced in prior treatment processes. SUVA values less than 2 indicate that large proportions of nonhumic material are present (Edzwald and Tobiason, 1999). Therefore, a large fraction of the organics present in the filter influent were easily biodegradable. SUVA values were typically found to increase in the filters, since the nonaromatic and more easily biodegradable fraction of organics are selectively biodegraded during this process. However, since UV254 reduction also

occurred in the filters, the comparison in SUVA change between filters must be done with caution.

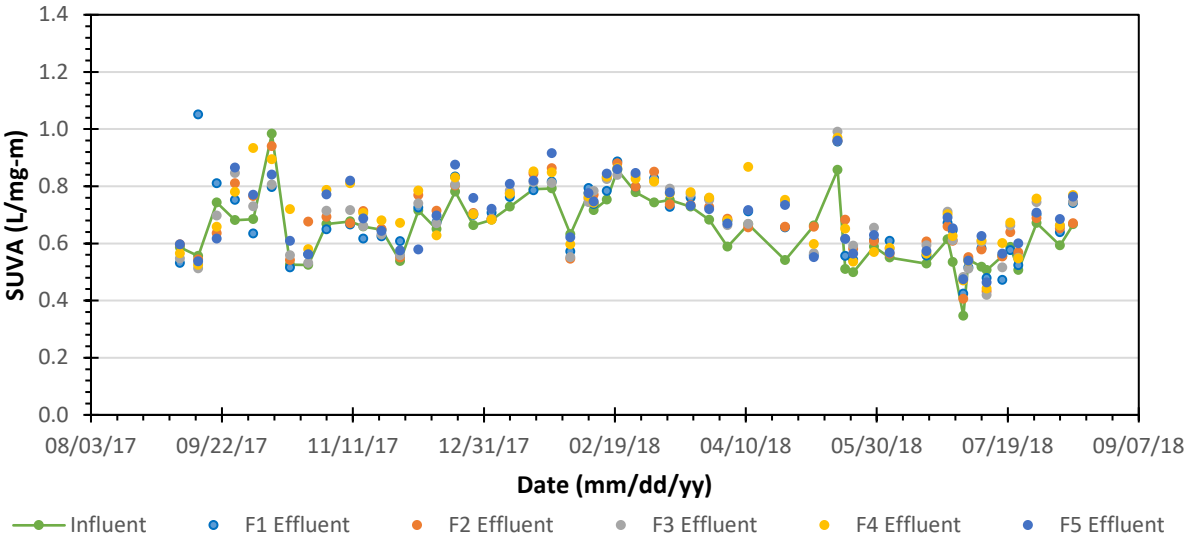

Figure 40. SUVA Values (L/mg-m) in Pilot Filters

SUVA value changes in the pilot filtration system are shown in Figure 41. The largest increase in SUVA was observed in Filters 4 and 5, at an average of 0.056 L/mg-m (7.5%) and 0.059 L/mg-m (7.0%), respectively. SUVA in Filter 2 increased by an average of 0.036 L/mg-m (5.0%); while Filters 3 and 1 increased by an average of 0.034 L/mg-m (4.5%) and 0.029 L/mg-m (3.5%), respectively. Although Filter 5 had the largest average increase in SUVA, this does not indicate that this filter produced the most biologically stable water. As previously described, UV254 reduction was the lowest in Filter 5. Since SUVA is the ratio of UV254 to DOC (more easily biodegradable organics), and DOC was reduced to a more significant extent than UV254, this resulted in a higher increase in SUVA. However, for filters with higher removals of UV254, such as Filter 1, a simultaneous decrease in UV254 and DOC occurred. As a result, SUVA values were not reduced as significantly.

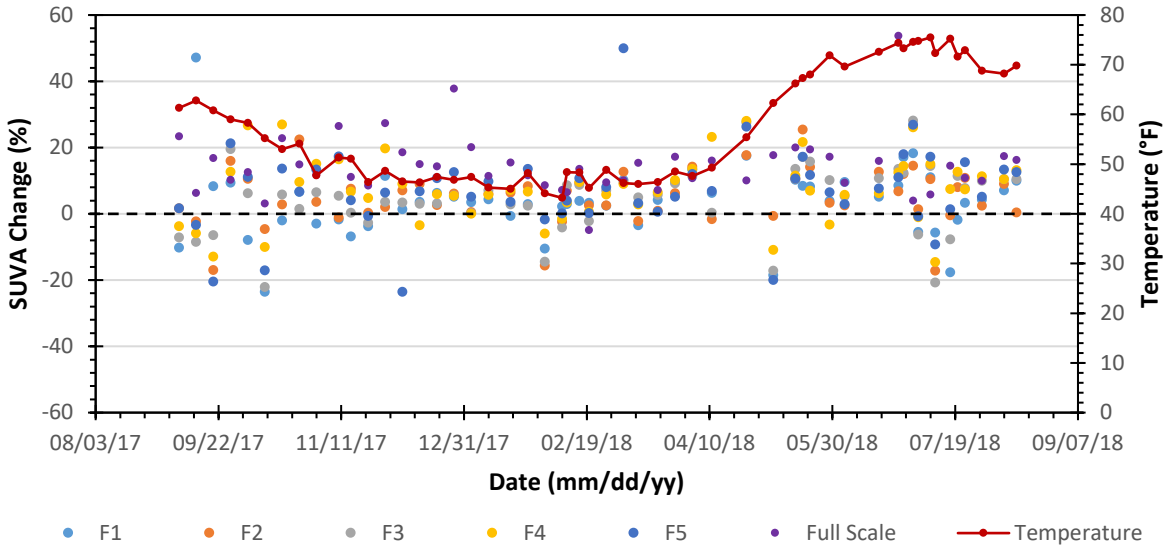

Figure 41. SUVA Change (%) and Temperature in Pilot Filters

5.3. T&O Data and Analysis

Results from the three T&O Challenge Tests carried out under cold and warm water temperature conditions in the pilot filtration system are presented and discussed in this section. A summary of the data presented in this section can be found in Appendix B.

5.3.1. T&O Challenge Test 1

The purpose of T&O Challenge Test 1 was to compare geosmin removal efficiencies in each pilot filter. T&O Challenge Test 1 was carried out during a mild cooling period, where temperatures decreased from 53.8 to 48.3°F. Influent and effluent geosmin concentrations were obtained for a total of six sampling periods, with results shown in Figure 42. Influent geosmin concentrations to the pilot filters ranged from between 91.9 to 292 ng/L. Difficulty was experienced in maintaining the target influent geosmin concentration of 100 ng/L to the pilot filters. This was likely due to the extremely low geosmin concentrations utilized in the study and the sensitivity of instrumentation analysis.

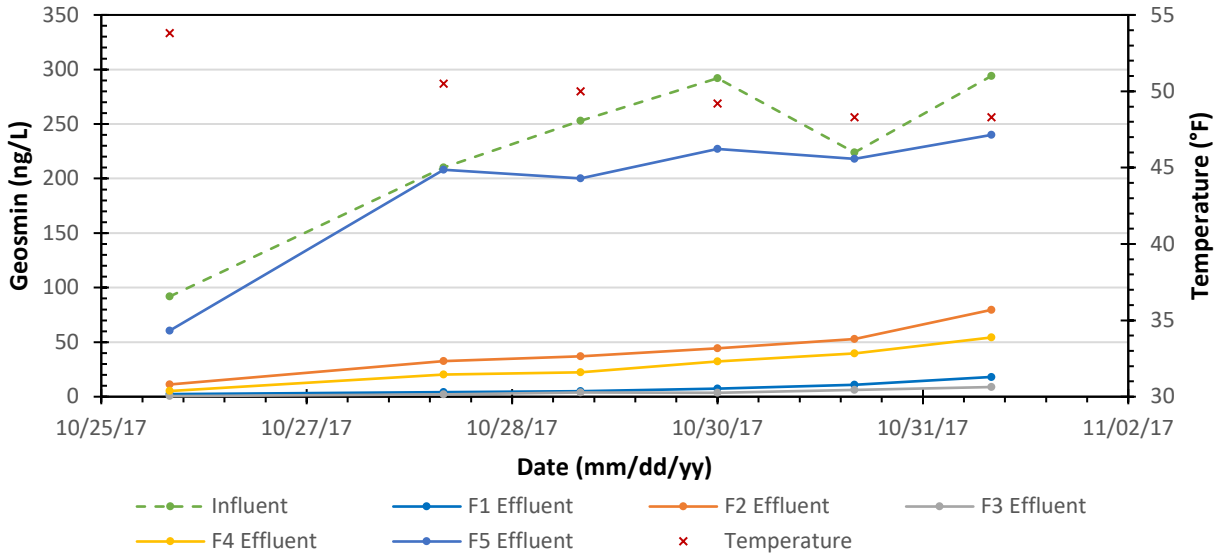

Figure 42. T&O Challenge Test 1 Data

Effluent geosmin concentrations were compared between the BAC and anthracite-sand filters. The treatment objective was to achieve an effluent geosmin concentration less than 10 ng/L, which is the approximate OTC of geosmin. The BAC filters had significantly lower effluent geosmin concentrations than the anthracite-sand filter. Average effluent geosmin concentrations in the BAC filters ranged from between 4.2 to 41.3 ng/L (82.0 to 98.3% removal). However, the average effluent geosmin concentration in the anthracite-sand filter was 192 ng/L (16.5% removal), which far exceeds the OTC. As previously mentioned, geosmin removal in the anthracite-sand filter was due solely to biodegradation since anthracite has a negligible adsorption capacity. However, adsorption may have played a significant role in the removal of geosmin in the BAC filters. Since the BAC filters were not preloaded with geosmin, a large adsorption capacity for geosmin may have remained. Adsorption may also help to explain the large difference in geosmin removal efficiencies between the BAC and anthracite-sand filters.

Effluent geosmin concentrations were also compared between each of the BAC filters. Similar to what was observed with organics removal efficiency data, the bituminous coal-based GACs (F300 and Norit 300) outperformed the coconut-based GAC (Jacobi). Out of the four

BAC filters evaluated, Filter 3 consistently achieved the lowest effluent geosmin concentrations, which averaged 4.2 ng/L (98.3% removal) and consistently remained below the OTC. Filter 2 had the highest average effluent geosmin concentration, which was 43.0 ng/L (82.0% removal). It was also observed that Filter 1 achieved notably higher geosmin removals than Filter 4. This may further support the theory that adsorption played a significant role in geosmin removal in the BAC filters. The higher geosmin removals observed in Filter 1 may have been due to the additional 12 inches of GAC, which would increase the surface area available for adsorption.

5.3.2. T&O Challenge Test 2

The purpose of Challenge Test 2 was to compare geosmin removals in the pilot filters over a longer period of time in the spring, when T&O typically occur at the MWTP. A geosmin dosing period of two weeks was followed by a geosmin-free period of a week, then geosmin was reintroduced for another week. This was done to better simulate the intermittent loading behavior of a real T&O event and to determine to what extent desorption would occur during the geosmin-free period. The test was carried out under relatively constant cold temperature conditions, which remained below 50°F. Influent and effluent geosmin concentrations measured during the study are shown in Figure 43. Influent geosmin concentrations to the pilot filters ranged from between 134 and 352 ng/L during the geosmin-loading periods.

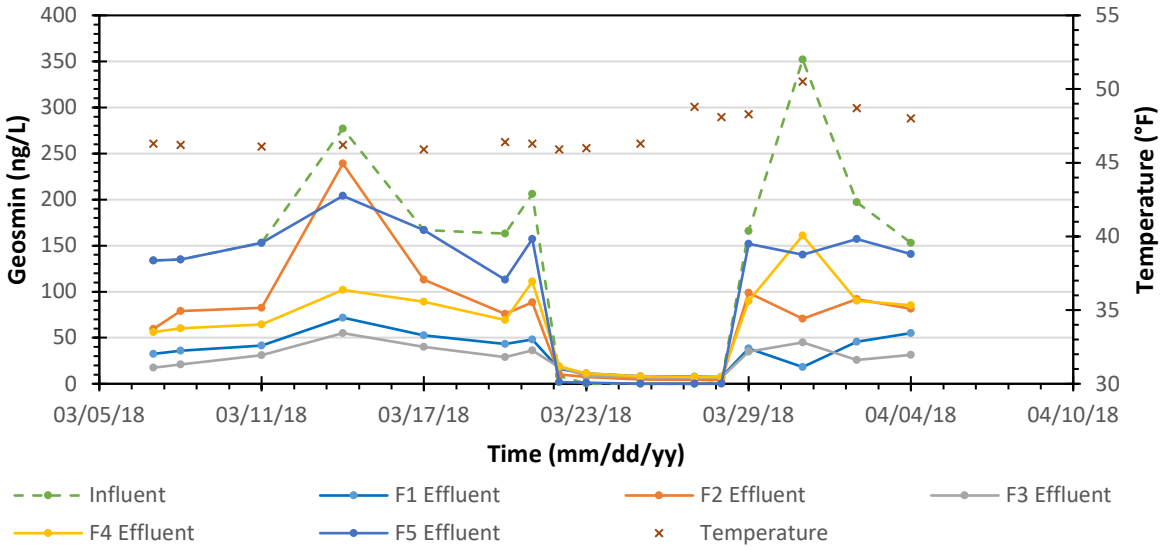

Figure 43. T&O Challenge Test 2 Data

Effluent geosmin concentrations were compared between the BAC and anthracite-sand filters. The BAC filters had significantly lower effluent geosmin concentrations than the anthracite-sand filter. Average effluent geosmin concentrations in the BAC filters ranged from between 33.4 to 98.2 ng/L (47.3 to 82.2% removal). However, the average effluent geosmin concentration in the anthracite-sand filter was 150 ng/L (16.1% removal). It was noted that the average geosmin removal efficiencies of the BAC filters significantly decreased since Challenge Test 1; however, the average geosmin removal efficiency in the anthracite-sand filter remained approximately the same. This may have been the result of the colder water temperatures in this study, which would decrease the intraparticle diffusion rate of adsorption in the BAC filters.

Effluent geosmin concentrations were also compared between each of the BAC filters. The performance of each filter ranked similarly to Challenge Test 1. Filter 3 consistently achieved the lowest effluent geosmin concentrations, which averaged 33.4 ng/L (82.2% removal). Filter 2 had the highest average effluent geosmin concentration, which was 98.2 ng/L (47.3% removal). The microporous structure of the Jacobi GAC contained in Filter 2 may have resulted in a further decrease in the intraparticle diffusion rate of adsorption than the filters

containing a larger volume of mesopores and macropores, such as the F300 and Norit 300 GACs. As recalled from the literature, most T&O compounds adsorb in the micropores (Yu et al., 2007). However, the mesopores and macropores are essential for the internal transport to the micropore surface area (Chowdhury et al., 2013). It was also observed that Filter 1 achieved significantly higher geosmin removals than Filter 4 (average of 75.2% compared to 53.0%). As previously mentioned, this may be indicative of adsorption playing a significant role in the removal of geosmin in the BAC filters, due to the higher surface area available for adsorption in Filter 1.

During the geosmin-free period, influent and effluent concentrations of geosmin were measured in the pilot filtration system, with data shown in Figure 44. One concern was that the reversal of the concentration gradient between the solid and liquid phases would result in the desorption of geosmin at levels above the OTC. However, as shown in Figure 44, the desorption of geosmin generally occurred at levels below the OTC. The period of desorption that occurred in the BAC filters also indicates that adsorption took place during the geosmin-loading period. The low concentrations of geosmin desorbed during the geosmin-free period may indicate that the BAC was not saturated with organics and a large adsorption capacity for geosmin remained. Negligible desorption occurred in Filter 5, since anthracite has little capacity for adsorption.

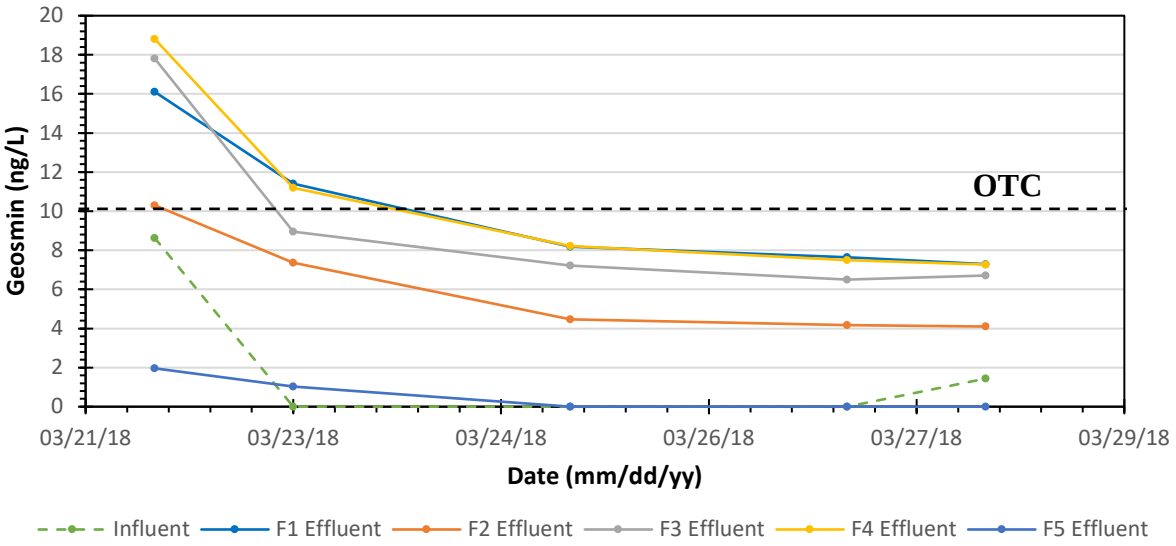

Figure 44. T&O Challenge Test 2 – Geosmin-Free Period Data

5.3.3. T&O Challenge Test 3

The purpose of T&O Challenge Test 3 was to compare geosmin removals between the BAC and anthracite-sand filters during a warm period. Filter 3 was selected to be compared against Filter 5 since it had the highest performance in the previous two tests. Temperatures remained above 68°F throughout the study. Influent and effluent geosmin concentrations were measured on 13 different sampling periods, with results shown in Figure 45. Influent geosmin concentrations to the pilot filters ranged from between 59.1 to 186 ng/L.

Effluent geosmin concentrations were compared between the BAC and anthracite-sand filters. The BAC filter had significantly lower effluent geosmin concentrations than the anthracite-sand filter. The average effluent geosmin concentration in the BAC filter was 11.4 ng/L (90.5% removal). Therefore, geosmin removals increased again from the cold to warm period in the BAC filter. This may be due to a faster intraparticle diffusion rate of adsorption for geosmin. The average effluent geosmin concentration in the anthracite-sand filter was 107 ng/L (6.3% removal), which decreased from the previous two tests.

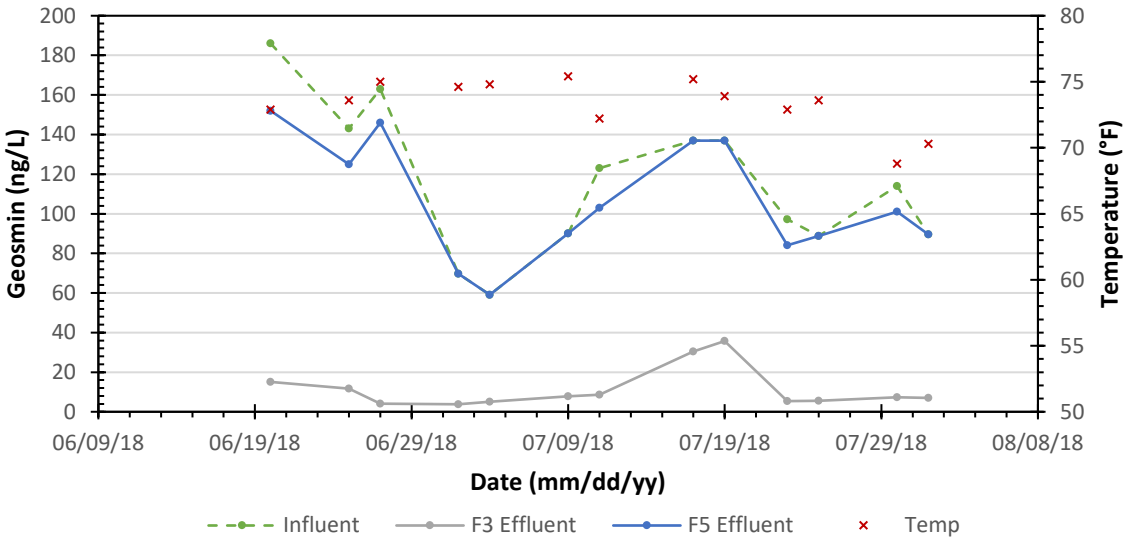

Figure 45. T&O Challenge Test 3 Data

5.4. Turbidity Data and Analysis

Results from the measurement of turbidity in water samples collected from the pilot filtration system are presented and discussed in this section. Effluent turbidities in Filter 5 were compared to effluent turbidities measured in full-scale filters during the study period. This was done to determine how well the pilot filtration system mimicked the full-scale filters in terms of turbidity removal. Results from the turbidity and head loss profile experiments are also discussed in this section. A summary of data presented in this section can be found in Appendices C and D.

5.4.1. Daily Effluent Turbidity Data

Influent turbidities to the pilot filters were relatively low and ranged between 0.3 and 4.1 NTU (average 1.0 NTU) throughout the study period. To evaluate and compare the effectiveness of turbidity removal in the BAC and anthracite-sand filters, effluent turbidities were measured daily in each pilot filter, with data shown in Figure 46. Effluent turbidities in each pilot filter ranged from 0.043 to 0.42 NTU. Overall, turbidity removals between the BAC and anthracite-sand filters were similar, with average effluent turbidities that ranged between 0.12 and 0.13 NTU. Evaluation of turbidity data demonstrated that effluent turbidities for all five pilot filters

met current standards. A summary of turbidity data is provided in Table 15, and box and whisker plots of turbidity data are shown in Figure 47.

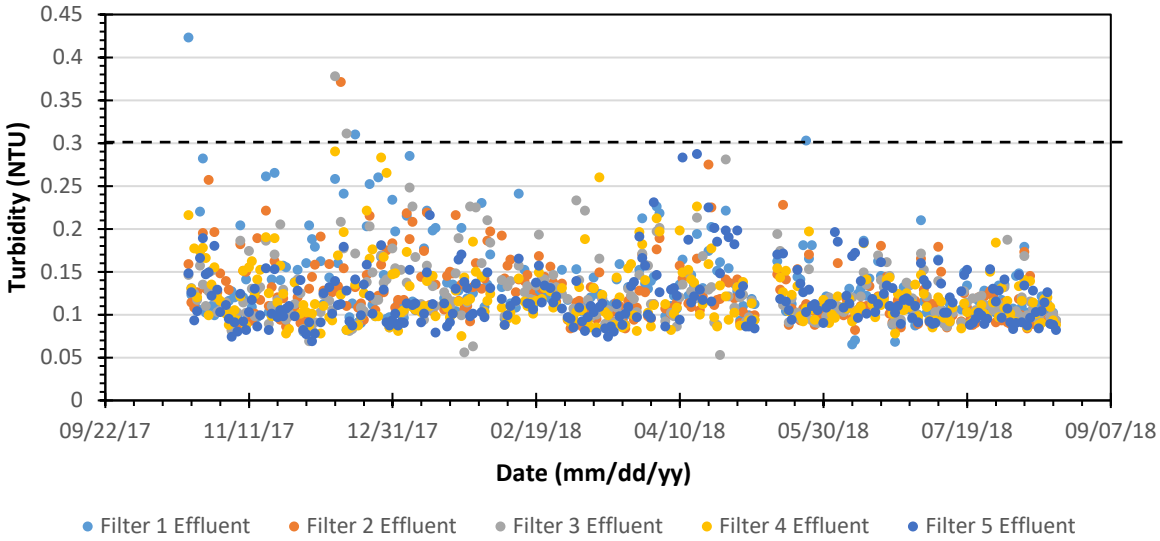

Figure 46. Turbidity Data in Pilot Filters

Table 15. Summary of Turbidity Data in Pilot and Full-Scale Filters

Sample Location	Minimum Turbidity (NTU)	Average Turbidity (NTU)	Maximum Turbidity (NTU)	Standard Deviation
Influent	0.30	1.0	4.1	±0.56
Filter 1 Effluent	0.065	0.13	0.42	±0.047
Filter 2 Effluent	0.082	0.13	0.37	±0.037
Filter 3 Effluent	0.053	0.13	0.38	±0.038
Filter 4 Effluent	0.075	0.12	0.29	±0.029
Filter 5 Effluent	0.069	0.12	0.29	±0.029
Full-Scale Filter Effluent	0.030	0.040	0.10	±0.0099

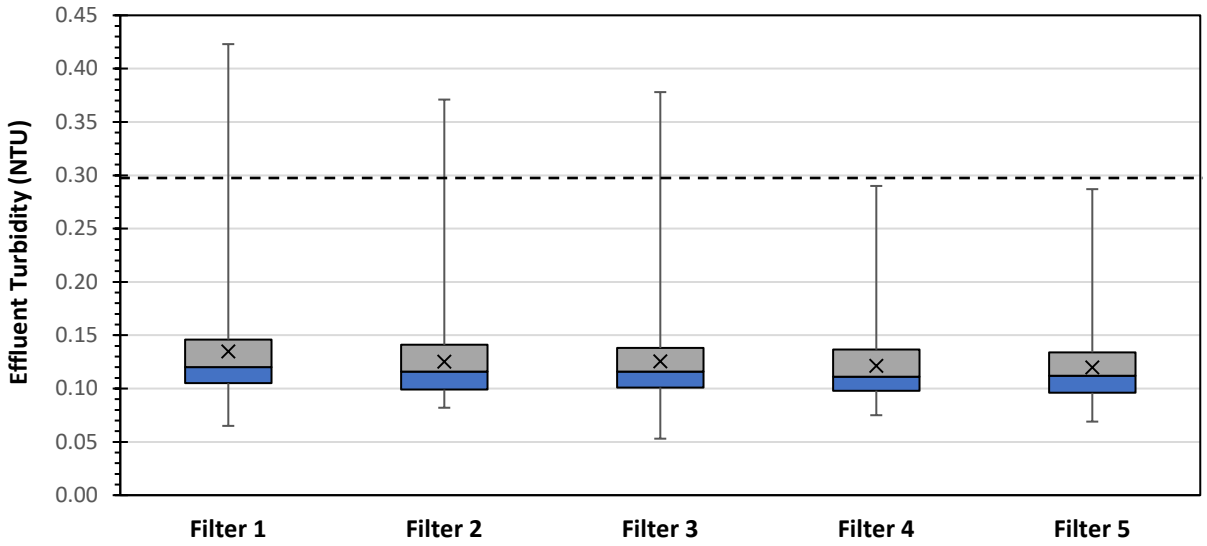

Figure 47. Turbidity Data in Pilot Filters – Box and Whisker Plots

Pilot filter effluent turbidities remained relatively stable throughout the study period and demonstrated no significant seasonal variations, as shown in Figure 46. However, slightly lower variations in effluent turbidities were observed in the filters containing a layer of sand (Filters 4 and 5). For example, standard deviations of turbidity in the BAC filters containing no sand layer (Filters 1 through 3) ranged between ± 0.037 and ± 0.047 NTU, and in the filters containing sand (Filters 4 and 5) standard deviations were ± 0.029 NTU. This is likely due to the sieve effect of the sand layer in which the smaller particles not removed by the GAC or anthracite layers are strained out by the sand. Therefore, filters containing sand may provide additional protection from turbidity breakthrough.

Effluent turbidities in Filter 5 were compared to those in the full-scale filters. Effluent turbidities in Filter 5 were found to be significantly higher than in the full-scale filters. The average effluent turbidity in Filter 5 was 0.12 NTU and in the full-scale filters, the average effluent turbidity was 0.040 NTU. This was likely due to differences in loading rates applied to the pilot filters, and wall effects from each column (media sticking to wall of column after

backwashing). The loading rate to the pilot filters was 2.8 gpm/ft^2 for a majority of the study; however, the average loading rate to the full-scale filters was 2.2 gpm/ft^2.

Overall, the results of this study demonstrate that filters containing larger GAC grain sizes (0.8-1.0 mm) can provide equivalent turbidity removal to filters containing smaller sand grain sizes (0.45-0.55 mm). It was initially presumed that the filters containing a layer of sand would provide better particle removal due to the mechanism of straining. However, since this was not the case, it was postulated that the relatively rougher surface (as observed in SEM analysis) and likely higher biomass content of the GAC media (as suggested by the higher organic removals achieved in the BAC filters) enhanced particle removal throughout the depth of the BAC filters.

The rougher surface of the GAC could enhance particle removal throughout the depth of the filter in different ways. First, the rougher surface would provide more opportunities for particles to contact the surface of the filter grain due to a correspondingly higher surface area. Second, the rougher surface provides recesses with decreased fluid shear stress. This could increase the chances of particle attachment due to decreased drag forces on the particles near the surface of the media. Furthermore, this could decrease the occurrence of detachment since some of the captured particles are shielded from fluid shear between asperities.

Higher biomass levels would result in a decrease in the pore volume of the filter, which could increase straining and other removal mechanisms. The sticky extracellular polymers contained within the biofilm may also increase particle capture. In fact, biological growth may be the dominant factor influencing the equivalent turbidity removals observed in each filter. During SEM analysis, the surface of the Jacobi GAC was observed to be relatively smooth; however, similar turbidity removals were achieved in Filter 2 (Jacobi GAC) as compared to Filters 1 and 3,

which contained GAC media that was relatively rougher in appearance (F300 and Norit 300). Therefore, surface roughness alone may not account for the equivalent turbidity removals observed in each filter. In addition, the larger asperities observed on the GAC media may be masked to some extent by the biofilm. To determine what influence filter media type had on particle removal, it was recommended to compare turbidity removals throughout the depth of the BAC and anthracite-sand filters.

5.4.2. Turbidity and Head Loss Studies

Turbidity and head loss studies were carried out to evaluate the impact of filter media type on particle removal and to explain the possible particle removal mechanisms operative in each filter. Two studies were carried out with results presented in the following sections.

5.4.2.1. Turbidity Profile and Head Loss Buildup Study

Turbidity at various filter bed depths and head loss buildup were compared in the BAC (Filter 3) and anthracite-sand (Filter 5) filters throughout a filter cycle. The study was conducted during a steady cold period from February 19th, 2019 to February 28th, 2019, with water temperatures ranging between 40.5 and 40.8°F. Turbidity and head loss buildup was measured in each pilot filter on 10 different sampling periods. Influent turbidity to the filters was relatively low and varied between 0.4 and 1.6 NTU throughout the study. Effluent turbidities were similar in each filter and remained relatively constant, as shown in Figure 48. Effluent turbidities never exceeded 0.1 NTU in either filter, which was likely due to the relatively low turbidity loading to the filters throughout the study. Therefore, the experiment was terminated when the water surface level reached the top of Column 5.

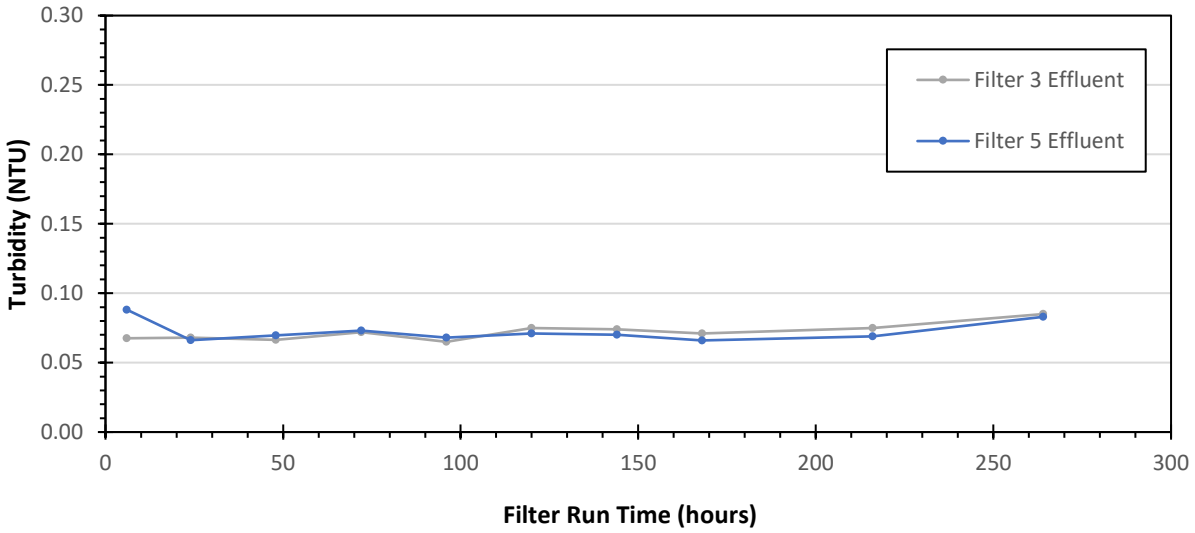

Figure 48. Effluent Turbidity over Time in Pilot Filters

To determine the impact of media type on turbidity removal, turbidity profiles were compared in each filter throughout a filter cycle, as shown in Figure 49 through Figure 58. Turbidity removals were also compared in each individual filter layer, as summarized in Table D6 and Table D7. Turbidity removal was evident in each layer of the filter bed. The top layer (0- to 8-inches) of each filter achieved the highest turbidity removal efficiencies throughout most of the filter cycle. As was observed during SEM analysis, most of the biological growth occurred in the top layer of each filter. This could help to explain why such a significant portion of the turbidity removal occurred in this region.

Turbidity removal was also compared in the top layer of the BAC and anthracite-sand filters. Significantly higher turbidity removals were observed in the top layer of the BAC filter throughout the filter cycle. This could have been due to the combined effect of better surface straining and depth removal. For example, the relatively higher UC of 2.1 in the GAC media as compared to 1.5 in the anthracite media may have resulted in more surface straining in the BAC filter. A higher UC indicates a wider range of grain sizes, which would result in more stratification of the filter media during backwashing, where smaller grains would settle on the

top of the filter bed. With a layer of finer grains on the top of the bed, the sieve effect would be enhanced. In addition to enhanced surface straining, the relatively rougher surface of the GAC and higher biomass levels may have enhanced particle deposition and retainment through the depth of the top layer.

It was also observed that turbidity removals gradually decreased over time in the top layer of each filter, as shown in Figure 59 and Figure 60. As particles collect in the filter bed, the filter bed porosity decreases, and the fluid drag forces on the surface of the media increase. This would make the capture of additional particles more difficult. Furthermore, it was found that turbidity removals decreased over time in the top layer of the anthracite-sand filter at a faster rate than in the BAC filter (slope of -0.0053 in Filter 5 as compared to -0.0036 in Filter 3), as shown in Figure 61. This suggests that the anthracite-sand filter will approach breakthrough faster than the BAC filter.

Higher turbidity removals were observed in the BAC filter through the second layer of the filter bed (8- to 14-inches) most of the time. Although the sieve effect could partially explain the relatively higher removals observed in the top layer of the BAC filter, the relatively higher removals observed in the second layer may be due to differences in surface characteristics or biological growth between the GAC and anthracite. However, since the difference in turbidity removals between the BAC and anthracite-sand layers is not significant in the second layer, this analysis should be approached with caution.

Turbidity removals were also observed to improve slightly over time through the second layer of each filter, as shown in Figure 59 and Figure 60. This was found to occur as turbidity removals decreased in the top layer. This may be attributed to the shearing off of captured particles from the top layer of the filter bed to the second layer of the filter bed. This would result

in ripening, as captured particles would be available to serve as collectors for other suspended particles.

The anthracite-sand filter demonstrated higher turbidity removals in the third layer (14- to 26-inches) of the filter bed most of the time. However, it is important to note that the 26-inch depth water sample port is located at the interface of the anthracite and sand media. Therefore, the relatively higher turbidity removals observed between the 14- and 26-inch depths in the anthracite-sand filter were likely due to the effect of surface straining in the sand layer, rather than better depth removal in the anthracite. Because of this, a direct comparison can only be made between the BAC and anthracite media from 0- to 14-inches of each filter bed.

In the fourth layer (26- to 32-inches) of the filter beds, the anthracite-sand filter consistently achieved the highest turbidity removal. However, both of the 26- and 32-inch depth sample ports are located within the sand layer; therefore, the relatively higher turbidity removal was likely due to surface straining. The effect of the sand layer on turbidity removals is clearly shown in Figure 49 through Figure 58, where a notable increase in turbidity removal is observed between the 26- and 32-inch filter bed depths.

Higher turbidity removals were observed most of the time in the BAC filter in the final layer of the filter bed (32- to 36-inches). This was likely due to the depth effect of removal in the GAC media; whereas, in the sand layer of the anthracite-sand filter, a majority of the turbidity removal occurred on the surface. Overall, more turbidity removal was observed throughout the depth of the BAC media as compared to the anthracite media during the filter cycle.

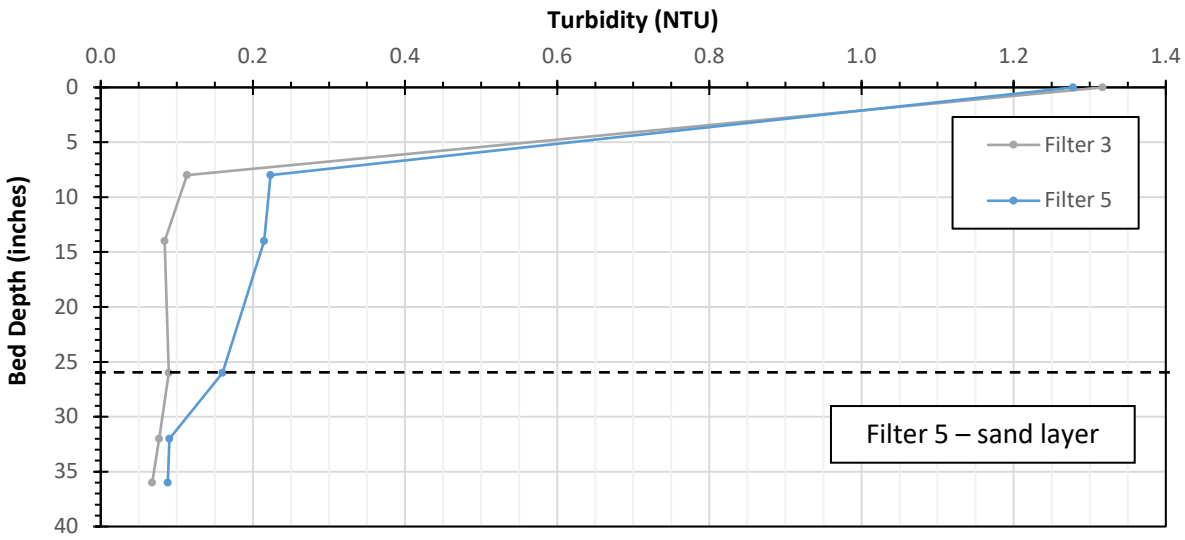

Figure 49. Turbidity Profiles in Pilot Filters (6 hours)

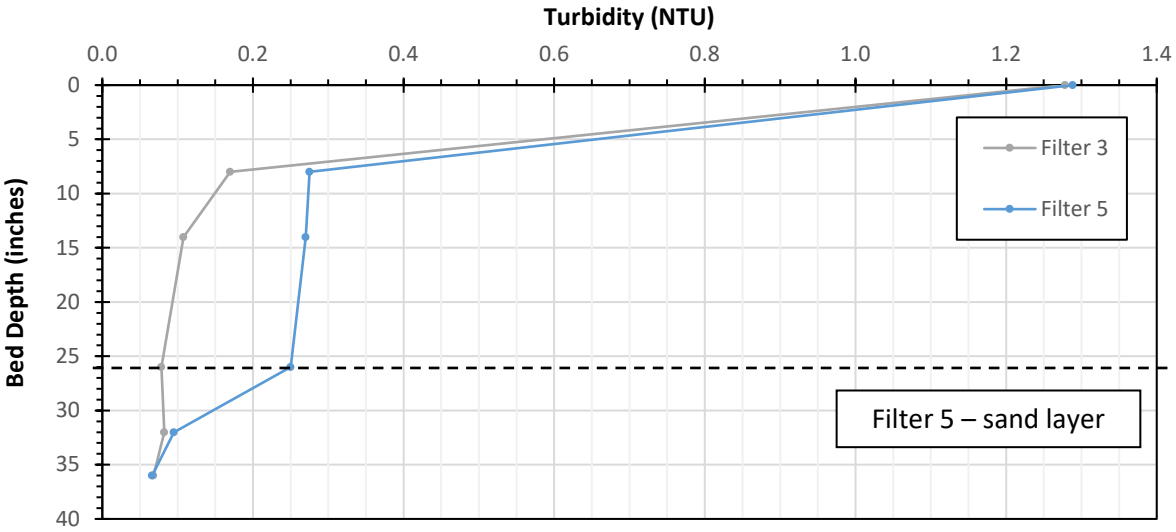

Figure 50. Turbidity Profiles in Pilot Filters (24 hours)

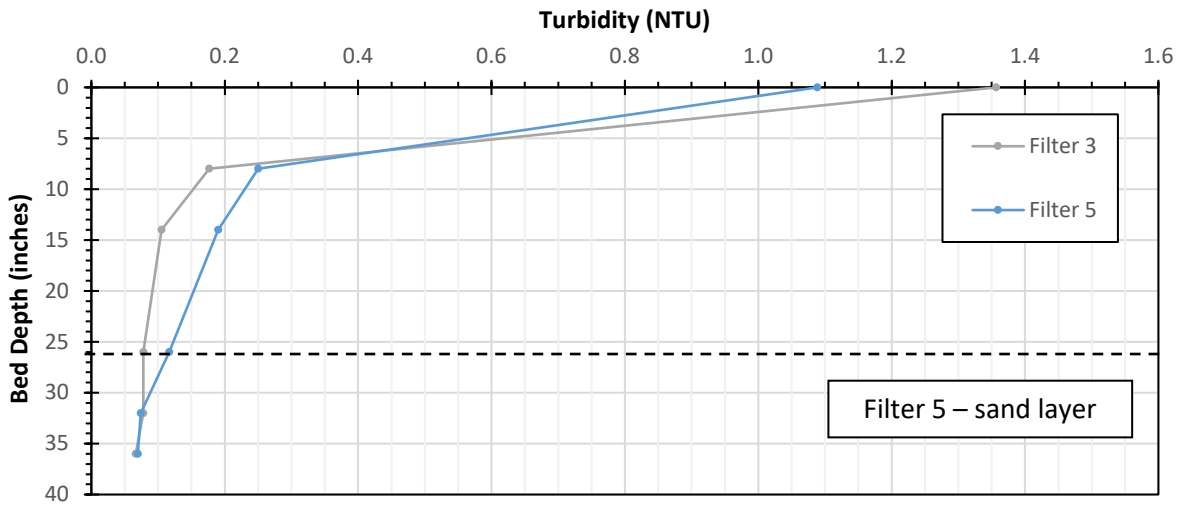

Figure 51. Turbidity Profiles in Pilot Filters (48 hours)

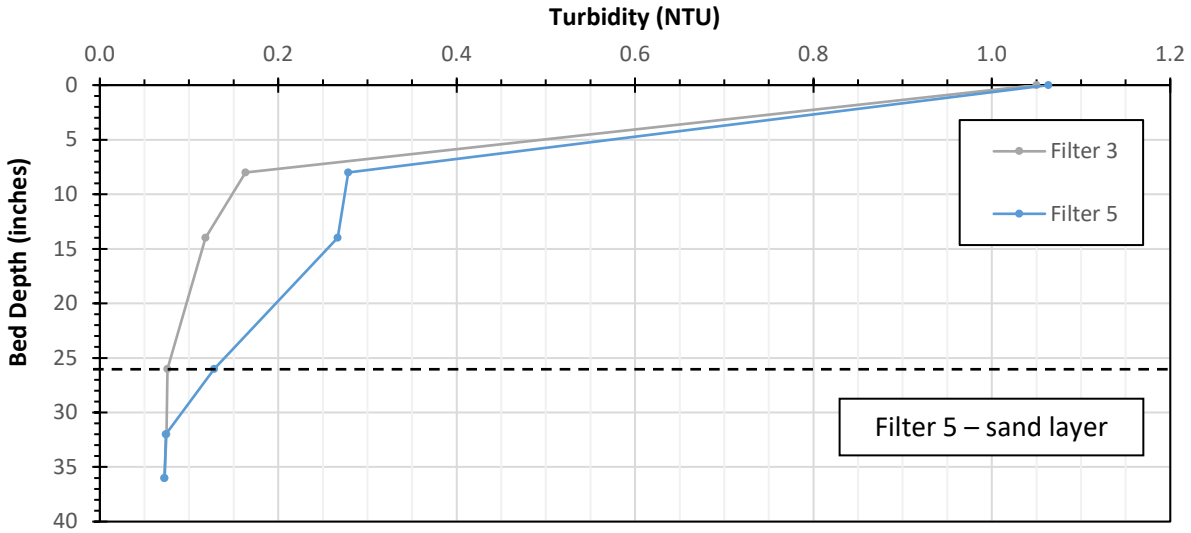

Figure 52. Turbidity Profiles in Pilot Filters (72 hours)

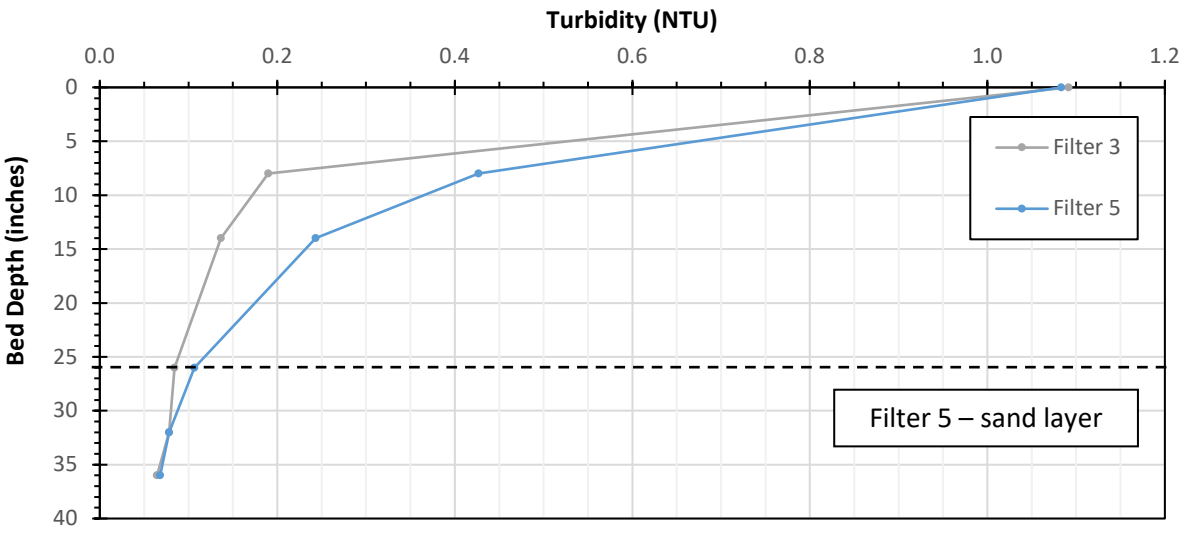

Figure 53. Turbidity Profiles in Pilot Filters (96 hours)

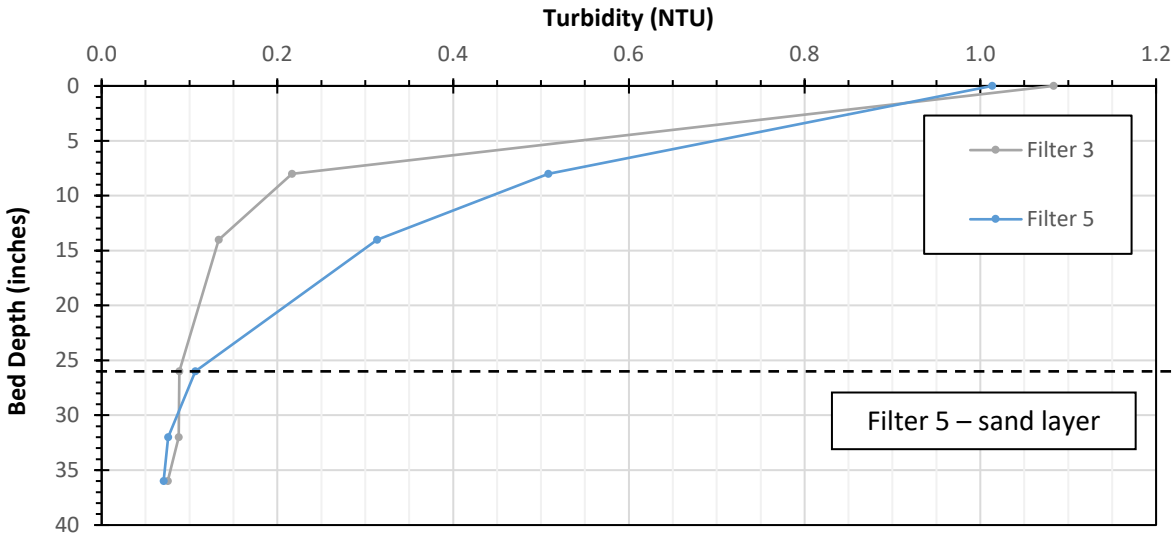

Figure 54. Turbidity Profiles in Pilot Filters (120 hours)

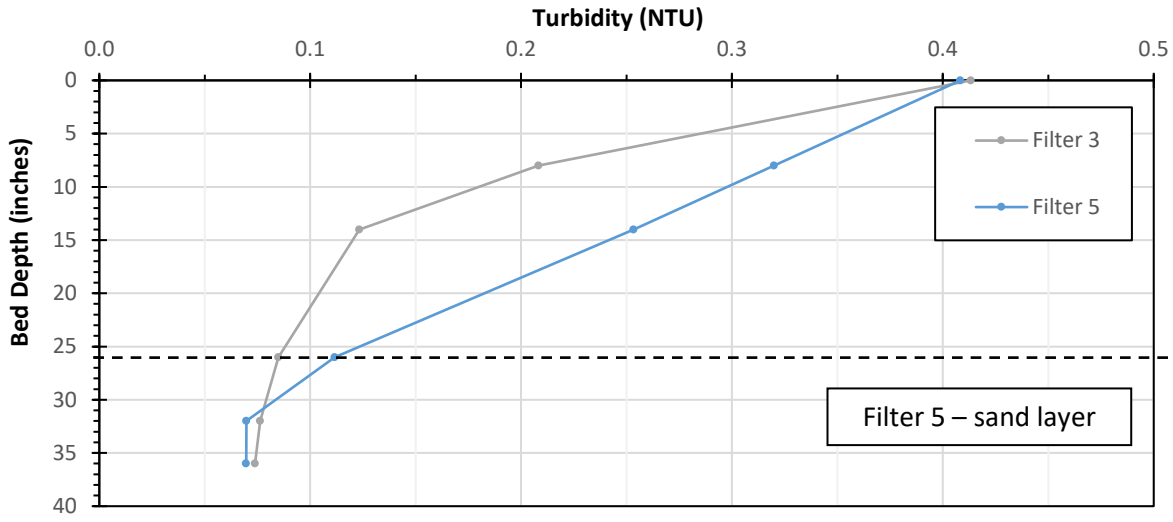

Figure 55. Turbidity Profiles in Pilot Filters (144 hours)

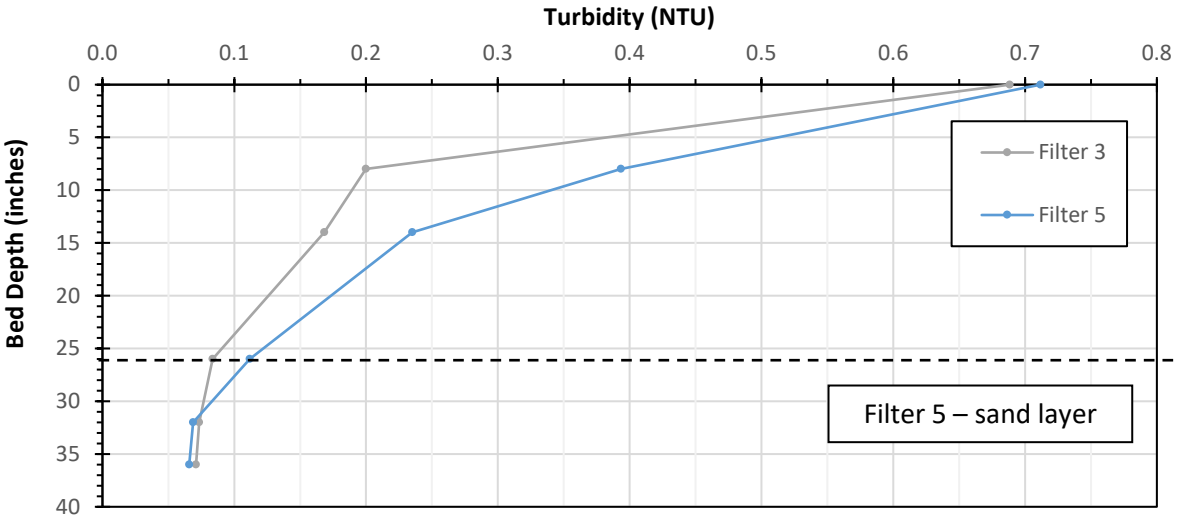

Figure 56. Turbidity Profiles in Pilot Filters (168 hours)

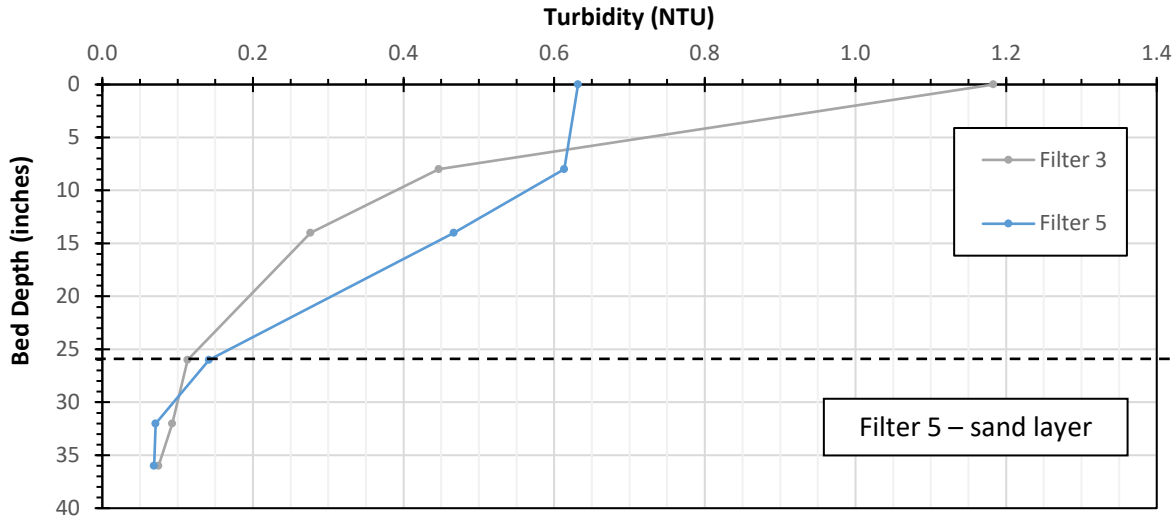

Figure 57. Turbidity Profiles in Pilot Filters (216 hours)

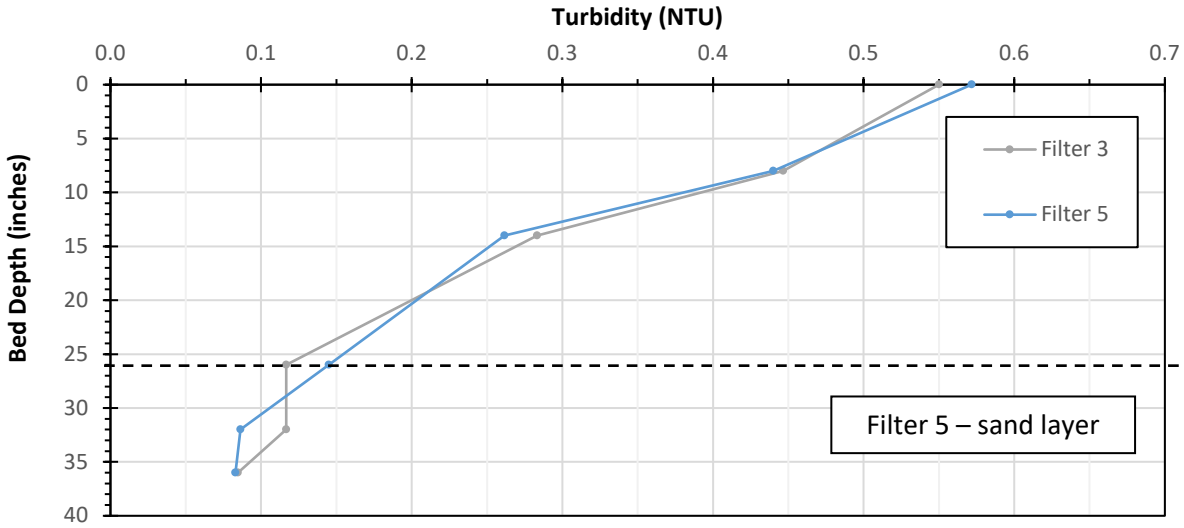

Figure 58. Turbidity Profiles in Pilot Filters (264 hours)

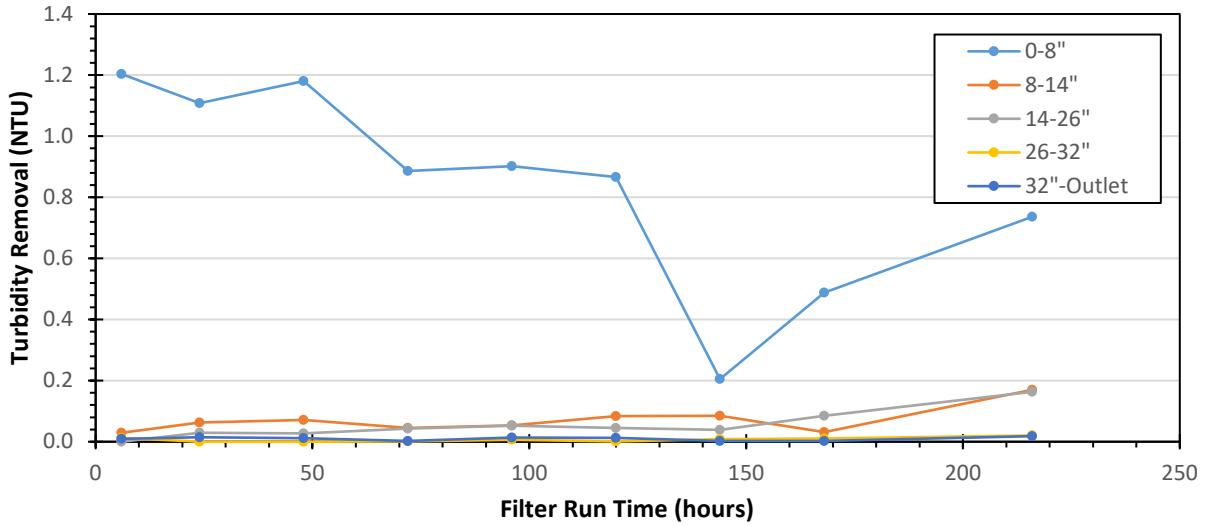

Figure 59. Turbidity Removal over Time in Filter 3

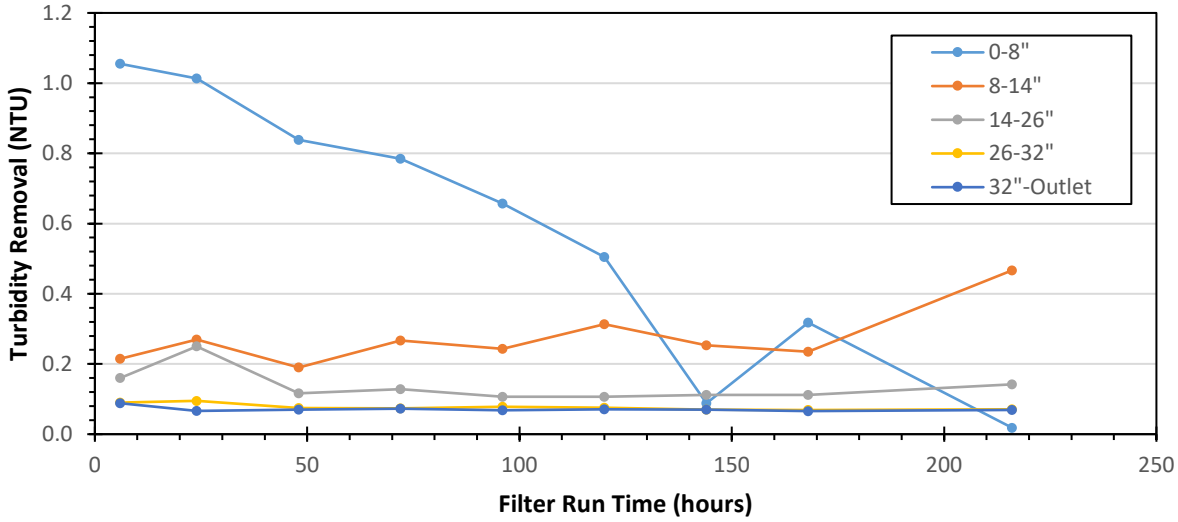

Figure 60. Turbidity Removal over Time in Filter 5

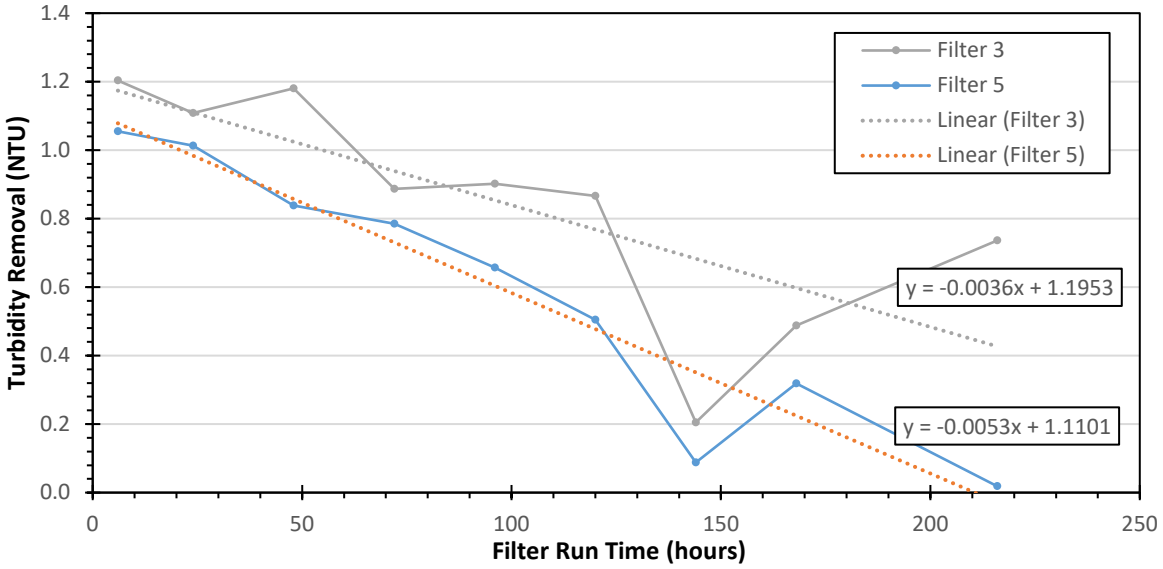

Figure 61. Turbidity Removal over Time (0- to 8-inches) in Pilot Filters

Head loss buildup was similar in both filters, as shown in Figure 62. However, head loss buildup overall was higher in the anthracite-sand filter. This was unexpected due to the relatively higher UC of the GAC media. In addition, it could be logically assumed that the relatively higher turbidity removals observed in the top layer of the BAC filter would have resulted in higher head loss development, however this was not the case. Therefore, it was postulated that the higher turbidity removals observed in the top layer of BAC filter were due to depth removal rather than surface straining.

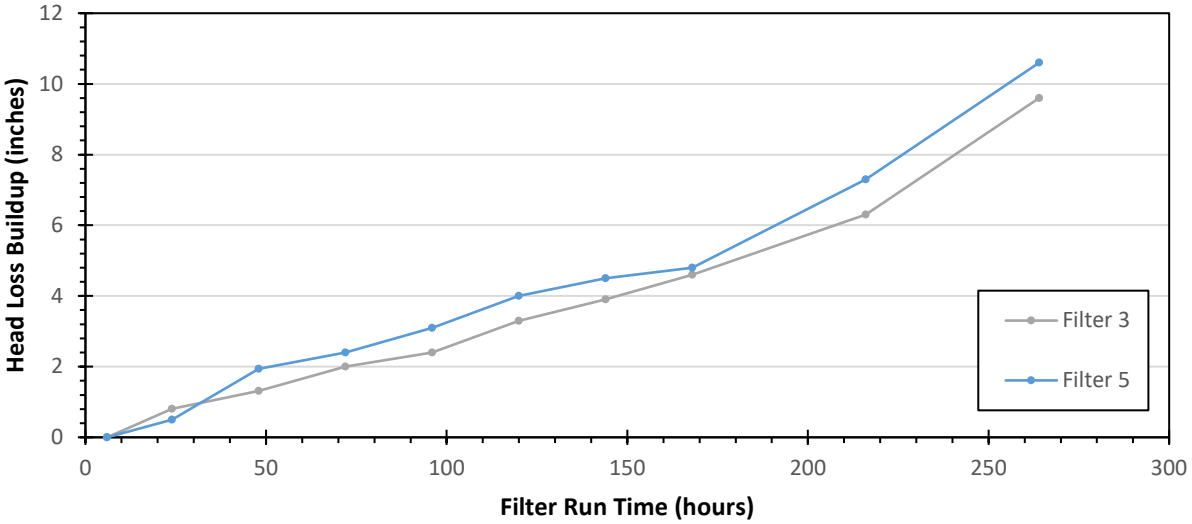

Figure 62. Head Loss Buildup in Pilot Filters over Time

5.4.2.2. Turbidity and Head Loss Profile Study

To provide a more complete picture of particle removal in the BAC and anthracite-sand filters, the original study was amended to include the measurement of total head loss and head loss profiles in each filter. Turbidity profiles were measured on five different sampling periods and head loss profiles were measured on seven different sampling periods in each filter. Organics (TOC and UV254) profiles were also measured on two different sampling periods in each filter as an indirect method to determine if relatively higher biomass levels were present in the BAC filter. Water temperatures throughout the study period were significantly warmer than in the previous test and ranged from between 55.9 and 56.4°F.

Influent turbidity to the filters was observed to be significantly higher than the previous experiment and varied between 0.9 and 2.1 NTU throughout the study. This was caused by surface runoff due to snowmelt from the warmer temperatures and rainfall. Effluent turbidities were similar in each filter and remained relatively constant, as shown in Figure 63. Effluent turbidities never exceeded 0.1 NTU in either filter. Therefore, the experiment was terminated when the water surface level reached the top of Column 5.

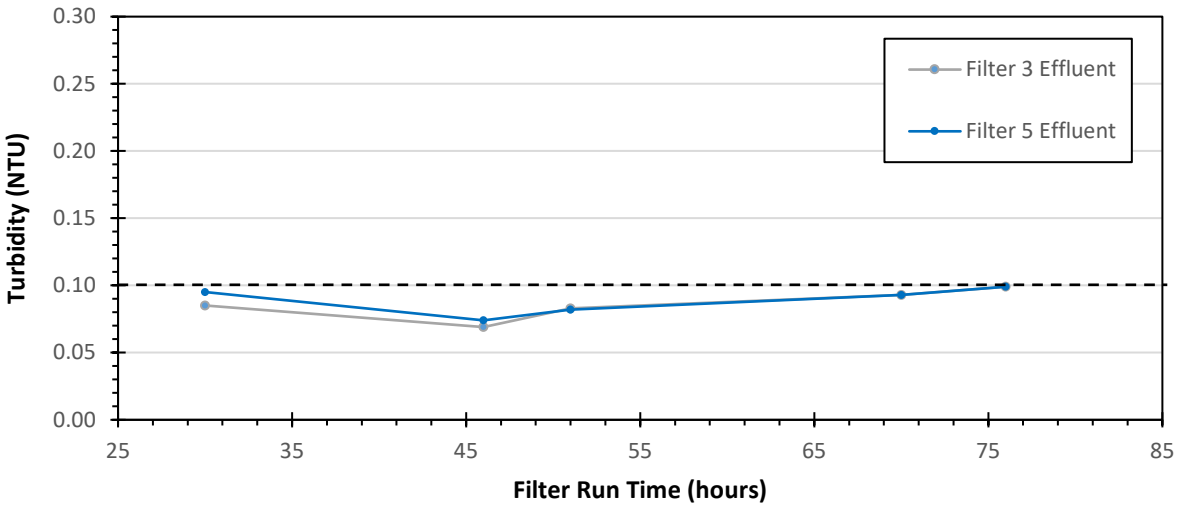

Figure 63. Effluent Turbidity over Time in Pilot Filters

To determine the impact of media type on turbidity removal, turbidity profiles were compared in each filter throughout a filter cycle, as shown in Figure 64 through Figure 68. Similar to the previous experiment, the top layer of each filter achieved the highest turbidity removals. In addition, the highest turbidity removals were consistently achieved in the top layer of the BAC filter. Minimal turbidity removal was observed in the subsequent layers of each filter, unlike the previous study. This may be attributed to the significantly warmer water temperatures during this study. First, particle removal efficiency typically increases with an increase in temperature due to lower water viscosities and higher rates of particle settlement. Second, relatively higher biomass levels may have been present in the media, which would

increase straining in the top layer of the filter and reduce the particle load through the rest of the filter. Therefore, a comparison of turbidity removals through the rest of the filter bed may not be meaningful in this study.

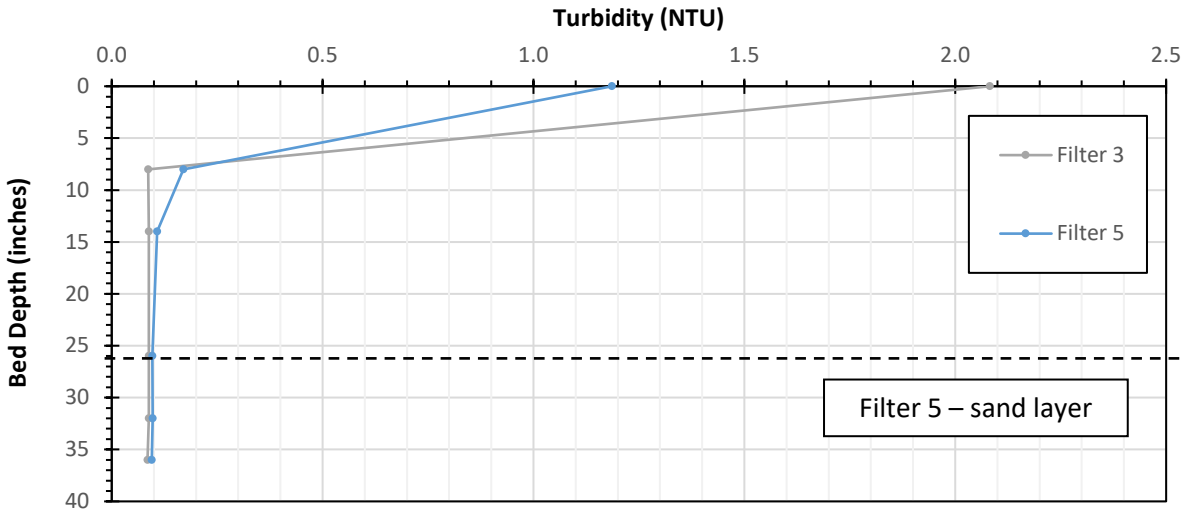

Figure 64. Turbidity Profiles in Pilot Filters (30 hours)

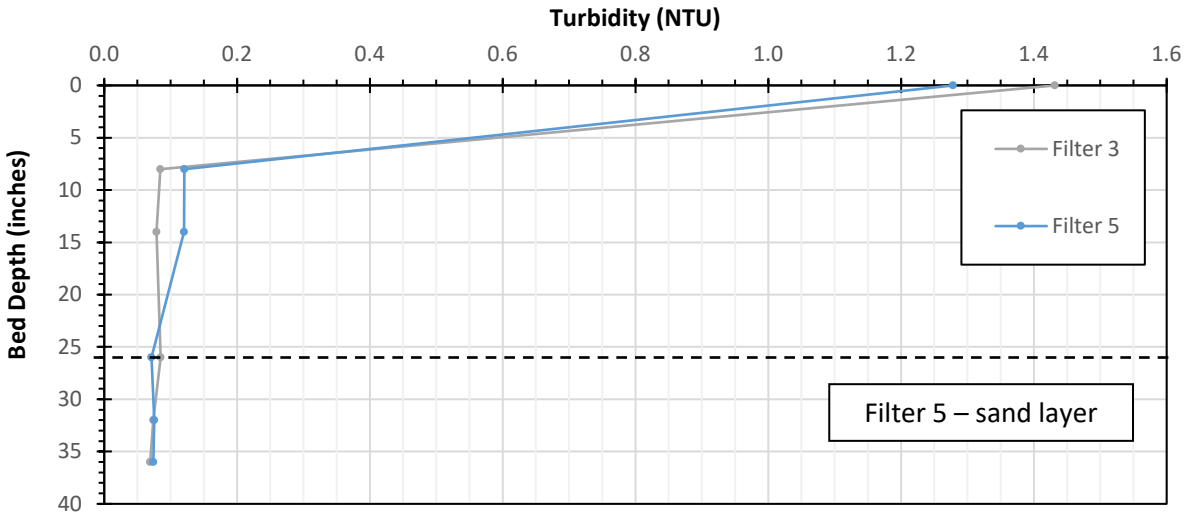

Figure 65. Turbidity Profiles in Pilot Filters (46 hours)

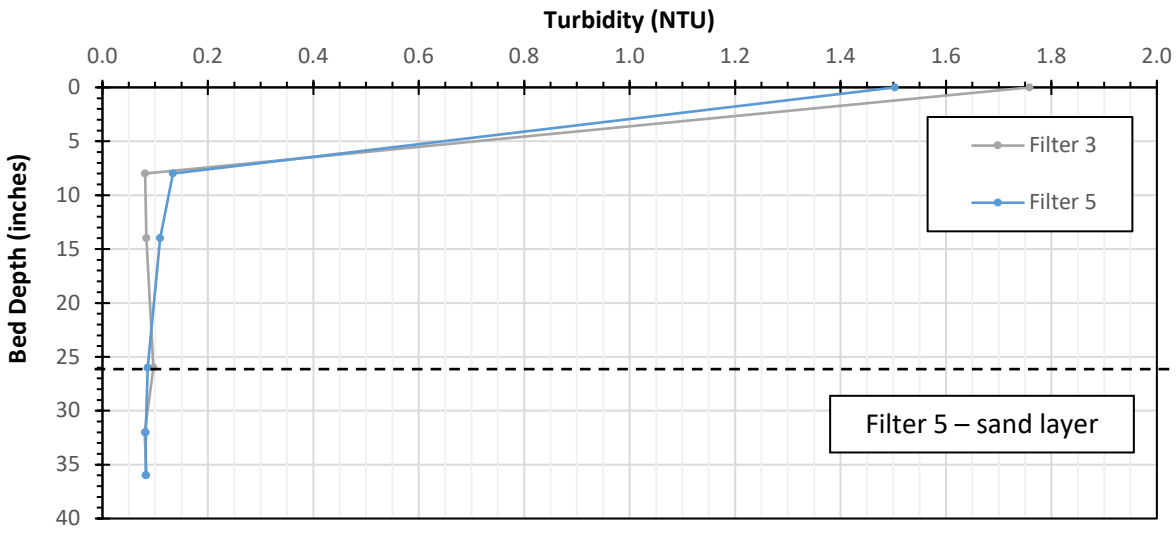

Figure 66. Turbidity Profiles in Pilot Filters (51 hours)

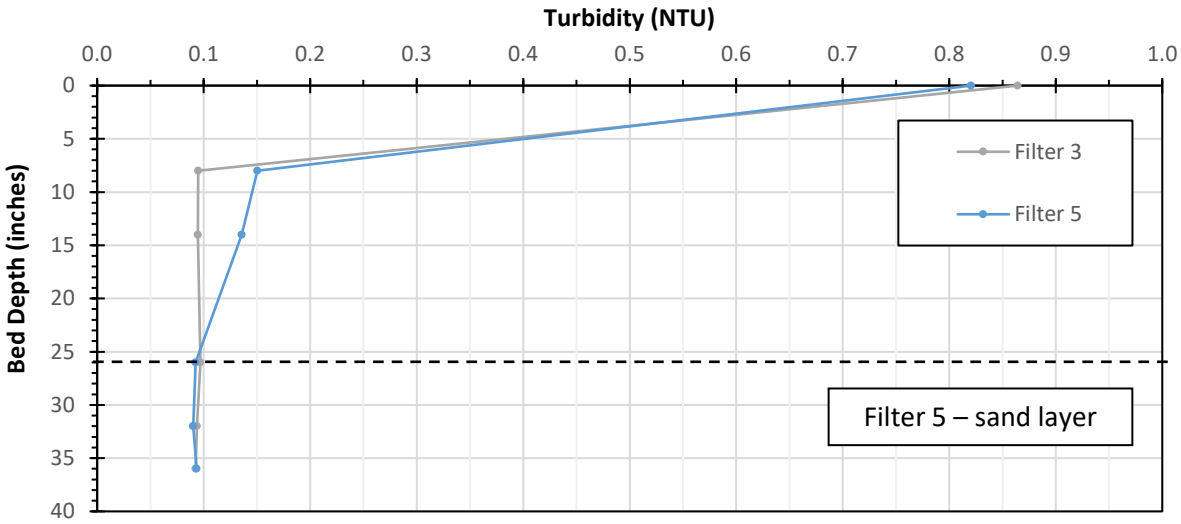

Figure 67. Turbidity Profiles in Pilot Filters (70 hours)

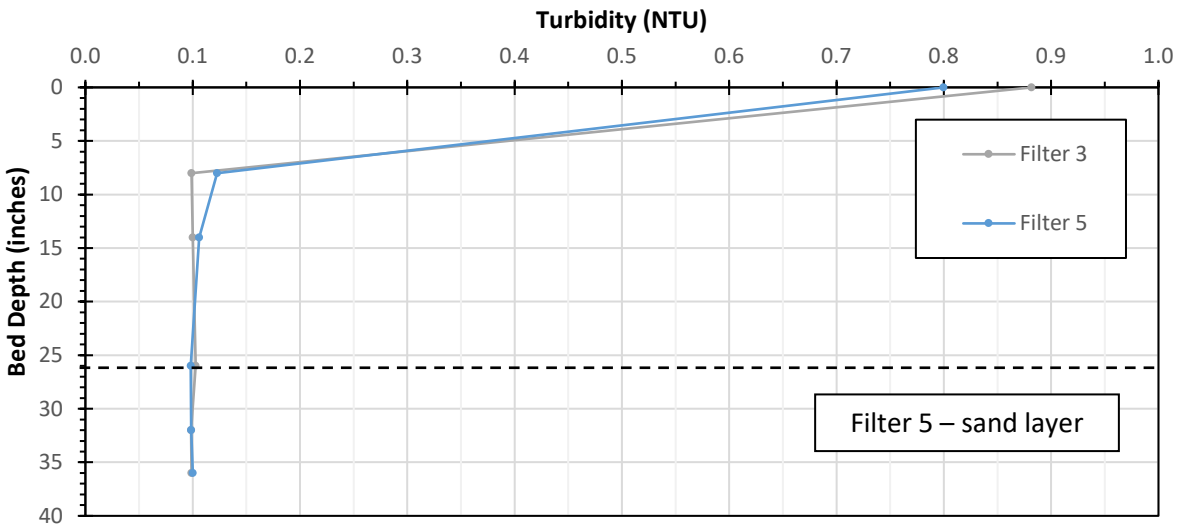

Figure 68. Turbidity Profiles in Pilot Filters (76 hours)

To better understand the potential removal mechanisms in each filter, head loss profiles were also compared between each filter, as shown in Figure 69 through Figure 72. Head loss buildup was found to mainly occur in the top layer of each filter and minimal head loss buildup occurred in subsequent layers. This was expected since a majority of the turbidity removal occurred in this region. Head loss buildup occurred initially at a higher rate in the BAC filter, as shown in Figure 73. However, by the end of the study period, the rate of head loss buildup was higher in the anthracite-sand filter. As previously mentioned, if surface straining was a significant factor in the higher turbidity removal efficiencies achieved in the top layer of the BAC filter, a relatively higher rate of head loss development would be expected in this layer. It was also observed that the total head loss in the anthracite-sand filter was significantly higher than in the BAC filter, as shown in Figure 74. This was expected, since the smaller interstices within the sand layer of cause flow constrictions and subsequent energy losses, which increases initial head loss. Overall, this suggests that the BAC filter may provide equivalent or longer filter run times than the anthracite-sand filter without compromising turbidity removal efficiency.

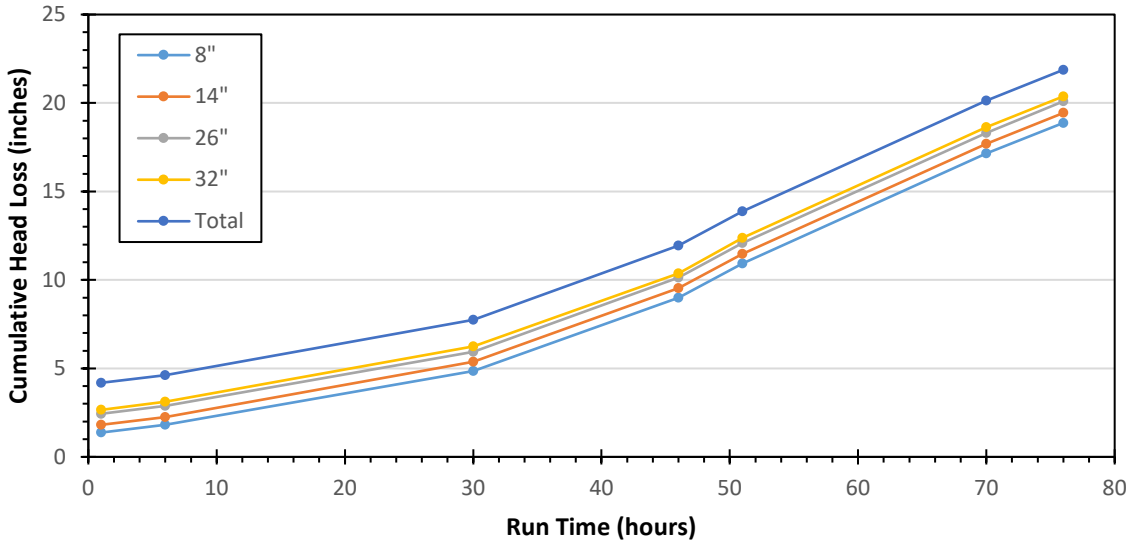

Figure 69. Cumulative Head Loss Profile in Filter 3

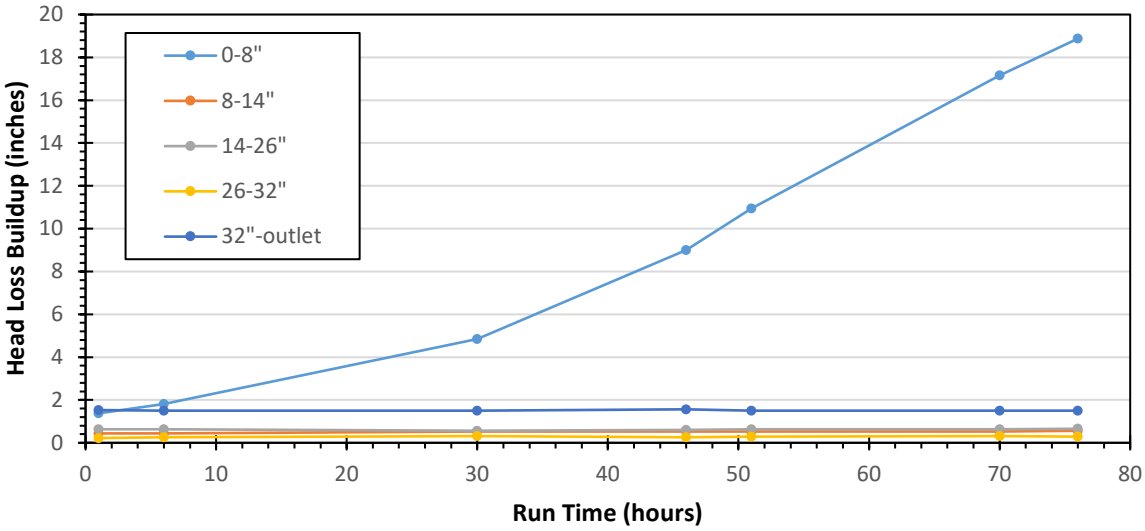

Figure 70. Head Loss Buildup Profile in Filter 3

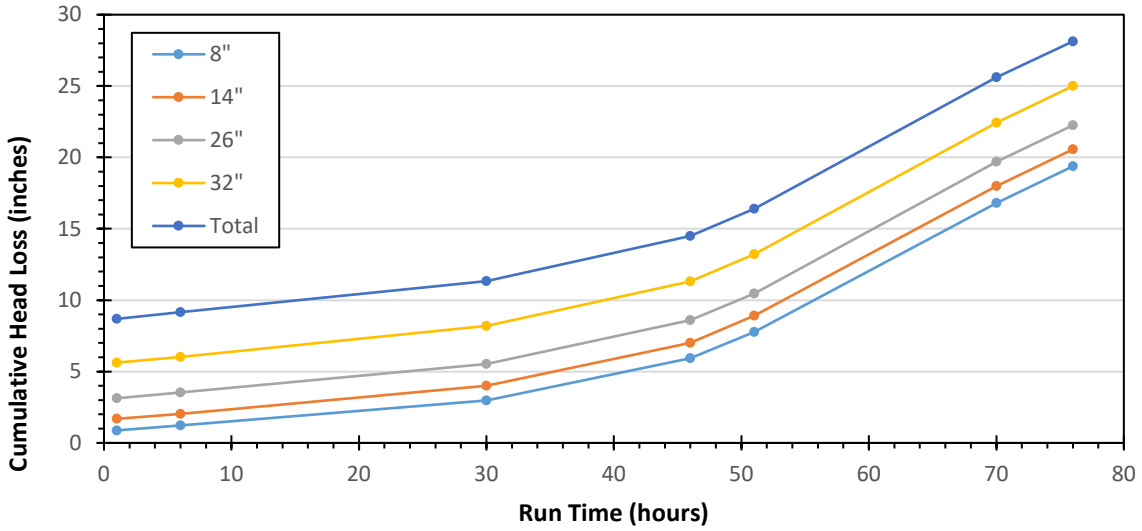

Figure 71. Cumulative Head Loss Profile in Filter 5

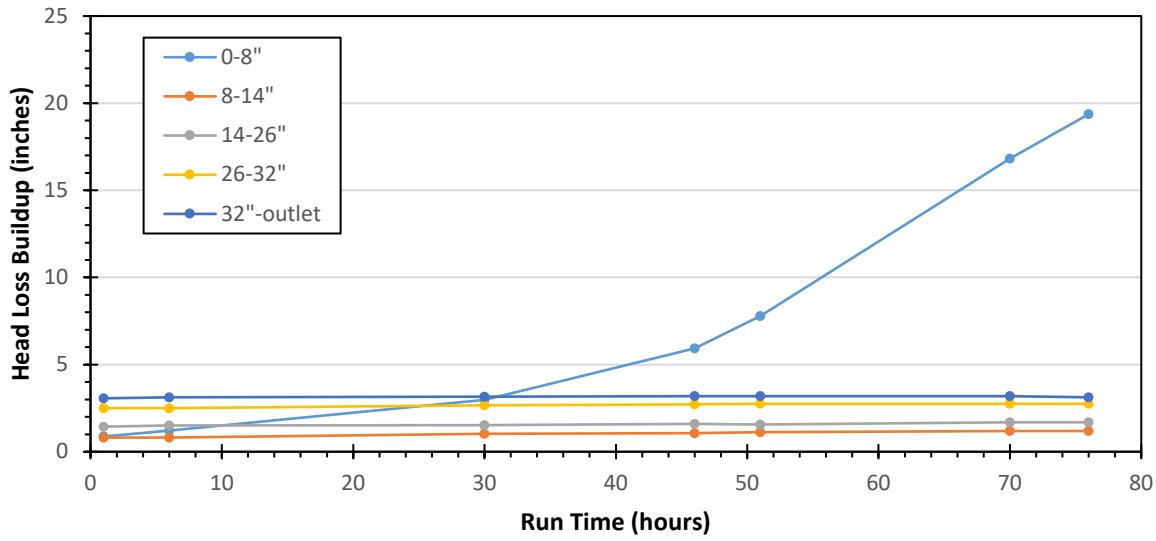

Figure 72. Head Loss Buildup Profile in Filter 5

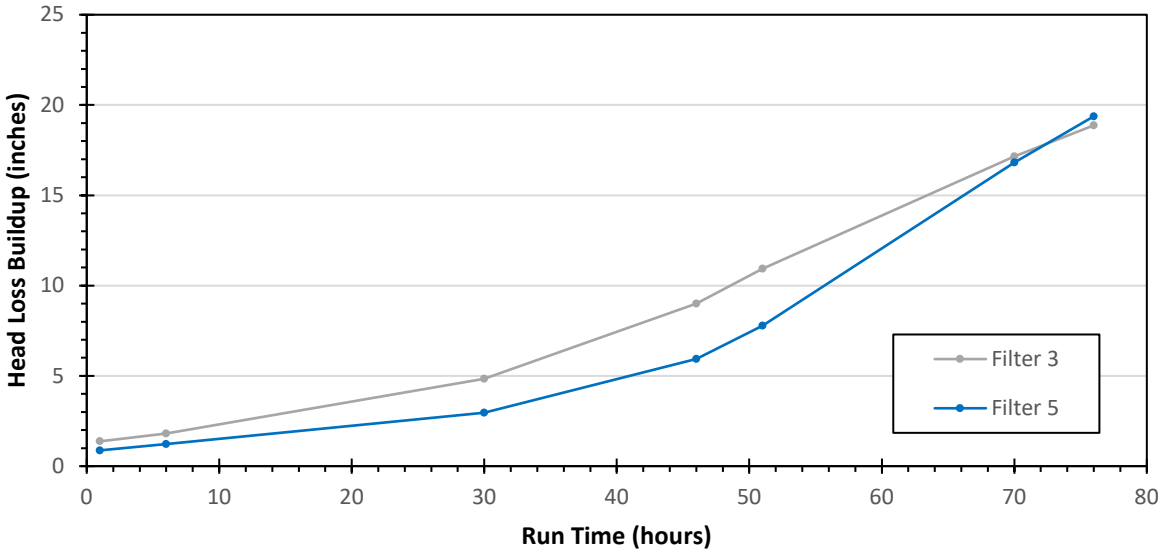

Figure 73. Head Loss Buildup at 8-inch Bed Depth in Pilot Filters

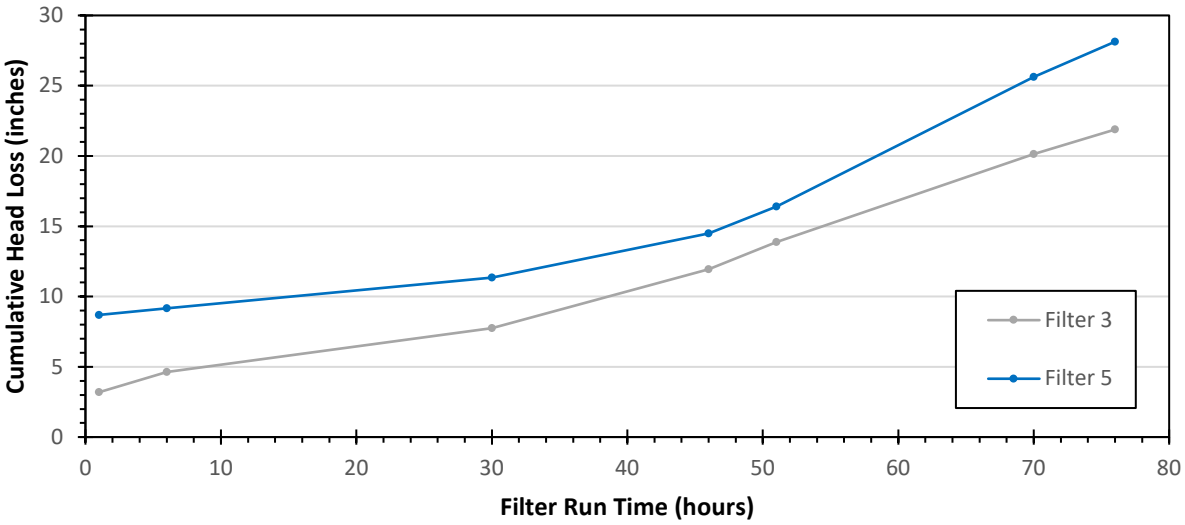

Figure 74. Cumulative Head Loss in Pilot Filters

To further evaluate potential particle removal mechanisms, organics profiles (TOC and UV254) were compared in each filter. TOC removal was evident throughout the depth of each filter during both sampling periods, as shown in Figure 75 and Figure 76. TOC removals were the highest in the top layer of each filter. This suggests that there are higher biomass levels in this region, as was observed during SEM analysis. As previously described, higher levels of biomass would decrease the porosity of the filter bed and increase straining and other removal

mechanisms. This could explain why higher turbidity removals were consistently achieved in the top layer of each filter. Higher UV254 reductions were also observed in the top layers of each filter during both sampling periods, as shown in Figure 77 and Figure 78. Minimal UV254 reductions were observed in subsequent layers of each filter bed.

Organic removals were also compared between the BAC and anthracite-sand filters. Higher TOC and UV254 reductions were observed in the top layer of the BAC filter during both sampling periods. This suggests that the higher turbidity removals observed in the top layer of the BAC filter as compared to the anthracite-sand filter was due to higher levels of biomass.

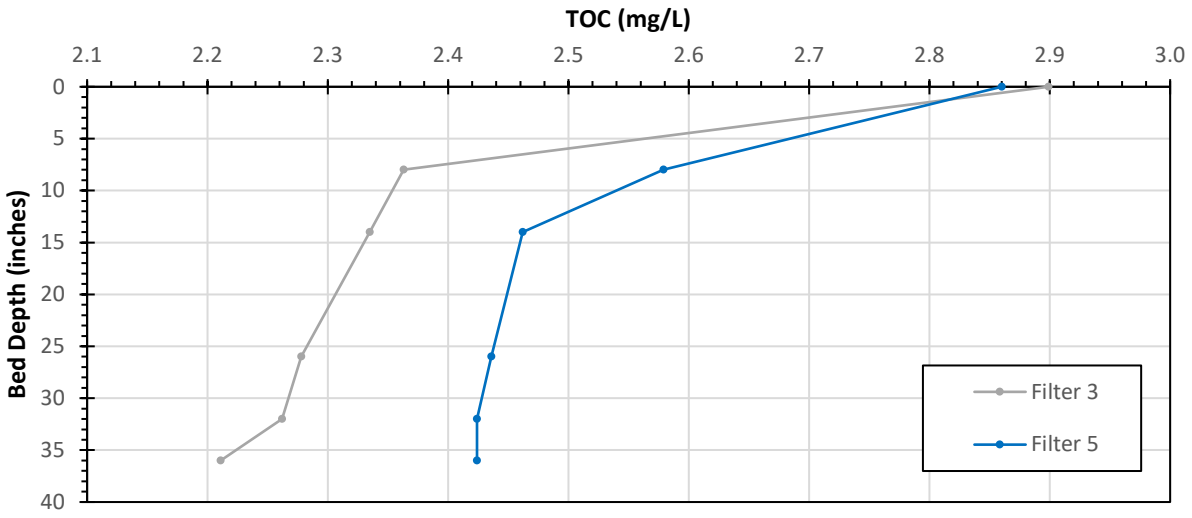

Figure 75. TOC Profiles in Pilot Filters (30 hours)

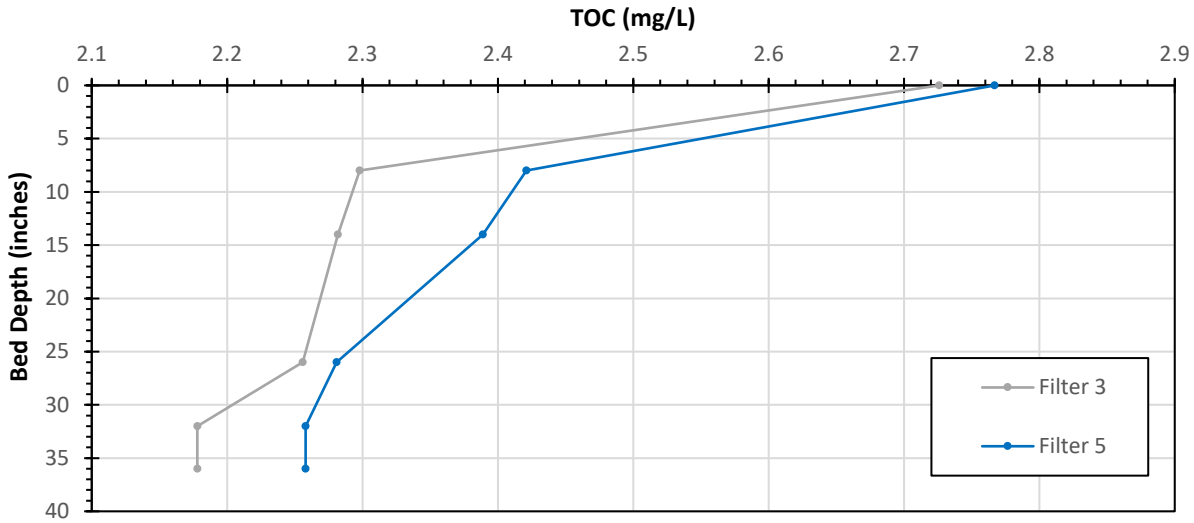

Figure 76. TOC Profiles in Pilot Filters (70 hours)

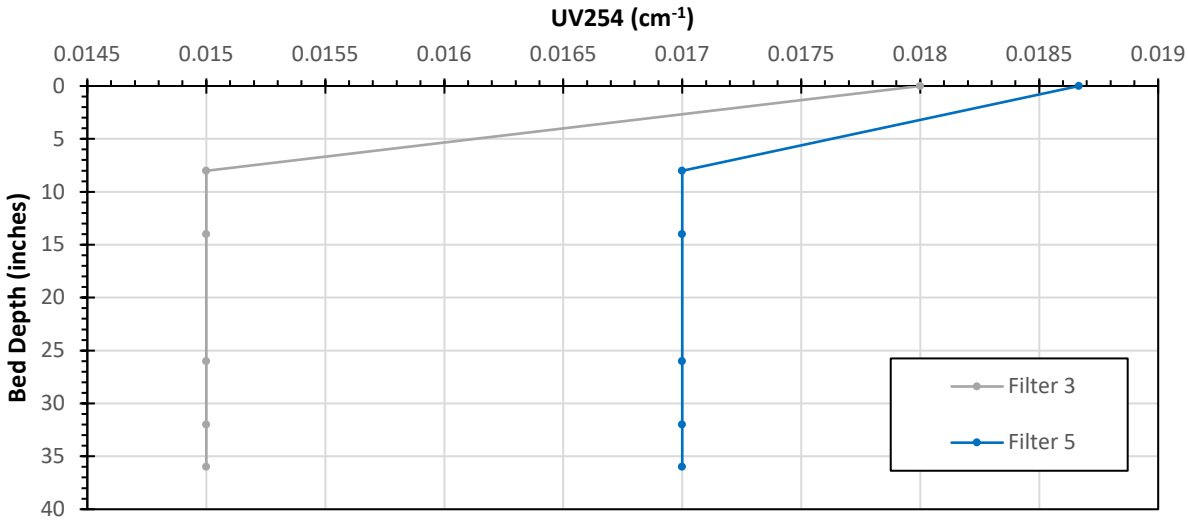

Figure 77. UV254 Profiles in Pilot Filters (30 hours)

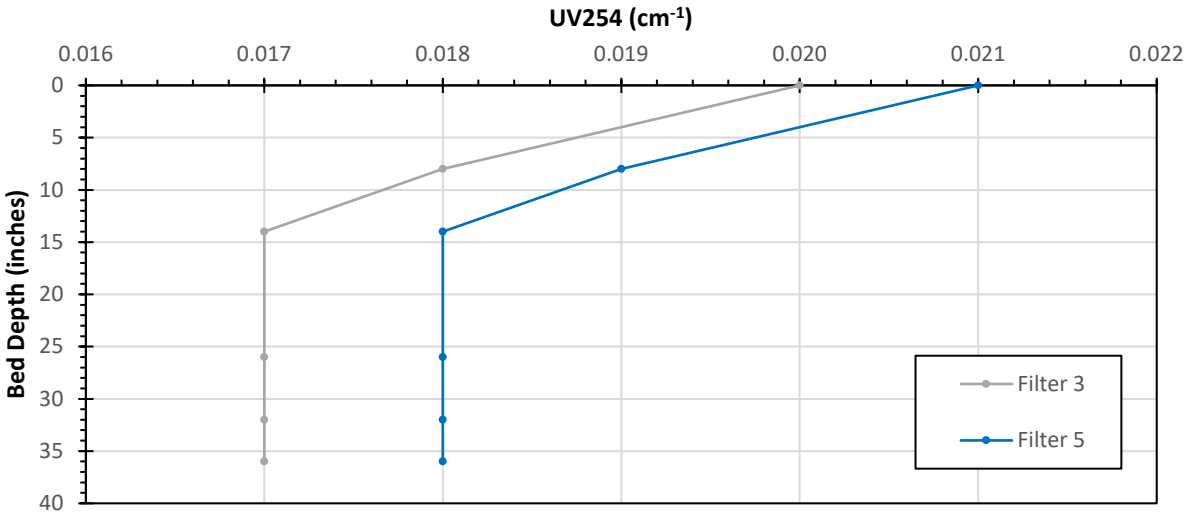

Figure 78. UV254 Profiles in Pilot Filters (70 hours)

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The purposes of this study were to determine if BAC filters enhanced the removal of organics and T&O under both high and low temperature conditions, to determine the effectiveness of turbidity removal in BAC filters as compared to the anthracite-sand filter, and to recommend a specific type of GAC to implement in the full-scale system based on a comprehensive analysis of different GAC media performances. The results of this study demonstrate that BAC, in particular the bituminous coal-based, provides a significant improvement over anthracite-sand, as described in detail in the section to follow.

6.1. Conclusions

Many conclusions can be drawn from the results of this study. The major conclusions of this study for each parameter investigated are as follows:

- Organics removal:
    - The BAC filters reduce organics significantly better than the anthracite-sand filter. The dominant removal mechanism is biodegradation since the media was preloaded with organics. However, adsorption may have played a more significant role in the removal of refractory organics. The macroporous structure and rougher surface of the GAC media (as observed during SEM analysis) provides a better surface for microbial growth and attachment.
    - The BAC filters can better handle shock loadings of organics due to their adsorptive properties.
    - The bituminous coal-based GACs (F300 and Norit 300) perform better than the coconut-based GAC (Jacobi) in the removal of organics. This is likely due to differences in surface characteristics. First, Jacobi is a microporous GAC and

microorganisms are unable to enter the small pores for attachment. Second, the surface of the Jacobi GAC is relatively smooth in comparison to the F300 and Norit 300 GACs and may provide a less suitable surface for microbial growth and attachment. Third, the microporous structure of the Jacobi GAC is not well-suited for the adsorption of refractory organics.

  - The decrease in organics removal efficiency that occurs with temperature is partially mitigated in the BAC filters. Cold water temperatures had the largest negative impact on organics removal in the anthracite-sand filter. The attachment benefits of the GAC media may help to maintain a minimum amount of biomass necessary to reduce organics during cold water temperatures.

- T&O removal:
  - The BAC filters reduce T&O significantly better than the anthracite-sand filter.
  - Evidence suggests that adsorption plays a significant role in the removal of T&O in the BAC filters. Since the BAC filters were not preloaded with geosmin, a large adsorption capacity for geosmin likely remained. Adsorption may also help to explain the very large differences in geosmin removal efficiencies between the BAC and anthracite-sand filters. Finally, the period of desorption that occurred in the BAC filters during the geosmin-free period is evidence that adsorption occurred during the geosmin-loading period.
  - A decrease in T&O removal efficiencies was observed in the BAC filters during cold conditions. This was likely due to a slower intraparticle diffusion rate of adsorption. However, significant T&O removal is still achieved in the BAC filters during cold conditions, when T&O events typically occur at the MWTP.

- The bituminous coal-based GACs (F300 and Norit 300) perform better than the coconut-based GAC (Jacobi) in the removal of T&O. The microporous structure of the Jacobi GAC may have resulted in a further decrease in the intraparticle diffusion rate of adsorption than the filters containing a larger volume of mesopores and macropores, such as the F300 and Norit 300 GACs. In addition, the relatively smoother surface of the Jacobi GAC would likely provide a less suitable surface for microbial growth and attachment.

- Turbidity:
  - The BAC filters containing larger grain size media (0.8-1.0 mm) provide equivalent turbidity removal as filters containing smaller grain size media (0.45-0.55 mm).
  - Most turbidity is removed in the top 8-inches of each filter throughout a filter cycle. This is likely due to the higher biomass levels in this region of each filter (as observed during SEM analysis and as suggested by organics profile data).
  - Relatively higher turbidity removals occur in the top 8-inches of the BAC filter, which is likely due to the relatively higher biomass levels in this layer as compared to the anthracite-sand filter. Overall, the BAC filter demonstrated better turbidity removal throughout the depth of the filter than the anthracite-sand. This is due to the combined effect of the relatively rougher surface of the GAC and higher biomass.
  - Most head loss buildup occurs in the top 8-inches of each filter since a majority of turbidity removal occurs in this region. Since higher head loss buildup was not observed in the BAC filter, it is postulated that the higher turbidity removals achieved in this layer are not the result of the relatively higher UC, but rather higher surface roughness and biomass levels.

6.2. Recommendations and Future Work

Based on a comprehensive analysis of different GAC media performances, the Norit 300 GAC should be considered for full-scale media replacement. The Norit 300 GAC consistently achieved the highest organic removals throughout the study, even during cold water conditions. The superior removal of easily biodegradable organics in the Norit 300 GAC filter would result in the production of more biologically stable water and prevent microbial regrowth in the Moorhead distribution system. Further, the adsorptive properties of the Norit 300 GAC were best suited for the attenuation of high influent loadings of organics. The Norit 300 GAC also demonstrated a significant improvement over the anthracite-sand filter in terms of T&O removal, even during cold water conditions. Finally, the Norit 300 GAC was able to provide equivalent turbidity removals as the anthracite-sand filter and may provide equivalent or longer filter run times based on the results of this study. Future work could seek to determine to what extent adsorption and biodegradation are operative in the BAC filters in the removal of T&O compounds.

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APPENDIX A. ORGANICS DATA

Table A1. TOC in Pilot Filtration System

Date	Time	Influent TOC (mg/L)	Effluent TOC (mg/L) Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
09/06/17		3.838	2.522	2.954	2.283	2.803	3.387
09/13/17		3.739	3.093	2.901	2.485	2.821	3.144
09/20/17		3.496	2.574	2.815	2.356	2.648	3.032
09/27/17	2:45 PM	3.331	2.731	2.790	2.486	2.658	2.946
10/04/17	1:30 PM	3.585	2.719	2.924	2.554	2.754	3.033
10/11/17	1:17 PM	3.259	2.529	2.694	2.414	2.524	2.876
10/18/17	4:11 PM	3.568	2.745	2.910	2.538	2.748	3.018
10/25/17	3:30 PM	3.729	2.893	3.064	2.773	2.853	3.211
11/01/17	3:30 PM	3.942	2.937	3.174	2.730	3.001	3.391
11/10/17	9:45 AM	3.444	2.904	3.068	2.718	2.916	3.193
11/15/17	1:30 PM	3.208	2.786	2.924	2.553	2.748	3.066
11/22/17	12:30 PM	4.199	3.759	3.979	3.509	3.888	4.071
11/29/17	1:00 PM	3.814	3.211	3.343	2.780	3.150	3.452
12/06/17	12:30 PM	3.849	3.223	3.323	3.074	3.286	3.461
12/13/17	11:00 AM	4.004	3.361	3.449	3.235	3.381	3.533
12/20/17	1:00 PM	3.784	3.174	3.331	3.061	3.242	3.405
12/27/17	1:30 PM	3.824	3.226	3.368	3.103	3.261	3.435
01/03/18	1:30 PM	3.971	3.355	3.489	3.196	3.454	3.653
01/10/18	12:30 PM	4.530	3.991	4.159	3.915	4.102	4.174
01/19/18	3:00 PM	4.027	3.815	3.686	3.486	3.598	3.771
01/26/18	12:30 PM	3.779	3.248	3.274	3.214	3.243	3.381
02/02/18	12:30 PM	5.525	4.442	4.246	4.007	4.469	4.871
02/09/18	4:00 PM	5.674	4.642	4.970	4.744	4.986	5.165
02/11/18	5:00 PM	5.311	3.806	4.664	3.889	4.740	4.829
02/16/18	12:30 PM	4.876	4.103	4.223	4.041	4.224	4.361
02/20/18	10:00 AM	5.082	4.284	4.326	4.161	4.302	4.419
02/27/18	10:30 AM	3.914	3.359	3.391	3.172	3.359	3.536
03/06/18	9:00 AM	3.296	2.874	2.965	2.826	2.933	3.069
03/12/18	3:15 PM	3.262	2.843	3.026	2.794	2.944	3.079
03/20/18	10:00 AM	3.565	3.225	3.311	3.213	3.174	3.458
03/27/18	11:00 AM	3.646	2.931	3.014	2.932	3.068	3.176

Table A1. TOC in Pilot Filtration System (continued)

Date	Time	Influent TOC (mg/L)	Effluent TOC (mg/L)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
04/03/18	11:15 AM	4.078	3.020	3.109	2.891	3.111	3.254
04/11/18	3:00 PM	2.914	2.301	2.378	2.276	2.397	2.513
04/25/18	1:00 PM	3.349	2.458	2.391	2.346	2.391	2.542
05/06/18	10:45 AM	3.269	2.654	2.671	2.623	2.704	2.724
05/15/18	10:00 AM	2.836	2.361	2.368	2.350	2.379	2.468
05/18/18	9:00 AM	2.819	2.232	2.197	2.277	2.273	2.274
05/21/18	12:30 PM	2.803	2.206	2.203	2.113	2.171	2.254
05/29/18	9:15 AM	2.725	2.260	2.321	2.218	2.303	2.347
06/04/18	9:00 AM	2.776	2.319	2.327	2.237	2.294	2.370
06/18/18	9:00 AM	2.716	2.228	2.198	2.128	2.163	2.244
06/26/18	8:45 AM	2.884	2.341	2.382	2.275	2.387	2.438
06/28/18	3:00 PM	2.975	2.387	2.453	2.375	2.463	2.483
07/02/18	10:20 AM	2.801	2.263	2.268	2.202	2.280	2.285
07/04/18	9:15 AM	2.632	2.319	2.193	2.072	2.386	2.320
07/09/18	9:00 AM	2.731	2.192	2.154	2.079	2.154	2.242
07/11/18	11:00 AM	3.139	2.488	2.542	2.400	2.503	2.571
07/17/18	2:00 PM	3.241	2.555	2.633	2.472	2.611	2.823
07/20/18	1:00 PM	2.724	2.042	2.161	2.026	2.174	
07/23/18	8:30 AM	2.588	2.162	2.069	1.957	2.163	2.169
07/30/18	9:00 AM	3.231	2.589	2.541	2.414	2.499	2.668
08/08/18	8:45 AM	3.034	2.458	2.529	2.393	2.506	2.619
08/13/18	8:45 AM	2.502	2.078	2.077	1.984	2.064	2.138

Table A2. DOC in Pilot Filtration System

Date	Time	Influent DOC (mg/L)	Effluent DOC (mg/L)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
09/06/17		3.924	2.822	3.022	2.377	2.832	3.357
09/13/17		3.779	3.142	2.946	2.539	2.859	3.350
09/20/17		3.636	2.716	2.993	2.438	2.738	3.083
09/27/17	2:45 PM	3.377	2.662	2.838	2.719	2.692	3.006
10/04/17	1:30 PM	3.651	2.836	3.004	2.603	2.786	3.116
10/11/17	1:17 PM	3.253	2.889	2.659	2.359	2.572	2.858
10/18/17	4:11 PM	3.613	2.910	2.958	2.686	2.779	3.121
10/25/17	3:30 PM	3.816	2.851	3.110	2.821	2.934	3.206
11/01/17	3:30 PM	4.044	3.084	3.323	2.801	3.052	3.504
11/10/17	9:45 AM	3.544	3.006	3.285	2.793	2.961	3.298
11/15/17	1:30 PM	3.341	2.921	3.089	2.726	2.834	3.204
11/22/17	12:30 PM	4.479	4.007	4.004	3.649	3.824	4.199
11/29/17	1:00 PM	3.900	3.291	3.456	3.044	3.130	3.478
12/06/17	12:30 PM	3.918	3.174	3.383	3.111	3.313	4.496
12/13/17	11:00 AM	4.004	3.415	3.504	3.286	3.664	3.733
12/20/17	1:00 PM	3.841	3.239	3.366	3.103	3.252	3.428
12/27/17	1:30 PM	3.920	3.289	3.399	3.134	3.281	3.428
01/03/18	1:30 PM	3.954	3.392	3.499	3.216	3.368	3.611
01/10/18	12:30 PM	4.666	4.069	4.256	3.953	4.142	4.212
01/19/18	3:00 PM	4.049	3.694	3.673	3.443	3.641	3.783
01/26/18	12:30 PM	3.789	3.189	3.244	3.206	3.301	3.386
02/02/18	12:30 PM	5.542	4.374	4.212	3.988	4.531	4.831
02/09/18	4:00 PM	5.678	4.667	5.024	4.706	4.979	5.159
02/11/18	5:00 PM	5.444	3.797	4.548	3.829	4.584	4.824
02/16/18	12:30 PM	4.782	4.087	4.219	4.004	4.206	4.269
02/20/18	10:00 AM	4.783	4.174	4.208	4.054	4.174	4.191
02/27/18	10:30 AM	3.983	3.384	3.383	3.224	3.389	3.546
03/06/18	9:00 AM	3.366	2.903	2.940	2.803	2.941	1.684
03/12/18	3:15 PM	3.323	2.888	2.990	2.781	2.971	3.087
03/20/18	10:00 AM	3.709	3.160	3.268	3.109	3.211	3.415
03/27/18	11:00 AM	3.664	2.909	3.024	2.928	3.028	3.197
04/03/18	11:15 AM	4.249	3.094	3.209	3.014	3.233	3.441
04/11/18	3:00 PM	3.001	2.391	2.440	2.395	2.422	2.655

Table A2. DOC in Pilot Filtration System (continued)

Date	Time	Influent DOC (mg/L)	Effluent DOC (mg/L)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
04/25/18	1:00 PM	3.326	2.439	2.434	2.412	2.526	2.589
05/06/18	10:45 AM	3.474	2.686	2.737	2.656	2.681	2.719
05/15/18	10:00 AM	2.917	2.408	2.502	2.322	2.374	2.503
05/18/18	9:00 AM	2.944	2.337	2.197	2.277	2.306	2.439
05/21/18	12:30 PM	2.810	2.211	2.241	2.199	2.241	2.304
05/29/18	9:15 AM	2.721	2.290	2.303	2.293	2.458	2.385
06/04/18	9:00 AM	2.726	2.301	2.304	2.238	2.228	2.293
06/18/18	9:00 AM	2.835	2.332	2.311	2.193	2.482	2.444
06/26/18	8:45 AM	2.929	2.382	2.428	2.393	2.423	2.463
06/28/18	3:00 PM	3.177	2.480	2.631	2.456	2.561	2.607
07/02/18	10:20 AM	2.883	2.358	2.464	2.488	2.343	2.319
07/04/18	9:15 AM	2.760	2.329	2.178	2.151	2.231	2.225
07/09/18	9:00 AM	3.089	2.233	2.247	2.315	2.298	2.397
07/11/18	11:00 AM	3.161	2.507	2.546	2.386	2.490	2.591
07/17/18	2:00 PM	3.239	2.541	2.711	2.519	2.664	2.841
07/20/18	1:00 PM	2.726	2.083	2.193	2.113	2.232	
07/23/18	8:30 AM	2.567	2.1	2.114	2.005	2.012	2.168
07/30/18	9:00 AM	3.131	2.569	2.618	2.418	2.512	2.689
08/08/18	8:45 AM	3.203	2.507	2.609	2.416	2.568	2.631
08/13/18	8:45 AM	2.548	2.024	2.091	2.014	2.083	2.096

Table A3. UV254 in Pilot Filtration System

Date	Time	Influent UV254 (cm^{-1})	Effluent UV254 (cm^{-1})				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
09/06/17		0.023	0.015	0.018	0.013	0.016	0.020
09/13/17		0.021	0.033	0.016	0.013	0.015	0.018
09/20/17		0.027	0.022	0.019	0.017	0.018	0.019
09/27/17	2:45 PM	0.023	0.020	0.023	0.023	0.021	0.026
10/04/17	1:30 PM	0.025	0.018	0.023	0.019	0.026	0.024
10/11/17	1:17 PM	0.032	0.023	0.025	0.019	0.023	0.024
10/18/17	4:11 PM	0.019	0.015	0.016	0.015	0.020	0.019
10/25/17	3:30 PM	0.020	0.016	0.021	0.015	0.017	0.018
11/01/17	3:30 PM	0.027	0.020	0.023	0.020	0.024	0.027
11/10/17	9:45 AM	0.024	0.020	0.022	0.020	0.024	0.027
11/15/17	1:30 PM	0.022	0.018	0.022	0.018	0.020	0.022
11/22/17	12:30 PM	0.029	0.025	0.026	0.023	0.026	0.027
11/29/17	1:00 PM	0.021	0.020	0.019	0.017	0.021	0.020
12/06/17	12:30 PM	0.028	0.023	0.026	0.023	0.026	0.026
12/13/17	11:00 AM	0.026	0.023	0.025	0.022	0.023	0.026
12/20/17	1:00 PM	0.030	0.027	0.027	0.025	0.027	0.030
12/27/17	1:30 PM	0.026	0.023	0.024	0.022	0.023	0.026
01/03/18	1:30 PM	0.027	0.024	0.024	0.022	0.023	0.026
01/10/18	12:30 PM	0.034	0.031	0.033	0.031	0.032	0.034
01/19/18	3:00 PM	0.032	0.029	0.031	0.028	0.031	0.031
01/26/18	12:30 PM	0.030	0.026	0.028	0.026	0.028	0.031
02/02/18	12:30 PM	0.035	0.025	0.023	0.022	0.027	0.030
02/09/18	4:00 PM	0.044	0.037	0.038	0.035	0.038	0.040
02/11/18	5:00 PM	0.039	0.028	0.035	0.030	0.034	0.036
02/16/18	12:30 PM	0.036	0.032	0.035	0.033	0.035	0.036
02/20/18	10:00 AM	0.041	0.037	0.037	0.034	0.036	0.036
02/27/18	10:30 AM	0.031	0.027	0.027	0.027	0.028	0.030
03/06/18	9:00 AM	0.025	0.024	0.025	0.023	0.024	0.025
03/12/18	3:15 PM	0.025	0.021	0.022	0.022	0.023	0.024
03/20/18	10:00 AM	0.027	0.024	0.024	0.024	0.025	0.025
03/27/18	11:00 AM	0.025	0.022	0.022	0.022	0.023	0.023
04/03/18	11:15 AM	0.025	0.021	0.022	0.020	0.022	0.023
04/11/18	3:00 PM	0.020	0.017	0.016	0.016	0.021	0.019

Table A3. UV254 in Pilot Filtration System (continued)

Date	Time	Influent UV254 (cm^{-1})	Effluent UV254 (cm^{-1})				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
04/25/18	1:00 PM	0.018	0.016	0.016	0.018	0.019	0.019
05/06/18	10:45 AM	0.023	0.015	0.018	0.015	0.016	0.015
05/15/18	10:00 AM	0.025	0.023	0.024	0.023	0.023	0.024
05/18/18	9:00 AM	0.015	0.013	0.015	0.014	0.015	0.015
05/21/18	12:30 PM	0.014	0.012	0.013	0.013	0.012	0.013
05/29/18	9:15 AM	0.016	0.014	0.014	0.015	0.014	0.015
06/04/18	9:00 AM	0.015	0.014	0.013	0.013	0.013	0.013
06/18/18	9:00 AM	0.015	0.013	0.014	0.013	0.014	0.014
06/26/18	8:45 AM	0.018	0.016	0.016	0.017	0.017	0.017
06/28/18	3:00 PM	0.017	0.016	0.016	0.015	0.016	0.017
07/02/18	10:20 AM	0.010	0.010	0.010	0.012	0.011	0.011
07/04/18	9:15 AM	0.015	0.012	0.012	0.011	0.012	0.012
07/09/18	9:00 AM	0.016	0.013	0.013	0.014	0.014	0.015
07/11/18	11:00 AM	0.016	0.012	0.011	0.010	0.011	0.012
07/17/18	2:00 PM	0.018	0.012	0.015	0.013	0.016	0.016
07/20/18	1:00 PM	0.016	0.012	0.014	0.014	0.015	0.012
07/23/18	8:30 AM	0.013	0.011	0.012	0.011	0.011	0.013
07/30/18	9:00 AM	0.021	0.018	0.018	0.018	0.019	0.019
08/08/18	8:45 AM	0.019	0.016	0.017	0.016	0.017	0.018
08/13/18	8:45 AM	0.017	0.015	0.014	0.015	0.016	0.016

Table A4. SUVA in Pilot Filtration System

Date	Time	Influent SUVA (mg/L-m)	Effluent SUVA (mg/L-m)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
09/06/17		0.586	0.532	0.596	0.547	0.565	0.596
09/13/17		0.556	1.050	0.543	0.512	0.525	0.537
09/20/17		0.743	0.810	0.635	0.697	0.657	0.616
09/27/17	2:45 PM	0.681	0.751	0.810	0.846	0.780	0.865
10/04/17	1:30 PM	0.685	0.635	0.766	0.730	0.933	0.770
10/11/17	1:17 PM	0.984	0.796	0.940	0.805	0.894	0.840
10/18/17	4:11 PM	0.526	0.515	0.541	0.558	0.720	0.609
10/25/17	3:30 PM	0.524	0.561	0.675	0.532	0.579	0.561
11/01/17	3:30 PM	0.668	0.649	0.692	0.714	0.786	0.771
11/10/17	9:45 AM	0.677	0.665	0.670	0.716	0.811	0.819
11/15/17	1:30 PM	0.658	0.616	0.712	0.660	0.706	0.687
11/22/17	12:30 PM	0.647	0.624	0.649	0.630	0.680	0.643
11/29/17	1:00 PM	0.538	0.608	0.550	0.558	0.671	0.575
12/06/17	12:30 PM	0.715	0.725	0.769	0.739	0.785	0.578
12/13/17	11:00 AM	0.649	0.673	0.713	0.670	0.628	0.696
12/20/17	1:00 PM	0.781	0.834	0.802	0.806	0.830	0.875
12/27/17	1:30 PM	0.663	0.699	0.706	0.702	0.701	0.758
01/03/18	1:30 PM	0.683	0.708	0.686	0.684	0.683	0.720
01/10/18	12:30 PM	0.729	0.762	0.775	0.784	0.773	0.807
01/19/18	3:00 PM	0.790	0.785	0.844	0.813	0.851	0.819
01/26/18	12:30 PM	0.792	0.815	0.863	0.811	0.848	0.916
02/02/18	12:30 PM	0.632	0.572	0.546	0.552	0.596	0.621
02/09/18	4:00 PM	0.775	0.793	0.756	0.744	0.763	0.775
02/11/18	5:00 PM	0.716	0.737	0.770	0.783	0.742	0.746
02/16/18	12:30 PM	0.753	0.783	0.830	0.824	0.832	0.843
02/20/18	10:00 AM	0.857	0.886	0.879	0.839	0.862	0.859
02/27/18	10:30 AM	0.778	0.798	0.798	0.837	0.826	0.846
03/06/18	9:00 AM	0.743	0.827	0.850	0.821	0.816	1.485
03/12/18	3:15 PM	0.752	0.727	0.736	0.791	0.774	0.777
03/20/18	10:00 AM	0.728	0.759	0.734	0.772	0.779	0.732
03/27/18	11:00 AM	0.682	0.756	0.728	0.751	0.760	0.719
04/03/18	11:15 AM	0.588	0.679	0.686	0.664	0.680	0.668
04/11/18	3:00 PM	0.666	0.711	0.656	0.668	0.867	0.716

Table A4. SUVA in Pilot Filtration System (continued)

Date	Time	Influent SUVA (mg/L-m)	Effluent SUVA (mg/L-m)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
04/25/18	1:00 PM	0.541	0.656	0.657	0.746	0.752	0.734
05/06/18	10:45 AM	0.662	0.558	0.658	0.565	0.597	0.552
05/15/18	10:00 AM	0.857	0.955	0.959	0.991	0.969	0.959
05/18/18	9:00 AM	0.510	0.556	0.683	0.615	0.650	0.615
05/21/18	12:30 PM	0.498	0.543	0.580	0.591	0.535	0.564
05/29/18	9:15 AM	0.588	0.611	0.608	0.654	0.570	0.629
06/04/18	9:00 AM	0.550	0.608	0.564	0.581	0.583	0.567
06/18/18	9:00 AM	0.529	0.557	0.606	0.593	0.564	0.573
06/26/18	8:45 AM	0.615	0.672	0.659	0.710	0.702	0.690
06/28/18	3:00 PM	0.535	0.645	0.608	0.611	0.625	0.652
07/02/18	10:20 AM	0.347	0.424	0.406	0.482	0.469	0.474
07/04/18	9:15 AM	0.543	0.515	0.551	0.511	0.538	0.539
07/09/18	9:00 AM	0.518	0.582	0.579	0.605	0.609	0.626
07/11/18	11:00 AM	0.506	0.479	0.432	0.419	0.442	0.463
07/17/18	2:00 PM	0.556	0.472	0.553	0.516	0.601	0.563
07/20/18	1:00 PM	0.587	0.576	0.638	0.663	0.672	
07/23/18	8:30 AM	0.506	0.524	0.568	0.549	0.547	0.600
07/30/18	9:00 AM	0.671	0.701	0.688	0.744	0.756	0.707
08/08/18	8:45 AM	0.593	0.638	0.652	0.662	0.662	0.684
08/13/18	8:45 AM	0.667	0.741	0.670	0.745	0.768	0.763

APPENDIX B. T&O DATA

Table B1. Geosmin Data - T&O Challenge Test 1

Date Sampled	Time Sampled	Date Analyzed	Sample Description	Geosmin (ng/L)
10/25/17	1:35 PM	10/30/17	4.5 mg/L geosmin feed	4,090,000
10/26/17	1:00 PM	10/30/17	Common filter influent	91.9
10/26/17	1:00 PM	10/27/17	Filter 1 effluent	2.37
10/26/17	1:00 PM	10/27/17	Filter 2 effluent	11.2
10/26/17	1:00 PM	10/27/17	Filter 3 effluent	0.530
10/26/17	1:00 PM	10/27/17	Filter 4 effluent	5.20
10/26/17	1:00 PM	10/27/17	Filter 5 effluent	60.6
10/27/17	1:35 PM	10/31/17	4.5 mg/L geosmin feed	2,030,000
10/27/17	3:00 PM	10/31/17	Common filter influent	90.0
10/28/17	4:00 PM	10/31/17	Common filter influent	210
10/28/17	4:00 PM	10/31/17	Filter 1 effluent	4.30
10/28/17	4:00 PM	10/31/17	Filter 2 effluent	32.5
10/28/17	4:00 PM	10/31/17	Filter 3 effluent	2.11
10/28/17	4:00 PM	10/31/17	Filter 4 effluent	20.4
10/28/17	4:00 PM	10/31/17	Filter 5 effluent	208
10/28/17	5:00 PM	11/01/07	4.5 mg/L geosmin feed	2,260,000
10/29/17	5:30 PM	11/01/17	4.5 mg/L geosmin feed	4,870,000
10/29/17	5:30 PM	10/31/17	Common filter influent	253
10/29/17	5:30 PM	11/01/17	Filter 1 effluent	5.09
10/29/17	5:30 PM	11/01/17	Filter 2 effluent	37.0
10/29/17	5:30 PM	11/01/17	Filter 3 effluent	3.93
10/29/17	5:30 PM	11/01/17	Filter 4 effluent	22.4
10/29/17	5:30 PM	11/01/17	Filter 5 effluent	200
10/30/17	1:30 PM	11/01/17	Common filter influent	292
10/30/17	1:30 PM	11/01/17	Filter 1 effluent	7.49
10/30/17	1:30 PM	11/01/17	Filter 2 effluent	44.5
10/30/17	1:30 PM	11/01/17	Filter 3 effluent	3.50
10/30/17	1:30 PM	11/01/17	Filter 4 effluent	32.3
10/30/17	1:30 PM	11/01/17	Filter 5 effluent	227
10/30/17	4:15 PM	11/03/17	4.5 mg/L geosmin feed	2,530,000
10/31/17	4:00 PM	11/03/17	Common filter influent	224
10/31/17	4:00 PM	11/06/17	Filter 1 effluent	11

Table B1. Geosmin Data - T&O Challenge Test 1 (continued)

Date Sampled	Time Sampled	Date Analyzed	Sample Description	Geosmin (ng/L)
10/31/17	4:00 PM	11/03/17	Filter 2 effluent	53
10/31/17	4:00 PM	11/03/17	Filter 3 effluent	6.27
10/31/17	4:00 PM	11/03/17	Filter 4 effluent	39.8
10/31/17	4:00 PM	11/03/17	Filter 5 effluent	218
10/31/17	6:00 PM	11/03/17	4.5 mg/L geosmin feed	3,980,000
11/01/17	3:10 PM	11/03/17	Common filter influent	294
11/01/17	3:10 PM	11/03/17	Filter 1 effluent	18.1
11/01/17	3:10 PM	11/03/17	Filter 2 effluent	79.6
11/01/17	3:10 PM	11/03/17	Filter 3 effluent	8.85
11/01/17	3:10 PM	11/03/17	Filter 4 effluent	54.3
11/01/17	3:10 PM	11/06/17	Filter 5 effluent	240

Table B2. Geosmin Data - T&O Challenge Test 2

Date Sampled	Time Sampled	Date Analyzed	Sample Description	Geosmin (ng/L)
03/04/18	6:00 PM	03/13/18	3,000 ppm geosmin stock	2615 (ppm)
03/07/18	2:00 PM	03/13/18	Common filter influent	134
03/07/18	2:00 PM	03/14/18	Filter 1 effluent	32.4
03/07/18	2:00 PM	03/14/18	Filter 2 effluent	59.5
03/07/18	2:00 PM	03/14/18	Filter 3 effluent	17.6
03/07/18	2:00 PM	03/14/18	Filter 4 effluent	56.1
03/07/18	2:00 PM	03/14/18	Filter 5 effluent	136
03/08/18	1:00 PM	03/13/18	Common filter influent	135
03/08/18	1:00 PM	03/14/18	Filter 1 effluent	36
03/08/18	1:00 PM	03/15/18	Filter 2 effluent	79.1
03/08/18	1:00 PM	03/15/18	Filter 3 effluent	21.1
03/08/18	1:00 PM	03/14/18	Filter 4 effluent	60.3
03/08/18	1:00 PM	03/14/18	Filter 5 effluent	152
03/08/18	1:00 PM	03/13/18	3,000 ppm geosmin stock	2768 (ppm)
03/11/18	12:15 PM	03/15/18	Common filter influent	153
03/11/18	12:15 PM	03/15/18	Filter 1 effluent	41.4
03/11/18	12:15 PM	03/15/18	Filter 2 effluent	82.6
03/11/18	12:15 PM	03/15/18	Filter 3 effluent	30.9
03/11/18	12:15 PM	03/15/18	Filter 4 effluent	64.5

Table B2. Geosmin Data - T&O Challenge Test 2 (continued)

Date Sampled	Time Sampled	Date Analyzed	Sample Description	Geosmin (ng/L)
03/11/18	12:15 PM	03/15/18	Filter 5 effluent	162
03/14/18	2:15 PM	03/16/18	Common filter influent	277
03/14/18	2:15 PM	03/16/18	Filter 1 effluent	71.8
03/14/18	2:15 PM	03/16/18	Filter 2 effluent	239
03/14/18	2:15 PM	03/16/18	Filter 3 effluent	55
03/14/18	2:15 PM	03/16/18	Filter 4 effluent	102
03/14/18	2:15 PM	03/16/18	Filter 5 effluent	204
03/14/18	2:15 PM	03/16/18	3,000 ppm geosmin stock	2,988 (ppm)
03/17/18	7:45 PM	03/20/18	Common filter influent	167
03/17/18	7:45 PM	03/20/18	Filter 1 effluent	52.5
03/17/18	7:45 PM	03/20/18	Filter 2 effluent	113
03/17/18	7:45 PM	03/20/18	Filter 3 effluent	40
03/17/18	7:45 PM	03/20/18	Filter 4 effluent	89.1
03/17/18	7:45 PM	03/20/18	Filter 5 effluent	209
03/20/18	12:00 PM	03/22/18	Common filter influent	163
03/20/18	12:00 PM	03/22/18	Filter 1 effluent	43.3
03/20/18	12:00 PM	03/23/18	Filter 2 effluent	76
03/20/18	12:00 PM	03/22/18	Filter 3 effluent	29
03/20/18	12:00 PM	03/23/18	Filter 4 effluent	69.2
03/20/18	12:00 PM	03/22/18	Filter 5 effluent	113
03/20/18	8:15 PM	03/23/18	3,000 ppm geosmin stock	3,440 (ppm)
03/21/18	2:30 PM	03/22/18	Common filter influent	206
03/21/18	2:30 PM	03/23/18	Filter 1 effluent	48
03/21/18	2:30 PM	03/23/18	Filter 2 effluent	88.5
03/21/18	2:30 PM	03/26/18	Filter 3 effluent	36.3
03/21/18	2:30 PM	03/26/18	Filter 4 effluent	111
03/21/18	2:30 PM	03/23/18	Filter 5 effluent	157
03/22/18	12:30 PM	03/26/18	Common filter influent	8.62
03/22/18	12:30 PM	03/26/18	Filter 1 effluent	16.1
03/22/18	12:30 PM	03/26/18	Filter 2 effluent	10.3
03/22/18	12:30 PM	03/26/18	Filter 3 effluent	17.8
03/22/18	12:30 PM	03/26/18	Filter 4 effluent	18.8
03/22/18	12:30 PM	03/26/18	Filter 5 effluent	1.96
03/23/18	12:45 PM	03/29/18	Common filter influent	0

Table B2. Geosmin Data - T&O Challenge Test 2 (continued)

Date Sampled	Time Sampled	Time Analyzed	Sample Description	Geosmin (ng/L)
03/23/18	12:45 PM	03/29/18	Filter 1 effluent	11.4
03/23/18	12:45 PM	03/29/18	Filter 2 effluent	7.36
03/23/18	12:45 PM	03/29/18	Filter 3 effluent	8.96
03/23/18	12:45 PM	03/29/18	Filter 4 effluent	11.2
03/23/18	12:45 PM	03/29/18	Filter 5 effluent	1.03
03/25/18	1:30 PM	03/29/18	Common filter influent	0
03/25/18	1:30 PM	03/29/18	Filter 1 effluent	8.18
03/25/18	1:30 PM	03/29/18	Filter 2 effluent	4.47
03/25/18	1:30 PM	03/29/18	Filter 3 effluent	7.22
03/25/18	1:30 PM	03/29/18	Filter 4 effluent	8.22
03/25/18	1:30 PM	03/29/18	Filter 5 effluent	0
03/27/18	11:00 AM	03/30/18	Common filter influent	0
03/27/18	11:00 AM	03/31/18	Filter 1 effluent	7.65
03/27/18	11:00 AM	03/31/18	Filter 2 effluent	4.18
03/27/18	11:00 AM	03/31/18	Filter 3 effluent	6.5
03/27/18	11:00 AM	03/31/18	Filter 4 effluent	7.5
03/27/18	11:00 AM	03/31/18	Filter 5 effluent	0
03/28/18	12:30 PM	03/30/18	Common filter influent	1.44
03/28/18	12:30 PM	03/31/18	Filter 1 effluent	7.29
03/28/18	12:30 PM	03/31/18	Filter 2 effluent	4.1
03/28/18	12:30 PM	03/31/18	Filter 3 effluent	6.71
03/28/18	12:30 PM	03/31/18	Filter 4 effluent	7.27
03/28/18	12:30 PM	03/31/18	Filter 5 effluent	0
03/28/18	12:30 PM	03/31/18	3,000 ppm geosmin stock	4,800 (ppm)
03/29/18	5:00 PM	04/04/18	Common filter influent	166
03/29/18	5:00 PM	04/03/18	Filter 1 effluent	38.5
03/29/18	5:00 PM	04/03/18	Filter 2 effluent	98.7
03/29/18	5:00 PM	04/03/18	Filter 3 effluent	34.9
03/29/18	5:00 PM	04/03/18	Filter 4 effluent	89.7
03/29/18	5:00 PM	04/04/18	Filter 5 effluent	152
03/31/18	5:30 PM	04/03/18	Common filter influent	352
03/31/18	5:30 PM	04/03/18	Filter 1 effluent	18.2
03/31/18	5:30 PM	04/03/18	Filter 2 effluent	70.8
03/31/18	5:30 PM	04/03/18	Filter 3 effluent	44.8

Table B2. Geosmin Data - T&O Challenge Test 2 (continued)

Date Sampled	Time Sampled	Time Analyzed	Sample Description	Geosmin (ng/L)
03/31/18	5:30 PM	04/04/18	Filter 4 effluent	161
03/31/18	5:30 PM	04/04/18	Filter 5 effluent	140
03/31/18	5:30 PM	04/04/18	3,000 ppm geosmin stock	2,900 (ppm)
04/02/18	1:00 PM	04/03/18	Common filter influent	197
04/02/18	1:00 PM	04/03/18	Filter 1 effluent	45.5
04/02/18	1:00 PM	04/03/18	Filter 2 effluent	91.7
04/02/18	1:00 PM	04/03/18	Filter 3 effluent	25.8
04/02/18	1:00 PM	04/03/18	Filter 4 effluent	90.1
04/02/18	1:00 PM	04/03/18	Filter 5 effluent	157
04/04/18	12:00 PM	04/05/18	Common filter influent	153
04/04/18	12:00 PM	04/05/18	Filter 1 effluent	55.1
04/04/18	12:00 PM	04/05/18	Filter 2 effluent	81.3
04/04/18	12:00 PM	04/05/18	Filter 3 effluent	31.5
04/04/18	12:00 PM	04/05/18	Filter 4 effluent	85.3
04/04/18	12:00 PM	04/05/18	Filter 5 effluent	141

Table B3. Geosmin Data - T&O Challenge Test 3

Date Sampled	Time Sampled	Date Analyzed	Sample Description	Geosmin (ng/L)
06/18/18	1:30 PM	06/21/18	3,000 ppm geosmin stock	2240 (ppm)
06/20/18	10:00 AM	06/21/18	Common filter influent	186
06/20/18	10:00 AM	06/21/18	Filter 3 Effluent	15.1
06/20/18	10:00 AM	06/21/18	Filter 5 Effluent	152
06/24/18	4:15 PM	06/28/18	3,000 ppm geosmin stock	2450 (ppm)
06/25/18	4:00 PM	06/28/18	Common filter influent	143
06/25/18	4:00 PM	06/28/18	Filter 3 Effluent	11.7
06/25/18	4:00 PM	06/28/18	Filter 5 Effluent	125
06/27/18	9:00 AM	06/28/18	Common filter influent	163
06/27/18	9:00 AM	06/28/18	Filter 3 Effluent	4.11
06/27/18	9:00 AM	06/28/18	Filter 5 Effluent	146
07/02/18	10:40 AM	07/06/18	Common filter influent	69.7
07/02/18	10:40 AM	07/06/18	Filter 3 Effluent	3.79
07/02/18	10:40 AM	07/06/18	Filter 5 Effluent	97.7
07/02/18	10:40 AM	07/06/18	3,000 ppm geosmin stock	3100 (ppm)
07/04/18	9:15 AM	07/06/18	Common filter influent	59.1
07/04/18	9:15 AM	07/06/18	Filter 3 Effluent	5.13

Table B3. Geosmin Data - T&O Challenge Test 3 (continued)

Date Sampled	Time Sampled	Date Analyzed	Sample Description	Geosmin (ng/L)
07/04/18	9:15 AM	07/06/18	Filter 5 Effluent	71.5
07/09/18	10:00 AM	07/20/18	Common filter influent	90.1
07/09/18	10:00 AM	07/20/18	Filter 3 Effluent	7.88
07/09/18	10:00 AM	07/20/18	Filter 5 Effluent	98.5
07/09/18	9:15 AM	07/21/18	3,000 ppm geosmin stock	3710 (ppm)
07/11/18	1:00 PM	07/20/18	Common filter influent	123
07/11/18	1:00 PM	07/20/18	Filter 3 Effluent	8.69
07/11/18	1:00 PM	07/20/18	Filter 5 Effluent	103
07/17/18	2:00 PM	07/21/18	Common filter influent	137
07/17/18	2:00 PM	07/21/18	Filter 3 Effluent	30.4
07/17/18	2:00 PM	07/21/18	Filter 5 Effluent	190
07/18/18	9:00 AM	07/21/18	3,000 ppm geosmin stock	3220 (ppm)
07/19/18	12:00 PM	07/21/18	Common filter influent	137
07/19/18	12:00 PM	07/21/18	Filter 3 Effluent	35.7
07/19/18	12:00 PM	07/21/18	Filter 5 Effluent	147
07/23/18	8:30 AM	07/30/18	Common filter influent	97.2
07/23/18	8:30 AM	07/30/18	Filter 3 Effluent	5.38
07/23/18	8:30 AM	07/30/18	Filter 5 Effluent	84.1
07/25/18	8:30 AM	07/30/18	Common filter influent	88.8
07/25/18	8:30 AM	07/30/18	Filter 3 Effluent	5.6
07/25/18	8:30 AM	07/30/18	Filter 5 Effluent	90.5
07/30/18	9:00 AM	08/02/18	Common filter influent	114
07/30/18	9:00 AM	08/02/18	Filter 3 Effluent	7.28
07/30/18	9:00 AM	08/02/18	Filter 5 Effluent	101
08/01/18	9:00 AM	08/02/18	Common filter influent	89.6
08/01/18	9:00 AM	08/02/18	Filter 3 Effluent	7.04
08/01/18	9:00 AM	08/02/18	Filter 5 Effluent	102

APPENDIX C. TURBIDITY DATA

Table C1. Turbidity in Pilot Filtration System

Date	Time	Influent Turbidity (NTU)	Effluent Turbidity (NTU)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
10/21/17	11:15 AM	1.43	0.423	0.159	0.146	0.216	0.148
10/22/17	11:27 AM	0.73	0.123	0.114	0.131	0.13	0.126
10/23/17	9:16 AM	2.54	0.12	0.108	0.125	0.177	0.093
10/24/17	9:02 AM	1.10	0.107	0.126	0.117	0.12	0.104
10/25/17	5:45 PM	0.92	0.22	0.174	0.157	0.174	0.166
10/26/17	3:00 PM	1.10	0.282	0.195	0.135	0.178	0.189
10/27/17	1:45 PM	0.91	0.102	0.13	0.11	0.166	0.147
10/28/17	11:40 AM	1.21	0.132	0.257	0.127	0.099	0.149
10/29/17	9:30 AM	0.70	0.11	0.127	0.151	0.135	0.122
10/30/17	1:30 PM	0.67	0.099	0.196	0.12	0.155	0.18
10/31/17	1:30 PM	1.10	0.117	0.126	0.103	0.12	0.129
11/01/17	1:00 PM	1.48	0.111	0.148	0.105	0.116	0.103
11/02/17		0.84					
11/03/17	5:00 PM	0.93	0.102	0.139	0.114	0.101	0.111
11/04/17	1:00 PM	0.80	0.116	0.129	0.104	0.088	0.095
11/05/17	1:15 PM	0.95	0.127	0.082	0.081	0.097	0.074
11/06/17	1:05 PM	0.80	0.12	0.085	0.092	0.105	0.091
11/07/17	1:00 PM	0.54	0.1	0.083	0.102	0.093	0.08
11/08/17	12:45 PM	0.42	0.204	0.182	0.186	0.121	0.124
11/09/17	12:58 PM	1.29	0.12	0.151	0.114	0.151	0.092
11/10/17	11:40 AM	1.04	0.141	0.15	0.102	0.087	0.082
11/11/17	11:41 AM	0.74		0.092	0.174	0.155	0.103
11/12/17	12:55 PM	0.88	0.109	0.093	0.13	0.162	0.117
11/13/17	3:30 PM	0.67	0.121	0.101	0.098	0.123	0.13
11/14/17	10:30 AM	1.15	0.097	0.189	0.129	0.141	0.086
11/15/17	7:05 PM	1.35		0.117	0.132	0.152	0.099
11/17/17	1:00 PM	3.30	0.261	0.221	0.186	0.19	0.154
11/18/17	1:00 PM	1.01	0.103	0.11	0.089	0.125	0.082
11/19/17	1:00 PM	0.87	0.141	0.132	0.11	0.098	0.101
11/20/17	4:00 PM	1.05	0.265	0.162	0.17	0.189	0.153

Table C1. Turbidity in Pilot Filtration System (continued)

Date	Time	Influent Turbidity (NTU)	Effluent Turbidity (NTU)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
11/21/17	9:00 AM	1.10	0.108	0.12	0.117	0.114	0.097
11/22/17	1:30 PM	0.62	0.14	0.094	0.205	0.157	0.105
11/23/17		0.76	0.157	0.119	0.129	0.124	0.098
11/24/17	5:45 PM	1.05	0.155	0.086	0.094	0.078	0.107
11/25/17	5:30 PM	0.44	0.109	0.098	0.102	0.083	0.11
11/27/17	1:30 PM	0.83	0.138	0.109	0.112	0.137	0.098
11/28/17	11:30 AM	1.00	0.152	0.12	0.141		0.128
11/29/17	11:30 AM	1.60	0.099	0.09	0.125	0.101	0.14
11/30/17	3:30 PM	0.99	0.08	0.082	0.083	0.111	0.082
12/01/17	3:30 PM	0.49	0.16	0.097	0.079	0.103	0.077
12/02/17	3:00 PM	1.10	0.204	0.13	0.069	0.087	0.091
12/03/17	1:00 PM	1.30	0.188	0.144	0.082	0.101	0.069
12/04/17	6:30 PM	1.30	0.179	0.158	0.091	0.112	0.078
12/06/17	1:00 PM	0.46	0.162	0.191	0.103	0.078	0.091
12/07/17	1:00 PM	0.75	0.112	0.128	0.123	0.11	0.125
12/09/17	6:00 PM	1.60	0.143	0.159	0.116	0.097	0.132
12/10/17	3:20 PM	0.92	0.132	0.126	0.105	0.093	0.101
12/11/17	1:50 PM	1.20	0.258		0.378	0.29	0.139
12/12/17		1.22	0.16	0.133		0.169	0.111
12/13/17	2:50 PM	0.97	0.128	0.371	0.208	0.123	0.112
12/14/17	4:48 PM	1.60	0.241	0.154	0.177	0.196	0.179
12/15/17	12:50 PM	1.90	0.082	0.11	0.311	0.082	0.128
12/16/17	12:40 PM	1.30	0.097	0.083	0.081	0.084	0.092
12/17/17		0.87	0.113	0.085	0.083	0.086	0.087
12/18/17	3:15 PM	1.01	0.31	0.132	0.171	0.135	0.141
12/19/17	10:45 AM	0.78	0.091	0.108	0.089	0.087	
12/20/17	12:45 PM	1.60	0.09	0.113	0.108	0.098	0.099
12/21/17	12:56 PM	1.07	0.102	0.094	0.104	0.125	0.135
12/22/17	12:41 PM	1.06	0.203	0.146	0.138	0.221	0.158
12/23/17	1:20 PM	1.90	0.252	0.215	0.203	0.165	0.122
12/24/17	1:18 PM	0.89	0.111	0.119	0.149	0.176	0.101
12/25/17	12:30 PM	0.88	0.098	0.105	0.117	0.098	
12/26/17	6:30 PM	0.81	0.26	0.122	0.117	0.098	

Table C1. Turbidity in Pilot Filtration System (continued)

Date	Time	Influent Turbidity (NTU)	Effluent Turbidity (NTU)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
12/27/17	1:36 PM	1.90	0.167	0.158	0.169	0.283	0.181
12/28/17	12:48 PM	0.96	0.146	0.126	0.137	0.167	0.129
12/29/17	1:27 PM	1.40	0.095	0.175	0.141	0.265	0.091
12/30/17	1:08 PM	0.54	0.097	0.091	0.085	0.085	0.087
12/31/17	1:10 PM	0.73	0.234	0.183	0.177	0.147	0.093
01/01/18	1:18 PM	0.88	0.197	0.108	0.154	0.148	0.101
01/02/18	1:40 PM	1.60	0.113	0.117		0.081	0.087
01/03/18	1:00 PM	1.90	0.1	0.104	0.152	0.102	0.091
01/04/18	1:10 PM	1.23	0.096	0.117	0.103	0.105	0.09
01/05/18	12:47 PM	1.25	0.215	0.218	0.137	0.173	0.113
01/06/18	12:59 PM	1.40	0.285	0.188	0.248	0.133	0.152
01/07/18	1:06 PM	1.20	0.115	0.208	0.226	0.109	0.111
01/08/18	12:50 PM	1.60	0.105	0.106	0.167	0.106	0.113
01/10/18	1:00 PM	0.79	0.111	0.144	0.112	0.103	0.091
01/11/18	4:00 PM	1.60	0.177	0.174	0.094	0.11	0.101
01/12/18	3:30 PM	1.50	0.221	0.219	0.157	0.139	0.149
01/13/18	12:30 PM	0.60	0.144	0.111	0.106	0.11	0.216
01/14/18	1:30 PM	0.76	0.198	0.104	0.133	0.145	0.112
01/15/18	3:00 PM	1.08	0.201	0.135	0.11	0.098	0.079
01/18/18	12:30 PM	1.21	0.119	0.106	0.126	0.113	0.113
01/19/18	3:30 PM	0.83	0.137	0.145	0.12	0.108	0.086
01/20/18	3:00 PM	1.18	0.148	0.15	0.11	0.097	0.091
01/21/18	3:00 PM	1.15	0.135	0.148	0.115	0.101	0.101
01/22/18	12:45 PM	0.60	0.104	0.216	0.148	0.128	0.13
01/23/18	3:00 PM	0.30	0.128	0.116	0.189	0.115	0.164
01/24/18	4:00 PM	0.26	0.201	0.135	0.099	0.075	0.17
01/25/18	1:30 PM	0.49	0.133	0.107	0.056	0.143	0.138
01/26/18	1:00 PM	0.42	0.119	0.11	0.114	0.116	0.131
01/27/18	1:00 PM	0.31	0.099	0.092	0.226	0.118	0.098
01/28/18	1:00 PM	0.40	0.125	0.132	0.063	0.185	0.101
01/29/18		0.54	0.133	0.16	0.225	0.15	0.136
01/31/18	1:30 PM	0.54	0.23	0.13	0.16	0.144	0.103
02/01/18	12:40 PM	0.35	0.109	0.142	0.104	0.103	0.097

Table C1. Turbidity in Pilot Filtration System (continued)

Date	Time	Influent Turbidity (NTU)	Effluent Turbidity (NTU)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
02/02/18	1:00 PM	0.71	0.135	0.186	0.21	0.116	0.149
02/03/18	1:00 PM	1.05	0.17	0.197	0.184	0.124	0.131
02/07/18	1:45 PM	0.48	0.132	0.192	0.14	0.108	0.118
02/08/18	3:45 PM	0.978	0.095	0.142	0.098	0.088	0.088
02/09/18		0.791		0.157	0.133	0.095	0.099
02/10/18	3:30 PM	0.41	0.113	0.164	0.139	0.102	0.11
02/12/18	3:00 PM	0.6	0.108	0.126	0.115	0.094	0.116
02/13/18	12:55 PM	0.413	0.241	0.141	0.157	0.142	0.165
02/15/18	4:50 PM	0.39	0.152	0.139	0.126	0.115	
02/16/18	1:30 PM	0.5	0.116	0.146	0.133	0.11	0.113
02/17/18	11:30 AM	0.832	0.109	0.126	0.118	0.114	0.112
02/18/18	11:15 AM	0.591	0.11	0.12	0.117	0.101	0.106
02/19/18	4:10 PM	1.33		0.117	0.134	0.116	0.137
02/20/18	11:21 AM	0.69	0.127	0.168	0.193	0.149	0.157
02/21/18	1:20 PM	0.62	0.121	0.13	0.142	0.118	0.114
02/22/18	1:25 PM	1.31	0.126	0.144	0.141	0.131	0.134
02/24/18	3:50 PM	0.5	0.119	0.156	0.132	0.127	0.131
02/25/18	2:40 PM	0.6	0.123	0.137	0.146	0.108	0.114
02/26/18	2:00 PM	0.65	0.13	0.115	0.132	0.111	0.121
02/27/18	1:00 PM	0.70					
02/28/18	6:45 PM	0.40	0.152	0.136	0.124	0.131	0.107
03/02/18	1:06 PM	0.58	0.117	0.094	0.118	0.095	0.097
03/03/18	5:10 PM	0.69	0.093	0.084	0.098	0.091	0.095
03/04/18	12:34 PM	0.63	0.095	0.087	0.107	0.093	0.085
03/05/18	1:35 PM	0.50	0.153	0.114	0.233	0.103	0.139
03/06/18	11:23 AM	0.90	0.104	0.116	0.14	0.132	0.108
03/07/18	12:35 PM	0.35	0.09	0.086	0.107	0.105	0.092
03/08/18	2:00 PM	0.39	0.103	0.091	0.221	0.188	0.081
03/09/18	1:01 PM	0.26	0.111	0.101	0.117	0.092	0.097
03/10/18	1:25 PM	0.45	0.12	0.132	0.097	0.085	0.11
03/11/18	1:14 PM	0.42	0.143	0.131	0.1	0.131	0.103
03/12/18	1:25 PM	0.78	0.124	0.095	0.1	0.085	0.079
03/13/18	3:30 PM	0.59	0.124	0.149	0.165	0.26	0.109

Table C1. Turbidity in Pilot Filtration System (continued)

Date	Time	Influent Turbidity (NTU)	Effluent Turbidity (NTU)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
03/14/18	1:28 PM	0.42	0.122	0.118	0.119	0.123	0.113
03/15/18	12:45 PM	0.95	0.112	0.085	0.089	0.103	0.084
03/16/18	2:00 PM	1.00	0.109	0.102	0.105	0.099	0.074
03/17/18	1:21 PM	0.98	0.109	0.093	0.088	0.082	0.086
03/18/18	5:35 PM	0.68	0.112	0.104	0.091	0.088	0.08
03/19/18	1:25 PM	0.66	0.141	0.114	0.108	0.143	0.112
03/20/18	3:00 PM	0.72	0.159	0.11	0.097	0.12	0.098
03/21/18	3:30 PM	1.40	0.094	0.093	0.099	0.085	0.088
03/22/18	3:50 PM	0.79	0.099	0.084	0.088	0.087	0.101
03/23/18	3:10 PM	1.02	0.132	0.116	0.13	0.154	0.109
03/24/18	11:30 AM	1.20	0.108	0.121	0.122	0.159	0.133
03/25/18	11:00 AM	1.10	0.105	0.094	0.118	0.099	0.138
03/26/18	12:50 PM	0.79	0.097	0.108	0.103	0.081	0.097
03/27/18	3:00 PM	0.92	0.152	0.128	0.146	0.196	0.191
03/28/18	1:00 PM	0.64	0.212	0.17	0.171	0.182	0.166
03/29/18	3:30 PM	0.50	0.136	0.126	0.158	0.14	0.157
03/30/18	12:55 PM	1.20	0.13	0.098	0.157	0.102	0.1
03/31/18	1:00 PM	1.52	0.139	0.095	0.112	0.086	0.096
04/01/18	1:00 PM	1.10	0.144	0.112	0.112	0.111	0.231
04/02/18	1:00 PM	1.10	0.226	0.176	0.197	0.212	0.146
04/03/18	1:20 PM	1.70	0.218	0.189	0.201	0.197	0.126
04/05/18	1:20 PM	0.40	0.098	0.107	0.092	0.112	0.086
04/07/18	1:30 PM	0.75	0.11	0.1	0.102	0.082	0.129
04/08/18	1:00 PM	0.99	0.122	0.109	0.098	0.101	0.131
04/09/18	6:40 PM	0.94	0.107	0.114	0.086	0.108	0.122
04/10/18	3:15 PM	0.88	0.135	0.157	0.12	0.198	0.094
04/11/18	3:30 PM	0.78	0.164	0.142	0.135	0.149	0.283
04/13/18	3:00 PM	1.20	0.122	0.113	0.148	0.152	0.187
04/14/18	6:50 PM	0.35	0.146	0.109	0.127	0.141	0.114
04/15/18	6:35 PM	0.81	0.134	0.125	0.118	0.137	0.121
04/16/18	3:30 PM	0.79	0.194	0.165	0.213	0.226	0.287
04/17/18	12:55 PM	0.64	0.119	0.105	0.129	0.1	0.129
04/18/18		1.11	0.131	0.121	0.168	0.112	0.117

Table C1. Turbidity in Pilot Filtration System (continued)

Date	Time	Influent Turbidity (NTU)	Effluent Turbidity (NTU)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
04/20/18	1:00 PM	0.28	0.174	0.275	0.129	0.159	0.225
04/21/18	3:00 PM	1.20	0.202	0.225	0.132	0.177	0.115
04/22/18	3:00 PM	1.01	0.201	0.111	0.091	0.097	0.201
04/23/18	5:40 PM	1.40	0.151	0.117	0.088	0.086	0.185
04/24/18	3:00 PM	0.45	0.161	0.118	0.053	0.134	0.148
04/25/18	1:00 PM	0.45					
04/26/18	3:30 PM	1.26	0.221	0.141	0.281	0.121	0.198
04/27/18	5:30 PM	1.30	0.154	0.137	0.121	0.094	0.19
04/29/18	2:46 PM	0.31	0.136	0.119	0.108	0.102	0.182
04/30/18	1:30 PM	0.57	0.127	0.141	0.131	0.132	0.198
05/01/18	1:10 PM	0.98	0.093	0.09	0.12	0.087	0.124
05/02/18	5:40 PM	0.50	0.11	0.103	0.123	0.138	0.133
05/03/18	6:45 PM	0.68	0.091	0.089	0.092	0.087	0.086
05/04/18	1:27 PM	0.69	0.099	0.092	0.097	0.093	0.086
05/05/18	5:15 PM	0.90	0.118	0.098	0.116	0.113	0.093
05/06/18	11:40 AM	0.95	0.112	0.099	0.094	0.094	0.084
05/14/18	1:55 PM	0.89	0.162	0.147	0.194	0.154	0.17
05/15/18	3:00 PM	1.48	0.146	0.129	0.174	0.143	0.118
05/16/18	4:55 PM	1.71	0.116	0.228	0.111	0.126	0.171
05/17/18	11:35 AM	1.30	0.104	0.141	0.11	0.151	0.115
05/18/18	1:15 PM	1.70	0.104	0.088	0.091	0.104	0.105
05/19/18	1:00 PM	0.65	0.112	0.107	0.119	0.123	0.094
05/21/18	1:25 PM	1.32	0.144	0.153	0.102	0.133	0.152
05/22/18	2:50 PM	1.30	0.141	0.093	0.095	0.098	0.136
05/23/18	12:45 PM	1.40	0.181	0.107	0.098	0.092	0.126
05/24/18	12:51 PM	1.24	0.303	0.112	0.099	0.107	0.103
05/25/18	10:45 AM	0.41	0.165	0.17	0.153	0.197	0.129
05/26/18	1:26 PM	0.80	0.181	0.105	0.093	0.106	0.11
05/27/18	1:00 PM	0.89	0.104	0.088	0.091	0.094	0.112
05/28/18	1:05 PM	0.35	0.107	0.1	0.09	0.108	0.105
05/30/18	1:00 PM	0.68	0.108	0.096	0.11	0.117	0.09
05/31/18	5:00 PM	1.10	0.121	0.102	0.098	0.11	0.108
06/01/18	12:45 PM	1.60	0.105	0.101	0.12	0.09	0.112

Table C1. Turbidity in Pilot Filtration System (continued)

Date	Time	Influent Turbidity (NTU)	Effluent Turbidity (NTU)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
06/02/18	12:40 PM	1.31	0.107	0.11	0.106	0.1	0.112
06/03/18	1:15 PM		0.101	0.1	0.101	0.096	0.196
06/04/18	4:30 PM	1.53	0.103	0.16	0.11	0.121	0.185
06/06/18	2:55 PM	2.40	0.106	0.099	0.103	0.109	0.108
06/07/18	11:05 PM	1.09	0.109	0.118	0.106	0.107	0.122
06/08/18	1:15 PM	1.93	0.13	0.111	0.112	0.118	0.113
06/09/18	4:00 PM	0.81	0.065	0.095	0.12	0.092	0.168
06/10/18	1:30 PM	0.63	0.07	0.082	0.095	0.102	0.172
06/11/18	3:00 PM	0.66	0.124	0.098	0.106	0.105	0.096
06/12/18	2:30 PM		0.13	0.11	0.121	0.109	0.139
06/13/18	11:30 AM	0.88	0.186	0.14	0.149	0.183	0.184
06/14/18	5:00 PM	1.50	0.122	0.11	0.135	0.141	0.101
06/15/18	1:00 PM	1.05	0.142	0.133			
06/16/18	12:50 PM	1.88	0.114	0.116	0.116	0.112	0.118
06/17/18	12:50 PM	1.21	0.109	0.104	0.106	0.097	0.103
06/18/18	3:00 PM	0.65	0.162	0.121	0.169	0.12	0.112
06/19/18	3:30 PM	1.40	0.145	0.18	0.14	0.111	0.161
06/20/18	6:55 PM	2.70	0.144	0.12	0.132	0.117	0.124
06/21/18	3:22 PM	1.76	0.143	0.144	0.161	0.141	0.134
06/22/18	5:45 PM	1.55	0.11	0.101	0.145	0.143	0.11
06/23/18	5:00 PM	3.20	0.088	0.091	0.089	0.101	0.131
06/24/18	5:30 PM	3.30	0.068	0.11	0.097	0.078	0.102
06/25/18	6:40 PM	1.44		0.117	0.106	0.124	0.11
06/26/18	1:00 PM	2.04	0.091	0.085	0.094	0.106	0.089
06/27/18	7:30 PM	1.06	0.132	0.108	0.112	0.105	0.117
06/28/18		2.11	0.119	0.123	0.137	0.125	0.119
06/29/18	6:53 PM	0.99	0.106	0.112	0.134	0.109	0.116
06/30/18	6:45 PM		0.095	0.107	0.119	0.113	0.096
07/01/18	6:52 PM		0.087	0.116	0.102	0.135	0.11
07/02/18	1:00 PM	0.44	0.1	0.089	0.094	0.098	0.091
07/03/18	11:16 AM	0.91	0.21	0.165	0.171	0.146	0.16
07/04/18	6:31 PM	0.43	0.115	0.129	0.152	0.124	0.14
07/05/18	6:40 PM		0.102	0.118	0.121	0.109	0.135

Table C1. Turbidity in Pilot Filtration System (continued)

Date	Time	Influent Turbidity (NTU)	Effluent Turbidity (NTU)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
07/06/18	12:36 PM		0.1	0.091	0.094	0.093	0.092
07/07/18	1:30 PM		0.106	0.112	0.091	0.085	0.089
07/08/18	12:30 PM	0.74	0.096	0.112	0.103	0.093	0.09
07/09/18	7:00 PM	0.93	0.164	0.179	0.139	0.12	0.163
07/10/18	10:50 AM	0.71	0.106	0.15	0.105	0.115	0.136
07/11/18	12:55 PM	4.10	0.103	0.095	0.089	0.096	0.102
07/12/18	2:40 PM	2.32	0.103	0.085	0.086	0.097	0.102
07/13/18	6:40 PM	2.30	0.112	0.094	0.091	0.092	0.12
07/14/18	6:50 PM	2.10	0.105	0.099	0.102	0.108	0.114
07/17/18	12:35 PM	1.13	0.106	0.092	0.091	0.084	0.127
07/18/18	7:00 PM	0.58	0.149	0.125	0.127	0.113	0.146
07/19/18	1:30 PM	0.44	0.134	0.108	0.114	0.103	0.152
07/20/18	1:10 PM	0.69	0.1	0.093	0.089	0.089	0.088
07/21/18	1:15 PM	0.50	0.097	0.088	0.119	0.092	0.09
07/22/18	2:45 PM	0.60	0.093	0.09	0.105	0.103	0.095
07/23/18	11:50 AM	0.48	0.116	0.12	0.12	0.099	0.102
07/24/18	3:00 PM	1.17	0.12	0.119	0.122	0.111	0.099
07/25/18	3:15 PM	1.63	0.128	0.121	0.111	0.101	0.089
07/26/18	4:35 PM	0.86	0.103	0.097	0.098	0.096	0.095
07/27/18	4:30 PM	1.57	0.124	0.127	0.111	0.15	0.153
07/28/18	11:30 AM	1.21	0.122	0.122	0.105	0.114	0.13
07/29/18	1:00 PM	2.50	0.102	0.091	0.105	0.184	0.115
07/30/18	11:30 AM	2.25	0.134	0.109	0.112	0.097	0.128
07/31/18	3:30 PM	2.35	0.117	0.093	0.107	0.131	0.096
08/01/18	11:27 AM	1.81	0.135	0.114	0.132	0.108	0.141
08/02/18	12:35 PM	0.94	0.103	0.091	0.187	0.116	0.107
08/03/18	1:35 PM	0.85	0.102	0.089	0.104	0.101	0.091
08/04/18	1:00 PM		0.107	0.091	0.096	0.0925	0.083
08/05/18	5:00 PM	0.98	0.145	0.102	0.104	0.091	0.09
08/06/18	12:55 PM	1.13	0.148	0.118	0.099	0.133	0.146
08/07/18	1:00 PM	1.10	0.109	0.099	0.12	0.116	0.091
08/08/18	4:35 PM	1.70	0.179	0.173	0.168	0.14	0.134
08/09/18	5:00 PM	0.81	0.102	0.084	0.099	0.085	0.087

Table C1. Turbidity in Pilot Filtration System (continued)

Date	Time	Influent Turbidity (NTU)	Effluent Turbidity (NTU)				
			Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
08/10/18	10:32 AM	0.54	0.101	0.145	0.115	0.139	0.096
08/11/18	11:45 AM	0.42	0.092	0.089	0.107	0.114	0.128
08/12/18	1:10 PM	0.52	0.103	0.09	0.096	0.101	0.103
08/13/18	2:15 PM	0.54	0.111	0.085	0.097	0.088	0.084
08/14/18	1:00 PM	0.48	0.121	0.101	0.103	0.09	0.104
08/15/18	1:25 PM	0.63	0.116	0.109	0.118	0.118	0.114
08/16/18	11:25 AM	0.49	0.104	0.092	0.113	0.12	0.126
08/17/18	1:27 PM	0.51	0.106	0.094	0.097	0.109	0.089
08/18/18	1:00 PM	0.95	0.102	0.099	0.101	0.093	0.088
08/19/18	1:00 PM	1.16	0.093	0.092	0.093	0.088	0.082

APPENDIX D. TURBIDITY AND HEAD LOSS STUDY DATA

Table D1. Filter 3 Turbidity at Various Bed Depths – Trial 1

Date	Time	Run Time (hours)	Bed Depth (in)	Turbidity (NTU) Sample 1 1	Sample 1 2	Sample 1 3	Sample 2 1	Sample 2 2	Sample 2 3
02/19/19	5:45 PM	6	0	1.30	1.30	1.36	1.27	1.31	1.36
			8	0.11	0.10	0.11	0.12	0.10	0.14
			14	0.094	0.085	0.087	0.074	0.082	0.082
			26	0.078	0.079	0.085	0.085	0.10	0.11
			32	0.081	0.087	0.078	0.068	0.069	0.078
			36	0.065	0.064	0.066	0.064	0.077	0.070
02/20/19	12:00 PM	24	0	1.24	1.32	1.31	1.33	1.23	1.24
			8	0.30	0.17	0.15	0.14	0.13	0.13
			14	0.10	0.086	0.11	0.11	0.13	0.11
			26	0.078	0.073	0.082	0.083	0.070	0.085
			32	0.12	0.084	0.086	0.07	0.068	0.066
			36	0.064	0.067	0.066	0.068	0.074	0.069
02/21/19	12:00 PM	48	0	1.39	1.37	1.38	1.3	1.37	1.33
			8	0.22	0.23	0.19	0.13	0.14	0.15
			14	0.10	0.11	0.11	0.10	0.10	0.11
			26	0.078	0.075	0.076	0.079	0.077	0.083
			32	0.083	0.085	0.083	0.076	0.073	0.068
			36	0.066	0.063	0.068	0.065	0.072	0.065
02/22/19	12:00 PM	72	0	1.00	1.00	1.10	1.00	1.10	1.10
			8	0.18	0.15	0.18	0.17	0.14	0.16
			14	0.12	0.12	0.13	0.11	0.12	0.11
			26	0.075	0.078	0.077	0.074	0.075	0.076
			32	0.076	0.072	0.085	0.07	0.071	0.075
			36	0.074	0.070	0.071	0.068	0.074	0.077
02/23/19	12:00 PM	96	0	1.15	1.16	1.14	1.00	1.10	1.00
			8	0.22	0.21	0.18	0.18	0.17	0.18
			14	0.14	0.14	0.14	0.13	0.14	0.13
			26	0.085	0.084	0.086	0.083	0.086	0.081
			32	0.079	0.077	0.075	0.082	0.078	0.078
			36	0.065	0.065	0.064	0.062	0.066	0.065

Table D1. Filter 3 Turbidity at Various Bed Depths – Trial 1 (continued)

Date	Time	Run Time (hours)	Bed Depth (inches)	Turbidity (NTU) Sample 1 1	Sample 1 2	Sample 1 3	Sample 2 1	Sample 2 2	Sample 2 3
02/24/19	12:48 PM	120	0	1.00	1.10	1.00	1.20	1.00	1.20
			8	0.22	0.22	0.21	0.22	0.22	0.21
			14	0.14	0.13	0.13	0.13	0.13	0.14
			26	0.087	0.091	0.088	0.087	0.087	0.091
			32	0.087	0.086	0.088	0.091	0.088	0.086
			36	0.079	0.075	0.078	0.073	0.074	0.072
02/25/19	12:15 PM	144	0	0.43	0.42	0.40	0.42	0.41	0.40
			8	0.21	0.20	0.22	0.21	0.21	0.20
			14	0.12	0.13	0.12	0.12	0.12	0.13
			26	0.086	0.086	0.085	0.084	0.085	0.084
			32	0.077	0.079	0.079	0.074	0.075	0.074
			36	0.072	0.077	0.074	0.072	0.072	0.076
02/26/19	12:15 PM	168	0	0.70	0.71	0.70	0.65	0.67	0.70
			8	0.21	0.22	0.20	0.19	0.18	0.20
			14	0.16	0.16	0.17	0.16	0.17	0.19
			26	0.090	0.087	0.085	0.082	0.08	0.083
			32	0.080	0.074	0.072	0.072	0.075	0.073
			36	0.070	0.071	0.069	0.074	0.073	0.069
02/28/19	12:06 PM	216	0	1.20	1.30	1.20	1.10	1.20	1.10
			8	0.45	0.44	0.46	0.44	0.44	0.45
			14	0.28	0.28	0.27	0.27	0.28	0.28
			26	0.12	0.12	0.11	0.11	0.11	0.11
			32	0.090	0.090	0.091	0.093	0.095	0.094
			36	0.070	0.076	0.076	0.075	0.075	0.073
03/02/19	12:02 PM	264	0	0.56	0.51	0.56	0.50	0.62	0.55
			8	0.41	0.42	0.48	0.41	0.50	0.46
			14	0.32	0.28	0.29	0.32	0.23	0.26
			26	0.12	0.12	0.12	0.11	0.12	0.11
			32	0.12	0.12	0.11	0.11	0.12	0.12
			36	0.080	0.083	0.091	0.083	0.087	0.084

Table D2. Filter 5 Turbidity at Various Bed Depths – Trial 1

Date	Time	Run Time (hours)	Bed Depth (in)	Turbidity (NTU) Sample 1 1	Sample 1 2	Sample 1 3	Sample 2 1	Sample 2 2	Sample 2 3
02/19/19	7:15 PM	6	0	1.3	1.21	1.3	1.24	1.31	1.31
			8	0.20	0.25	0.30	0.24	0.17	0.18
			14	0.25	0.22	0.21	0.18	0.18	0.25
			26	0.19	0.16	0.15	0.16	0.14	0.16
			32	0.11	0.082	0.091	0.088	0.084	0.087
			36	0.080	0.11	0.090	0.084	0.080	0.085
02/20/19	1:30 PM	24	0	1.24	1.33	1.25	1.35	1.28	1.28
			8	0.28	0.29	0.27	0.27	0.26	0.28
			14	0.27	0.25	0.26	0.28	0.29	0.27
			26	0.26	0.25	0.24			
			32	0.11	0.10	0.098	0.086	0.088	0.088
			36	0.064	0.067	0.074	0.067	0.062	0.063
02/21/19	1:30 PM	48	0	1.10	1.00	1.13	1.10	1.10	1.10
			8	0.26	0.27	0.25	0.23	0.25	0.24
			14	0.21	0.18	0.21	0.18	0.18	0.18
			26	0.11	0.12	0.11	0.13	0.10	0.13
			32	0.081	0.073	0.072	0.074	0.074	0.071
			36	0.069	0.067	0.068	0.071	0.074	0.069
02/22/19	1:30 PM	72	0	1.00	1.10	1.20	1.00	0.98	1.10
			8	0.28	0.27	0.28	0.27	0.28	0.29
			14	0.29	0.27	0.26	0.25	0.26	0.27
			26	0.13	0.13	0.13	0.13	0.12	0.13
			32	0.078	0.072	0.074	0.073	0.075	0.072
			36	0.068	0.072	0.069	0.078	0.078	0.071
02/23/19	1:30 PM	96	0	1.10	1.00	1.10	1.10	1.10	1.10
			8	0.41	0.42	0.41	0.44	0.44	0.44
			14	0.27	0.26	0.25	0.22	0.23	0.23
			26	0.11	0.10	0.10	0.11	0.11	0.11
			32	0.083	0.085	0.079	0.075	0.073	0.073
			36	0.067	0.067	0.067	0.067	0.072	0.068

Table D2. Filter 5 Turbidity at Various Bed Depths – Trial 1 (continued)

Date	Time	Filter Run Time (hours)	Bed Depth (in)	Turbidity (NTU) Sample 1 1	Sample 1 2	Sample 1 3	Sample 2 1	Sample 2 2	Sample 2 3
02/24/19	2:18 PM	120	0	1.00	1.00	0.98	1.00	1.00	1.10
			8	0.52	0.53	0.50	0.51	0.48	0.51
			14	0.29	0.31	0.32	0.33	0.32	0.31
			26	0.10	0.11	0.10	0.11	0.11	0.11
			32	0.076	0.077	0.075	0.076	0.072	0.079
			36	0.068	0.070	0.070	0.071	0.073	0.071
02/25/19	1:45 PM	144	0	0.40	0.42	0.41	0.42	0.39	0.41
			8	0.33	0.32	0.32	0.32	0.32	0.31
			14	0.27	0.25	0.26	0.24	0.24	0.26
			26	0.11	0.12	0.12	0.10	0.12	0.10
			32	0.069	0.070	0.068	0.069	0.071	0.072
			36	0.071	0.067	0.070	0.070	0.069	0.071
02/26/19	1:45 PM	168	0	0.71	0.72	0.71	0.69	0.72	0.72
			8	0.42	0.41	0.42	0.37	0.37	0.37
			14	0.25	0.24	0.24	0.22	0.23	0.23
			26	0.11	0.12	0.11	0.11	0.11	0.11
			32	0.067	0.070	0.073	0.066	0.067	0.07
			36	0.065	0.066	0.065	0.064	0.067	0.068
02/28/19	1:36 PM	216	0	0.65	0.64	0.67	0.61	0.62	0.60
			8	0.60	0.61	0.61	0.60	0.62	0.64
			14	0.51	0.50	0.51	0.42	0.41	0.45
			26	0.14	0.15	0.15	0.14	0.13	0.14
			32	0.072	0.068	0.072	0.068	0.071	0.073
			36	0.066	0.072	0.068	0.067	0.069	0.071
03/02/19	1:32 PM	264	0	0.60	0.63	0.60	0.50	0.48	0.62
			8	0.42	0.44	0.41	0.45	0.46	0.46
			14	0.26	0.24	0.29	0.25	0.25	0.28
			26	0.16	0.15	0.16	0.12	0.13	0.15
			32	0.085	0.085	0.087	0.088	0.090	0.083
			36	0.082	0.081	0.091	0.083	0.080	0.081

Table D3. Effluent Turbidity Data – Trial 1

	Effluent Turbidity (NTU)	
Run Time (hours)	Filter 3	Filter 5
6	0.068	0.088
24	0.068	0.066
48	0.067	0.070
72	0.072	0.073
96	0.065	0.068
120	0.075	0.071
144	0.074	0.070
168	0.071	0.066
216	0.075	0.069
264	0.085	0.083

Table D4. Filter 3 Head Loss Buildup over Time – Trial 1

Date	Time	Run Time (hours)	Δ Head Loss (in)	Cumulative Head Loss (in)
02/19/19	5:45 PM	6	0.00	0.00
02/20/19	12:00 PM	24	0.81	0.81
02/21/19	12:00 PM	48	0.50	1.31
02/22/19	12:00 PM	72	0.69	2.00
02/23/19	12:00 PM	96	0.44	2.40
02/24/19	12:48 PM	120	0.81	3.30
02/25/19	12:15 PM	144	0.63	3.90
02/26/19	12:15 PM	168	0.69	4.60
02/28/19	12:06 PM	216	1.75	6.30
03/02/19	12:02 PM	264	3.30	9.60

Table D5. Filter 5 Head Loss Buildup over Time – Trial 1

Date	Time	Run Time (hours)	ΔHead Loss (in)	Cumulative Head Loss (in)
02/19/19	7:15 PM	6	0.00	0.00
02/20/19	1:30 PM	24	0.50	0.50
02/21/19	1:30 PM	48	1.44	1.94
02/22/19	1:30 PM	72	0.50	2.40
02/23/19	1:30 PM	96	0.63	3.10
02/24/19	2:18 PM	120	0.91	4.00
02/25/19	1:45 PM	144	0.56	4.50
02/26/19	1:45 PM	168	0.25	4.80
02/28/19	1:36 PM	216	2.60	7.30
03/02/19	1:32 PM	264	3.30	10.60

Table D6. Turbidity Removal Comparison per Layer – Trial 1

Run Time (hours)	Filter Bed Layer	Turbidity Removal (NTU)		Filter with Highest Turbidity Removal
		Filter 3	Filter 5	
6	0-8"	1.2033	1.0550	3
	8-14"	0.0293	0.0083	3
	14-26"	0.0000	0.0550	5
	26-32"	0.0127	0.0697	5
	32-36"	0.0092	0.0022	3
	0-36"	1.2545	1.1902	3
24	0-8"	1.1083	1.0133	3
	8-14"	0.0623	0.0050	3
	14-26"	0.0292	0.0200	3
	26-32"	0.0000	0.1550	5
	32-36"	0.0143	0.0288	5
	0-36"	1.2142	1.2222	5
48	0-8"	1.1800	0.8383	3
	8-14"	0.0717	0.0600	3
	14-26"	0.0270	0.0733	5
	26-32"	0.0000	0.0425	5
	32-36"	0.0115	0.0045	3
	0-36"	1.2902	1.0187	3

Table D6. Turbidity Removal Comparison per Layer – Trial 1 (continued)

Run Time (hours)	Filter Bed Layer	Turbidity Removal (NTU)		Filter with Highest Turbidity Removal
		Filter 3	Filter 5	
72	0-8"	0.8867	0.7850	3
	8-14"	0.0450	0.0117	3
	14-26"	0.0425	0.1383	5
	26-32"	0.0010	0.0543	5
	32-36"	0.0025	0.0013	3
	0-36"	0.9777	0.9907	5
96	0-8"	0.9017	0.6567	3
	8-14"	0.0533	0.1833	5
	14-26"	0.0525	0.1367	5
	26-32"	0.0060	0.0287	5
	32-36"	0.0137	0.0100	3
	0-36"	1.0272	1.0153	3
120	0-8"	0.8667	0.5050	3
	8-14"	0.0833	0.1950	5
	14-26"	0.0448	0.2067	5
	26-32"	0.0008	0.0308	5
	32-36"	0.0125	0.0053	3
	0-36"	1.0082	0.9428	3
144	0-8"	0.2050	0.0883	3
	8-14"	0.0850	0.0667	3
	14-26"	0.0383	0.1417	5
	26-32"	0.0087	0.0418	5
	32-36"	0.0025	0.0002	3
	0-36"	0.3395	0.3387	3
168	0-8"	0.4883	0.3183	3
	8-14"	0.0317	0.1583	5
	14-26"	0.0847	0.1233	5
	26-32"	0.0102	0.0428	5
	32-36"	0.0025	0.0030	5
	0-36"	0.6173	0.6458	5

Table D6. Turbidity Removal Comparison per Layer – Trial 1 (continued)

Run Time (hours)	Filter Bed Layer	Turbidity Removal (NTU)		Filter with Highest Turbidity Removal
		Filter 3	Filter 5	
216	0-8"	0.7367	0.0183	3
	8-14"	0.1700	0.1467	3
	14-26"	0.1633	0.3250	5
	26-32"	0.0205	0.0710	5
	32-36"	0.0182	0.0018	3
	0-36"	1.1087	0.5628	3
264	0-8"	0.1033	0.1317	5
	8-14"	0.1633	0.1783	5
	14-26"	0.1667	0.1167	3
	26-32"	0.0000	0.0587	5
	32-36"	0.0320	0.0033	3
	0-36"	0.4653	0.4887	5

Table D7. Summary of Turbidity Removal Comparison per Layer – Trial 1

Filter Bed Layer	Filter with Highest Turbidity Removal
0-8"	3
8-14"	3
14-26"	5
26-32"	5
32-36"	3
0-36"	3

Table D8. Filter 3 Turbidity at Various Bed Depths – Trial 2

Date	Time	Run Time (hours)	Bed Depth (in)	Turbidity (NTU) Sample 1 1	Sample 1 2	Sample 1 3	Sample 2 1	Sample 2 2	Sample 2 3
05/01/19	4:48 PM	30	0	2.23	2.65	2.96	1.55	1.99	1.11
			8	0.083	0.079	0.091	0.083	0.092	0.092
			14	0.082	0.092	0.087	0.089	0.088	0.089
			26	0.084	0.088	0.094	0.092	0.085	0.086
			32	0.120	0.095	0.107	0.085	0.091	0.087
			36	0.083	0.082	0.082	0.086	0.092	0.084
05/02/19	9:30 AM	46	0	1.21	1.88	1.23	1.46	1.34	1.47
			8	0.076	0.097	0.074	0.086	0.088	0.086
			14	0.075	0.079	0.086	0.080	0.075	0.077
			26	0.084	0.085	0.09	0.082	0.084	0.086
			32	0.070	0.070	0.071	0.084	0.075	0.074
			36	0.067	0.068	0.067	0.069	0.068	0.076
05/02/19	3:17 PM	51	0	2.13	1.87	1.18	1.86	1.62	1.89
			8	0.083	0.085	0.076	0.075	0.086	0.080
			14	0.081	0.090	0.078	0.080	0.079	0.092
			26	0.097	0.098	0.100	0.091	0.093	0.100
			32	0.082	0.076	0.080	0.080	0.085	0.077
			36	0.092	0.083	0.084	0.083	0.078	0.079
05/03/19	9:29 AM	70	0	0.76	0.91	0.84	0.70	0.96	1.02
			8	0.088	0.101	0.094	0.086	0.096	0.104
			14	0.095	0.091	0.090	0.094	0.105	0.092
			26	0.094	0.091	0.107	0.090	0.102	0.098
			32	0.102	0.090	0.105	0.088	0.089	0.087
			36	0.096	0.085	0.109	0.086	0.087	0.092
05/03/19	2:48 PM	76	0	0.74	0.68	0.89	0.94	0.89	1.15
			8	0.100	0.102	0.092	0.096	0.102	0.102
			14	0.099	0.103	0.096	0.105	0.101	0.097
			26	0.105	0.102	0.107	0.098	0.101	0.104
			32	0.094	0.095	0.099	0.103	0.096	0.104
			36	0.099	0.103	0.105	0.090	0.104	0.092

Table D9. Filter 5 Turbidity at Various Bed Depths – Trial 2

Date	Time	Run Time (hours)	Bed Depth (in)	Turbidity (NTU)					
				Sample 1			Sample 2		
				1	2	3	1	2	3
05/01/19	6:38 PM	30	0	1.18	1.26	1.10	1.21	0.97	1.39
			8	0.190	0.207	0.174	0.121	0.147	0.181
			14	0.139	0.100	0.119	0.086	0.118	0.085
			26	0.092	0.091	0.094	0.093	0.100	0.109
			32	0.097	0.093	0.091	0.096	0.106	0.100
			36	0.099	0.095	0.094	0.097	0.093	0.092
05/02/19	11:10 AM	46	0	1.10	1.15	1.62	1.29	1.38	1.13
			8	0.136	0.134	0.145	0.113	0.096	0.099
			14	0.122	0.120	0.119	0.109	0.121	0.131
			26	0.072	0.070	0.072	0.072	0.071	0.070
			32	0.075	0.078	0.082	0.071	0.070	0.076
			36	0.074	0.073	0.072	0.075	0.077	0.072
05/02/19	4:57 PM	51	0	1.58	1.20	1.57	1.56	1.39	1.72
			8	0.125	0.137	0.171	0.128	0.111	0.131
			14	0.101	0.090	0.120	0.094	0.135	0.117
			26	0.081	0.083	0.083	0.089	0.096	0.083
			32	0.083	0.085	0.083	0.082	0.080	0.080
			36	0.079	0.084	0.082	0.082	0.084	0.082
05/03/19	11:09 AM	70	0	0.81	0.87	0.91	0.76	0.85	0.73
			8	0.129	0.171	0.162	0.171	0.133	0.137
			14	0.123	0.116	0.161	0.137	0.155	0.123
			26	0.094	0.096	0.094	0.095	0.086	0.090
			32	0.092	0.091	0.092	0.089	0.087	0.090
			36	0.098	0.095	0.101	0.090	0.089	0.087
05/03/19	4:28 PM	76	0	0.72	0.85	0.91	0.87	0.79	0.67
			8	0.121	0.116	0.138	0.120	0.114	0.127
			14	0.128	0.099	0.103	0.096	0.111	0.100
			26	0.094	0.102	0.098	0.102	0.097	0.096
			32	0.099	0.105	0.096	0.102	0.096	0.094
			36	0.095	0.097	0.106	0.105	0.098	0.100

Table D10. Effluent Turbidity Data – Trial 2

	Effluent Turbidity (NTU)	
Run Time (hours)	Filter 3	Filter 5
30	0.085	0.095
46	0.069	0.074
51	0.083	0.082
70	0.093	0.093
76	0.099	0.099

Table D11. Filter 3 Head Loss at Various Filter Bed Depths – Trial 2

Date	Time	Run Time (hours)	Bed Depth (in)	Head Loss (in)
04/30/19	11:34 AM	1	8	1.38
			14	1.81
			26	2.44
			32	2.66
			36	4.19
04/30/19	4:34 PM	6	8	1.81
			14	2.25
			26	2.88
			32	3.13
			36	4.63
05/01/19	4:58 PM	30	8	4.84
			14	5.38
			26	5.94
			32	6.25
			36	7.75
05/02/19	9:30 AM	46	8	9.00
			14	9.53
			26	10.13
			32	10.38
			36	11.94
05/02/19	3:17 PM	51	8	10.94
			14	11.47
			26	12.10
			32	12.38
			36	13.88

Table D11. Filter 3 Head Loss at Various Filter Bed Depths – Trial 2 (continued)

Date	Time	Run Time (hours)	Bed Depth (in)	Head Loss (in)
05/03/19	9:29 AM	70	8	17.16
			14	17.69
			26	18.31
			32	18.63
			36	20.13
05/03/19	2:48 PM	76	8	18.88
			14	19.44
			26	20.09
			32	20.38
			36	21.88

Table D12. Filter 5 Head Loss at Various Filter Bed Depths – Trial 2

Date	Time	Run Time (hours)	Bed Depth (in)	Head Loss (in)
04/30/19	1:14 PM	1	8	0.88
			14	1.69
			26	3.13
			32	5.63
			36	8.69
04/30/19	6:08 PM	6	8	1.22
			14	2.03
			26	3.53
			32	6.03
			36	9.16
05/01/19	6:38 PM	30	8	2.97
			14	4.00
			26	5.53
			32	8.19
			36	11.34
05/02/19	11:10 AM	46	8	5.94
			14	7.00
			26	8.59
			32	11.31
			36	14.50

Table D12. Filter 5 Head Loss at Various Filter Bed Depths – Trial 2 (continued)

Date	Time	Run Time (hours)	Bed Depth (in)	Head Loss (in)
05/02/19	4:57 PM	51	8	7.78
			14	8.91
			26	10.47
			32	13.22
			36	16.41
05/03/19	11:09 AM	70	8	16.81
			14	18.00
			26	19.69
			32	22.44
			36	25.63
05/03/19	4:28 PM	76	8	19.38
			14	20.56
			26	22.25
			32	25.00
			36	28.13

Table D13. Total Head Loss – Trial 2

	Total Head Loss (in)	
Run Time (hours)	Filter 3	Filter 5
1	3.19	8.69
6	4.63	9.16
30	7.75	11.34
46	11.94	14.5
51	13.88	16.41
70	20.13	25.63
76	21.88	28.13

Table D14. Filter 3 Organics at Various Filter Bed Depths – Trial 2

Date	Run Time (hours)	Temperature (°F)	Bed Depth (in)	UV254 (cm^{-1})	TOC (mg/L)	DOC (mg/L)
05/01/19	30	57.8	0	0.020	0.018	0.018
			8	0.015	0.015	0.015
			14	0.015	0.015	0.015
			26	0.015	0.015	0.015
			32	0.015	0.015	0.015
			36	0.015	0.015	0.015
05/03/19	70	57.6	0	0.020	0.020	0.020
			8	0.018	0.018	0.018
			14	0.017	0.017	0.017
			26	0.017	0.017	0.017
			32	0.017	0.017	0.017
			36	0.017	0.017	0.017

Table D15. Filter 5 Organics at Various Filter Bed Depths – Trial 2

Date	Run Time (hours)	Temperature (°F)	Bed Depth (in)	UV254 (cm^{-1})	TOC (mg/L)	DOC (mg/L)
05/01/19	30	57.8	0	0.019	0.018	0.019
			8	0.017	0.017	0.017
			14	0.017	0.016	0.016
			26	0.017	0.017	0.016
			32	0.016	0.017	0.017
			36	0.018	0.018	0.018
05/03/19	70	57.6	0	0.021	0.021	0.021
			8	0.020	0.019	0.019
			14	0.018	0.019	0.018
			26	0.020	0.020	0.019
			32	0.018	0.019	0.019
			36	0.018	0.018	0.018