BASIS OF DESIGN REPORT

Plum Creek Water Purification Facility Expansion — Final

September 7, 2017

ch2m

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List of Acronyms

AFD	Adjustable Frequency Drive
BAC	Biologically Activated Carbon
BDR	Basis of Design Report
CEC	Chemicals of Emerging Concern
CCP	Critical Control Point
DOC	Dissolved Organic Carbon
EBCT	Empty Bed Contact Time
EPC	East Plum Creek
ESB	Engineered Storage Buffer
GAC	Granular Activated Carbon
MCL	Maximum Contaminant Level
MF	Microfiltration
MPN	Most Probable Number
NDMA	N-Nitrosodimethylamine
NF	Nanofiltration
PCWPF	Plum Creek Water Purification Facility
PCWRA	Plum Creek Water Reclamation Authority
RO	Reverse Osmosis
SDWA	Safe Drinking Water Act
SWTR	Surface Water Treatment Rule
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
UV	Ultraviolet
UVAOP	UV Advanced Oxidation Process
UW&SD	United Water & Sanitation District

1.0 Introduction

This Basis of Design Report (BDR) summarizes the anticipated water quality and the recommended advanced treatment processes necessary to incorporate a new source water supply at the Plum Creek Water Purification Facility (PCWPF). Three potential new sources were considered as part of this BDR; a new diversion in East Plum Creek (directly downstream of the PCWRA outfall), the Plum Creek Water Reclamation Authority (PCWRA) effluent, and water from an existing diversion structure in Plum Creek at Sedalia. Each source will provide the Town of Castle Rock (Town) a renewable water source that, along with the current deep ground water and alluvial well sources, will contribute to the overall water portfolio for the Town. The current PCWPF has a treatment capacity of 6 MGD. In the future, the facility could be expanded up to 12 MGD which would require additional treatment for all processes (both current and any additional treatment that may be added as part of the expansion associated with a new source).

A multiple barrier, advanced treatment approach has been developed in this BDR for the PCWPF to treat the potential new sources that utilizes the existing infrastructure to the fullest extent while adding treatment processes to enhance removal of pathogens, organics, regulated drinking water contaminants, and chemicals of emerging concern (CECs). This approach will provide a robust and sustainable advanced treatment process as an essential part of incorporating the new source water supply into the PCWPF. Numerous advanced treatment technologies were initially considered for implementation; however, some technologies were eliminated due to the cost of treatment.

The scope of this BDR was limited to evaluating the treatment processes necessary to incorporate a new water supply from a water quality perspective and therefore a comprehensive evaluation of existing processes was not conducted. In addition, solids handling was not included as part of the scope of this BDR. Further evaluation of these processes should be conducted prior to or during preliminary design.

2.0 Water Quality Analysis

Prior to selecting treatment processes to add to the PCWPF, an abbreviated source water characterization program was implemented. Although water supplies heavily influenced by wastewater discharges will contain elevated concentrations of organics, pathogens and likely CECs when compared to conventional surface water sources, several other water quality parameters can also impact treatment process selection such as color, total dissolved solids (TDS), hardness, and select inorganics (e.g., nitrate, ammonia). A sampling protocol was developed to characterize water quality parameters requiring consideration in treatment process selection by collecting samples from five locations in the system:

1. **East Plum Creek (EPC)** – This sample location is upstream of the PCWRA discharge and was sampled to show the background water quality in EPC. This source includes natural flow as well as the United Water and Sanitation District's Bell Mountain wells and effluent from one small wastewater treatment plant, the Sageport WWTP in Larkspur.
2. **Source 1 (East Plum Creek Diversion)** – This sample location (referred to as New Source during sampling) is in East Plum Creek, approximately 50-100 feet downstream of the PCWRA outfall. This source represents the location of a new diversion structure that would be constructed to capture PCWRA return flows as well as free river conditions within EPC.
3. **Source 2 (PCWRA Outfall)** – Samples taken from this location were collected downstream of the drop from the outfall pipe, prior to the confluence with East Plum Creek. This source represents the water that would be utilized when East Plum Creek is dry or in a potential direct potable reuse

application. If implemented, this water would be diverted to a settling pond prior to pumping to the PCWPF raw water pipeline.

4. **PCWPF Raw Water** – Samples were collected at the influent to the PCWPF, prior to any treatment or chemical application. The water quality measured from these samples demonstrated a consistent baseline of current source water (for the period sampled) and for that reason has been assumed to be representative of the blend water that would be utilized with the new sources for treatment.
5. **PCWPF Finished Water** – Samples collected from the high service pump station demonstrate the finished water quality currently delivered to customers in the Town. Understanding the current finished water quality is important so that treatment may be tailored to meet current aesthetic qualities or future differences can be identified in order to mitigate potential public perception issues associated with the new source water.

Six sampling events were conducted from November 2015 through January 2016 (for locations 1-5 only). The parameters were grouped into categories; basic water quality, inorganics, organics, pathogens, regulated compounds (Safe Drinking Water Act (SDWA) parameters), future regulatory concerns, and CECs. The sampling protocol was tailored such that not every compound was measured in each sampling event in order to summarize the water quality from the various sample locations as quickly and as cost-efficiently as possible. For example, the basic water quality parameters, inorganic, and organic parameters were sampled bi-weekly for EPC, Source 1, and Source 2. CECs were measured monthly for Source 1 and Source 2, but only a single time for EPC and the PCWPF finished water.

After the initial sampling campaign was completed and the treatment process was initially selected, a single sample was collected from the existing Sedalia Diversion (Source 3) in August 2016. This location was added at the end of the BDR development phase of the project as a third potential source. The parameters analyzed in this single sample matched the parameters analyzed for the previous sampling events. Sources 1 and 2 were also sampled in August for comparison between the three potential source locations as well to provide a water quality data point in a different season.

2.1 Water Quality Considerations

The results of the sampling provide an important basis for the subsequent selection and future design of advanced treatment for the PCWPF. Table 1 provides a summary of the key water quality considerations based on the analysis of the data received to date for the two new source locations that will provide new supply to PCWPF.

In order to further characterize and classify the selected new source, monthly sampling is recommended to be conducted for all regulated parameters and other parameters of interested for a period of 1 year. While extensive CEC characterization is not needed, it is recommended that 1-2 additional rounds of samples should be analyzed for the full suite of CECs since all CEC data collected to this point has been during the winter months.

Table 1. Summary of Key Water Quality Considerations

Parameter	Source 1	Source 2	Source 3	Notes	Treatment Approach
Number of Samples and time period	6 (Nov 2015-Jan 2016); 1 (August 2016)	6 (Nov 2015-Jan 2016); 1 (August 2016)	1 (August 2016)		
Pathogens	Crypto: <0.1 oocysts/L Giardia: 0.3-26 cysts/L E. coli: 23 – 42 MPN/100 mL	Crypto: <0.1-3 oocysts/L Giardia: 2-38 cysts/L E. coli: 8-57 MPN/100 mL	Crypto: <0.1 oocysts/L Giardia: 0.6 cysts/L E. coli: 44 MPN/100 mL	If Sources 1 or 2 are implemented, CDPHE will likely classify the PCWRA outfall in Bin 4 per the Long-Term 2 Enhanced SWTR, which requires at least an additional 2.5 log Crypto removal beyond conventional treatment. Source 3 requires additional characterization and sampling for bin classification.	Provide multiple barriers to pathogens, including the existing floc/sed, granular media filters, MF, and chlorine disinfection, as well as new "upper-bin" technology processes such as ozone and UV.
DOC and color	DOC: 5.5-7.3 mg/L Color: 7-36	DOC: 6.4-7.0 mg/L Color: 18-38	DOC: 3.4 mg/L Color: 15	Target less than 2 mg/L of DOC prior to chlorine disinfection to avoid excessive THM and HAA production. Color removal is required to meet secondary MCL (sMCL) of 15 color units.	For Sources 1 and 2, blend 50% with groundwater and alluvial wells, which will reduce DOC to approximately 3.5 mg/L. Target 40-50% reduction through F/S and O_3/BAC to meet 2 mg/L goal. Significant blending of groundwater and alluvial wells with Source 3 may not be required depending on the consistency of TOC in Source 3. More sampling required.
TDS	540-683 mg/L, Avg. = 624 mg/L	505-628 mg/L, Avg. = 581 mg/L	380 mg/L (from previous sampling conducted outside of this study in 2014)	Current source = 300 mg/L, maintaining a finished water TDS between 400-500 mg/L should be targeted. A slight increase (~20 mg/L) in TDS is currently measured at the PCWPF, likely due to chemical additions in the treatment process.	50% blend of current and new sources will result in acceptable TDS concentrations below the sMCL (500 mg/L). Significant blending of groundwater and alluvial wells with Source 3 may not be required depending on the consistency of TDS in Source 3. More sampling required.
Hardness	Avg. = 190 mg/L as $CaCO_3$	Avg. = 150 mg/L as $CaCO_3$	180 mg/L (from previous sampling conducted outside of this study in 2014)	Current source = 130 mg/L as $CaCO_3$. 2014-2015 downstream data had an average of 190 mg/L as $CaCO_3$ and additional sampling is recommended to verify hardness.	50% blend yields 140 or 160 mg/L as $CaCO_3$.
Ammonia	Avg. (grab) = 0.17-0.42 mg/L as N	Avg. (grab) = 0.15-0.62 mg/L as N From diurnal data, Min/Avg/Max = 0.1/2.0/3.5 mg/L	ND (from previous sampling conducted outside of this study in 2014)	Diurnal sampling was conducted in 2006 and 2016 by PCWRA with similar results. Effluent ammonia varies throughout the day with peak concentrations around 7 p.m. and a peaking factor between 1.75-2.0. Ammonia after BAC could range from 0.75-1.0 mg/L. Ammonia attenuation in Plum Creek at Source 3 is anticipated.	Ammonia concentrations will be reduced in multiple ways: attenuation in the EPC (source 3) and/or pre-settling pond, dilution with groundwater supplies, removal via nitrification in the BAC filters, and oxidation with chlorine addition (breakpoint chlorination). If Sources 1 or 2 are implemented, operational or infrastructure improvements at PCWRA should be implemented.
Iron	Avg. = 0.21 mg/L	Avg. = 0.05 mg/L	0.49 mg/L (from previous sampling conducted outside of this study in 2014)	Current source water average is 1.7 mg/L. The secondary MCL for iron is 0.3 mg/L.	Blending with either Source 1, 2 or 3 will reduce the blended raw water iron.
Manganese	Avg. = 0.14 mg/L	Avg. = 0.12 mg/L	0.049 mg/L (from previous sampling conducted outside of this study in 2014)	Current source water average is 0.34 mg/L. The secondary MCL for manganese is 0.05 mg/L.	Blending with Source 1, 2, or 3 will reduce the blended raw water manganese.
Positive hits for Inorganic Chemicals with MCLs:					
Barium	0.21 mg/L	0.062 – 0.08 mg/L	0.14 mg/L (0.11 mg/L measured in previous sampling conducted outside of this study)	MCL = 2 mg/L	With the exception of nitrate, the concentration of inorganic chemicals in both sources are well below the MCLs and action limits (AL). Continuous monitoring of nitrate at PCWRA and/or the settling pond will be required for the PCWPF Expansion Project.
Copper	ND	0.0072–0.0075 mg/L	ND-0.002 mg/L	AL= 1.3 mg/L	
Fluoride	0.81-0.89 mg/L	0.78 mg/L	1.1-1.2 mg/L	MCL = 4 mg/L	
Lead	ND – 0.0007 mg/L	ND	ND	AL = 0.015 mg/L	
Nitrate	0.44 – 0.53 mg/L	1.4 – 3.4 mg/L	0.96 mg/L	MCL = 10 mg/L	
Positive hits for Organic Chemicals with MCLs:					
Aldicarb Sulfone	0.00089 mg/L	0.0015 mg/L	ND	MCL = 2 mg/L	The concentration of these organic chemicals are well below the MCLs. However, it is important to determine the possible sources in the wastewater collection system and to eliminate through a pretreatment
Cyanide	ND	0.026 mg/L	ND	MCL = 0.2 mg/L	

Table 1. Summary of Key Water Quality Considerations

Parameter	Source 1	Source 2	Source 3	Notes	Treatment Approach
Ethylene dibromide	0.0067 mg/L	0.014 mg/L	ND	MCL = 0.05 mg/L	program. In addition, regular sampling of all organic chemicals in the future is recommended.
CECs	Many measured	Many measured	Many measured	None of these compounds are currently regulated by the USEPA.	Multiple barriers, including O_3+BAC+GAC

Note: Radionuclides were not analyzed during these sampling events. It is recommended to include these parameters in future sampling.

2.2 Blend Strategy

Depending on the new source selected for implementation, a blend of the current source waters (deep and alluvial wells) is expected to be treated at the PCWPF. The blend approach is an important part of achieving the full 6 mgd capacity due to current limitations in the return flows available to the Town from the PCWRA. Moreover, the blend will be leveraged to take advantage of water quality benefits from each source (i.e., current and new) to optimize the overall treatment and finished water quality at the PCWPF. The cycling and concentration of certain parameters (i.e., TDS) should be taken into consideration as the alluvial wells might not provide any TDS dilution depending on the TDS in EPC.

In order to avoid the need to use high pressure membranes (e.g., nanofiltration or reverse osmosis), total dissolved solids (TDS) has been initially identified as the controlling water quality parameter to define the blend ratio of water sources to be treated. Defining the acceptable finished water TDS will dictate the raw water quality blending assumptions used for the basis of design for new and existing treatment processes. Based on the water quality data, a finished water TDS between 400-500 mg/L is readily achievable with a 40-60% blend ratio of new and current source waters. To balance the various water quality factors, a 50:50 blend of new to existing source waters will be assumed in this BDR. Based on this blend, the relevant water quality parameters considered as a result of the blend strategy include:

- **TDS** – A target finished water TDS between 400-500 mg/L is recommended based on aesthetic impacts of elevated TDS. The secondary MCL (sMCL) for TDS is 500 mg/L and based on measured TDS concentrations at the various sources maintaining the finished PCWPF finished water below this threshold can be achieved with by blend 50% (or less) of current sources with the new sources. The TDS concentration of the finished water will vary with the actual TDS concentrations in the various water supplies, particularly in Sources 1 and 3 where the seasonal variability in flow can impact TDS concentrations. Since limited water quality data is available for Source 3, additional sampling is recommended to characterize the seasonal TDS concentrations in this source.
- **Hardness** – The existing PCWPF raw water hardness is approximately 130 mg/L as $CaCO_3$. The blended raw water hardness would be 140 to 160 mg/L as $CaCO_3$, depending on the source. Because the background hardness in EPC is significantly higher than the other source waters (270 mg/L as $CaCO_3$), the PCWRA outfall results in a lower blended hardness. Note that on 11/23/15, the Source 1 hardness was significantly higher (360 mg/L as $CaCO_3$) than the typical average of 190 mg/L. This sample is considered an outlier and has not been included in the average hardness calculation for Source 1, however additional sampling is recommended to demonstrate the average hardness (and resulting blended hardness) in order to determine if additional treatment is needed to address high hardness.

  Waters in the 60-120 mg/L as $CaCO_3$ range are typically considered moderately hard while 120-180 mg/L as $CaCO_3$ is considered hard water and hardness greater than 180 mg/L as $CaCO_3$ is very hard water (McGowan, 2000). Many water providers in the Denver metro area provide water in the 100-230 mg/L as $CaCO_3$ range and therefore neither source water likely warrants the implementation of chemical softening or other treatment (e.g., NF or RO). However, the Town should remain cognizant that high EPC background hardness and variability in the concentration could result in spikes in Source 1 and Source 3 which could require additional blend consideration with current sources.
- **Chloride and Sulfate** – Elevated chloride concentrations in EPC (upstream) were observed and ranged from 140-240 mg/L. This is significantly higher than the current sources, where concentrations range from 39-58 mg/L. Although the background concentration in EPC is approaching the sMCL of 250 mg/L, none of the proposed new sources exceeded 160 mg/L in the samples collected for this BDR.

Sulfate concentrations were remained well below the sMCL of 250 mg/L for all sources as well as the EPC upstream of Source 2 and were consistently in the 50-60 mg/L range throughout the sampling conducted for this BDR.

- **TOC** – The TOC concentration in the existing PCWPF source water is approximately 1 mg/L. The average TOC from the available data of Source 1 is 5.9 mg/L, 7.2 mg/L for Source 2, and 3 mg/L from Source 3. The blended raw water TOC entering the PCWPF is expected to range from 2 to 4 mg/L depending on the new source. Note that the dissolved organic carbon (DOC) concentrations were nearly identical to the TOC concentrations for each sampling event.
- **Iron/Manganese** – The existing well sources have relatively high concentrations of both iron (average of 1.7 mg/L, sMCL=0.3 mg/L) and manganese (0.34 mg/L, sMCL=0.05 mg/L)). These constituents are typically removed with pre-oxidation and flocculation/sedimentation, however the greensand filters at the PCWPF were originally designed for additional removal upstream of the MF membranes. Both of these parameters will be at lower concentrations after blending with any of the new sources and oxidation will be maintained so that iron and manganese in the filter effluent is below the sMCL concentrations.
- **Bromide** – Similar to TDS, hardness, and chloride, the background concentration of bromide in EPC is about twice the concentration of the new sources (and triple the existing sources). Elevated concentrations of bromide could impact bromate formation if not blended. Additional sampling is recommended to characterize the variability of this parameter in the selected source water.
- **Ammonia** – The ammonia concentration from the PCWRA fluctuates diurnally as well as throughout the week, with PCWRA reporting that the highest concentrations occur on Sunday/Monday and then decline throughout the week. A diurnal ammonia sampling study was conducting in January 2006 and was repeated in January 2016 (as part of this project) to demonstrate the diurnal variation of ammonia in the PCWRA outfall (Figure 1). Both sampling events showed similar results with concentrations ranging from approximately 0.4 to 3.5 mg/L and an average concentration of 2.0 mg/L. The variable ammonia concentrations and the maximum ammonia measured must be mitigated if using Source 2 in order to ensure that free chlorine disinfection is provided at PCWPF.

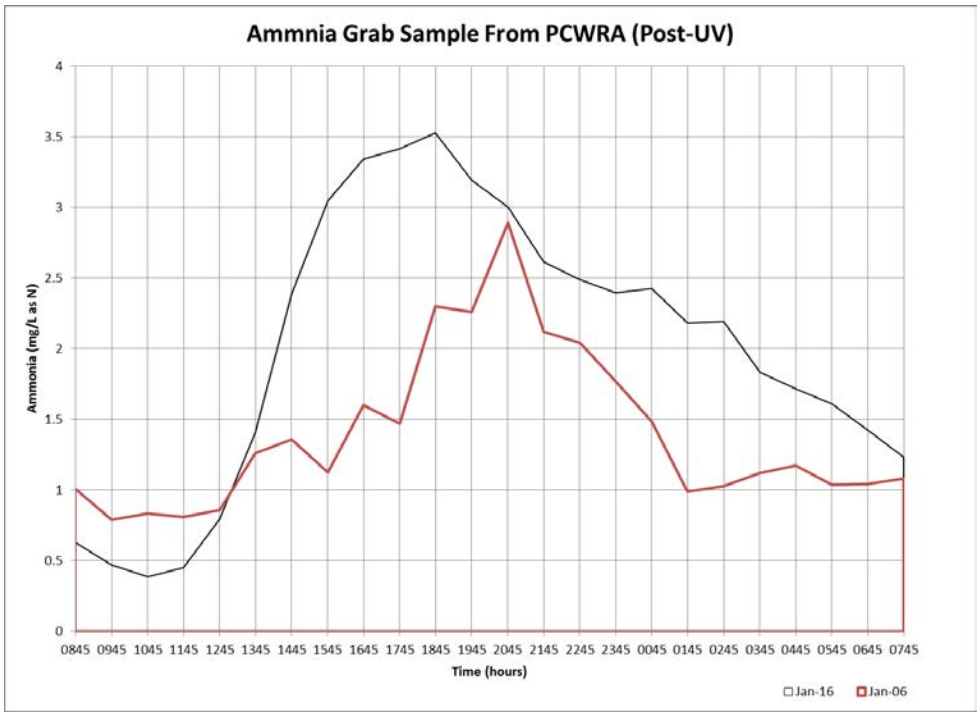


Figure 1. Diurnal Ammonia Data from PCWRA Outfall

The diversion structures for either Source 1 or 3 would include a settling pond where some nitrification and homogenization may occur. Additional nitrification of the blended water in EPC at Source 3 is expected. The current well sources have an average ammonia concentration of 0.14 mg/L, which will further blend down the ammonia concentration entering the PCWPF. Through some nitrification in the settling pond and blending with existing well sources, the PCWPF influent ammonia concentration will range between 0.9-1.2 mg/L. Nitrification in the BAC filters prior to MF membranes could range between 0-50% depending on the BAC operational parameters. The nitrification through the BAC will also rely on a relatively consistent feed concentration as the microbial community acclimates. High ammonia spikes could upset nitrification through BAC creating elevated concentrations passing through the treatment process. High chlorine doses would be required to breakpoint chlorinate and quench the residual ammonia.

- **CECs –** Many common CECs measured in sources with significant contributions of wastewater effluent were also measured in each of the new sources. Although none of these compounds are currently regulated by the USEPA, public perception can drive the need to provide treatment that addresses the removal of these compounds. Some dilution was observed by EPC flows for Sources 1 and 3, however this dilution cannot be relied on as a consistent or controlled means of mitigation. The multiple barrier treatment approach proposed in this BDR will reduce many of these parameters through a variety of treatment mechanisms (i.e., blending, oxidation, metabolization, and adsorption).

2.3 East Plum Creek Flows

Considerations for upstream water quality in the EPC play an important role in the future implementation of a diversion structure in the creek in order to utilize return flow and free river water rights. The water quality sampling conducted and background data show that there are various point and non-point discharges that impact the overall water quality in EPC. The two known point discharges in EPC upstream of Source 1 are the effluent from the Perry Park Water and Sanitation District's Sageport WWTP (permitted for 0.1 mgd capacity with discharge to EPC in the area of the Bear Dance Golf Course) and the United Water and Sanitation District wells (i.e., Bell Mountain Ranch Wells). Note that the Waucodah WWTP is also owned by the Perry Park Water and Sanitation District (permitted for 0.32 mgd) but discharges to West Plum Creek.

The United Water and Sanitation District (UW&SD) discharges deep ground water from three wells located in Bell Mountain Ranch into EPC in order to recapture water rights from EPC at the diversion in Sedalia (Source 3). Monthly flow data from the UW&SD well is only available from 2004-2013. This flow data has been overlaid with EPC flow data from 2013-2015 (Figure 2). In 2013, there were two months with no well flow and other months with no flow from two of the three wells. In peak months, the wells are capable of delivering over 100 acre-ft (32.6 MG/month). There was no flow reported in December 2015 or January 2016 from the UW&SD wells.

Flow from the Bell Mountain Ranch wells is sporadic and the Town of Castle Rock has no control over the operation of the wells. With the only overlap in 2013, it can be seen that the contribution of flow from the UW&SD well is typically less than 20 percent of the total flow in EPC. Although the contribution of the well water improves the overall quality of EPC, this flow is not a reliable source for water quality improvement by dilution of the PCWRA outfall at the location of Source 1 or Source 3.

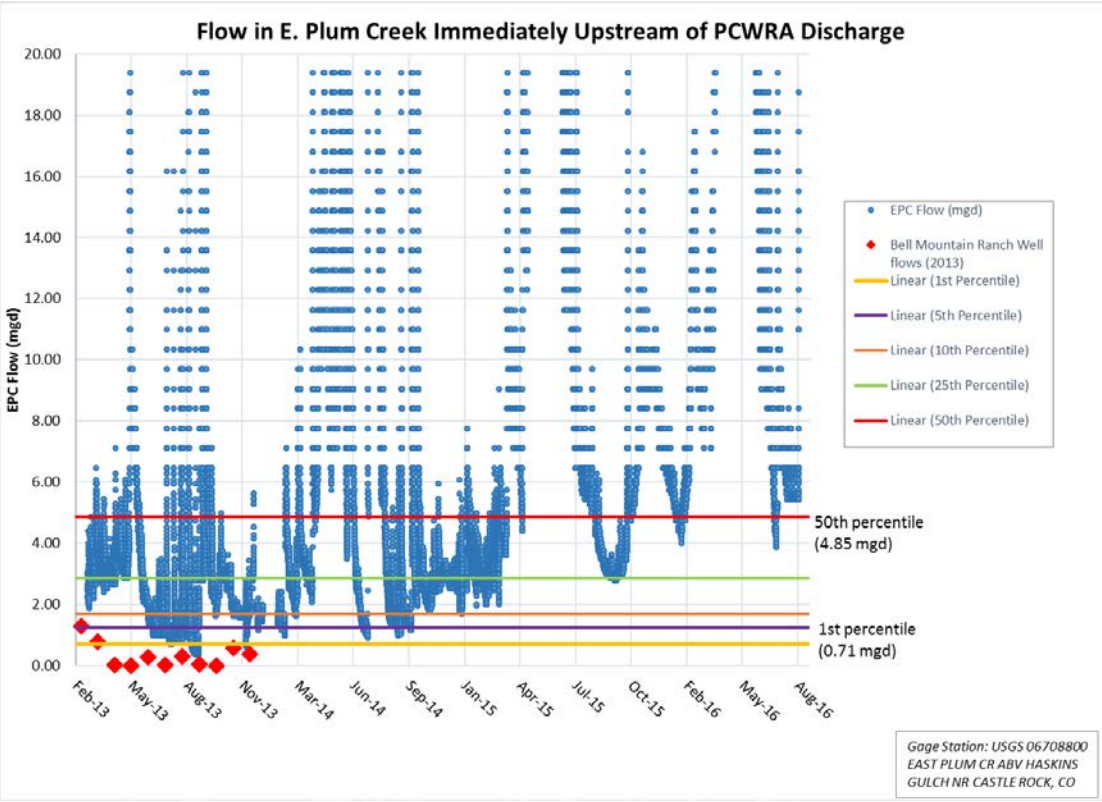


Figure 2. EPC and Bell Mountain Ranch Flow Data

3.0 Advanced Treatment Selection

A large number of treatment technologies available for a multiple barrier treatment approach were evaluated for the PCWPF Expansion with the focus on utilizing and building around the existing treatment processes to maximize the efficiency and operational flexibility of new treatment. Some technologies such as reverse osmosis (RO) were initially explored but quickly eliminated due to the costs (both capital and life cycle) of treatment and brine disposal.

The current flocculation/sedimentation, greensand filters, and microfiltration membranes are a robust treatment combination that will be utilized in conjunction with additional treatment processes to address the treatment and/or removal of CECs, pathogens, organics, and meet SDWA requirements. The proposed modifications to the existing treatment process include Pre-Ozone, Biologically Active Carbon (BAC) filtration, Ozone disinfection, Granular Activated Carbon (GAC) adsorption, and UV disinfection. The incorporation of these treatment processes into the facility are shown in the updated process flow diagram (PFD) (Figure 3), but the final combination of treatment processes (new and modified) is ultimately dependent on the selected source to be treated at the PCWPF.

The multiple barrier treatment process addresses a range of CECs present in the source waters through a variety of treatment mechanisms including advanced oxidation (ozone), coagulation and sedimentation (existing process), biological removal (BAC), and adsorption (GAC). Each of the new processes is described in greater detail herein.

Improvements to the existing solids handling process may be necessary to address ongoing concerns with the discharge of solids to PCWRA. Since PCWRA effluent constitute a significant proportion of the source water supply, recycling (and potentially increasing the concentration) of contaminants in the overall water system could eventually impair the ability of the PCWPF to maintain acceptable treatment. In addition, more solids will be generated from the PCWPF which will impact the ability for PCWRA to

handle the quantity of solids from the PCWPF. Evaluation of the solids handling process is beyond the scope of this study.

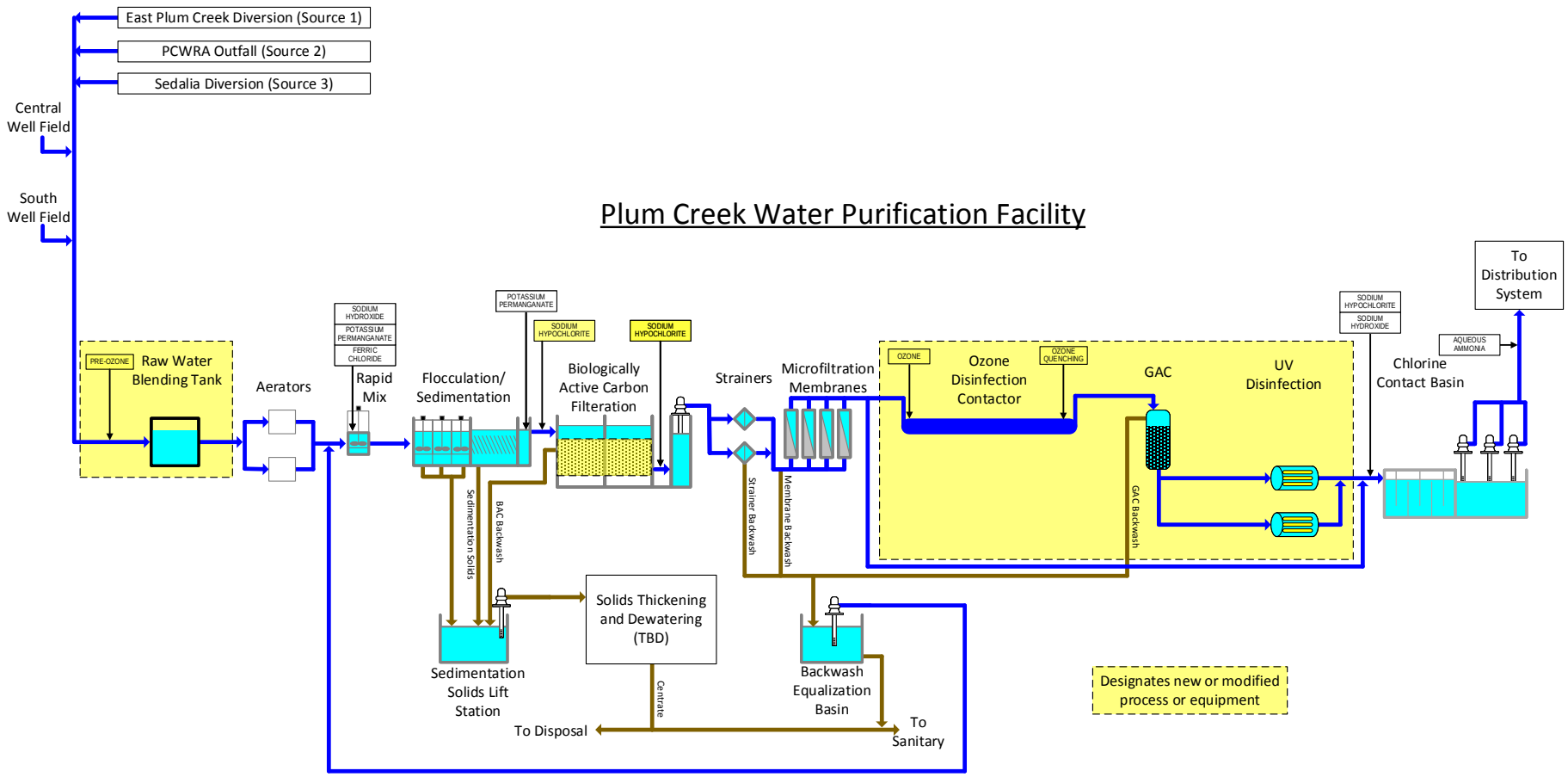


Figure 3. PCWPF updated Process Flow Diagram

3.1 Ozone

Ozone is a powerful oxidant with numerous treatment benefits including the oxidation of CECs, oxidation of complex organic matter to form more biodegradable compounds, reduction in color, improved downstream filter or membrane performance (reduced fouling), and disinfection credit for pathogens. Because of its many benefits, the use of ozone is widely accepted in a variety of potable water treatment applications. For the PCWPF, there are multiple ozone application points that balance the benefit to water quality, impact on downstream process(es), and the resulting size (and cost) of the ozone system. Bench top testing for the ozone demand and decay characteristics at the various application points was critical to estimate the size of the ozone system required as well as determining the possible formation of byproducts, such as bromate and n-nitrosodimethylamine (NDMA).

A contact time of approximately 60 seconds is sufficient when ozone is applied at sub-residual doses for oxidation of organics. The proposed application point at PCWPF is the blended raw water due to the physical configuration of the flocculation/sedimentation basin and the filters. A sub-residual dose of ozone applied at the Raw Water Blending Tank will allow for ozone contact to occur upstream of the existing aerators. Since the TOC of the blended water will be highest at this point, the sub-residual dose will serve as a preliminary oxidation step to support downstream TOC removal (i.e., in flocculation/sedimentation) and biological degradation (in biological filtration). For potable reuse applications, ozone is typically dosed at an ozone to TOC ratio between 0.5-1.5 to break down organics and CECs. The results of the bench testing for this treatment step (as described in Appendix B) demonstrated that an ozone to TOC ratio of 0.5 was successful at breaking down organics without excessive formation of bromate and NDMA.

A secondary ozone application point is also included upstream of the GAC contactors for disinfection as well as additional oxidation of CECs. At this point in the process, TOC will have been significantly reduced through floc/sed and BAC and therefore an ozone residual can be achieved at a reasonable dosage to achieve additional disinfection credits for the overall treatment process, as demonstrated at in bench testing. For example, a CT of 1 mg/L-min would provide 3 log virus and 1.5 log *Giardia* disinfection credit (at 5 deg. C). The downstream pressure available from the membranes would allow the pipeline contactor to be fit in either upstream or downstream of the GAC contactors.

The use of ozone at multiple application points will efficiently and effectively make use of this chemical. The raw water application point is a critical pre-oxidation step prior to biofiltration. Ozone disinfection upstream of GAC is preferred since any biodegradable organic carbon created from the ozone will be removed by the GAC. Bromate formation potential is reduced due to average bromide concentrations less than 0.15 mg/L and pH in the range of 6.5-7.5. Bench testing indicated that bromate and NDMA formation was within acceptable levels.

Ozone residual can be adjusted based on the disinfection target, impacting the residual at the end of the contactor. Since a short contact time is targeted due to site space limitations, quenching of the ozone residual prior to GAC must be included. Sodium bisulfite is a common ozone quenching agent that rapidly reacts with ozone in a 2.2:1 (sodium bisulfite to ozone) ratio. Other chemicals such as hydrogen peroxide may also be utilized for ozone quenching. Although hydrogen peroxide requires a lower dose ratio (0.6:1), the actual ratio required may vary based on pH and the presence of scavenger ions. In addition, hydrogen peroxide is an expensive and hazardous chemical and therefore sodium bisulfite is initially recommended for ozone residual quenching. Pilot testing is recommended to determine the ozone to sodium bisulfite ratio as well as to periodically check the formation of bromate and NDMA based on the variability of source water characteristics and treatment. Table 2 summarizes some of the key ozone system design assumptions.

Table 2. Ozone System Design Criteria Summary Table

Item	Units	Value	Notes
Maximum Plant Flow	mgd	6	Expandable to 12 MGD
Raw Water Feed Point[1]			
TOC	mg/L	4.0	Assumes 50% blending of Source 2 and existing supplies.
Nitrite	mg/L	0.1	
Ozone Dose	mg/L	2.0	Based on bench testing results the optimal ratio was approximately 0.5:1 O3:DOC ratio.
Ozone Feed Rate	lb/d	100	At 6 mgd
Post-Membrane Feed Point			
Post-BAC TOC	mg/L	3.0	Assumes approximately 15% reduction through BAC.
Target Ozone Residual	mg/L	1.8	To provide 0.7 to 1.0 mg-min/L CT
Ozone Dose	mg/L	3.0	Based on bench testing results to maintain a 1.85 mg/L residual.
Ozone Feed Rate (lb/d)	lb/d	150	Used for system sizing purposes
Contact Time	min	0.5	To achieve a CT of approximately 1 mg/L-min
General System Components			
LOX Storage Tank[2]	gal	3,000	Provides 15 days of storage at 250 lb/d usage
Ozone generator maximum capacity	lb/d	250	Generators have a 50:1 turndown capacity
Number of generators	#	2	1 duty and 1 standby
Power	kW	105	Maximum power draw for one generator
Sodium bisulfite dose	mg/L	2.5	Theoretical ratio is 2.2
Sodium bisulfite storage	gallons	1,600	For 30 days of storage at maximum dose and average flow

[1]The ozone design criteria are based on the bench testing results for the 50:50 blend of Source 2 and current sources.

[2]It is common to only provide a single LOX tank and storage capacity between 15-30 days. This is a readily available chemical locally and due to cryogenic storage considerations, it is important to not store excessive amounts of LOX.

3.2 Raw Water Blending Tank

A 1.0 million gallon Raw Water Blending Tank has been added at the beginning of the treatment process to provide mixing of the various source waters to be treated at the PCWPF. This volume will provide four hours of hydraulic retention time at the maximum plant flow rate of 6 mgd. This engineered buffer will provide homogenization of the sources as well as time for operators to respond to water quality deviations or process upsets that would require intervention or diversion. A small concrete structure will be added immediately upstream of the tank to provide a point for pre-ozone application.

3.3 Aeration, Rapid Mix, Flocculation, and Sedimentation

The existing aerators and rapid mix were not evaluated as part of this BDR. The existing flocculation and sedimentation process at PCWPF consists of a single train rated at 6 mgd and therefore no mechanical or structural modifications are required for this process as part of the facility upgrades. Bench testing was conducted to determine coagulant dose and optimal pH conditions for TOC removal of the 50:50 blend of Source 2 and the current sources. Based on the bench testing, a ferric chloride dose of 60 mg/L without supplemental pH depression was selected for this pre-treatment process. Reference the bench testing results in the Appendix for coagulant doses tested.

3.4 Biologically Active Carbon Filtration

Retrofitting the PCWPF existing greensand filters to accommodate BAC filtration will provide multiple benefits including removal of some CECs as well as additional TOC and ammonia removal. Properly designed biological filters are also excellent particle and pathogen barriers, provided they are designed and operated to produce low filter effluent turbidity. The implementation of BAC filtration is a growing practice for potable water and potable reuse treatment because of these many benefits. Utilizing GAC for the biological filter media, as opposed to other filter media, is common to maximize biological growth on the filter media. Numerous drinking water facilities have implemented BAC as an alternative to conventional filtration with anthracite. The BAC for the PCWPF is proposed to accomplish the following treatment goals:

- **Organics removal** – this includes TOC, DBP precursors, and taste and odor compounds.
- **CECs** – Biofiltration can be an important barrier in a multi-faceted treatment approach for CEC management.
- **Ammonia removal** – nitrification can be expected from aerobic biological filters. The removal of ammonia will depend on the variations in influent ammonia concentration and spikes in ammonia may not be well removed. Bench testing does not gauge the response to fluctuations in the influent ammonia concentration and the removal of ammonia should be monitored during pilot testing and/or at full scale.
- **Turbidity and particle removal** – The relationship of filter media particle size and bed depth (L/D) should be at least 1,000-1,200 (or higher) for a dual media filter designed for particle removal efficiency. In order to receive pathogen removal credit, the filters must operate with turbidity less than 0.3 NTU greater than 95 percent of the time and never above 1 NTU. The use of filter to waste is an important operational tool to ensure that the filter effluent turbidity thresholds are not exceeded for treated flow passing downstream. Although most of the existing media will be replaced with GAC, a 6-9 inch layer of the greensand will be maintained as an additional particle barrier.
- **Iron and manganese** – The majority of iron and manganese is currently removed through the flocculation/sedimentation process (in conjunction with pre-oxidation). Although the blended source water will be much lower in iron and manganese concentrations than the current sources, the existing treatment approach of pre-oxidation and removal through sedimentation will be maintained. Low levels of particulate iron or manganese may also be removed through the BAC filters similar to current operations.

Utilizing ozone upstream of BAC has synergistic benefits as the ozone oxidizes many compounds and contaminants in the water into biodegradable organic compounds that are more readily metabolized through the filter. In addition to ozone, oxidants such as potassium permanganate and even low doses

of chlorine have proven to enhance the performance of biofilters. The use of pre-oxidation upstream of biofilters is also important to control excessive biofilm on the BAC. A potassium permanganate addition point is available in the sedimentation collection channel and a sodium hypochlorite addition point will also be considered in this location. Sodium hypochlorite addition to the filter effluent (for backwash supply and upstream of the membranes) should also be implemented as operational tools.

In order to efficiently utilize the existing greensand filter infrastructure, replacement of the top two feet of media (6 inches of anthracite and 1.5 feet of sand) with 3.5 feet of GAC, which will provide approximately 6.5 minutes of empty bed contact time (EBCT), at 6 mgd and all 4 filters online. This will raise the top of the media by 1.5 feet and will require raising the backwash troughs 9 inches. With this media configuration, WesTech has confirmed that the backwash troughs may be raised without impacting hydraulics for filtration or backwashing. Since the GAC has a much lower specific gravity than sand (or anthracite) position control must be added to the effluent control valves to control the backwash flow. This will also allow for low and high rate backwash for the GAC media. WesTech has also confirmed that the existing nozzle/plenum underdrain assembly in these filters is well suited for biological filtration. In fact, the equipment installed at the PCWPF is what the vendor recommends for tertiary wastewater treatment applications.

EBCTs between 4 to 5 minutes in biofilters have been demonstrated to achieve 80 to 95 percent of the biological treatment that will occur in a BAC process. If only 2 feet of GAC was installed (requiring no modifications to the backwash troughs) the EBCT would be 3.7 minutes. Figure 4 depicts a study where detention times of 10 to 40 minutes were evaluated with only marginal improvement in effluent quality at the O3:TOC ratios relevant in this project. Calculated removals of the biodegradable fraction of TOC in the biofilters with an EBCT of 4 minutes ranged from 88 to 97 percent. Increasing the EBCT to 10 or 20 minutes resulted in increases in the calculated biodegradable TOC removal of 3 to 12 percent (Bouwer, 1995). However, removal of certain classes of compounds of emerging concern, taste and odor compounds or other secondary substrates may be significantly increased at longer EBCTs (i.e., greater than 5 minutes).

Carlson (1996) observed approximately the same results. An EBCT of 5 minutes was capable of removing greater than 80 percent of the biodegradable portion of the DOC. For an aerobic biological drinking water filter, a 5-minute EBCT is typically considered to be optimal from a treatment and cost efficiency standpoint.

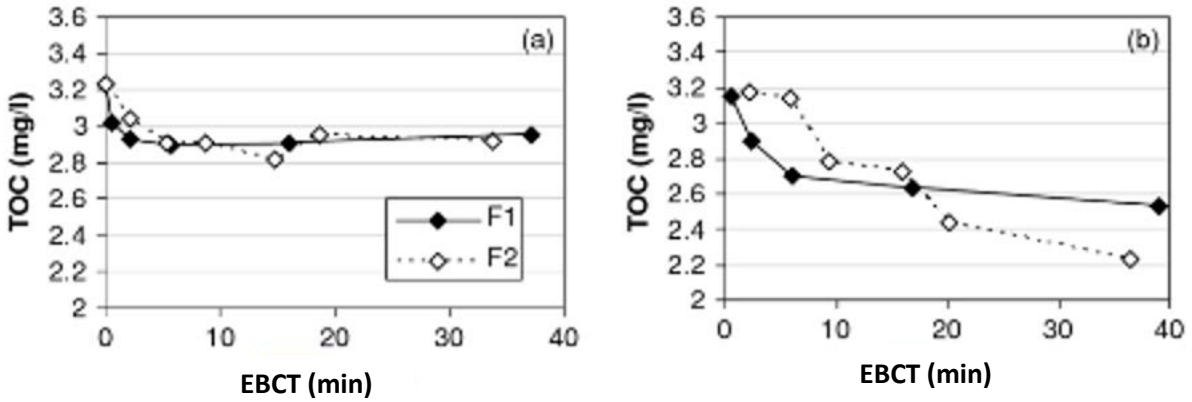


Figure 4. TOC Removal profiles in biofilters with ozone does of 0.36 mg O_3/mg TOC (a) and 1.6 mg O_3/mg TOC (b) (Melin and Odegaard, 2006).

After an initial adsorption period (likely less than three to six months), the GAC will lose its adsorptive capacity for TOC; however, in a much shorter period of time, the biological community will become established for removal of the water quality parameters previously discussed. Table 3 summarizes the design assumptions for the BAC filter modifications.

Table 3. BAC Filter Modifications Design Criteria Summary Table

Item	Units	Value	Notes
Filter Cell Size	Sf	256	
Number of Filter Cells	#	4	
Filter Loading Rate[1]	gpm/sf	5.42	At 6 mgd and one filter in backwash (firm capacity)
Max Treatment Capacity	mgd	6.45	With all filters in service (from WesTech)
Firm Treatment Capacity	mgd	4.84	With 1 filter out of service (from WesTech)
GAC Media Depth	ft	3.5	Approximately 1.2 mm GAC
Sand Media Depth	ft	0.5	Existing 0.45-0.55 mm sand
Empty Bed Contact Time	min	6.5	For GAC media only
L/D	mm/mm	1,200	1,000-1,200 is necessary for proper particle removal
Backwash Rate (maximum)	gpm/sf	20	Will vary based on water temperature and differential level between the effluent weir and the backwash trough
GAC Media Expansion During Backwash	%	20-30%	This equates to 0.7 to 1.1 ft of expansion at high water temperature.

[1]CDPHE requires approval and pilot or full scale demonstration for filter loading rates over 5 gpm/sf.

3.5 Microfiltration

Wastewater influenced water supplies are typically more fouling of microfiltration (MF) membranes due to high concentrations of organic matter present in the wastewater. Ozone addition upstream of MF has been shown to reduce fouling of MF membranes and improve overall performance. The effectiveness of regular maintenance cleans and CIPs should also be carefully monitored during plant startup to determine if modifications are necessary.

3.6 Granular Activated Carbon Adsorption

GAC adsorption is an effective treatment barrier that removes DOC as well as trace organics. GAC contactors require periodic removal and replacement of the media to maintain the adsorptive capacity of the GAC. The frequency of GAC replacement varies depending on the inlet water quality (upstream treatment), design parameters (i.e., type of GAC, empty bed contact time), treated flows, and finished water quality goals. The implementation of vertical pressure contactors is common for this type of application as they will allow for a smaller footprint, streamlined piping and valve configuration, and facilitate media replacement. Additionally, because the vessels are closed, they will prevent the need for installation of an intermediate pump station as the residual piping pressure downstream of the MF system can be used to drive the water through the GAC vessels. Another benefit of using this proposed design is that the residual pressure in online vessels can be utilized to backwash other vessels, eliminating the need for an addition backwash supply pump station. Due to the minimal solids removed from this process, backwashing will be infrequent and the backwash waste can be sent to the existing Backwash Equalization Tank, where it will be returned to the head of the treatment process.

The GAC regeneration frequency is estimated to range between 30,000 and 60,000 bed volumes depending on the EBCT selected. At an annual average daily flow of 4.5 mgd, 30,000 bed volumes equates to GAC replacement every 1. 5 years. The replacement frequency will ultimately be determined during operations based on the indicator compound(s) selected.

Table 4. GAC Contactors Design Criteria Summary Table

Item	Units	Value	Notes
Vessel size	Sf	113	12 foot diameter vessels
Number of Vessels	#	8	
Empty Bed Contact Time	min	15	10-20 minutes is typical for this application
Loading Rate	gpm/sf	5	
GAC Media Depth	ft	9.25	GAC vessel height will be approximately 13 ft.
Height of Vessels	ft	13	
Backwash rate	gpm/sf	8-12	Backwash flow from online contactors

3.7 UV Disinfection

The use of Ultraviolet (UV) technology can be implemented for either disinfection at low doses or as part of an advanced oxidation process (UVAOP) at high dose with the addition of an oxidant (i.e., hydrogen peroxide, ozone, or chlorine at low pH). UVAOP is a common technology in potable reuse treatment and is effective at destroying a number of CECs, trace organics, and other compounds (particularly nitrosamines such as NDMA) as well as inactivating pathogens. UVAOP is almost always used in conjunction with other treatment technologies as part of a multiple-barrier treatment approach, mainly because it does not provide a physical removal barrier. Although UVAOP is an accepted reuse treatment technology, it is often not the most cost-effective approach if NDMA is not a target compound of concern in the source water. Limited historical water quality data (2 samples) has shown less than 10 ng/L of NDMA in Source 2. After blending of the source waters during bench testing, all nitrosamines were measured at or below 2 ng/L. Due to the lack of data available for these compounds, additional sampling for nitrosamines is recommend for the selected new source.

For the PCWPF Expansion, a UV disinfection system designed at a validated dose of 58 mJ/cm^2 is recommended to provide 1 log virus and >4 log *Cryptosporidium* and *Giardia* inactivation. This dose is significantly less than the typical UVAOP dose range of 750-1,250 mJ/cm^2. Utilizing UV for disinfection will provide a broad pathogen barrier as shown in Figure 5, which coupled with the other pathogen removal and inactivation processes will provide robust disinfection for any source water blend option.

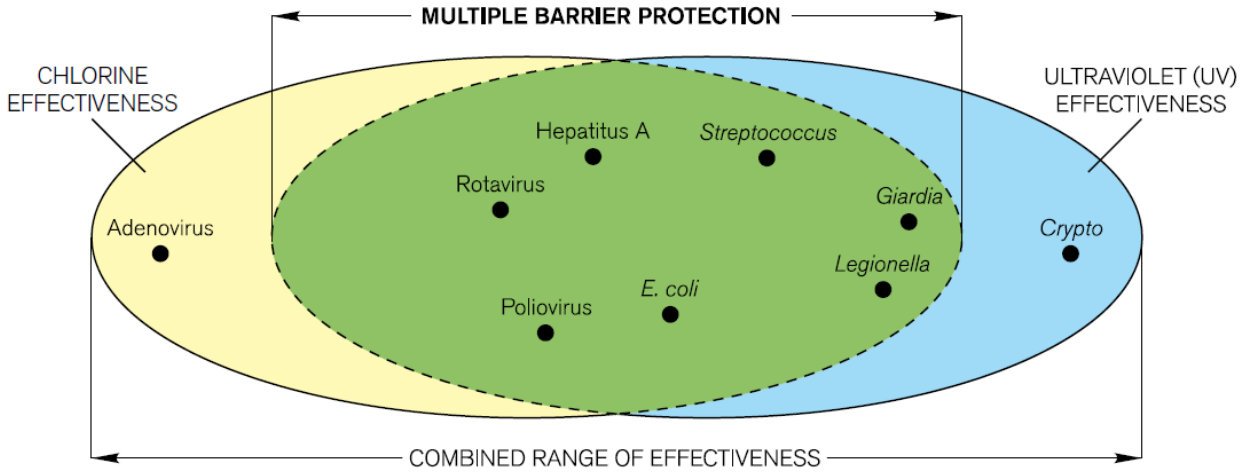


Figure 5. (Trojan Technologies)

Table 5. UV Design Criteria Summary Table

Item	Units	Value	Notes
Design UVT	%	95	Bench testing UVT for column 2 (15 min EBCT) demonstrated 98% UVT after 30,000 bed volumes. Selected 95% for design basis.
Number of Vessels	#	2	1 duty and 1 standby
Number of Lamps/Vessel	#	4-24	Number of lamps vary for each manufacturer
Validated Dose	mJ/cm^2	58	Low or medium pressure lamps
Disinfection credit	logs	1/4/4	Virus/*Cryptosporidium/Giardia*
Maximum Headloss	ft	<0.5	Actual headloss depends on selected vendor and actual flow rate

Note: Vendors contacted include Xylem, Trojan, Calgon, and Ozonia

3.8 Chlorine Disinfection

The existing chlorine contact basin (CCB) has been permitted to provide 4 log virus credit with a 0.28 mg/L free chlorine residual at the finished water pump station clearwell. To maintain this level of disinfection, a minimum CT of 12 mg/L-min must be maintained at a temperature of 0.5 deg. C and pH between 6-9.

3.9 Chemical Systems

The chemical storage and feed systems at the PCWPF were not evaluated in detail as part of this BDR and should be further analyzed during Preliminary Design. Based on the ferric chloride and sodium hypochlorite doses determined during the bench testing, more than 30 days of storage is currently available at the maximum dose and maximum flow conditions. The actual dose range will greatly dependent on the source water blend treated and chemical storage should be evaluated in the future when the PCWPF will ultimately expand to treat 12 mgd (buildout).

3.10 Regulatory Considerations and Pathogen Log Summary

In addition to the non-regulated CECs, regulated water quality parameters, as determined by the SDWA were analyzed as part of the water quality characterization and treatment selection process. Meeting

the finished water requirements of the SDWA as well as supplemental requirements from CDPHE are a critical success factor for the PCWPF. Additional TOC removal may also be required for compliance with disinfection byproduct requirements. If Source 2 is utilized, the PCWPF Expansion could set the stage for future projects of this kind in Colorado, therefore, leveraging established water reuse regulations in other states (e.g., California, Texas, and Florida) was used as a basis for regulatory treatment drivers.

Regardless of the new source option selected, a multiple barrier approach to organics and pathogen removal is the fundamental basis for the treatment approach for the PCWPF expansion. Pathogen credit is cumulative across each process. The Surface Water Treatment Rule (SWTR) dictates additional *Cryptosporidium* log removal requirements based on Bin Classification. CDPHE has indicated that the Source 2 would be classified as Bin 4 if it were used as a water supply for PCWPF. As a result, it would require an additional 2.5 log treatment for *Cryptosporidium*. CDPHE has not commented on the bin classification for Sources 1 or 3, and additional characterization may be necessary if either of these source options is implemented. Regardless of the new source selected for implementation, the significant change in source water characteristics for the PCWPF will require modifications to the existing permit which gives the Town the opportunity to renegotiate pathogen credits for the new and existing treatment processes (i.e., floc/sed/filtration, MF membranes, ozone) as well as conditions for the disinfection credit applied to the CCB.

In additional to targeting *Cryptosporidium* for pathogen treatment, virus and *Giardia* treatment is incorporated as part of the PCWPF Expansion treatment process as these are pathogens that must be factored into the treatment process. The precedent for pathogen requirements has been established by the Texas Commission of Environmental Quality (TCEQ) for direct potable reuse projects, which CDPHE has suggested they might follow for a direct potable reuse application in Colorado. The TCEQ requires a minimum of 8/5.5/6 log for virus/*Cryptosporidium*/*Giardia* log removal. The California Department of Public Health (CDPH) requires 12/10/10 disinfection for indirect potable reuse projects utilizing direct groundwater injection.

Table 6 summarizes the pathogen removal proposed for this project compared to the SWTR and Table 7 summarizes the pathogen removal compared to other potable reuse regulatory criteria. Note that Table 6 assumes that the BAC system would be operated as contactors without specific turbidity goals whereas Table 7 assumes that the BAC system would be operated as filters producing a filter effluent turbidity of less than 0.3 NTU. These assumptions result in different pathogen log reduction credits. Review of Tables 6 and 7 show that the proposed treatment process will exceed the current USEPA and TCEQ requirements for pathogen treatment.

Table 6. Pathogen Removal Summary to Address SWTR

Process	Virus	Cryptosporidium	Giardia
Ozone (sub-residual oxidation)	0	0	0
BAC contactors[1]	0	0	0
MF[2]	0	3	3
Ozone (disinfection)[3]	3	0	1.5
GAC	0	0	0
UV disinfection[4]	1	4	4
Chlorine disinfection	4	0	0[5]
PCWPF Total	**8**	**7**	**8.5**
SWTR/LT2ESWTR (Bin 4 classification)	4	5.5	3

[1]In this scenario, the BAC would not be classified as filters and no disinfection credit would be accounted for based on their performance.

[2]Based on CDPHE letter to Pall Membranes for the Microza microfiltration membranes used as an alternative filtration technology.

[3]Achieved with CT of 1 mg/L-min at 5 deg C.

[4]It is possible to put reactors in series and add log removal credits.
[5]CCBs with 4 log virus are often capable of also receiving 0.5 log Giardia credit.

Table 7. Pathogen Removal Summary for Potable Reuse

Process	Virus	Cryptosporidium	Giardia
Ozone (sub-residual oxidation)	0	0	0
Floc/sed/BAC	2	3[1]	2.5
MF[2]	0	3	3
Ozone (disinfection)[3]	3	0	1.5
GAC	0	0	0
UV disinfection[4]	1	4	4
Chlorine disinfection	4	0	0
PCWPF Total	**10**	**10**	**11**
TCEQ[5]	8	5.5	6

[1]3-log credit is granted when the combined filter effluent turbidity is less than 0.3 NTU at least 95% of the time; the combined filter effluent turbidity must be less than 0.15 NTU 95% of the time for an extra 0.5 log Crypto credit for individual filter effluent and another 0.5 log credit for combined filter effluent (up to 4.0 log total).
[2]Based on CDPHE letter to Pall Membranes for the Microza microfiltration membranes used as an alternative filtration technology.
[3]Achieved with CT of 1 mg/L-min at 5 deg C.
[4]It is possible to put reactors in series and add log removal credits.
[5]The Big Spring Direct Potable Reuse Project (Texas) is permitted for 8, 15, and 15 log removal for viruses, *Cryptosporidium*, and *Giardia*, respectively.

4.0 Electrical System Analysis

The evaluation of the existing electrical system and standby generator was conducted in conjunction with the determination of the treatment alternative recommendations to size a new generator capable of powering all necessary processes at the PCWPF at the design flow rate of 6 mgd. Many of the recommended treatment alternatives (i.e., BAC retrofit and GAC contactors) have a minimal impact on the size of the standby power required for the PCWPF while other systems such as ozone and UV represent relatively large power consumption. The existing 480V distribution system at the PCWPF includes a 500 kW standby engine-generator set. The plant infrastructure, including the main switchboard (SWBD1), the automatic transfer switch, and the power distribution switchboard (SWBD2) are all capable of handling up to approximately 2000 kW (2500kVA at 0.8 power factor). Table 8 summarizes the existing loads as depicted in the facility one-line diagrams prepared by Burns & McDonnell in July 2013.

Table 8. Existing Electrical Load Summary

Equipment ID	Rating	Duty	Standby	AFD (Y/N)
PC-MFP-2010	75HP		X	YES
PC-MFP-2020	150HP	X		YES
PC-MFP-2030	150HP	X		YES
RC-RFP-2312	20HP	X		YES
PC-CIP-5730	10HP	X		NO
PC-CIP-5740	10HP		X	NO

Table 8. Existing Electrical Load Summary

Equipment ID	Rating	Duty	Standby	AFD (Y/N)
PC-CDP-5751	10HP	X		NO
PC-CDP-6009	10HP	X		NO
PC-HTR-5719	65KW	X		NO
PC-HTR-5706	65KW	X		NO
PC-BRP-4010	5HP	X		YES
PC-BRP-4020	5HP		X	YES
PC-HSP-3100	150HP		X	YES
PC-HSP-3200	250HP	X		YES
PC-HSP-3300	250HP	X		YES
FLOCCULATORS (LUMPED LOAD)	10HP	X		YES
PC-MMX-1070	25HP	X		YES
GS FILTER BLOWER	40HP	X		NO
PANELBOARDS	220KVA	X		NO

Note: Based on Conformed Documents Facility one-line diagrams.

4.1 New Loads and Generator Capacity Sizing

The new treatment processes for the PCWPF system will add the following loads to the existing system:

Table 9. Existing Electrical Load Summary

Equipment	Rating	AFD (Y/N)
Ozone System	110 kW, 0.9 PF	Yes
UV Disinfection	20 kW, 0.85 PF	Yes
Solids Thickening and Dewatering	125 HP	Yes

Note: Assumes gravity thickener, sludge feed pumps, and mechanical dewatering.

Electrical calculations for the recommended processes for the PCWPF Expansion would require a new 1,250 kW standby generator. At this size, the performance of a turbocharged diesel engine does not diminish substantially when operated in hot temperatures (i.e., 100 deg. F) at an elevation of 6,200 feet and therefore the 1,250 kW of generator capacity is sufficient to run all processes at the PCWPF at 6 mgd.

Generator manufacturers provide software to select an engine/generator combination based on user-provided information on loads and operating conditions. Motors powered by AC drives (both existing and new) were modeled as 18-pulse drives to account for the harmonic-cancelling effect of the harmonic control unit (HCU) at SWBD2. The new generator would replace the existing, undersized, generator. Similar to the existing generator, the new unit would be provided in a weather-protective, sound-attenuating enclosure and will fit on the existing generator pad.

5.0 Opinion of Cost

This cost estimate is based on a conceptual level of development for all project components to accommodate the treatment of Source 2 blended with current supplies. Treatment of Source 1 or 3 could impact the operational approach to pathogens, organics, and CECs, however it is assumed that all treatment processes outlined in this BDR would be constructed as part of the PCWPF Expansion. Solids handling equipment was outside of the scope of this project and is not included in this BDR. The project elements included in the cost estimate include:

- Raw Water Blending Tank
- Ozone system
- BAC filter conversion
- GAC contactors
- UV Disinfection System
- Standby Generator

A Class 4 Cost Estimate, as defined by the Association for the Advancement of Cost Engineering International (AACE-International), was developed for the PCWPF Expansion project. The accuracy range for the estimate is -30 percent on the low side and +50 percent on the high side. Many of the project elements are derived from vendor quotations based on the design criteria and assumptions presented in this BDR. Since detailed evaluations or comparisons of the various systems were not performed, engineering judgment was applied to balance differences in equipment costs from the vendors.

The final costs of the project will depend on actual labor and material costs, competitive market conditions, actual site conditions, final project scope, implementation schedule, and other variable factors. Because of these factors, project feasibility, benefit/cost ratios, risks, and funding needs must be carefully reviewed prior to making specific financial decisions or establishing project budgets to help ensure proper project evaluation and adequate funding.

Cost allowances were added to the estimate to cover costs of miscellaneous construction items that could not be reasonably estimated at this time (i.e., site work, SCADA modifications, yard piping, and yard electrical). Also included in the estimate are contractor markups (overhead, profit, mobilization, demobilization, bonds, and insurance) and overall project contingency. The costs presented in Table 10 were compiled in January and February 2016 and escalated to July 2017. Equipment is subject to vendor price adjustments, at their discretion at the time of Bid. The following is a summary of the construction cost estimate.

Table 10. PCWPF Construction Cost Estimate

Treatment Process	Installed Cost	Notes
Raw Water Blending Tank	$1,100,000	1 MG tank will provide a minimum of 4 hour detention time (at 6 mgd). Includes an ozone feed point at the entry to the tank and mixing to even out variability in source water supplies.
Ozone	$3,670,000	250 lb/d system enclosed in a building; includes duty/standby ozone generators, power supply units, cooling water loop, destruct units, analyzers, as well as a 3,000 gallon LOX storage tank and vaporizer system located outside the facility.
BAC Filter Conversion	$290,000	Replacement of media with GAC, includes media handling and disposal as well as resetting of the backwash trough elevation and effluent valve modulation.
GAC Contactors	$3,800,000	Eight 12-foot diameter vessels including GAC media and interconnecting piping and valves housed within a new facility.

Table 10. PCWPF Construction Cost Estimate

Treatment Process	Installed Cost	Notes
UV Disinfection	$1,510,000	1 duty and 1 standby reactor and electrical gear located in a building
Standby Generator	$800,000	New, stand-alone unit located outside in a sound attenuating enclosure
Miscellaneous Construction	$1,140,000	Sitework, SCADA modifications, yard piping, and yard electrical
Sub-Total	$12,490,000	Procurement and installation of all equipment and materials
Contractor Markups (20%)	$2,460,000	Includes overhead, profit, bonds, insurance, and mobilization applied to the sub-total of construction costs.
Contingency (30%)	$4,425,000	Contingency was applied to the subtotal of Construction Costs, plus contractor markups for the cumulative project components based on this conceptual level design. Contingency has been included in this cost estimate as a provision for unforeseeable, additional costs within the general bounds of the project scope, particularly where previous experience has shown that unforeseeable events that will increase costs are likely to occur. The contingency is used as a means to reduce the risk of possible cost overruns.
Escalation	$1,145,00	Escalation to the midpoint of construction.
Total PCWPF Expansion Construction Cost	$20,320,000	This includes all project components discussed in this BDR. It does not include engineering, permitting, commissioning, or services during construction.

Note: Construction cost estimate does not include solids handling facilities, if necessary.

5.1 Other Project Costs

Costs associated with Permitting, Engineering Design Fees, Services During Construction, Commissioning and Startup, and Legal/Admin are not included in the construction cost estimate. Other project elements such as the EPC diversion structure, settling pond, pump station, or the new source pipeline to the PCWPF are not included in the cost of construction. The solids handling facilities that may eventually be necessary at the PCWPF have also not been included in this cost estimate.

The life cycle O&M for three new treatment processes that present the highest costs are Ozone, GAC, and UV. Table 11 summarizes the 20-year life cycle cost of ownership. Additional operations and maintenance staff needs are excluded from this table.

Table 11. Annual Operating Costs for New Treatment Processes

Treatment Process	Annual Costs	Assumptions
Ozone	Power[2] = $45,200 LOX = $3,500	85 kW system running at an average of 75% capacity. LOX costs $0.0507/lb, per Airgas quote from 2014
GAC Contactors	GAC Replacement = $270,100	Media is replaced every 30,000 bed volumes (1.5 years at average plant flow of 4.5 mgd). GAC is $41/cf, per Calgon Carbon cost from July 2017.
UV Disinfection[3]	Power[2] = $13,400 Lamp replacement = $2,200	20.4 kW system running at an average of 75% capacity. 4 lamp replacements per year at $550/lamp for Trojan

Table 11. Annual Operating Costs for New Treatment Processes

Treatment Process	Annual Costs	Assumptions
Total for new processes	$334,330	Typical annual additional cost to operate the PCWPF with the proposed advanced treatment processes.

[1]This does not include solids thickening and dewatering facilities.

[2]IREA power cost assumed to be $0.10/kW-hr

[3]Power and lamp replacement based on Trojan Swift model 4L24 medium pressure system.

6.0 Summary and Next Steps

The additional treatment processes recommended for the PCWPF described in this BDR represents a multiple barrier treatment approach for potable reuse (direct or indirect) based on the evaluation of the preliminary water quality data gathered as part of this study. The unit processes described will address organics, pathogens, CECs, and other water quality parameters necessary to ultimately deliver safe drinking water to the Town of Castle Rock. A preliminary site layout has been developed to conceptually demonstrate how the new process would fit on the site. Most of the new treatment process would be within a new Advanced Treatment Building and the Raw Water Blending Tank would be located adjacent to the existing raw water line on the east side of the site. See the Conceptual Site Plan in Appendix A.

In addition to the various treatment additions and modifications outlined in this BDR, there are several considerations that require additional analysis, described herein, that are critical to the implementation of treatment of either of the new sources at the PCWPF.

6.1 PCWRA Evaluation

A study was previously conducted to evaluate the performance constraints and opportunities for optimization of the PCWRA (Evaluation of Plum Creek Water Reclamation Authority, Carollo 2016). The general assessment from the evaluation was that the PCWRA is well operated and effluent water quality is consistently within the current discharge permit limits. Since the overall performance of the PCWRA facility will have direct and potentially immediate impacts on the treatability at the PCWPF, dynamic treatment simulations were conducted targeting the optimization of treatment for several water quality parameters. The parameters identified as the focus of the evaluation were ammonia, nitrate, and nitrite.

6.1.1 Ammonia

Ammonia variability was initially identified as a key process variable that could impact treatment at the PCWPF. The 90th percentile ammonia concentration from the data analyzed in the PCWRA Evaluation was below 2.0 mg/L threshold established for the PCWRA outfall concentration, however when the data was analyzed on an hourly basis, there were several deviations above 2.0 mg/L. Elevated ammonia was most often correlated to higher flow rates, particularly in the winter months.

The report indicated that modifications to the setpoints that control the aeration blowers (i.e., decreasing step time and reducing setpoint) could likely eliminate nearly all hourly excursions. Operating all three oxidation ditches (not modeled in the evaluation) during the winter months could also likely eliminate elevated ammonia concentrations by increasing the solids retention time (SRT) in the process. Another approach to optimizing nitrification, an ammonia probe could be added at the PCWRA headworks to allow for feed-forward DO control in the oxidation ditches.

6.1.2 Nitrate/Nitrite

Nitrate is a regulated drinking water parameter with an MCL of 10 mg/L. Controlling and minimizing this regulated compound in any of the potential source blends for PCWPF is critically important and

therefore a 5 mg/L threshold was established for PCWRA outfall concentration for the purposes of this evaluation. The report indicated that nitrate concentration varied seasonally but ranged between 2 and 6 mg/L with exceedances above the 5 mg/L threshold observed approximately 10% of the time. A recommendation in the report was to implement seasonal carbon addition to enhance denitrification during periods where nitrate treatment is challenged. Nitrite was negligible at all times during the process simulation.

6.1.3 Source Control

Development of a source water characterization and control program for PCWRA is an important part of protecting against plant upsets or passage of contaminants that should not be introduced to the potable water supply. Identifying key parameters that were identified in the water quality sampling (i.e., aldicarb sulfone, cyanide, and ethylene dibromide) would target specific industries or facilities that should be included in a pre-treatment program. Additional characterization of the selected source water is recommended to identify chemicals that should be monitored and specifically targeted in a PCWRA source control and pre-treatment program.

6.1.4 Conclusions and Recommendations for PCWRA

Identifying and implementing improvements at the PCWRA focused on treatment plant performance and reliability have the potential to reduce operational costs at both facilities and ultimately improve the water quality in the potable water supply. A significant expansion project at the PCWRA is anticipated to commence in the fourth quarter of 2017 and the operational parameters discussed in this BDR should be considered in that project.

6.2 Settling Basin

The additional detention time provided with a settling basin (or pond) at either Source 1 or 3 will provide an essential buffer for ammonia and other diurnal fluctuation attenuation, as well as providing response time in the event of a plant upset condition at PCWRA. The size and configuration at Source 1 is still to be determined while the Source 3 infrastructure is already in place. Although this buffer can provide attenuation of some water quality parameters, the design and operation of the settling pond should consider residence time, short circuiting, and means to access the interior for periodic cleaning and maintenance.

6.3 Engineered Storage Buffer

The incorporation of a finished water engineered storage buffer (ESB) has been proposed in at least one WateReuse Research Foundation project as a good practice for direct potable reuse projects. The purpose of the ESBs is to provide the ability to hold and sample the finished water prior to distribution. Implementation of finished water ESBs of a size that provides sufficient water quality analysis and reaction time can be expensive and can occupy large amounts of land. The need for ESBs can be reduced through the use of extensive on-line monitoring (i.e., critical control points) of water quality parameters that automatically shut down or diverts water from the potable supply. Other “wide spots” (i.e., settling ponds and the Raw Water Blending Tank) are already include in the project for either source. Critical control points are discussed in a subsequent section and finished water ESBs are not recommended at the PCWPF due to the additional cost to the project and limited space available on site.

6.4 Critical Control Points

The analysis of critical control points (CCP) throughout the PCWRA and the PCWPF is an important component of the conversion of the PCWPF to a potable reuse facility. The methodology for conducting a hazard analysis and CCP assessment has been established to protect public health and has more

recently been applied to the concept of potable reuse. Online analyzers at the PCWRA and at strategic locations throughout the PCWPF process will be necessary (particularly for Sources 1 and 2) to ensure proper plant performance. The implementation of CCPs are important considerations for the implementation of potable reuse projects. The CCPs identified for the PCWRA are summarized in Table 10. Table 11 summarize the CCPs initially identified for the PCWPF.

Table 10. PCWRA Critical Control Points

Critical Control Point	Values	Note
PCWRA Influent Flow	Critical = Exceeds peak instantaneous	High flows may impact the ability to meet treatment goals
Oxidation Ditch Ammonia	Alarm = 2.0 mg/L Critical = 3.0 mg/L	Indicator of ditch performance and low ammonia important for free chlorine disinfection
Oxidation Ditch Nitrate	Alarm = 5.0 mg/L Critical = 7.5 mg/L	Indicator of ditch performance
UV RED	Critical = low dose alarm	Disinfection performance
Discharge Turbidity	Alarm/Critical	Correlate TSS to turbidity
Conductivity	Alarm	For TDS blend
UV_{254}	Alarm/Critical	For organics

The addition of these analyzers is less critical if Source 3 is implemented.

Table 11. PCWPF Critical Control Points

Critical Control Point	Values	Note
Ozone Dose[1]	+/-15% of setpoint	Pre-oxidation
Coagulant Dose	Alarm = -5%, Critical = -10% of setpoint	TOC removal
Settled Water Turbidity[1]	Alarm = 1.5 NTU, Critical = 2.0 NTU	Floc/sed performance
Filter Effluent Turbidity[1]	Alarm = 0.15 NTU, Critical = 0.3 NTU	Pathogen/particle removal
Filter Effluent UV_{254}	Alarm = 0.05 cm^-1	TOC removal
Filter Effluent DO[1]	Alarm = tbd	Maintain aerobic
MF Pressure Decay[1]	Critical = Fail test	Pathogen removal
MF Turbidity	Alarm = 0.05 NTU, critical = 0.1 NTU	Particle removal
Ozone Residual	Alarm = -5%, critical = -10% of setpoint	For CT calculation
GAC UV_{254}[1]	Alarm = tbd	For GAC breakthrough
UV RED	Critical = Low dose alarm	Pathogen inactivation
Ammonia	Alarm = 0.5 mg/L, Critical = 1.0 mg/L	Free Cl_2 residual
Chlorine Feed	Alarm = -5%, Critical = -10% of setpoint	Disinfection
Chlorine Residual/CT	Critical = less than CT required	Calculated

[1]The addition of these analyzers may not be necessary if Source 3 is implemented.

6.5 Solids Handling valuation

Since the PCWPF currently returns all waste streams to the PCWRA, the Town should initiate coordination with CDPHE to determine how solids handling is to be implemented as part of the PCWPF Expansion project. A solids handling evaluation was not conducted as part of this BDR. Based on CDPHE solids handling requirements, a solids handling study will be conducted during preliminary design of the PCWPF or in a subsequent project to determine the appropriate thickening and dewatering necessary to handle the solids generated at the PCWPF on site prior to disposal.

6.6 Pilot Testing

Preliminary sizing for the unit processes is based on initial water quality estimates through the treatment process from the results of the bench testing (Appendix B). The operation of each process (both new and existing) will significantly change as a result of the introduction of the new source water. In order to hone the design of the new processes, pilot testing of the new treatment train is recommended to further evaluate the overall treatment process and confirm the initial design assumptions. Pilot testing would provide an opportunity to adjust and optimize the design basis of these processes.

CDPHE requires approval and pilot (or full scale) demonstration for filter loading rates over 5 gpm/sf. The operation of the existing filters for particle removal and pathogen reduction credit would require demonstration of performance at 5.42 gpm/sf (i.e., 6 mgd when 1 filter is in backwash). Pilot or full-scale testing could be conducted such that once the facility is constructed, allowing rerating of the filters.

Pilot testing of the proposed treatment process is recommended to verify process performance and demonstrate the effectiveness of treatment for all stakeholders. Not only would a pilot plant provide process confirmation (reducing overall risk to the project), but maintaining a permanent pilot plant at the PCWPF would allow operations to optimize the process or test alternate operational strategies in parallel to full scale operations.

6.7 Project Schedule

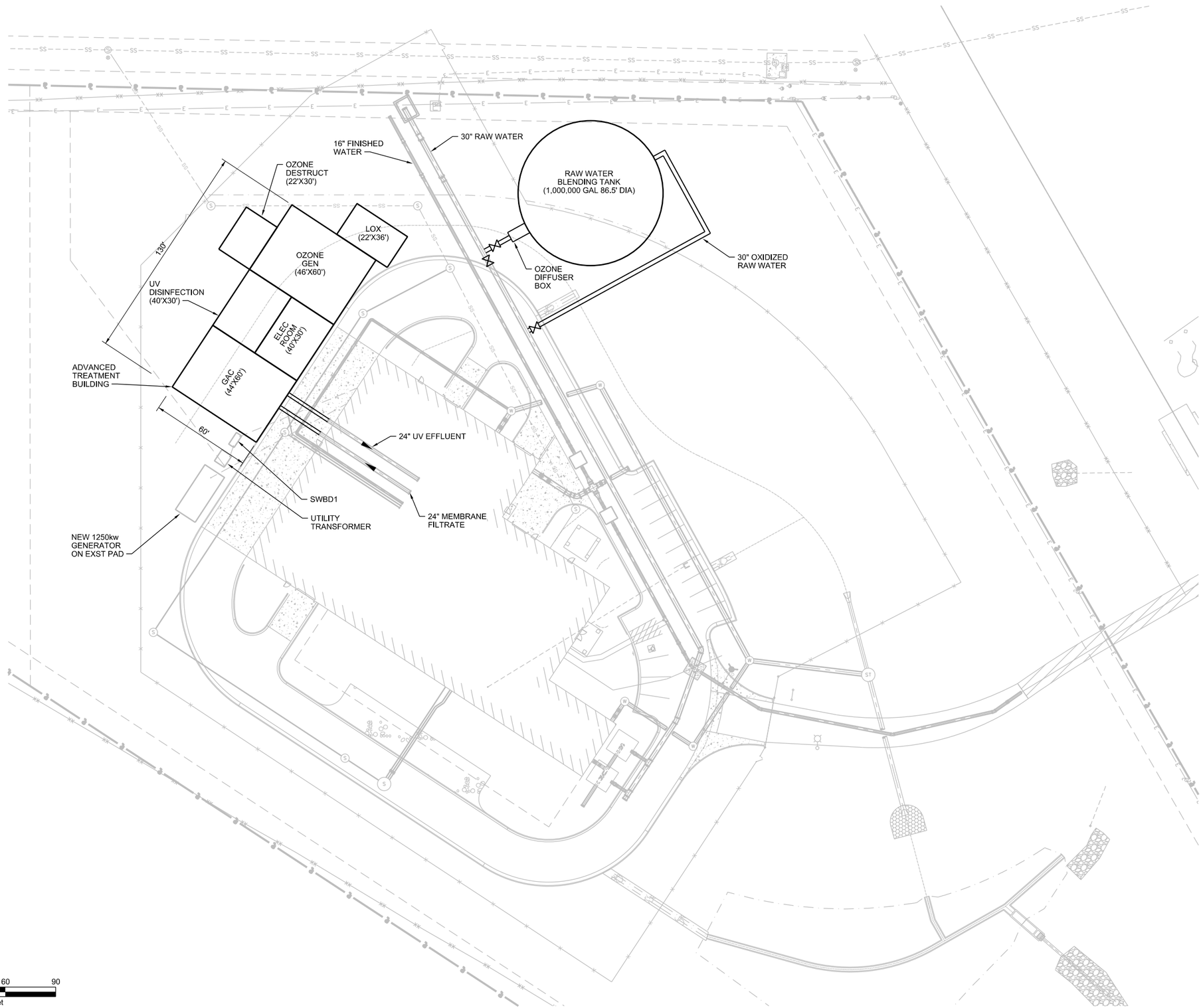
The proposed timeline for incorporating the selected new source at the PCWPF treatment process will likely require a phased implementation schedule. Phase 1 would be targeted to be online in the summer of 2019 while the balance of the project components would be included in Phase 2, to be completed in the summer of 2020. A preliminary schedule is summarized in Table 12 to outline the major project components.

Table 12. Proposed Schedule

Activity	Date	Duration	Notes
Preliminary Design	October 2017 to February 2018	4 months	Schematic design developed for selection of GMP/GC
Pilot Plant Operation	February to July 2018	6 months	Design, procurement, and installation of the pilot plant would occur concurrent to the Preliminary Design
GMP/GC solicitation and selection	February to April 2018	2 months	Bid and selection based on preliminary design documents
Work Package 1 Design Final Design	February to June 2018	4 months	Work Package 1 to include Raw Water Blending Tank, tie-in of raw water pipeline, underslab piping and foundation of WP 2 facility. Could also include conversion of filters to BAC.
Work Package 2 Final Design	February 2018 to October 2018	10 months	Will overlap with GMP/GC for long lead equipment selection/procurement and the start of construction.
Construction	May 2018 to June 2020	24 months	Will allow sufficient time for procurement and installation of new equipment and facilities
Startup/Commissioning of Work Package 1	June 2019	1 month	This includes the Raw Water Blending Tank and tie-in of raw water pipeline.
Startup/Commissioning of Work Package 2	March to June 2020	2 months	Will allow for integration and testing of new processes
PCWPF Online	June 2020		Completed in time for 2020 water season

Notes: Assumes an accelerated schedule for a project of this size and nature with all entities collaborating. This also assumes that the permitting approvals from CDPHE and the Town will not delay the implementation of the project.

Appendix A – Conceptual Site Plan



NO.	DATE	REVISION	BY	APVD

DSGN J ASSOULINE | DR M MONAHAN | CHK J CURL | APVD L SCHIMMOLER

PCWPF EXPANSION
PLUM CREEK WATER PURIFICATION FACILITY
TOWN OF CASTLE ROCK
CASTLE ROCK, CO

ch2m

CONCEPTUAL SITE PLAN

1" = 30'
VERIFY SCALE
BAR IS ONE INCH ON ORIGINAL DRAWING.
0 1"

DATE
PROJ
DWG
SHEET of

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Appendix B – Bench Testing Report

Appendix B: Plum Creek Water Purification Facility (PCWPF) Bench-Scale Treatability Testing Report

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Section 1.0 – Background and Objectives

The purpose of this Bench Testing Report is to further define the process selection and design criteria for the existing and future treatment processes described in the PCWPF Expansion BDR. The bench-scale testing included the following objectives:

- Provide data to allow refinement of PCWPF Expansion design criteria
- Demonstrate successful treatment scheme to support permitting
- Assess anticipated operational performance for the PCWPF
- Provide performance data to refine facility cost estimates

The key processes that were evaluated at the bench-scale included the following:

- Pre-ozonation
- Rapid Mix/Flocculation/Sedimentation
- Biologically Active Carbon (BAC) Filtration
- Microfiltration (MF) and post-BAC/MF Ozonation
- Granular Activated Carbon (GAC) Adsorption
- Free Chlorine Disinfection
- Chloramine Formation and Simulated Distribution System (SDS)

This technical memorandum summarizes the bench-scale treatability testing results.

Section 2.0 – Sample Collection

Four 55-gal drums were prepared by CH2M's Applied Sciences Laboratory (ASL) and sent to the treatment facility. Two drums of well water (deep and alluvial wells based on that day's operations) and two drums of Plum Creek Water Reclamation Authority (PCWRA) outfall water were collected and shipped to ASL in Corvallis, Oregon.

Section 3.0 – Water Quality Characterization

Upon arrival at the ASL, the two different source waters were blended in a 50:50 ratio, and homogenized. The selection of the 50:50 blend was based on previous work documented in the Basis of Design Report (BDR). The homogenized blend water was submitted for characterization analysis and the results are listed in *Table 1 and 2*. The purpose of this water quality characterization was to provide a baseline of the raw water quality and chemistry prior to bench-scale testing efforts.

Observations of the untreated water made during sample collection include:

- Highly colored and turbid (color was orange/brown)
- Strong, distinct wastewater odor
- Foams slightly when agitated

The blended water characterization indicates that the sample water had moderate hardness and alkalinity, as well as elevated levels of total iron and manganese. The color observed was likely caused by the elevated iron and manganese.

The total organic carbon (TOC) and DOC concentrations were also moderate, and based on the calculated specific ultraviolet absorbance (SUVA) values the organics were predominately characterized as low aromacity, transphilic acids, and hydrophilic compounds.

Table 1. Blend Water Characterization (Untreated): metals, general chemistry, volatile organic carbon (VOCs), and total fluorescence.

Sample Information			
Project Name	Castle Rock		
Sample Description	PCWPF : PCWRA Blended (50:50)		EPA MCL
Sample Collection Date	5/14/2016		
ASL Metals Analysis			
Aluminum, total	µg/L	16.0	50-200*
Antimony, total	µg/L	0.12 J	6
Arsenic, total	µg/L	0.52	10
Barium, total	µg/L	122	2,000
Beryllium, total	µg/L	<0.025 U	4
Cadmium, total	µg/L	<0.030 U	5
Calcium, soluble	µg/L	51,900	
Chromium, total	µg/L	0.34 J	100
Cobalt, total	µg/L	0.51	
Copper, total	µg/L	0.56 J	1,300
Iron, total	µg/L	1,290	300*
Iron, soluble	µg/L	10.0 J	
Lead, total	µg/L	0.22 J	15
Magnesium, soluble	µg/L	6,590	
Manganese, total	µg/L	177	50*
Manganese, soluble	µg/L	0.45 J	
Molybdenum, total	µg/L	0.97 J	
Nickel, total	µg/L	2.12	
Selenium, total	µg/L	1.18	50
Silver, total	µg/L	<0.025 U	100*
Thallium, total	µg/L	<0.025 U	2
Vanadium, total	µg/L	0.18 J	
Zinc, total	µg/L	21.1	5,000*
Hardness, calcium	mg/L as $CaCO_3$	130	
Hardness, magnesium	mg/L as $CaCO_3$	27.1	
Hardness, total	mg/L as $CaCO_3$	157	
ASL General Chemistry Analysis			
Alkalinity, total	mg/L as $CaCO_3$	120	
pH	s.u.	7.4	6.5-8.5*
Turbidity	NTU	13.8	
Conductivity	µS/cm	593	
Ammonia	mg/L-N	0.27	
Bromide	µg/L	83.8	
Bromate	µg/L	<5.00 U	10
Nitrate/Nitrite	mg/L-N	0.86	10
Nitrite	mg/L-N	0.12	1
TDS	mg/L	306	500*
TOC	mg/L	4.32	
DOC	mg/L	4.04	
UVA_{254}, unfiltered	abs/cm	0.115	
UVA_{254}	abs/cm	0.076	
UVT_{254}, unfiltered	%	76.8	
UVT_{254}	%	84.0	

Table 1. Blend Water Characterization (Untreated): metals, general chemistry, volatile organic carbon (VOCs), and total fluorescence.

Sample Information			
SUVA, with filtered analytes	L/mg*m	1.87	
ASL Volatile Organic Carbon (VOC) Analysis			
Chloroform	µg/L	0.19 J	70[α]
**Non-detect on all other volatile compounds; see analytical report for details.*			
University of Arizona, Snyder Labs Total Fluorescence (TF) Analysis			
UVA_{254}	abs/cm	0.082	
UVT_{254}	%	82.8	
Total Fluorescence	R.U. nm^2	103,887	

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.
* = Secondary Maximum Contaminant Level (MCL)
[α] = Stage 2 Disinfection Byproduct Rule (DBPR) Maximum Contaminant Level Goal (MCLG)

Table 2 summarizes the results of the synthetic organic carbon (SOCs), CECs, and nitrosamines analyzed in the untreated blend water. Only the compounds with a detection are included in this summary table.

Table 2. Blend Water Characterization (Untreated): SOCs, CECs, and nitrosamines.

Sample Information		
Project Name	Castle Rock	
Sample Description	PCWPF : PCWRA Blended (50:50)	
Sample Collection Date	5/14/2016	
Eurofins Synthetic Organic Carbon (SOC) Analysis		
*Non-detect on all synthetic organic carbon compounds; see analytical report for details.		
Eurofins Selected Contaminants of Emerging Concern (CEC) Analysis		
1,4-Dioxane	ng/L	270
17β-estradiol	ng/L	0.45
Perfluorooctanoic acid (PFOA)	ng/L	12
Perfluorooctanesulfonic acid (PFOS)	ng/L	<2.5 U
Eurofins Contaminants of Emerging Concern (CEC) Analysis		
2,4-D	ng/L	110
4-nonylphenol - semi quantitative	ng/L	2,000
Acesulfame-K	ng/L	580
Amoxicillin (semi-quantitative)	ng/L	480
Atenolol	ng/L	66
Azithromycin	ng/L	550
BPA	ng/L	<10 U
Caffeine	ng/L	69
Carbamazepine	ng/L	58
Cotinine	ng/L	34
DEET	ng/L	31
Diclofenac	ng/L	44
Diltiazem	ng/L	15
Fluoxetine	ng/L	22
Gemfibrozil	ng/L	140
Iohexal	ng/L	110

Table 2. Blend Water Characterization (Untreated): SOCs, CECs, and nitrosamines.

Sample Information		
Lidocaine	ng/L	130
Lopressor	ng/L	140
Naproxen	ng/L	59
Perfluorooctanoic acid (PFOA)	ng/L	12
Perfluorooctanesulfonic acid (PFOS)	ng/L	<2.5 U
Primidone	ng/L	27
Quinoline	ng/L	16
Sucralose	ng/L	18,000
Sulfadimethoxine	ng/L	23
Sulfamethoxazole	ng/L	290
TCEP	ng/L	36
TCPP	ng/L	300
TDCPP	ng/L	220
Trimethoprim	ng/L	120
TOTAL CECs	ng/L	23,675
Eurofins Nitrosamines Analysis		
N-Nitrosodibutylamine (NDBA)	ng/L	2.00
N-Nitrosodiethylamine (NDEA)	ng/L	<2.00 U
N-Nitroso-dimethylamine (NDMA)	ng/L	<2.00 U
N-Nitrosodi-n-propylamine (NDPA)	ng/L	<2.00 U
N-Nitrosomethylethylamine (NMEA)	ng/L	<2.00 U
N-Nitrosomorpholine (NMOR)	ng/L	2.00
N-Nitrosopiperidine (NPIP)	ng/L	<2.00 U
N-Nitrosopyrollidine (NPYR)	ng/L	<2.00 U
TOTAL NITROSAMINES	ng/L	4.00

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

No detections were reported for the SOCs list. Of the full list of 60 compounds included in the CEC analysis, there were 30 compounds detected. Most notably, 4-nonylphenol, Acesulfame-K, Amoxicillin, Azithromycin, and sucralose. For ease of comparison across treatment evaluations, the CECs were summed together for a total mass-based CEC result of 23,675 ng/L.

The nitrosamines were present in low concentrations in the untreated blend water. However, it is known that low levels of nitrosamine formation can occur during ozonation, and therefore nitrosamines were monitored closely throughout the bench-scale testing efforts.

Also included in the untreated water characterization were EEM and total fluorescence (TF). Note, a greater total fluorescence value generally indicates hydrophobic natural organic matter as opposed to neutral and hydrophilic constituents. From *Table 1*, the total fluorescence was measured at 103,887 R.U. nm^2, and the corresponding EEM heat map is depicted in *Figure 1* below.

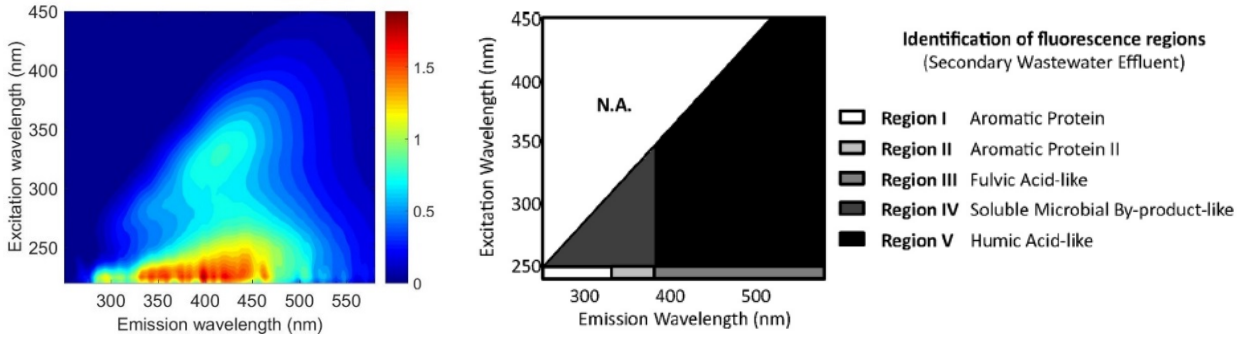

Figure 1. (Left) Exitation Emission Matrix heat map for untreated blend water (Snyder labs, University of Arizona) & (right) identification of fluorescence regions (S. Merel, et al.).

The EEM heat map is consistent with wastewater results reported in technical literature, and indicates that the majority of organics present fall within regions II and III corresponding to *aromatic protein II* and *fulvic acid-like* compounds, respectively. Moderate levels of organics appear in regions IV and V corresponding to *soluble microbial by-product-like* and *humic acid-like* constituents, respectively. For more information on TF and EEM, see complete report attached (*Appendix C*).

Section 4.0 – Pre-Ozonation

Ozone demand and decay testing was conducted in a semi-batch mode: the reactor was charged with a known volume of water, and ozone added at a known concentration and rate. The applied ozone dose was thus proportional to elapsed time during the run.

Ozone demand and decay testing was accomplished using the bench scale system depicted in *Figure 2*.

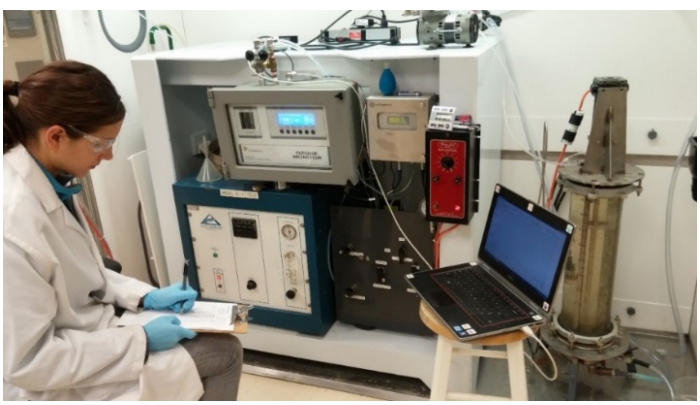

Figure 2. Lab technician operating the ozone system during the PCWPF benchscale testing at ASL.

The ASL ozone system consists of the following equipment:

- 11-L nominal capacity glass ozone contactor (reactor)
- Ozone generator
- Aqueous phase dissolved ozone monitor
- In-line dissolved ozone senor
- Gas phase mass flow controller
- Gas phase ozone analyzer
- Off-gas pump equipped with pressure gauge and rotameter
- Data acquisition module connected to both the gas phase and aqueous phase monitors

During the tests, ozone was applied for approximately 3 minutes to simulate the full-scale ozone dissolution chamber. The semi-batch technique mimics a typical bubble-diffuser contactor, where water flows downward through a contactor cell while ozone gas bubbles upward through it. The dissolved ozone residual was monitored every 5 seconds via a data logger to develop the ozone demand curves. After the application of ozone ceased, the dissolved ozone residual was also recorded every 5 seconds until the decay was complete. At the end of the test, the ozonated water was analyzed for pH, turbidity, DOC, UV_{254}, TF, bromate, iron, and manganese.

Section 4.1 – Pre-Ozonation Demand/Decay

Round one of ozone testing was conducted on the blended raw water. First, a 'raw screen' was completed to determine the best feed-gas ozone concentration for the demand-decay runs. Three demand-decay tests were conducted at 2.44, 4.46, and 6.48 mg/L O_3 target doses, corresponding to the Ozone:TOC sub-residual dose calculations below (adjusted to incorporate additional expected nitrite demand):

- Dose 1, 0.5:1 ratio: (3.4 * nitrite-N) + (0.5*DOC)
- Dose 2, 1:1 ratio: (3.4 * nitrite-N) + (1*DOC)
- Dose 3, 1.5:1 ratio: (3.4 * nitrite-N) + (1.5*DOC)

Figure 3 below displays the color removal achieved with each of the three ozone doses (no appreciable color difference among ozonated waters discerned).

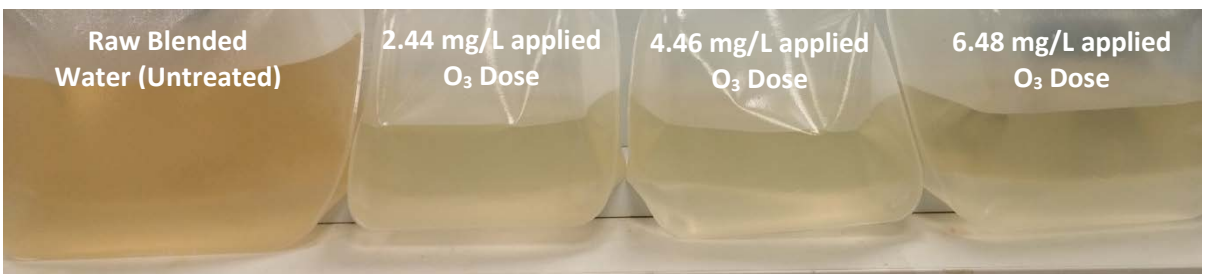

Figure 3. Comparison of color removal with the three ozone pretreatments.

Actual applied ozone doses are shown in *Table 3* below, along with the results of the post-ozonation final water quality analyses for each test.

Table 3. Pre-Ozonation: Ozone Demand/Decay data, and final WQ summary.

Ozone Test Conditions	Units	Run 0 (Untreated) (Raw Screen)	Run 4 (Optimum) (Demand/Decay) 2.0 mg/L O_3 Dose	Run 1 (Demand/Decay) 2.44 mg/L O_3 Dose	Run 2 (Demand/Decay) 4.46 mg/L O_3 Dose	Run 3 (Demand/Decay) 6.48 mg/L O_3 Dose
Target Ozone Dose	mg/L	-	**2.0**	2.44	4.46	6.48
Applied Ozone Dose	mg/L	4.91	**1.97**	2.44	4.42	6.34
Terminal Ozone Residual	mg/L	1.12	**0.21**	0.22	0.99	0.99
Ozone Demand/Decay	***Units***					
Immediate Ozone Demand	mg/L	1.70	**1.30**	1.64	1.75	2.50
Ozone Demand Slope		0.362	**0.309**	0.271	0.376	0.261
Initial Decay Residual	mg/L	1.14	**0.23**	0.24	1.01	1.97
Decay k		-0.660	**-2.355**	-2.279	-0.764	-0.398
Final WQ Data	***Units***					
pH	s.u.	7.76	**7.88**	7.85	7.91	7.77
Turbidity	NTU	9.66	**10.6**	10.7	9.67	10.3
DOC	mg/L	-	**4.53**	4.08	4.29	4.31

Table 3. Pre-Ozonation: Ozone Demand/Decay data, and final WQ summary.

Ozone Test Conditions	Units	Run 0 (Untreated) (Raw Screen)	Run 4 (Optimum) (Demand/Decay) 2.0 mg/L O_3 Dose	Run 1 (Demand/Decay) 2.44 mg/L O_3 Dose	Run 2 (Demand/Decay) 4.46 mg/L O_3 Dose	Run 3 (Demand/Decay) 6.48 mg/L O_3 Dose
UVA_{254} (unfiltered)	abs/cm	-	**0.086**	0.077	0.067	0.058
UVA_{254} (0.45 µm filtered)	abs/cm	-	**0.050**	0.045	0.037	0.031
UVT_{254} (0.45 µm filtered)	%	-	**89.2**	90.2	91.9	93.1
SUVA (filtered)	L/mg*m	-	**1.10**	1.10	0.86	0.72
Total Fluorescence	R.U. nm^2	-	**35,978**	32,889	21,338	15,525
Bromate	µg/L	-	**<5.00 U**	<5.00 U	<5.00 U	<5.00 U
Iron, total	µg/L	-	**1,270**	1,260	1,140	1,220
Iron, soluble	µg/L	-	**29.5 J**	16.6 J	11.9 J	12.1 J
Manganese, total	µg/L	-	**197**	174	160	165
Manganese, soluble	µg/L	-	**74.8**	2.68	3.14	1.59

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

Figure 4 depicts the filtered and unfiltered post-ozonation UVA_{254} and SUVA results. A 2.0 mg/L applied ozone dose was selected as the optimum treatment for the pre-ozonation step. This dose was selected because it established a low ozone residual, providing oxidation of organics and inorganics and removing most of the color from the water.

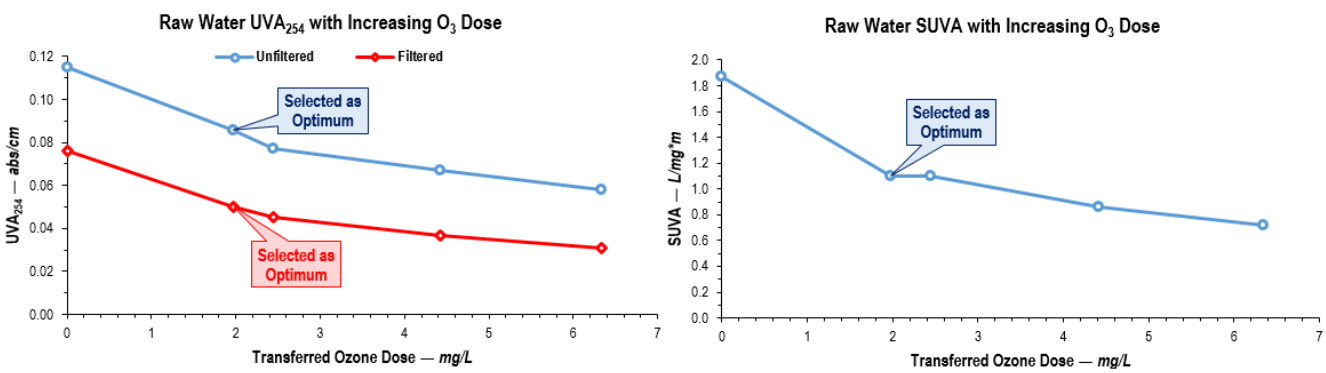

Figure 4. The (right) filtered and unfiltered UVA_{254} results and (left) SUVA results with increasing ozone dose.

The remaining ~800-L of blended raw water was treated in 11-L batches with an average applied ozone dose of 2.01 mg/L O_3. The ozone demand curve of a single semi-batch test of the optimum treated runs is included in *Figure 5* below, for direct comparison with the other three demand-decay tests.

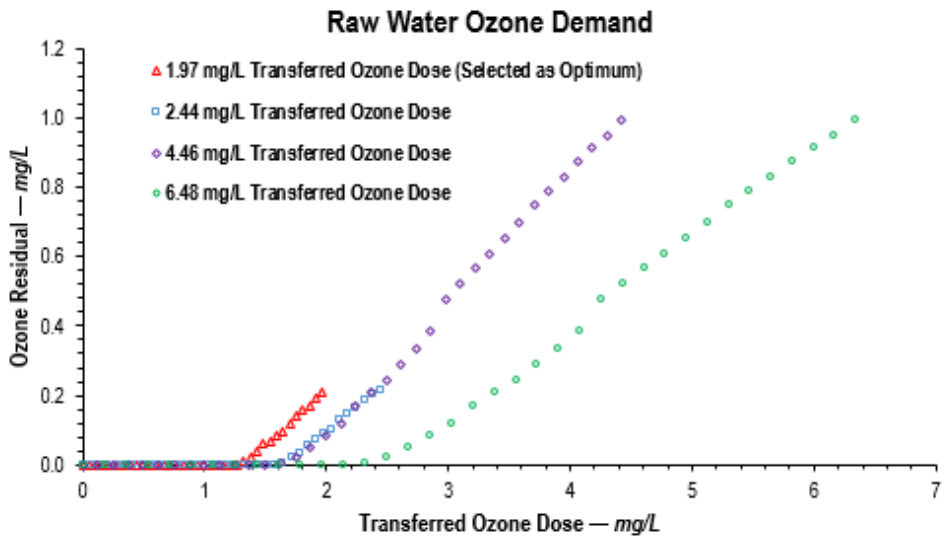

Figure 5. Ozone demand curves for the pre-ozonation demand-decay tests

Section 4.2 – Nitrosamine Formation Potential

Samples for the analysis of nitrosamine formation potential were also analyzed post-ozonation for the three demand-decay tests and the optimum bulk-treated water; results are shown in *Table 4* below.

Table 4. Pre-Ozonation: Nitrosamine results.

Ozone Test Conditions	Units	Run 0 (Untreated) (Raw Screen)	Run 4 (Optimum) (Demand/Decay) 2.0 mg/L O_3 Dose	Run 1 (Demand/Decay) 2.44 mg/L O_3 Dose	Run 2 (Demand/Decay) 4.46 mg/L O_3 Dose	Run 3 (Demand/Decay) 6.48 mg/L O_3 Dose
Target Ozone Dose	mg/L	-	**2.0**	2.44	4.46	6.48
Applied Ozone Dose	mg/L	4.91	**1.97**	2.44	4.42	6.34
Terminal Ozone Residual	mg/L	1.12	**0.21**	0.22	0.99	0.99
Ozone Demand/Decay	***Units***					
Immediate Ozone Demand	mg/L	1.70	**1.30**	1.64	1.75	2.50
Ozone Demand Slope		0.362	**0.309**	0.271	0.376	0.261
Initial Decay Residual	mg/L	1.14	**0.23**	0.24	1.01	1.97
Decay k		-0.660	**-2.355**	-2.279	-0.764	-0.398
Final WQ Data	***Units***					
N-Nitrosodibutylamine (NDBA)	ng/L	-	<2.00 U	<2.00 U	<2.00 U	<2.00 U
N-Nitrosodiethylamine (NDEA)	ng/L	-	<2.00 U	<2.00 U	<2.00 U	<2.00 U
N-Nitroso-dimethylamine (NDMA)	ng/L	-	9.70	14.0	14.0	12.0
N-Nitrosodi-n-propylamine (NDPA)	ng/L	-	<2.00 U	<2.00 U	<2.00 U	<2.00 U
N-Nitrosomethylethylamine (NMEA)	ng/L	-	<2.00 U	<2.00 U	<2.00 U	<2.00 U
N-Nitrosomorpholine (NMOR)	ng/L	-	<2.00 U	<2.00 U	<2.00 U	<2.00 U
N-Nitrosopiperidine (NPIP)	ng/L	-	<2.00 U	<2.00 U	2.10	<2.00 U
N-Nitrosopyrollidine (NPYR)	ng/L	-	<2.00 U	<2.00 U	<2.00 U	<2.00 U
TOTAL NITROSAMINES	ng/L	-	9.70	14.0	16.1	12.0

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

As with the raw blended water characterization, six of the eight nitrosamine compounds analyzed were not present above a 2.00 ng/L detection limit post-ozonation. N-Nitroso-dimethylamine (NDMA) and N-Nitrosopiperidine (NPIP), however, increased the total post-ozonation nitrosamine concentration from the blended raw water baseline of 4.00 ng/L by 8-12 ng/L. Nitrosamines in the optimum treated water totaled 9.70 ng/ L.

Section 4.3 – CEC Reduction on Selected Pre-Ozonation Dose (2.0 mg/L O_3)

The bulk-treated post-ozonated water was also analyzed for CEC- results shown in *Table 5* below along with the untreated blended water CECs.

Table 5. Pre-Ozonation: Reduction in CECs with a 2.0 mg/L O_3 dose.

Sample Information			
Sample Description		PCWPF : PCWRA Blended (50:50) (Untreated)	Pre-Ozonated 2.0 mg/L O_3
Eurofins Selected Contaminants of Emerging Concern (CEC) Analysis			
1,4-Dioxane	ng/L	270	190
17β-estradiol	ng/L	0.45	<0.4 U
Perfluorooctanoic acid (PFOA)	ng/L	12	11
Perfluorooctanesulfonic acid (PFOS)	ng/L	<2.5 U	<2.5 U
Eurofins Contaminants of Emerging Concern (CEC) Analysis			
2,4-D	ng/L	110	53
4-nonylphenol - semi quantitative	ng/L	2,000	1,600
Acesulfame-K	ng/L	580	300
Amoxicillin (semi-quantitative)	ng/L	480	<20 U
Atenolol	ng/L	66	<5 U
Azithromycin	ng/L	550	25
BPA	ng/L	<10 U	<10 U
Caffeine	ng/L	69	<5 U
Carbamazepine	ng/L	58	<5 U
Cotinine	ng/L	34	28
DEET	ng/L	31	15
Diclofenac	ng/L	44	<5 U
Diltiazem	ng/L	15	<5 U
Fluoxetine	ng/L	22	<10 U
Gemfibrozil	ng/L	140	<5 U
Iohexal	ng/L	110	100
Lidocaine	ng/L	130	<5 U
Lopressor	ng/L	140	<20 U
Naproxen	ng/L	59	<10 U
Primidone	ng/L	27	34
Quinoline	ng/L	16	10
Sucralose	ng/L	18,000	15,000
Sulfadimethoxine	ng/L	23	15
Sulfamethoxazole	ng/L	290	31
TCEP	ng/L	36	44
TCPP	ng/L	300	310
TDCPP	ng/L	220	170
Trimethoprim	ng/L	120	<5 U
TOTAL CECs	ng/L	23,675	17,735

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

Of the full list of 60 compounds included in the CEC analysis, 15 compounds were detected post 2.0 mg/L ozone dose treatment, totaling 17,735 ng/L (a 25.1 percent reduction in total CECs from the untreated blend water). 13 compounds were reduced to below the detection limit with partial removal of the remaining compounds. Most notably, 4-nonylphenol was reduced by 20 percent, Acesulfame-K was reduced by 48 percent, Azithromycin was reduced by 95 percent, and sucralose was reduced by 17 percent compared to the untreated blend water. Also, Amoxicillin was reduced beyond detection post 2.0 mg/L ozonation treatment. *Figure 6* below overlays the EEM heat maps associated with the finished water quality of each ozone test onto a total fluorescence versus increasing ozone dose graph for ease of visual comparison.

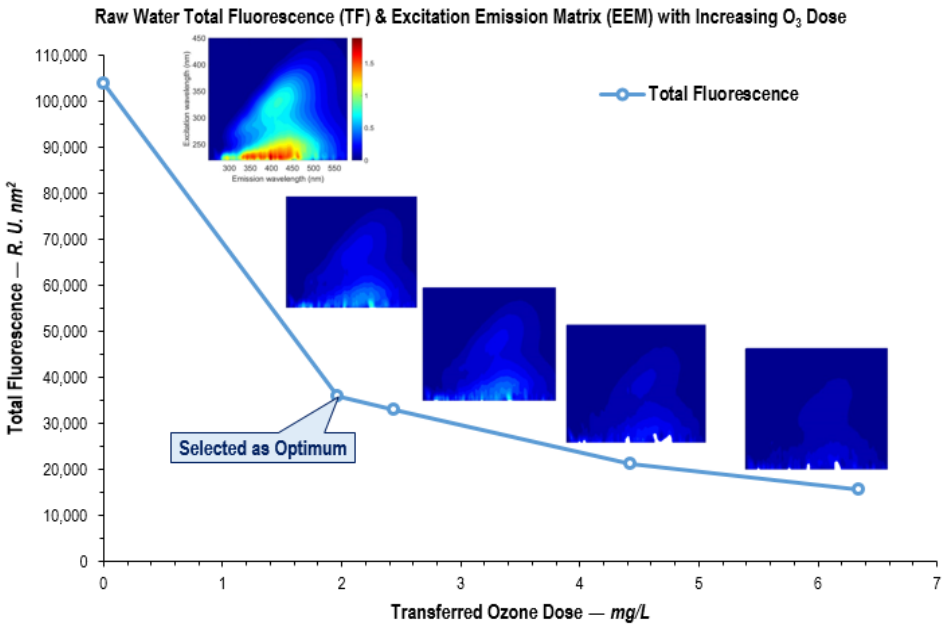

Figure 6. EEM and TF with increasing ozone dose.

Section 5.0 – Coagulation, Flocculation & Sedimentation

Jar tests to simulate coagulation, flocculation, and clarification were conducted on the pre-ozonated sample water to determine the optimum coagulant dose and pH based on organics and turbidity removal. One coagulant was tested: ferric chloride provided by the PCWPF. The coagulant was prepared as a dilution of 10,000 mg/L as $FeCl_3$ to facilitate more accurate pipetting during the tests. The full details of the coagulant dose basis is summarized in the Jar Test Summary found in Appendix A.

Section 5.1 – Jar Test Procedure

- Rapid mix at 300 rpm for 30 seconds
- Add coagulant
- Rapid Mix coagulant at 300 rpm for 30 seconds
- Flocculation Mix at 60 rpm for 10 minutes
- Flocculation Mix at 40 rpm for 10 minutes
- Flocculation Mix at 20 rpm for 10 minutes
- Settle for 30 minutes and decant supernatant

- Measure the settled supernatant pH, turbidity, alkalinity, total iron, total manganese, total dissolved solids, TOC, and UVA254
- Filter an aliquot of the supernatant with a 0.45 micron membrane filter and measure UV254, soluble iron, and soluble manganese.

On the clarified water pre-treated at optimum conditions for the ozone testing, samples were also collected for CECs, EEM, nitrosamines, and bromide analyses. CECs and nitrosamines were subcontracted to Eurofins and EEM samples to University of Arizona; all other analyses were conducted in-house at CH2M's ASL.

Section 5.2 – Ferric Chloride Dose Optimization at Ambient pH

Jar Test 1 focused on optimization of the ferric chloride dose at ambient pH. The doses applied to each jar are summarized in *Table 6*.

Table 6. Jar Test Series 1: Ferric chloride dose optimization at ambient pH.

Jar Test No.	Ferric Chloride Dose mg/L as $FeCl_3$	Target pH s.u.
1.1	10	Ambient
1.2	20	Ambient
1.3	30	Ambient
1.4	40	Ambient
1.5	60	Ambient
1.6	80	Ambient

The pH was monitored during the tapered flocculation stages of the tests, and as expected, the various ferric chloride doses suppressed the sample pH. The initial starting pH was recorded at 8.0 s.u., while the actual coagulation pHs were as follows:

Table 7. Jar Test Series 1: Ferric chloride dose optimization at ambient pH test data.

Jar Test No.	Ferric Chloride Dose mg/L as $FeCl_3$	Actual Coagulation pH s.u.
1.1	10	7.4
1.2	20	7.1
1.3	30	6.9
1.4	40	6.8
1.5	60	6.5
1.6	80	6.2

During the jar tests, it was observed that the various tests formed medium to large floc formations with good settling. The selected photographs in Figure 7 show the observed floc formations and the final water clarity at the end of the settling period.

Figure 7. From left to right, jars 1.1 to 1.6, respectively, at (top) the end of the 20 RPM flocculation stage and (bottom) at the end of 30 minutes of settling.

The analytical results gathered from supernatant analyses are summarized in Tables 8 and 9, as well as Figures 8 and 9.

Table 8. Jar Test Series 1: Clarified supernatant water quality analysis (no filtration).

Jar Test No.	Final pH s.u.	ALK mg/L as $CaCO_3$	Turbidity NTU	TDS mg/L	TOC mg/L	UVA_{254} abs/cm	UVT_{254} %	Fe µg/L	Mn µg/L
1.1	7.5	108	0.59	323	4.06	0.071	85.0	539	87.2
1.2	7.3	96.5	0.39	315	3.90	0.062	86.8	546	108
1.3	7.2	85.7	0.42	349	3.62	0.056	88.0	563	131
1.4	7.0	75.5	0.37	351	3.43	0.055	88.1	669	160
1.5	6.8	58.1	0.52	327	2.97	0.049	89.4	740	207
1.6	6.6	40.5	0.68	392	2.74	0.050	89.2	980	246

Table 9. Jar Test Series 1: Soluble supernatant water quality analysis (0.45 µm filtration).

Jar Test No.	UVA_{254} abs/cm	UVT_{254} %	Fe µg/L	Mn µg/L
1.1	0.043	90.7	12.6 J	87.3
1.2	0.038	91.6	11.6 J	108
1.3	0.035	92.2	27.4 J	132
1.4	0.033	92.8	23.6 J	159
1.5	0.030	93.3	78.9 J	209
1.6	0.028	93.8	167	251

J = Estimated value below reporting limit.

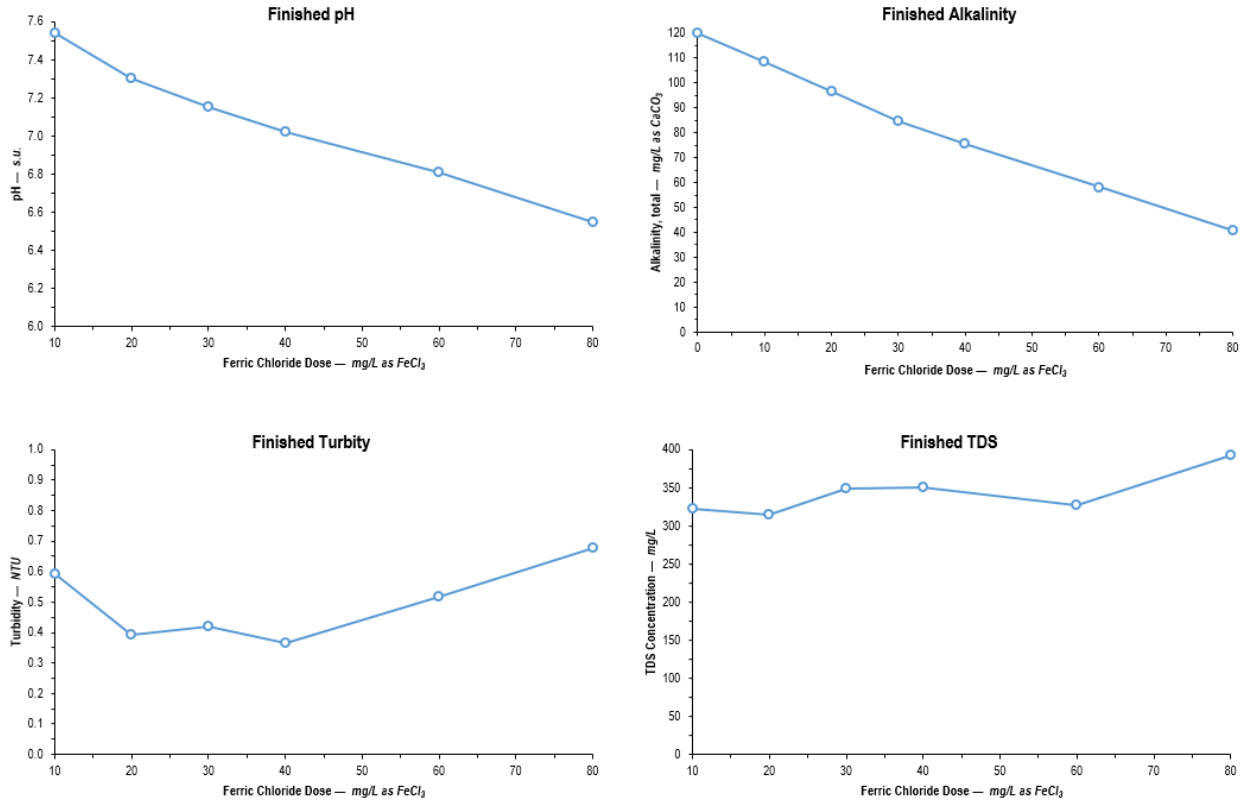

Figure 8. Graphical results from Jar Test series 1 for clarified water quality analyses including finished pH, alkalinity, turbidity, and TDS.

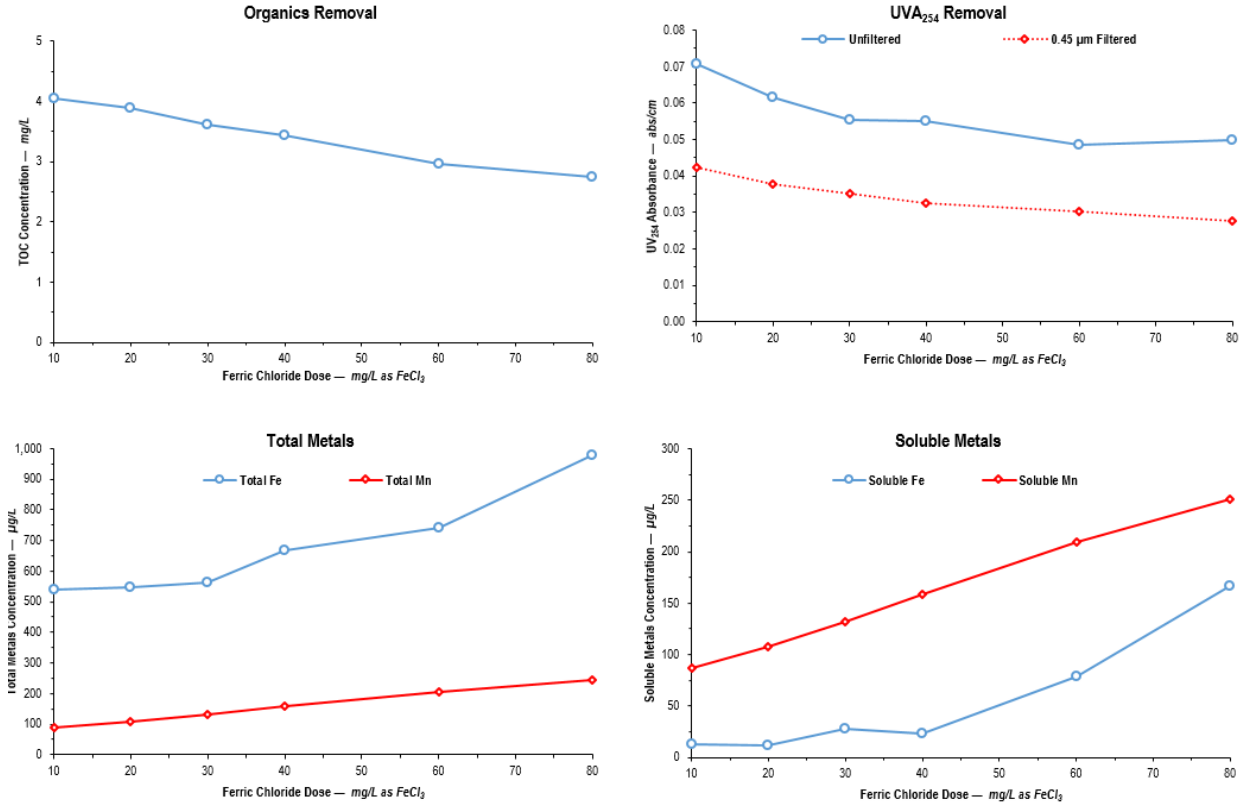

Figure 9. Graphical results from Jar Test series 1 for clarified water quality analyses including TOC, UV_{254} absorbance, total/soluble Fe, and total soluble Mn.

Doses of 40 and 60 mg/L as FeCl3 were selected for evaluation in the pH optimization testing. These two doses were selected based on the final turbidity and TOC concentrations, achieving a total TOC reduction of 25 and 35 percent, respectively.

Section 5.3 – pH Optimization & Enhanced Coagulation Evaluation

Coagulation and flocculation is a highly pH-dependent process, and TOC removal performance can be significantly increased with properly optimized pH control. Jar test series 2 focused on evaluating two coagulant doses at three target pHs with the intention of determining if pH adjustment could significantly improve the total TOC removal during the treatment process. *Table 10* summarizes the target conditions for this jar test series.

Table 10. Jar Test Series 2: pH optimization and enhanced coagulation evaluation.

Jar Test No.	Ferric Chloride Dose mg/L as $FeCl_3$	Target pH s.u.
2.1	40	6.0
2.2	40	6.3
2.3	40	6.6
2.4	60	6.0
2.5	60	6.3
2.6	60	6.6

After the coagulant addition, the pH was adjusted in each jar to the specified target and the pH adjustment reagent dose was recorded. The initial starting pH was recorded at 7.9 s.u.; the adjusted coagulation pHs and pH adjustment reagent dosages were as follows:

Table 11. Jar Test Series 2: pH optimization and enhanced coagulation evaluation test data.

Jar Test No.	Ferric Chloride Dose mg/L as $FeCl_3$	Actual Coagulation pH s.u.	Sulfuric Acid Dose mg/L	Sodium Hydroxide Dose mg/L
2.1	40	6.0	49.0	--
2.2	40	6.3	28.2	--
2.3	40	6.6	8.58	--
2.4	60	6.0	29.4	--
2.5	60	6.3	11.0	--
2.6	60	6.7	--	12.0

During the jar tests, it was observed that the various tests formed small to medium floc with good settling. The selected photographs in Figure 10 show the observed floc formations and the final water clarity at the end of the settling period.

Figure 10. From left to right, jars 2.1 to 2.6, respectively, at (top) the end of the 20 RPM flocculation stage and (bottom) at the end of 30 minutes of settling.

The analytical results gathered from supernatant analyses are summarized in *Tables 12 and 13*, as well as *Figures 11 and 12*.

Table 12. Jar Test Series 2: Clarified supernatant water quality analysis (no filtration).

Jar Test No.	Final pH s.u.	ALK mg/L as $CaCO_3$	Turbidity NTU	TOC mg/L	UVA_{254} abs/cm	UVT_{254} %	Fe µg/L	Mn µg/L
2.1	6.2	31.4	0.46	2.63	0.044	90.4	539	142
2.2	6.5	50.0	0.60	2.88	0.050	89.2	657	137
2.3	6.8	67.2	0.56	3.05	0.051	88.9	548	133
2.4	6.3	30.8	0.59	2.62	0.043	90.7	713	188
2.5	6.5	47.8	0.44	2.65	0.046	89.9	675	185
2.6	7.0	71.2	0.38	2.96	0.051	89.0	670	177

Table 13. Jar Test Series 2: Soluble supernatant water quality analysis (0.45 µm filtration).

Jar Test No.	UVA_{254} abs/cm	UVT_{254} %	Fe µg/L	Mn µg/L
2.1	0.026	94.1	35.3 J	142
2.2	0.029	93.5	37.8 J	138
2.3	0.031	93.1	28.5 J	137
2.4	0.025	94.4	79.9 J	192
2.5	0.028	93.8	74.7 J	189
2.6	0.030	93.4	27.5 J	181

J = Estimated value below reporting limit.

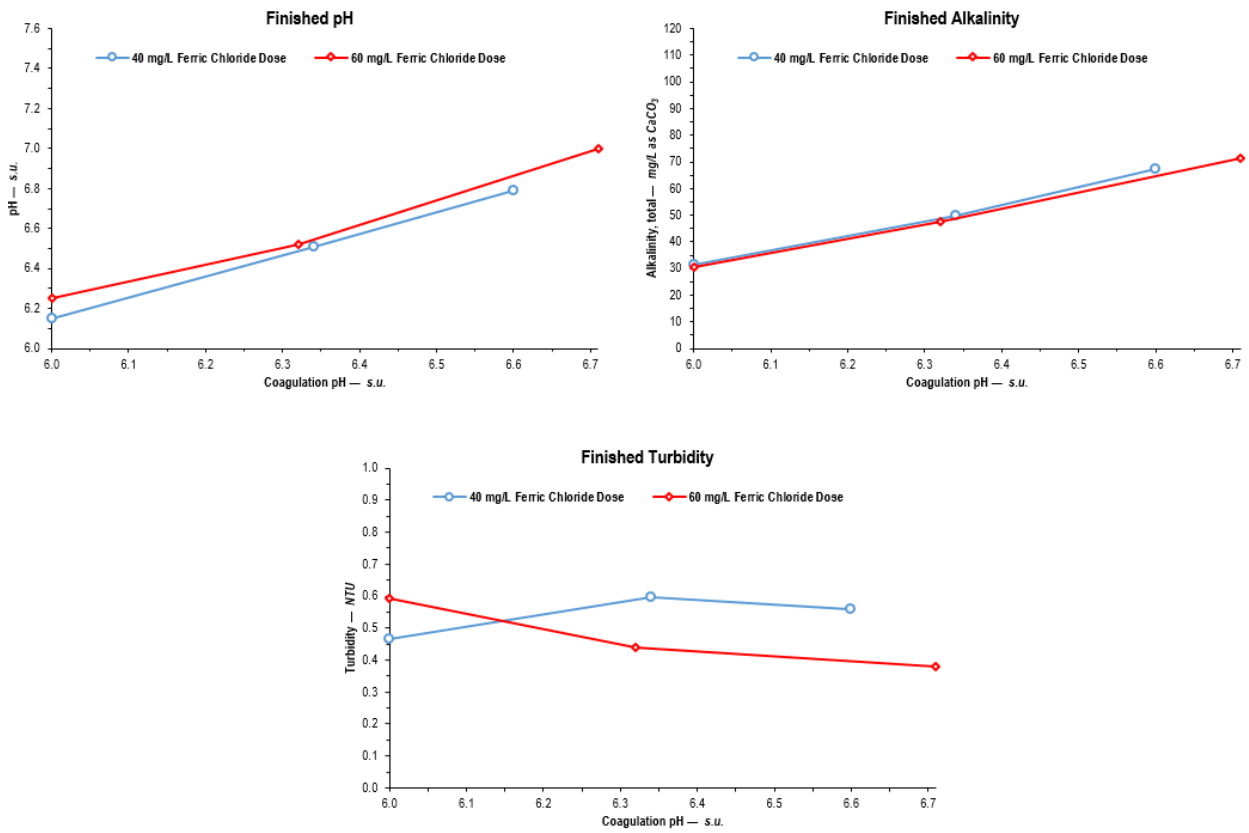

Figure 11. Graphical results from Jar Test series 1 for clarified water quality analyses including finished pH, alkalinity, and turbidity.

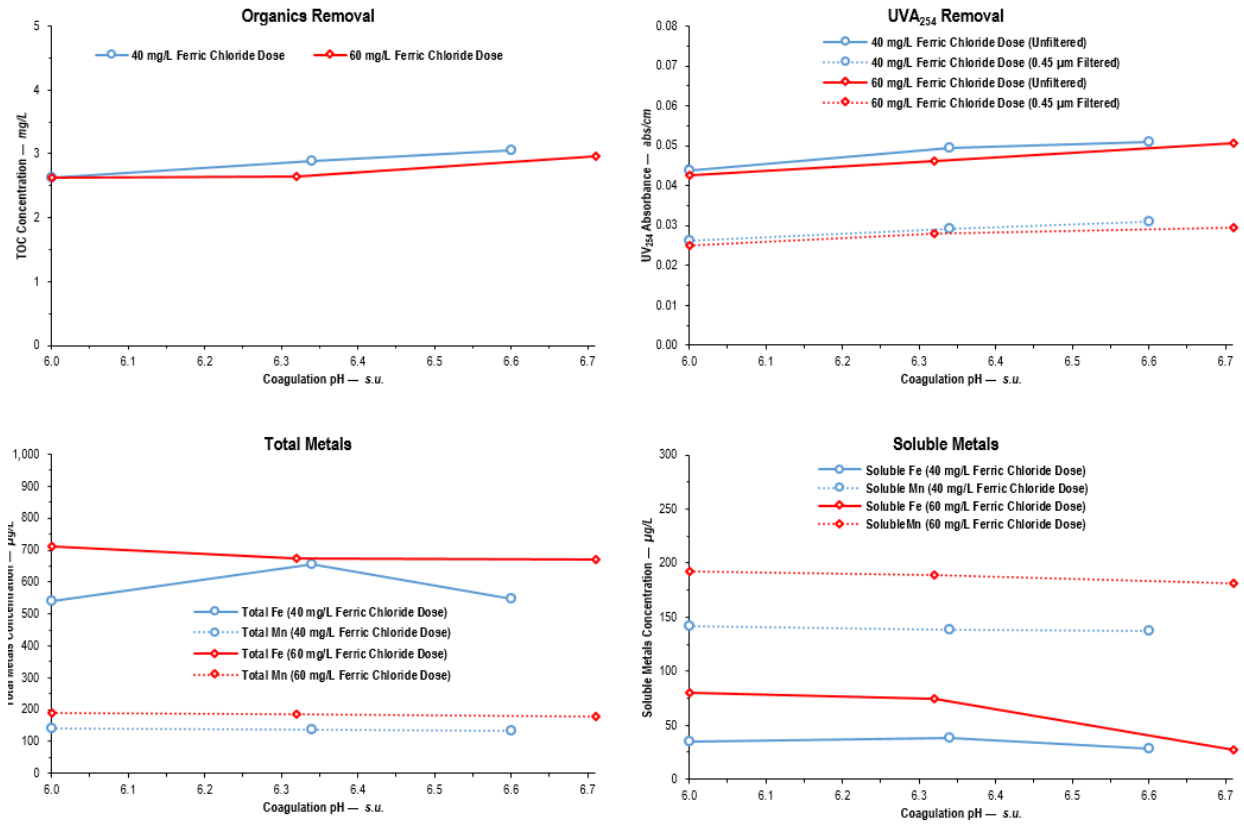

Figure 12. Graphical results from Jar Test series 1 for clarified water quality analyses including TOC, UV_{254} absorbance, total/soluble Fe, and total soluble Mn.

Based on these results, and in conjunction with the results from jar test series 1, it was determined that pH depression improved TOC removal.

Section 5.4 – Bulk Treatment with Ferric Chloride & Final Water Quality Comparison

The remaining pre-ozonated water was treated in bulk for subsequent testing. The optimum ferric chloride dose of 60 mg/L at ambient pH was implemented for simplicity. In total, approximately 700 liters (185 US gallons) was treated using a 200-gal tank and mixer. *Figure 13* depicts the bulk treatment in progress.

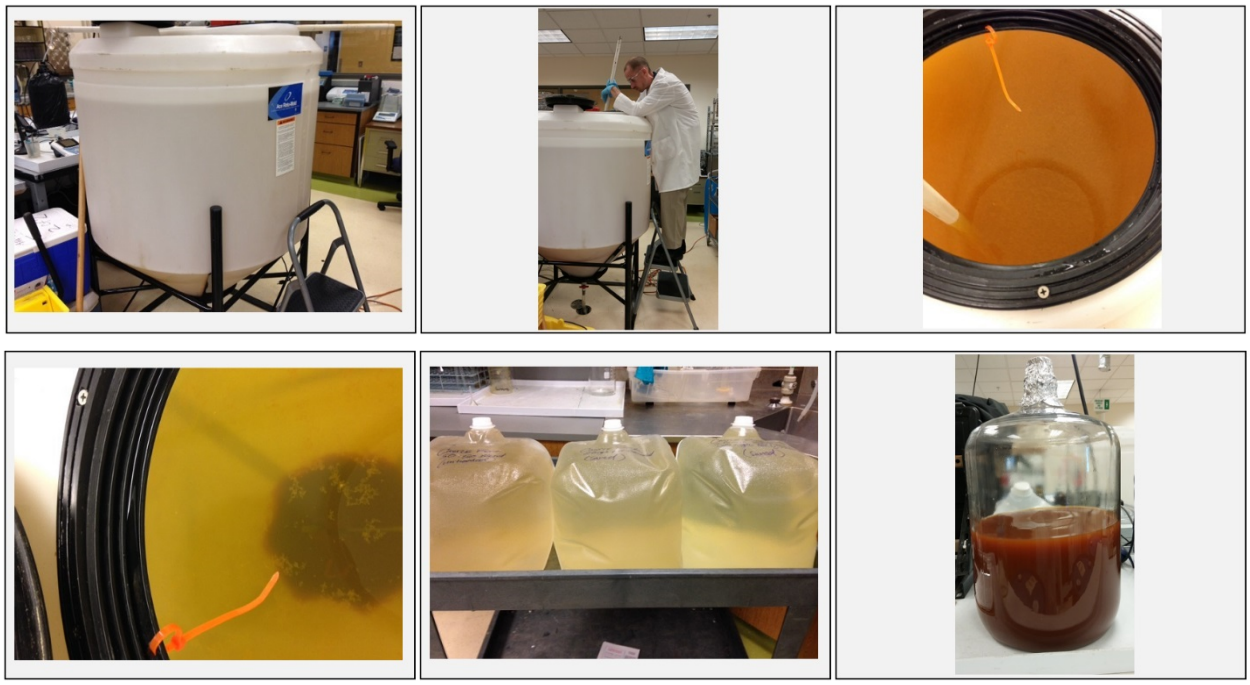

Figure 13. Bulk treatment of remaining pre-ozonated water with ferric chloride: (top left) 200-gal tank used; (top middle) bulk treatment preparation; (top right) top view immediately following ferric chloride addition; (bottom left) end of bulk treatment after ferric chloride floc has settled out; (bottom middle) qualitative comparison of raw water, pre-ozonated water and ferric chloride treated water; (bottom right) settled sludge.

Following the bulk treatment process, the water was re-characterized for selected metals, general chemistry parameters, nitrosamines and CECs. The results of the re-characterization can be found in *Tables 14 and 15* along side the characterization of the untreated blend water and the pre-ozonated water for comparison.

Table 14. Water Characterization Comparison Post-Ferric: metals, general chemistry, and total fluorescence.

Sample Information				
Sample Description		Blended (Untreated)	Pre-Ozonation 2.0 mg/L O_3	60 mg/L $FeCl_3$ at Ambient pH
ASL Metals Analysis				
Calcium, soluble	µg/L	51,900	n/a	51,200
Iron, total	µg/L	1,290	1,270	2,500
Iron, soluble	µg/L	10.0 J	29.5 J	69.9 J
Magnesium, soluble	µg/L	6,590	n/a	6,890
Manganese, total	µg/L	177	197	193
Manganese, soluble	µg/L	0.45 J	78.4	188
Hardness, calcium	mg/L as $CaCO_3$	130	n/a	128
Hardness, magnesium	mg/L as $CaCO_3$	27.1	n/a	28.4
Hardness, total	mg/L as $CaCO_3$	157	n/a	156
ASL General Chemistry Analysis				
Alkalinity, total	mg/L as $CaCO_3$	120	n/a	61.9
pH	s.u.	7.4	7.9	6.9
Turbidity	NTU	13.8	10.6	1.66
Conductivity	µS/cm	593	555	611
Ammonia	mg/L-N	0.27	n/a	0.055 J

Table 14. Water Characterization Comparison Post-Ferric: metals, general chemistry, and total fluorescence.

Sample Information				
Bromide	µg/L	83.8	n/a	88.5
Bromate	µg/L	<5.00 U	<5.00 U	n/a
Nitrate/Nitrite	mg/L-N	0.86	n/a	n/a
Nitrite	mg/L-N	0.12	n/a	n/a
TDS	mg/L	306	n/a	353
TOC	mg/L	4.32	n/a	2.21
DOC	mg/L	4.04	3.21	2.24
UVA_{254}, unfiltered	abs/cm	0.115	0.085	n/a
UVA_{254}	abs/cm	0.076	0.047	0.029
UVT_{254}, unfiltered	%	76.8	82.2	n/a
UVT_{254}	%	84.0	89.8	93.6
SUVA, with filtered analytes	L/mg*m	1.87	1.45	1.29
University of Arizona, Snyder Labs Total Fluorescence (TF) Analysis				
UVA_{254}	abs/cm	0.082	0.050	0.033
UVT_{254}	%	82.8	89.1	92.7
Total Fluorescence	R.U. nm^2	103,887	35,978	24,016

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

The results summarized in *Table 14* show a total reduction in DOC of 44.6 percent from the untreated blend water; the SUVA decreased from 1.87 to 1.29. Additionally, the total fluorescence dropped by a total of 76.9 percent from the untreated blend water.

Table 15. Water Characterization Comparison Post-Ferric: CECs and nitrosamines.

Sample Information				
Sample Description		Blended (Untreated)	Pre-Ozonation 2.0 mg/L O_3	60 mg/L $FeCl_3$ at Ambient pH
Eurofins Selected Contaminants of Emerging Concern (CEC) Analysis				
1,4-Dioxane	ng/L	270	190	n/a
17β-estradiol	ng/L	0.45	<0.4 U	n/a
Perfluorooctanoic acid (PFOA)	ng/L	12	11	n/a
Perfluorooctanesulfonic acid (PFOS)	ng/L	<2.5 U	<2.5 U	n/a
Eurofins Contaminants of Emerging Concern (CEC) Analysis				
2,4-D	ng/L	110	53	56
4-nonylphenol - semi quantitative	ng/L	2,000	1,600	1,200
Acesulfame-K	ng/L	580	300	310
Amoxicillin (semi-quantitative)	ng/L	480	<20 U	<20 U
Atenolol	ng/L	66	<5 U	<5
Azithromycin	ng/L	550	25	<20 U
BPA	ng/L	<10 U	<10 U	48
Caffeine	ng/L	69	<5 U	<5 U
Carbamazepine	ng/L	58	<5 U	<5 U
Cotinine	ng/L	34	28	26
DEET	ng/L	31	15	16
Diclofenac	ng/L	44	<5 U	<5 U
Diltiazem	ng/L	15	<5 U	<5 U

Table 15. Water Characterization Comparison Post-Ferric: CECs and nitrosamines.

Sample Information				
Fluoxetine	ng/L	22	<10 U	<10 U
Gemfibrozil	ng/L	140	<5 U	<5 U
Iohexal	ng/L	110	100	89
Lidocaine	ng/L	130	<5 U	<5 U
Lopressor	ng/L	140	<20 U	<20 U
Naproxen	ng/L	59	<10 U	<10 U
Primidone	ng/L	27	34	38
Quinoline	ng/L	16	10	9.5
Sucralose	ng/L	18,000	15,000	14,000
Sulfadimethoxine	ng/L	23	15	<5 U
Sulfamethoxazole	ng/L	290	31	<5 U
TCEP	ng/L	36	44	62
TCPP	ng/L	300	310	330
TDCPP	ng/L	220	170	100
Trimethoprim	ng/L	120	<5 U	<5 U
TOTAL CECs	ng/L	23,675	17,735	16,285
Eurofins Nitrosamines Analysis				
N-Nitrosodibutylamine (NDBA)	ng/L	2.00	<2.00 U	2.20
N-Nitrosodiethylamine (NDEA)	ng/L	<2.00 U	<2.00 U	<2.00 U
N-Nitroso-dimethylamine (NDMA)	ng/L	<2.00 U	9.70	12.0
N-Nitrosodi-n-propylamine (NDPA)	ng/L	<2.00 U	<2.00 U	<2.00 U
N-Nitrosomethylethylamine (NMEA)	ng/L	<2.00 U	<2.00 U	<2.00 U
N-Nitrosomorpholine (NMOR)	ng/L	2.00	<2.00 U	<2.00 U
N-Nitrosopiperidine (NPIP)	ng/L	<2.00 U	<2.00 U	<2.00 U
N-Nitrosopyrollidine (NPYR)	ng/L	<2.00 U	<2.00 U	<2.00 U
TOTAL NITROSAMINES	ng/L	4.00	9.70	14.2

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

Of the full list of 60 compounds included in the CEC analysis, there were 13 compounds detected post ferric chloride treatment, with a total CEC mass of 16,285 ng/L (an additional 8.18 percent reduction in total CECs; 31.2 percent from the untreated blend water). Most notably, additional reduction in 4-nonylphenol, Azithromycin, and sucralose was observed. The 4-nonylphenol was reduced by a total of 40.0 percent, Azithromycin was reduced to non-detection levels, and sucralose was reduced by 22.2 percent compared to the untreated blend water following both pre-ozonation and ferric chloride treatments. The EEM heat maps across all three treatment steps are depicted below in *Figure 14*, and show a marked decrease in aromatic proteins, fulvic acid-like, humic-acid like and soluble microbial by-product-like organics from the untreated blend water.

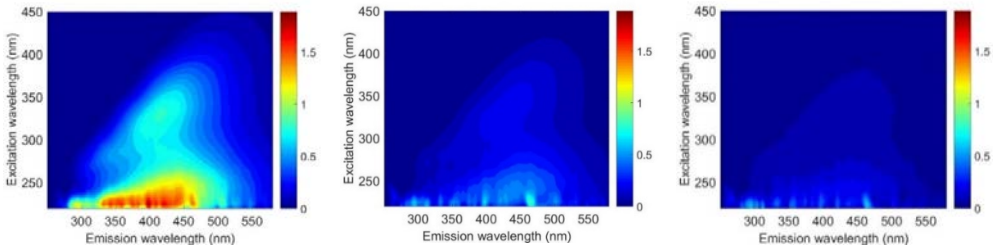

Figure 14. Exitation Emission Matrix heat map for (left) untreated blend water, (middle) pre-ozonated with 2.0 mg/L O_3, and (right) 60 mg/L ferric chloride treated at ambient pH (ALL EEM heat maps normalized to untreated water; Snyder labs, University of Arizona).

Section 6.0 – Biologically Active Carbon (BAC) Filtration

Following the pre-ozonation, and ferric chloride coagulation treatments, the water was processed through a BAC filter. The BAC system used was composed of a two inch diameter glass column loaded with one liter of biologically active *spent*-anthracite (acquired from PCWPF). The column was established free of air bubbles and oriented in an up-flow configuration to prevent clogging. Spent anthracite was used as the medium for the organisms to attach to, minimizing contributions to organics removal via adorptive processes. The column was inoculated with the test organisms two weeks prior to testing, and increasing concentrations of the pre-treated sample water were gradually introduced to allow the organisms time to acclimate to the water quality. The column was covered to protect it from light and prevent algae growth. During the acclimation period, a covered reactor was used as a recirculation basin to keep fresh feed water flowing through the column continuously while the organism population was established. *Figure 15* depicts the BAC system setup.

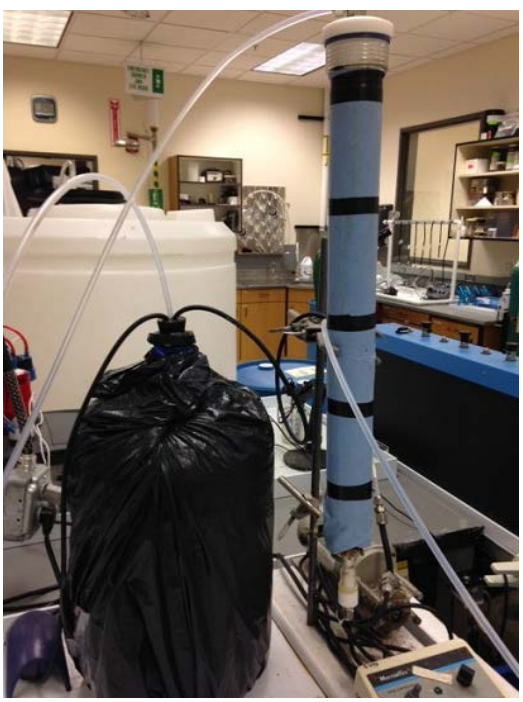

Figure 15. BAC system setup including the two inch diameter glass column (blue) in an upflow configuration with a recirculation basin (black reactor) used during the acclimation period.

Prior to processing the treated water through the BAC filter, a set of screening tests were performed to determine the appropriate EBCT for organics removal. The EBCT screening test consisted of setting the

BAC system flow rate to approximately 142.9 mL/min (1-L of water processed every 7 minutes) to establish a 7 minute EBCT. A small batch of water was recirculated through the column several times to achieve a sequential application of 7, 14, 21 and 28 minute EBCTs, and DOC analyzed in each interval to determine the most appropriate EBCT. *Figure 16* depicts the results of the BAC screening tests.

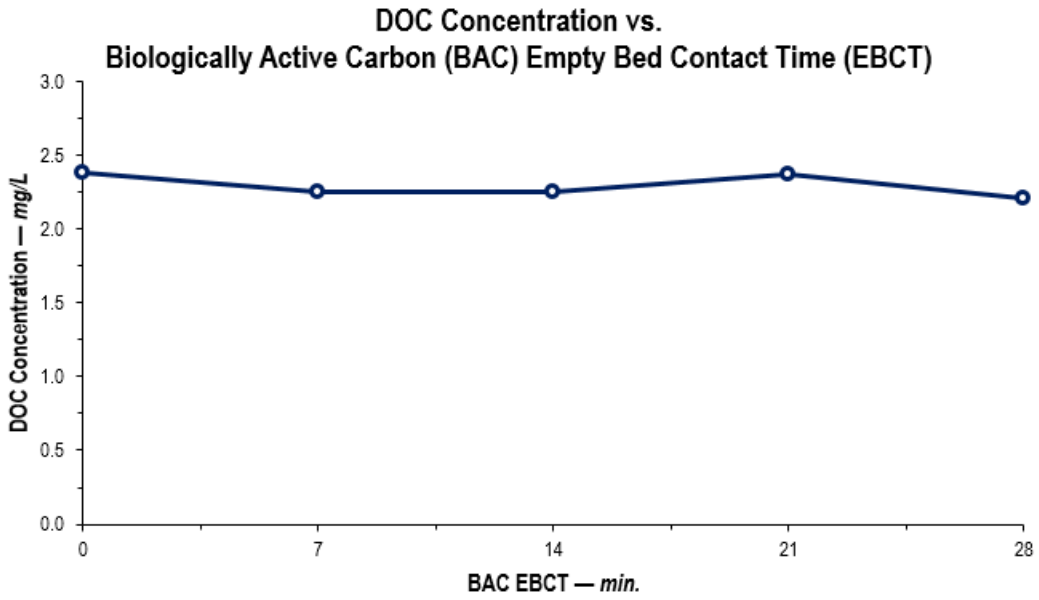

Figure 16. BAC EBCT screening tests.

Based on these results, it was determined that an EBCT of 7 minute or less was optimum- with an achieved 5.46 percent reduction in DOC concentration. One week following the BAC screening tests, the rest of the bulk treated water was processed through the BAC column at a flow rate of approximately 142.9 mL/min to simulate a 7 minute EBCT. The BAC effluent was characterized for water quality parameters of interest, summarized below in *Table 16* along side the characterization of the other treatment steps for comparison.

Table 16. Water Characterization Comparison Post BAC: metals, general chemistry, and total fluorescence.

Sample Information					
Sample Description		Blended (Untreated)	Pre-Ozonation 2.0 mg/L O_3	60 mg/L $FeCl_3$ at Ambient pH	7.0 min EBCT BAC Effluent
ASL Metals Analysis					
Calcium, soluble	µg/L	51,900	n/a	51,200	n/a
Iron, total	µg/L	1,290	1,270	2,500	26.4 J
Iron, soluble	µg/L	10.0 J	29.5 J	69.9 J	15.7 J
Magnesium, soluble	µg/L	6,590	n/a	6,890	n/a
Manganese, total	µg/L	177	197	193	12.8
Manganese, soluble	µg/L	0.45 J	78.4	188	13.4
Hardness, calcium	mg/L as $CaCO_3$	130	n/a	128	n/a
Hardness, magnesium	mg/L as $CaCO_3$	27.1	n/a	28.4	n/a
Hardness, total	mg/L as $CaCO_3$	157	n/a	156	n/a
ASL General Chemistry Analysis					
Alkalinity, total	mg/L as $CaCO_3$	120	n/a	61.9	n/a
pH	s.u.	7.4	7.9	6.9	7.0
Turbidity	NTU	13.8	10.6	1.66	0.22
Conductivity	µS/cm	593	555	611	642

Table 16. Water Characterization Comparison Post BAC: metals, general chemistry, and total fluorescence.

Sample Information					
Ammonia	mg/L-N	0.27	n/a	0.055 J	0.13
Bromide	µg/L	83.8	n/a	88.5	n/a
Bromate	µg/L	<5.00 U	<5.00 U	n/a	n/a
Nitrate/Nitrite	mg/L-N	0.86	n/a	n/a	n/a
Nitrite	mg/L-N	0.12	n/a	n/a	n/a
TDS	mg/L	306	n/a	353	n/a
TOC	mg/L	4.32	n/a	2.21	2.01
DOC	mg/L	4.04	3.21	2.24	2.00
UVA_{254}, unfiltered	abs/cm	0.115	0.085	n/a	0.027
UVA_{254}	abs/cm	0.076	0.047	0.029	0.026
UVT_{254}, unfiltered	%	76.8	82.2	n/a	93.9
UVT_{254}	%	84.0	89.8	93.6	94.2
SUVA, with filtered analytes	L/mg*m	1.87	1.45	1.29	1.29
University of Arizona, Snyder Labs Total Fluorescence (TF) Analysis					
UVA_{254}	abs/cm	0.082	0.050	0.033	0.030
UVT_{254}	%	82.8	89.1	92.7	93.3
Total Fluorescence	R.U. nm^2	103,887	35,978	24,016	26,587

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

In total, the BAC treatment achieved a total DOC reduction of 10.7 percent, or 0.24 mg/L, following the ferric chloride coagulation. There was no appreciable change in UVA_{254}, SUVA, or total fluorescence post-BAC filtration. See *Figure 17* for visual comparison of water quality through treatment process to this point. It was also observed that the water color was completely removed, as depicted below in *Figure 17*.

Figure 17. Visual WQ comparison (left) untreated, (middle-left) pre-ozonated, (middle-right) bulk $FeCl_3$ treated and (right) BAC effluent.

Additional water quality analyses included CECs and nitrosamines, summarized below in Table 17 along side the CEC and nitrosamine results from the other treatment steps.

Table 17. Water Characterization Comparison Post BAC: CECs and nitrosamines.

Sample Information					
Sample Description		Blended (Untreated)	Pre-Ozonation 2.0 mg/L O_3	60 mg/L $FeCl_3$ at Ambient pH	7.0 min EBCT BAC Effluent
Eurofins Selected Contaminants of Emerging Concern (CEC) Analysis					
1,4-Dioxane	ng/L	270	190	n/a	160
17β-estradiol	ng/L	0.45	<0.4 U	n/a	n/a
Perfluorooctanoic acid (PFOA)	ng/L	12	11	n/a	n/a
Perfluorooctanesulfonic acid (PFOS)	ng/L	<2.5 U	<2.5 U	n/a	n/a
Eurofins Contaminants of Emerging Concern (CEC) Analysis					
2,4-D	ng/L	110	53	56	68
4-nonylphenol - semi quantitative	ng/L	2,000	1,600	1,200	1,900
Acesulfame-K	ng/L	580	300	310	300
Amoxicillin (semi-quantitative)	ng/L	480	<20 U	<20 U	<20 U
Atenolol	ng/L	66	<5 U	<5	<5
Azithromycin	ng/L	550	25	<20 U	<20 U
BPA	ng/L	<10 U	<10 U	48	48
Caffeine	ng/L	69	<5 U	<5 U	<5 U
Carbamazepine	ng/L	58	<5 U	<5 U	<5 U
Cotinine	ng/L	34	28	26	27
DEET	ng/L	31	15	16	15
Diclofenac	ng/L	44	<5 U	<5 U	<5 U
Diltiazem	ng/L	15	<5 U	<5 U	<5 U
Fluoxetine	ng/L	22	<10 U	<10 U	<10 U
Gemfibrozil	ng/L	140	<5 U	<5 U	<5 U
Iohexal	ng/L	110	100	89	85
Lidocaine	ng/L	130	<5 U	<5 U	<5 U
Lopressor	ng/L	140	<20 U	<20 U	<20 U
Naproxen	ng/L	59	<10 U	<10 U	<10 U
Primidone	ng/L	27	34	38	54
Quinoline	ng/L	16	10	9.5	11
Sucralose	ng/L	18,000	15,000	14,000	14,000
Sulfadimethoxine	ng/L	23	15	<5 U	<5 U
Sulfamethoxazole	ng/L	290	31	<5 U	<5 U
TCEP	ng/L	36	44	62	42
TCPP	ng/L	300	310	330	320
TDCPP	ng/L	220	170	100	140
Trimethoprim	ng/L	120	<5 U	<5 U	<5 U
TOTAL CECs	ng/L	23,675	17,735	16,285	17,010
Eurofins Nitrosamines Analysis					
N-Nitrosodibutylamine (NDBA)	ng/L	2.00	<2.00 U	2.20	<2.00 U
N-Nitrosodiethylamine (NDEA)	ng/L	<2.00 U	<2.00 U	<2.00 U	<2.00 U
N-Nitroso-dimethylamine (NDMA)	ng/L	<2.00 U	9.70	12.0	12.0
N-Nitrosodi-n-propylamine (NDPA)	ng/L	<2.00 U	<2.00 U	<2.00 U	<2.00 U
N-Nitrosomethylethylamine (NMEA)	ng/L	<2.00 U	<2.00 U	<2.00 U	<2.00 U

Table 17. Water Characterization Comparison Post BAC: CECs and nitrosamines.

Sample Information					
N-Nitrosomorpholine (NMOR)	ng/L	2.00	<2.00 U	<2.00 U	<2.00 U
N-Nitrosopiperidine (NPIP)	ng/L	<2.00 U	<2.00 U	<2.00 U	<2.00 U
N-Nitrosopyrollidine (NPYR)	ng/L	<2.00 U	<2.00 U	<2.00 U	<2.00 U
TOTAL NITROSAMINES	ng/L	4.00	9.70	14.2	12.0

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

The EEM heat maps across all four treatment steps are depicted below in *Figure 18*, and support the findings from the CEC analysis; a slight increase in CECs following the BAC treatment compared to the ferric chloride coagulation treatment.

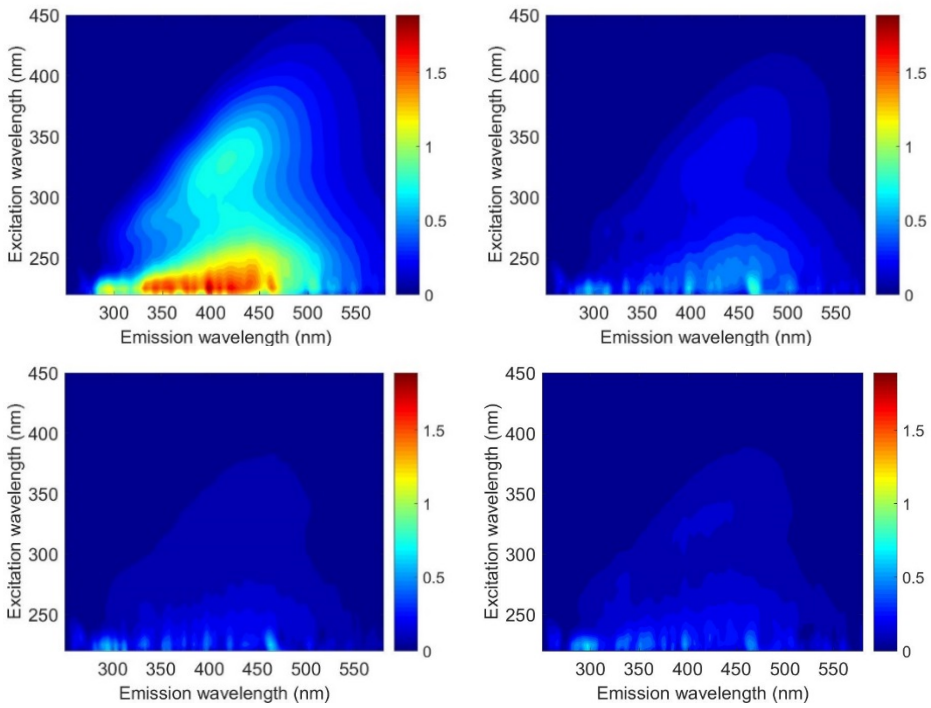

Figure 18. Exitation Emission Matrix heat map for (top-left) untreated blend water, (top-right) pre-ozonated with 2.0 mg/L O_3, (bottom left) 60 mg/L ferric chloride treated at ambient pH, and (bottom right) 7.0 min EBCT BAC Effluent (ALL EEM heat maps normalized to untreated water; Snyder labs, University of Arizona).

Section 7.0 – Microfiltration (MF) & Post BAC/MF Ozonation

Immediately following the BAC treatment, the water was processed through a 10 inch, double open ended, polypropylene cartridge filter with a 0.20 µm exclusion size to simulate microfiltration. Currently, PCWPF operates with microfiltration membranes with a 0.10 µm nominal pore size. No water quality analysis was conducted following the MF step. *Figure 19* below illustrates the filtration process used, as well as the appearance of the filter after all of the water had been processed through it.

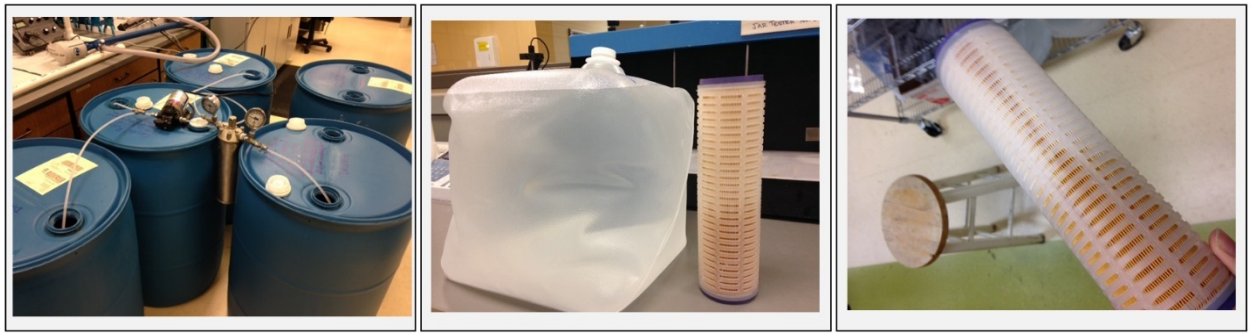

Figure 19. Microfiltration simulation: (left) system setup with pump and cartridge filter; (middle) cartridge filter following filtration and water effluent; (right) close up of used cartridge filter.

Section 7.1 – Post-BAC/MF Ozonation Demand/Decay

Post BAC and microfiltration, round two of the ozone demand and decay testing was conducted in semi-batch mode. In these tests, ozone was applied until a target aqueous residual was reached; ozone doses to achieve 0.3 mg/L, 1.0 mg/L, and a 2.0 mg/L target ozone residuals were used. These residuals support the design of an ozone system to achieve 0.5-log, 2-log, and 3-log giardia disinfection credits, respectively. Two additional ozone demand-decay tests were performed at the 1.0 mg/L target residual: one with 5 mg/L hydrogen peroxide (H_2O_2) addition to explore the impact of ozone-AOP on CEC oxidation, and the other with a 0.5 mg/L-N ammonia addition pre-ozonation for potential bromate mitigation. *Table 18* summarizes the test conditions, ozone demand/decay data, and the general resulting water quality data, while *Figure 20* depicts the ozone demand/decay, *Figure 21* depicts the resultant UVA_{254} and SUVA with increasing ozone dose, and *Figure 22* depicts the resultant UVA_{254} and SUVA for all post-BAC/MF ozonation tests.

Table 18. Post-BAC/MF Ozonation: Ozone Demand/Decay data, and final WQ summary.

Ozone Test Conditions	Units	Run 1 (0.3 mg/L Residual) (Demand/Decay)	Run 2 (1.0 mg/L Residual (Demand/Decay)	Run 6 (Optimum) (1.8 mg/L Residual) (Demand/Decay)	Run 3 (2.0 mg/L Residual) (Demand/Decay)	Run 4 (Ozone AOP) (5.0 mg/L H_2O_2)	Run 5 Bromate Mitigation) (0.5 mg/L NH_3-N)
Target Ozone Residual	mg/L	0.30	1.00	**1.80**	2.00	1.00	1.00
Applied Ozone Dose	mg/L	1.08	2.47	**2.85**	5.11	2.50	2.45
Terminal Ozone Residual	mg/L	0.33	1.09	**1.76**	2.14	0.00	1.10
Ozone Demand/Decay	***Units***						
Immediate Ozone Demand	mg/L	0.41	0.40	**0.31**		n/a	0.36
Ozone Demand Slope		0.513	0.553	**0.735**	0.463	n/a	0.553
Initial Decay Residual	mg/L	0.36	1.09	**1.79**	2.15	n/a	1.10
Decay k		-0.222	-0.103	**-0.085**	-0.078	n/a	-0.102
Final WQ Data	***Units***						
pH	s.u.	7.68	7.69	**7.66**	7.82	7.70	7.87
Turbidity	NTU	0.18	0.33	**0.34**	0.31	0.22	0.29
DOC	mg/L	1.97	1.99	**2.01**	1.99	2.02	2.05
UVA_{254} (unfiltered)	abs/cm	0.023	0.021	**0.019**	0.021	0.021	0.021
UVA_{254} (0.45 µm filtered)	abs/cm	0.020	0.018	**0.015**	0.018	0.021	0.018
UVT_{254} (0.45 µm filtered)	%	95.5	95.9	**96.6**	96.1	95.4	95.9
SUVA (filtered)	L/mg*m	1.01	0.91	**0.74**	0.87	1.01	0.89

Table 18. Post-BAC/MF Ozonation: Ozone Demand/Decay data, and final WQ summary.

Ozone Test Conditions	Units	Run 1 (0.3 mg/L Residual) (Demand/Decay)	Run 2 (1.0 mg/L Residual (Demand/Decay)	Run 6 (Optimum) (1.8 mg/L Residual) (Demand/Decay)	Run 3 (2.0 mg/L Residual) (Demand/Decay)	Run 4 (Ozone AOP) (5.0 mg/L H_2O_2)	Run 5 Bromate Mitigation) (0.5 mg/L NH_3-N)
Total Fluorescence	R.U. nm²	n/a	n/a	**8,782**	n/a	8,917	n/a
Ammonia	mg/L-N	n/a	n/a	**0.097 J**	n/a	n/a	n/a
Bromate	µg/L	<5.00 U	<5.00 U	**<5.00 U**	<5.00 U	<5.00 U	<5.00 U
Iron, total	µg/L	n/a	n/a	**29.0 J**	n/a	n/a	n/a
Iron, soluble	µg/L	n/a	n/a	**12.2 J**	n/a	n/a	n/a
Manganese, total	µg/L	n/a	n/a	**39.9**	n/a	n/a	n/a
Manganese, soluble	µg/L	n/a	n/a	**18.8**	n/a	n/a	n/a

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

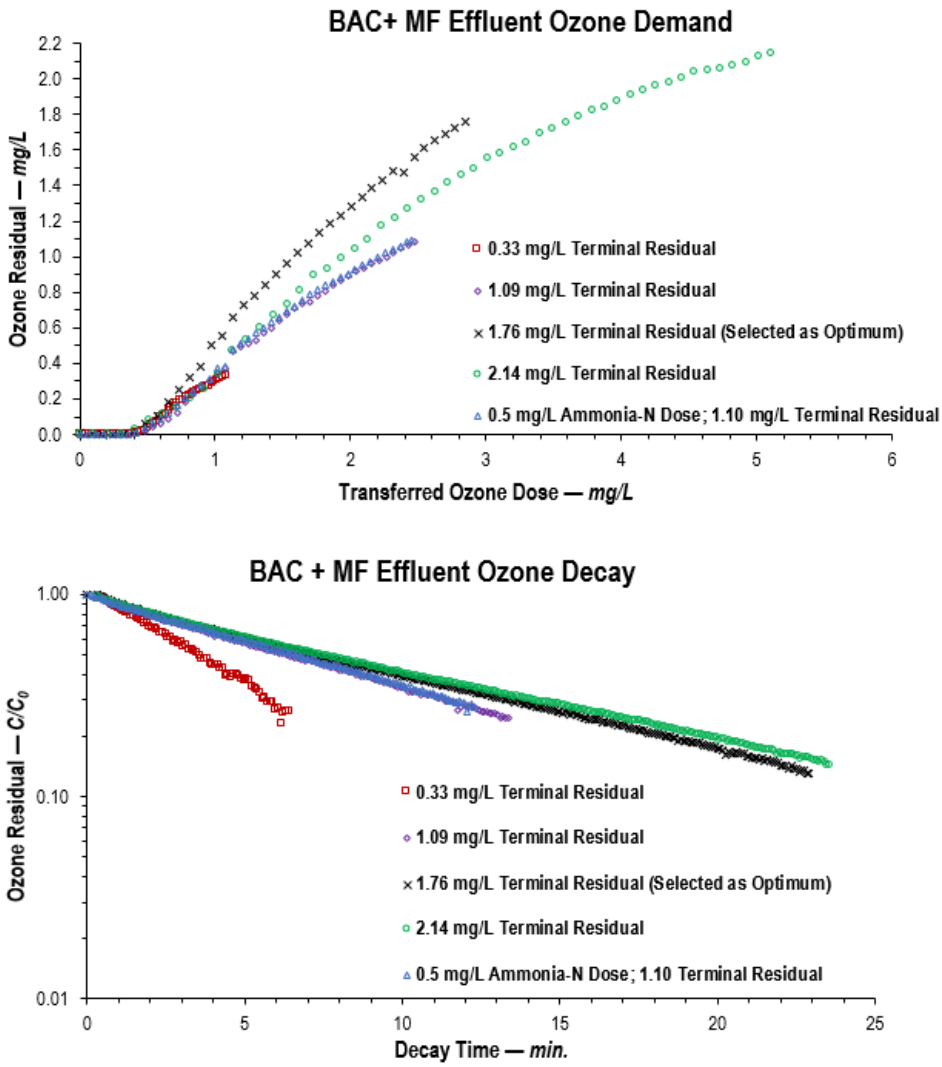

Figure 20. Post-BAC/MF Ozonation (top) demand curves and (bottom) decay curves.

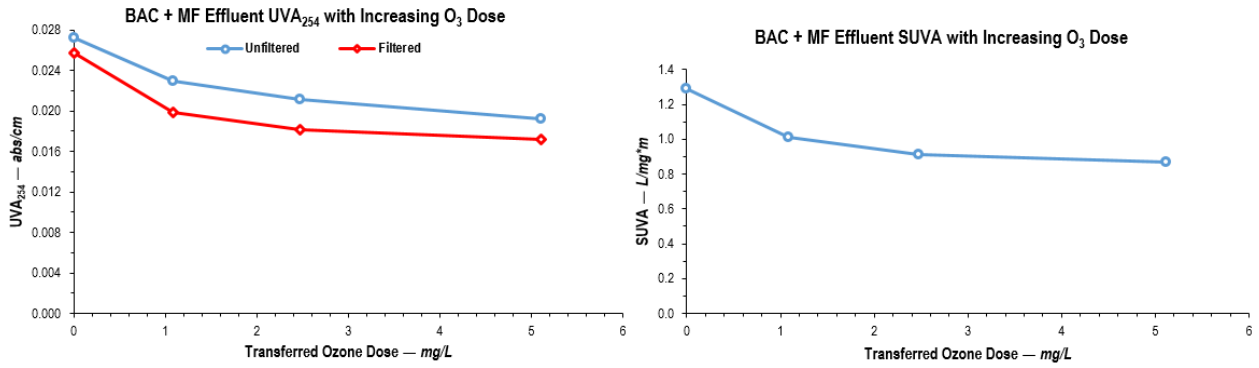

Figure 21. Post-BAC/MF ozonation (left) UVA_{254} and (right) SUVA curves with increasing ozone dose.

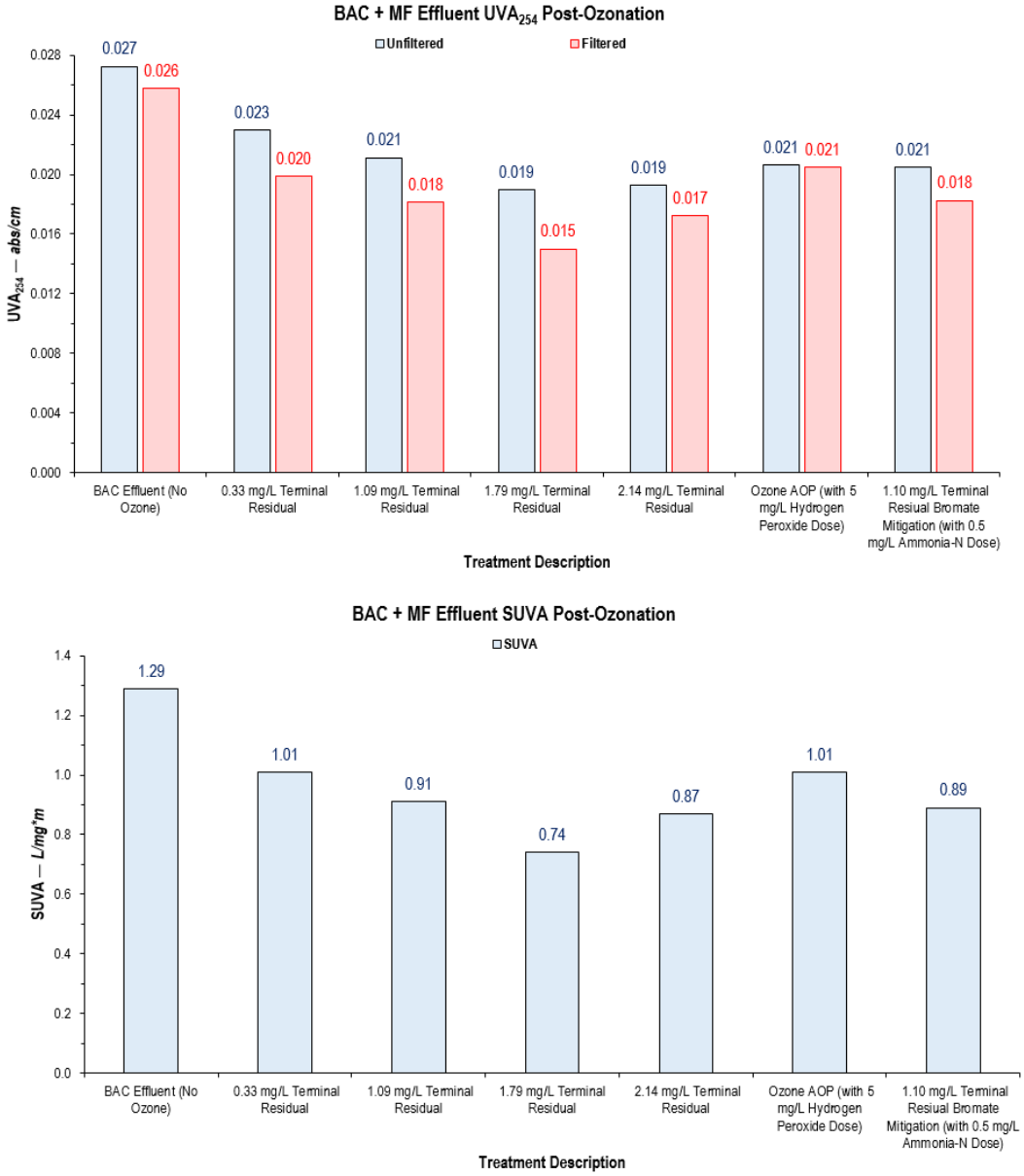

Figure 22. Post-BAC/MF Ozonation (top) UVA_{254} and (bottom) SUVA results.

Figure 23. Post-BAC/MF Ozonation color comparison (pink coloration temporarily develops).

Given the UVA_{254} and DOC results from the demand-decay testing, an ozone dose of 3.0 mg/L (approximately 1.8 mg/L residual) was selected as optimum for round two of the ozonation. The remaining ~670-L of blended raw water was treated in 11-L batches with an average applied ozone dose of 3.01 mg/L O_3. It was noted that this applied ozone dose resulted in a temporary development of a pink hue to the water as well and stained the inside of the contactor (glass, stainless steel, and tephlon components) yellow-orange by the completion of bulk treatment.

Section 7.2 – Nitrosamine Formation Potential

Nitrosamines were analyzed in the final treatment of each post-BAC ozonation test. These results are summarized in Table 19, and it was found that nitrosamine formation did not significantly increase from the BAC effluent concentration (12 ng/L total from *Table 18*). At the optimum selected ozone dose of 2.85 mg/L transferred ozone dose (1.8 mg/L residual) the nitrosamine formation remained largely unchanged at 11 ng/L compared to the previous 12 ng/L, with the entirety of the nitrosamines being in the form of N-Nitroso-dimethylamine (NDMA). It is expected that improved effectiveness of NDMA removal and formation mitigation would be observed at pilot-scale testing and/or full scale operation.

Table 19. Post-BAC/MF Ozonation: Ozone Demand/Decay data, and nitrosamine results.

Ozone Test Conditions	Units	Run 1 (0.33 mg/L Residual) (Demand/Decay)	Run 2 (1.09 mg/L Residual (Demand/Decay)	Run 6 (Optimum) (1.76 mg/L Residual) (Demand/Decay)	Run 3 (2.14 mg/L Residual) (Demand/Decay)	Run 4 (Ozone AOP) (5.0 mg/L H_2O_2)	Run 5 (Bromate Mitigation)
Target Ozone Residual	mg/L	0.30	1.00	**1.80**	2.00	1.00	1.00
Applied Ozone Dose	mg/L	1.08	2.47	**2.85**	5.11	2.50	2.45
Terminal Ozone Residual	mg/L	0.33	1.09	**1.76**	2.14	0.00	1.10
Ozone Demand/Decay	***Units***						
Immediate Ozone Demand	mg/L	0.41	0.40	**0.31**	0.00	n/a	0.36
Ozone Demand Slope		0.513	0.553	**0.735**	0.463	n/a	0.553
Initial Decay Residual	mg/L	0.36	1.09	**1.79**	2.15	n/a	1.10
Decay k		-0.222	-0.103	**-0.085**	-0.078	n/a	-0.102
Final WQ Data	***Units***						
N-Nitrosodibutylamine (NDBA)	ng/L	3.60	2.40	**<2.00 U**	<2.00 U	<2.00 U	<2.00 U
N-Nitrosodiethylamine (NDEA)	ng/L	<2.00 U	<2.00 U	**<2.00 U**	<2.00 U	<2.00 U	<2.00 U
N-Nitroso-dimethylamine (NDMA)	ng/L	10.0	10.0	**11.0**	9.20	7.10	9.40
N-Nitrosodi-n-propylamine (NDPA)	ng/L	<2.00 U	<2.00 U	**<2.00 U**	<2.00 U	<2.00 U	<2.00 U
N-Nitrosomethylethylamine (NMEA)	ng/L	<2.00 U	<2.00 U	**<2.00 U**	<2.00 U	<2.00 U	<2.00 U
N-Nitrosomorpholine (NMOR)	ng/L	<2.00 U	<2.00 U	**<2.00 U**	<2.00 U	<2.00 U	<2.00 U
N-Nitrosopiperidine (NPIP)	ng/L	<2.00 U	<2.00 U	**<2.00 U**	<2.00 U	<2.00 U	<2.00 U
N-Nitrosopyrollidine (NPYR)	ng/L	<2.00 U	<2.00 U	**<2.00 U**	<2.00 U	<2.00 U	<2.00 U
TOTAL NITROSAMINES	ng/L	13.6	12.4	**11.0**	9.20	7.10	9.40

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

Section 7.3 – CEC Reduction on Selected Ozonation Doses & AOP

With respect to the post-BAC ozone dose applied, total CEC reduction was substantial. Compared to the untreated water, the optimum selected ozone dose achieved a total of 69.2 percent reduction in total

CECs. Compared to the BAC effluent (summarized in *Table 18*), the total reduction in CECs was 57.3 percent. Beyond this ozone dose (residual of 2.14 mg/L; highest dose applied) the CEC reduction was not greatly improved, thus confirming the ozone dose selected had reached the point of diminishing returns with respect to CEC reduction as illustrated in *Figure 24*. *Figure 25* illustrates the total CEC reduction across each treatment process. The Ozone AOP test achieved even greater reduction in CECs; with a lower ozone dose applied than the optimum conditions selected (2.50 mg/L ozone dose instead of 2.85 mg/L) in conjunction with a 5 mg/L hydrogen peroxide dose, the total reduction compared to the untreated water was 82.7 percent, and compared to the BAC effluent 75.9 percent reduction. *Table 20* summarizes these results.

Table 20. Post-BAC/MF Ozonation: Reduction in CECs.

Sample Information						
Sample Description		Blended (Untreated)	0.3 mg/L Residual	1.76 mg/L Residual	2.14 mg/L Residual	Ozone AOP 5.0 mg/L H_2O_2
Eurofins Selected Contaminants of Emerging Concern (CEC) Analysis						
1,4-Dioxane	ng/L	270	n/a	<70 U	n/a	n/a
17β-estradiol	ng/L	0.45	n/a	<0.4 U	n/a	n/a
Perfluorooctanoic acid (PFOA)	ng/L	12	n/a	14	n/a	n/a
Perfluorooctanesulfonic acid (PFOS)	ng/L	<2.5 U	n/a	<2.5 U	n/a	n/a
Eurofins Contaminants of Emerging Concern (CEC) Analysis						
2,4-D	ng/L	110	<5 U	<5 U	<5 U	<5 U
4-nonylphenol - semi quantitative	ng/L	2,000	<100 U	<100 U	140	190
Acesulfame-K	ng/L	580	220	<20 U	24	29
Amoxicillin (semi-quantitative)	ng/L	480	<20 U	<20 U	<20 U	<20 U
Atenolol	ng/L	66	<5	<5	<5	<5
Azithromycin	ng/L	550	<20 U	<20 U	<20 U	<20 U
BPA	ng/L	<10 U	<10 U	<10 U	<10 U	<10 U
Caffeine	ng/L	69	<5 U	<5 U	<5 U	<5 U
Carbamazepine	ng/L	58	<5 U	<5 U	<5 U	<5 U
Cotinine	ng/L	34	25	12	11	<10 U
Cyanazine	ng/L	<5 U	<5 U	7.5	<5 U	<5 U
DEET	ng/L	31	<10 U	<10 U	<10 U	<10 U
Diclofenac	ng/L	44	<5 U	<5 U	<5 U	<5 U
Diltiazem	ng/L	15	<5 U	<5 U	<5 U	<5 U
Fluoxetine	ng/L	22	<10 U	<10 U	<10 U	<10 U
Gemfibrozil	ng/L	140	<5 U	<5 U	<5 U	<5 U
Iohexal	ng/L	110	120	90	200	180
Lidocaine	ng/L	130	<5 U	<5 U	<5 U	<5 U
Lopressor	ng/L	140	<20 U	<20 U	<20 U	<20 U
Naproxen	ng/L	59	<10 U	<10 U	<10 U	<10 U
Primidone	ng/L	27	15	<5 U	<5 U	<5 U
Quinoline	ng/L	16	<5 U	<5 U	<5 U	<5 U
Sucralose	ng/L	18,000	12,000	6,700	5,800	3,200
Sulfadimethoxine	ng/L	23	<5 U	<5 U	<5 U	<5 U
Sulfamethoxazole	ng/L	290	<5 U	<5 U	<5 U	<5 U
TCEP	ng/L	36	30	31	36	34
TCPP	ng/L	300	410	430	440	340
TDCPP	ng/L	220	<100 U	<100 U	110	120
Trimethoprim	ng/L	120	<5 U	<5 U	<5 U	<5 U
TOTAL CECs	ng/L	23,675	12,820	7,271	6,621	4,093

Table 20. Post-BAC/MF Ozonation: Reduction in CECs.

Sample Information						
Total CEC Removal (Compared to Untreated)	%	n/a	45.6	69.2	72.0	82.7
Total CEC Removal (Compared to BAC Effluent)	%	n/a	24.6	57.3	61.1	75.9

J = Estimated value below reporting limit.
E = Estimated value above calibration range.
U = Not detected at specified detection limit.

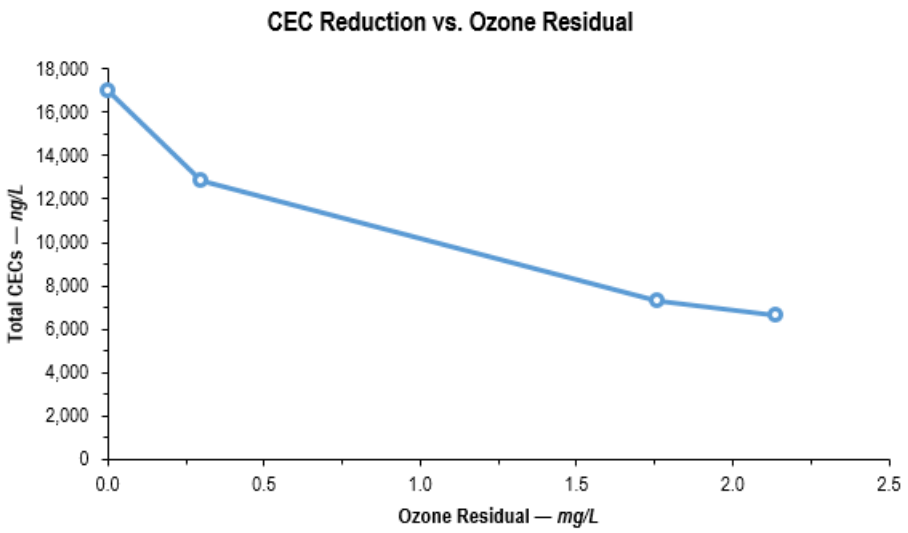

Figure 24. Total CEC removal vs. ozone residual, with the starting point of 17,010 ng/L (BAC effluent concentration).

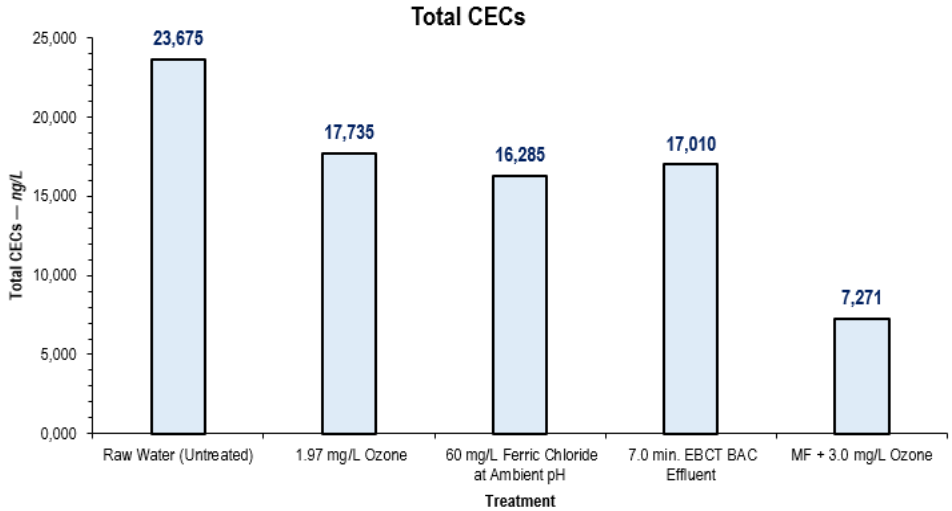

Figure 25. Total CEC removal across each treatment process.

As tabulated previously, the total fluorescence has a very similar trend across each treatment process compared to the CEC reduction depicted in *Figure 25*. This trend is illustrated in *Figure 26* below. This trend is indicative of a strong correlation between total fluorescence and CEC concentrations, similar to the strong correlation between DOC and UVA_{254}. Additionally, *Figure 27* depicts the EEM heat maps which show that organics present in all regions are almost completely eradicated at the optimum ozone dose of 3.0 mg/L as well as with the ozone-AOP test, when compared to the untreated blend water.

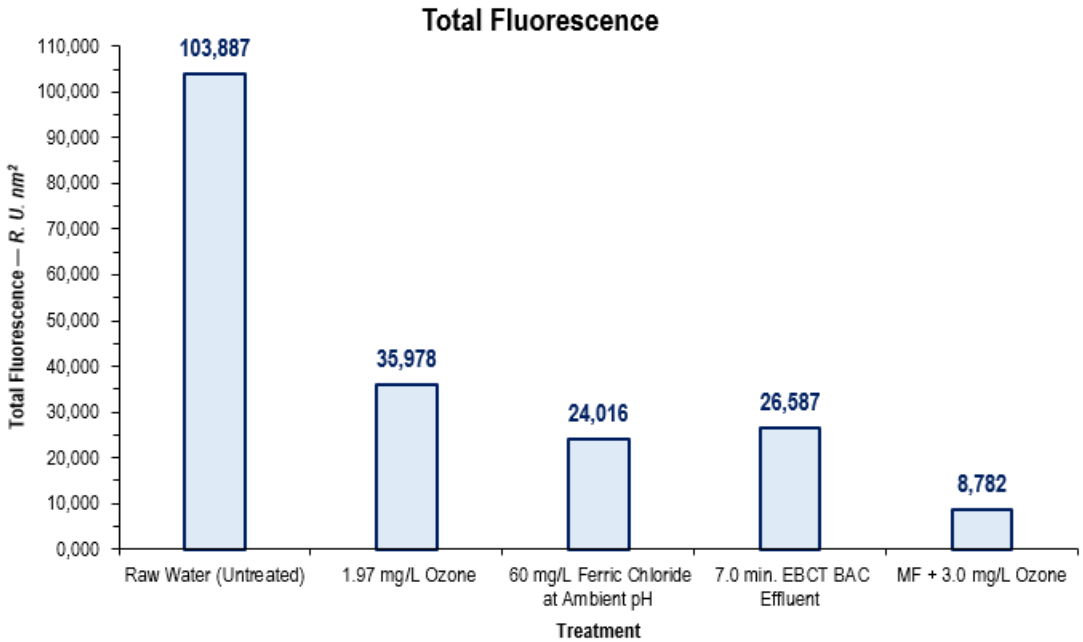

Figure 26. Total fluorescence reduction across each treatment process (Snyder labs, University of Arizona).

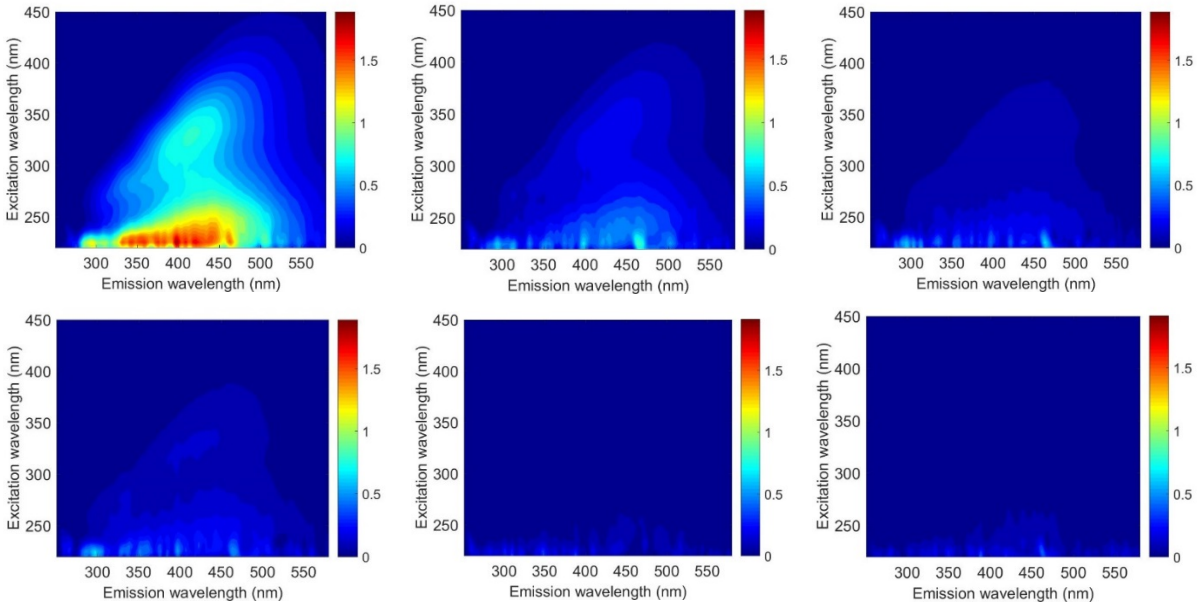

Figure 27. Exitation Emission Matrix heat map for (top-left) untreated blend water, (top-middle) pre-ozonated with 2.0 mg/L O_3, (top-right) 60 mg/L ferric chloride treated at ambient pH, (bottom-left) 7.0 min EBCT BAC Effluent, (Bottom-middle) Post-BAC/MF Ozonation, and (bottom-right) Ozone AOP with 5 mg/L H_2O_2 (ALL EEM heat maps normalized to untreated water; Snyder labs, University of Arizona).

Section 8.0 – Granular Activated Carbon (GAC) Contactors

Following the post-BAC/MF ozonation treatment, the water was treated using a GAC contactors test known as a Rapid Small-Scale Column Test (RSSCT). The RSSCT method is based on *EPA-814-B-96-003 ICR Manual for Bench- and Pilot-Scale Treatment Studies* and is used to model treatment with GAC based on various EBCTs. The method uses a small diameter column and a limited amount of carbon. The sample is processed through the column and the effluent is monitored for organics breakthrough. The test is designed for a 2 to 4 week run time. The RSSCT provides information for adsorption capacity

(extent of adsorption) and the rate of adsorption (adsorption kinetics), which are the two dominant factors impacting breakthrough in GAC columns. Three RSSCT columns were tested with the pre-treated sample water to simulate 10 minute, 15 minute and 20 minute EBCTs. The type of GAC for this test was based on recommendations from a GAC filter media supplier and past experience. The test was conducted with Calgon Carbon F300, which is a bituminous coal based media.

During the tests, water samples were collected and analyzed for DOC and UV_{254} content. The columns were operated until effluent DOC exceeded 70% breakthrough for two consecutive samples or when 30,000 bed volumes (BV) was reached, which ever occurred first, at which time the columns were discontinued.

Graphs of TOC breakthrough vs. bed volumes treated at each EBCT were developed and are provided later in this document.

Section 8.1 – Rapid Small Scale Column Tests (RSSCTs)

The purpose of the column tests was to evaluate the carbon media effectiveness in removing organics in a continuous flow system. The testing was performed using Calgon Carbon F300, and at the following conditions:

Table 21. Testing conditions for the RSSCT three columns.

Carbon Manufacturer and Trade Name	Calgon F300
Test pH	Ambient
Test Temperature	Lab temp (21-22 °C)
Influent TOC	2.00 mg/L

The design criteria for the columns were developed under the guidance of a CH2M expert on RSSCT testing, using baseline water quality parameters provided by the project team. The test equipment used, including pumps, tubing, columns, and fittings, were made of inert materials such as Teflon, glass, and stainless steel.

Section 8.2 – Preparation of Carbon Media

Representative samples of the carbon media were ground and sieved to a standard mesh size, as determined in the RSSCT design. A step-wise decantation process using organics free water was used to wash the sieved carbon media. After washing, the media was dried to a constant weight in a drying oven set to 100 °C, and stored in a capped bottle in a desiccator until ready for use.

Section 8.3 – Column Setup

The media for each column was weighed, saturated with ultrapure water, and de-aerated under a vacuum prior to loading the columns. Ultrapure water was used during the packing process to pack the media wet and avoid entrapment of air in the column. Once the media was transferred into the column, a brief backwashing cycle using ultrapure water was performed to remove any residual fines and to remove air from the bottom of the column.

Section 8.4 – Start-up and Operation

A collapsible 5-gallon plastic cube reservoir was filled with the optimum pre-treated water as determined in the previous bench-scale testing efforts. The column was placed into position and the flow rate was adjusted to the desired rate. The flow rate was checked daily to assure that the flow did not vary more than 5 percent. The effluent line was placed above the RSSCT column with an opening to the atmosphere to avoid siphoning and the column running dry. The amount of water passing through the column was measured by capturing the water in an effluent container and weighing the volume passed when a sample was collected.

Section 8.5 – Sampling

Table 23 shows the analyses that were performed. The samples were collected at regular intervals throughout the test. The test was operated until the effluent total TOC concentration had reached 70% on two consecutive sample dates for column 1, after 46 days of operation for column 2 and after 47 days of operation for column 3.

The columns were designed to have a 10-minute, 15-minute and 20-minute full-scale EBCTs, respectively, and the design is detailed in *Table 22*.

Table 22. Design parameters for each RSSCT column.

Parameter	Units	Column 1 10-min EBCT	Column 1 15-min EBCT	Column 2 20-min EBCT
Full-scale EBCT	min.	10	15	20
Full-scale Particle Size (Mesh)	Sieve	8 x 30	8 x 30	8 x 30
Full-scale Particle Size	mm	1.49	1.49	1.49
RSSCT Particle Size (Mesh)	Sieve	60 x 80	60 x 80	60 x 80
RSSCT Particle Size	mm	0.214	0.214	0.214
RSSCT EBCT	min.	1.44	2.15	2.87
RSSCT Diameter	mm	8.00	8.00	8.00
RSSCT Media Depth	cm	9.09	13.6	18.2
RSSCT Media Volume	cm^3	4.57	6.86	9.14
RSSCT Flow Rate	mL/min.	3.18	3.18	3.18
Scaling Factor	--	6.97	6.97	6.97
Media Density	g/cm3	0.56	0.56	0.56
RSSCT Media Mass	g	2.56	3.84	5.12

The sampling schedule for the RSSCT tests are presented in Table 23.

Table 23. Sampling schedule for RSSCT columns.

Sample Parameter	Sample Frequency	Last Sample Collected
DOC, UVA254	Once a day	When DOC reaches 70% breakthrough for two consecutive samples or 30,000 bed volumes, which ever occurs first.
CECs, PFOS + PFOA, 17β-estradiol	Two samples per column total at 10,000 and 20,000 Bed Volumes	20,000 Bed Volumes.
1,4-Dioxane	One sample per column at 20,000 Bed Volumes	20,000 Bed Volumes.
EEM & TF (Column 2 only)	Three samples total at 10,000, 20,000 and 30,000 Bed Volumes	30,000 Bed Volumes (or 70% breakthrough).
VOCs & SOCs (Column 2 only)	One sample at 30,000 Bed Volumes	30,000 Bed Volumes (or 70% breakthrough).
SDS Test Sample (Column 2 only)	Once at 10,000 Bed Volumes	10,000 Bed Volumes.

In addition to the proposed sampling schedule outlined in *Table 23* a second sample for DOC and UVA_{254} was collected each day and archived in case a need to confirm results or fill in data gaps became necessary. The flow rate was measured while collecting each effluent sample and the total volume of sample water passing through the column was tracked in order to accurately maintain and confirm the flow rate was within 5% variation of the target design flow.

Section 8.6 – RSSCT QA/QC Measures

The flow rate, total operational time, and total volume of water processed was monitored and recorded throughout the testing to ensure no more than 5 percent variation from the target design flow rate. *Table 24* shows these parameters as monitored throughout the testing.

Table 24. Monitored Parameters for QA/QC.

Parameter	Units	Column 1 10 min. EBCT	Column 1 15 min. EBCT	Column 2 20 min. EBCT
Total Vol. of Water Processed	L	127	210	216
Total Time of Operation	min.	40,301	66,267	67,266
Average Flow Rate*	mL/min.	3.16	3.17	3.21
Percent Variation from Design Flow	%	0.92	0.56	0.82

* = Average is weighted based on the time elapsed during effluent sample collection.

Analysis of column effluent samples followed ASL Standard Operating Procedures, which include duplicate analyses, blank spikes, and matrix spikes. All QA/QC criteria stated in the test plan were met and maintained throughout the duration of the tests.

UVA_{254} and water temperature were monitored throughout the test and are discussed further in the RSSCT Testing Results section of this memorandum (Section 8.7).

Section 8.7 – RSSCT Testing Results

The testing was conducted for a total of 6.67 weeks (46.7 days), and the columns operated to approximately 23,462 to 30,758 BV. The data acquired from the tests were used to extrapolate the BV at which the DOC concentration would reach 70% breakthrough for the full-scale system using equations of similarity stated in *EPA-814-B-96-003 ICR Manual for Bench- and Pilot-Scale Treatment Studies*, as well as the Step-Lag Logistic Model used to develop the best possible curve fit for DOC and UVA_{254} as described in *EPA 815-C-99-002 Analysis of GAC Effluent Blending During the ICR Treatment Studies*.

After 17 days of operation, biological growth was discovered in both the influent and effluent ends of all three columns. In an attempt to prevent further growth, the columns and influent container were covered with aluminum foil and electrical tape to block out ambient light in case the occurrence was aglae growth related. T

Column 1

The 10 minute EBCT column was evaluated over 28,020 BV total. *Table 25* shows the results for the various analyses performed at different bed volumes throughout the test.

Table 25. Column 1 RSSCT results.

Bed Volumes RSSCT	UVA254 abs/cm	DOC mg/L	SUVA L/mg-m	Cumulative DOC Loading mg/mg media	Cumulative DOC Adsorbed mg/mg media	Applied DOC Loading kBV*mg/L
681	<0.0001 U	0.19 J	n/a	0.00	0.00	1.36
1,658	0.0015	0.29 J	0.52	0.01	0.01	3.32
2,660	0.0013	0.38 J	0.33	0.01	0.01	5.32
3,673	0.0028	0.50	0.55	0.01	0.01	7.35
4,679	0.0043	0.47 J	0.90	0.02	0.01	9.36
5,682	0.0054	0.57	0.95	0.02	0.02	11.4
6,701	0.0056	0.66	0.85	0.02	0.02	13.4
7,708	0.0061	0.63	0.97	0.03	0.02	15.4
8,723	0.0063	0.74	0.84	0.03	0.02	17.4

Table 25. Column 1 RSSCT results.

Bed Volumes RSSCT	UVA254 abs/cm	DOC mg/L	SUVA L/mg-m	Cumulative DOC Loading mg/mg media	Cumulative DOC Adsorbed mg/mg media	Applied DOC Loading kBV*mg/L
9,699	0.0070	0.89	0.78	0.03	0.03	19.4
10,719	0.0064	1.15	0.55	0.04	0.03	21.4
11,700	0.0065	1.20	0.54	0.04	0.03	23.4
12,716	0.0078	1.13	0.69	0.05	0.03	25.4
13,705	0.0076	1.20	0.64	0.05	0.03	27.4
14,700	0.0080	1.18	0.68	0.05	0.03	29.4
15,744	0.0095	1.27	0.75	0.06	0.03	31.5
16,714	0.0093	1.27	0.73	0.06	0.04	33.4
17,732	0.0083	1.45	0.57	0.06	0.04	35.5
18,753	0.0081	1.45	0.56	0.07	0.04	37.5
19,733	0.0080	1.58	0.51	0.07	0.04	39.5
20,754	0.0085	1.47	0.58	0.07	0.04	41.5
21,758	0.0083	1.79	0.46	0.08	0.04	43.5
22,785	0.0085	1.63	0.52	0.08	0.04	45.6
23,784	0.0085	1.58	0.54	0.08	0.04	47.6
24,733	0.0085	1.52	0.56	0.09	0.04	49.5
25,739	0.0089	1.60	0.56	0.09	0.04	51.5
26,749	0.0089	1.50	0.59	0.10	0.04	53.5
27,743	0.0088	1.38	0.64	0.10	0.04	55.5

The DOC concentration after 17,732 BVs had climbed to 1.45 mg/L, or 72 percent of the influent. The UVA_{254} measurement at this point was determined to be 0.083 abs/cm or 55 percent of the measured influent UVA_{254}. *Figure 28* depicts graphical representations of the organics breakthrough results (DOC and UVA_{254}) over the course of the test.

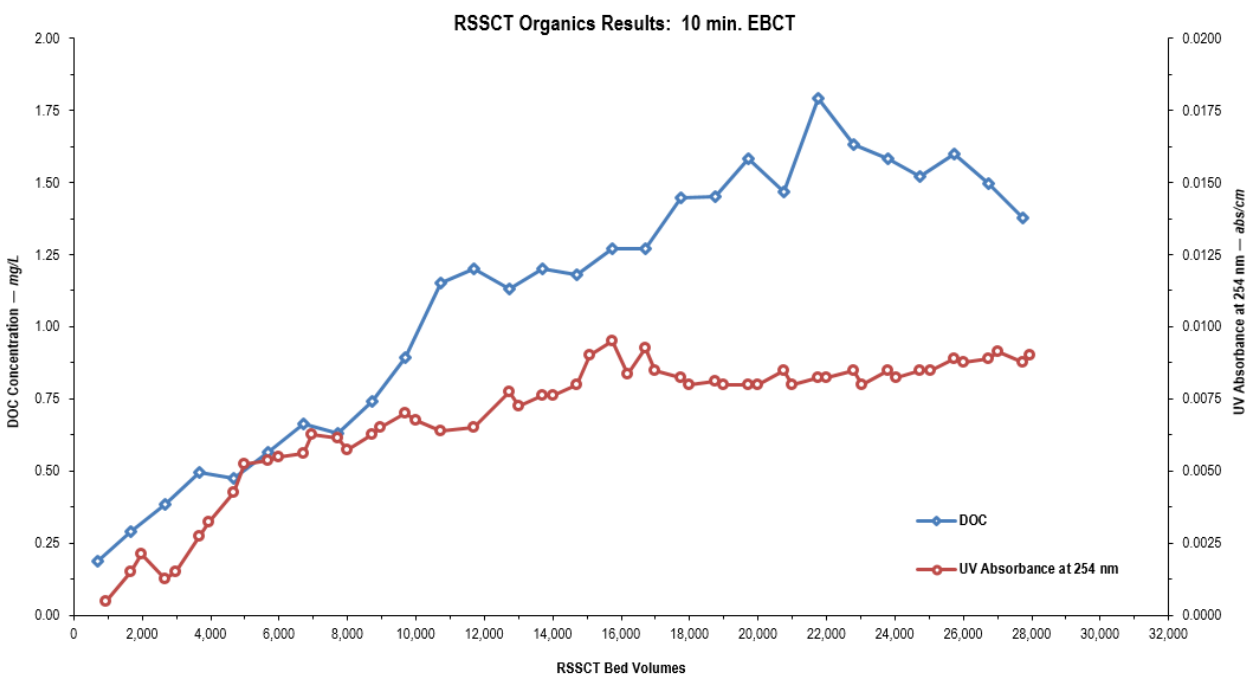

Figure 28. 10 min EBCT RSSCT Test results for organics breakthrough.

Using selected data generated from the RSSCT, the DOC and UVA_{254} results were used to develop the *Step-Lag Logistic Model*, for a better curve fit of the organics breakthrough. The EPA's *Analysis of GAC Effluent Blending During ICR Treatment Studies* lists the following equation for the development of the Step-Lag Logistic Model curve fit:

$$\boldsymbol{C(x) = \frac{A}{1+Be^{-Dx}} + A_0} \qquad \textbf{EQ. 1}$$

Where:	C(x)	=	DOC result as a function of bed volumes (and UVA_{254})
	x	=	Bed volumes
	A	=	Asymptote of logistic curve fit
	A_0	=	Step applied to the logistic curve fit
	B	=	Variable determined experimentally
	D	=	Variable determined experimentally

A CH2M developed, MS Excel based calculator was used to analyze the RSSCT data and the solver function was used to simultaneously determine the values of multiple variables by minimizing the sum of squares (least squares). These variables included A, A_0, B and D from *Equation 1*. *Figure 29* displays the results of the Step-Lag Logistic Model, with an R^2 value determined to be 0.9982 and 0.9994 for DOC and UVA_{254}, respectively. The R^2 values show very strong curve fits were developed for the Step-Lag Logistic Model based on the RSSCT data generated during the bench-scale testing effort. *Table 26* summarizes the results of the experimentally determined values listed in *Equation 1*.

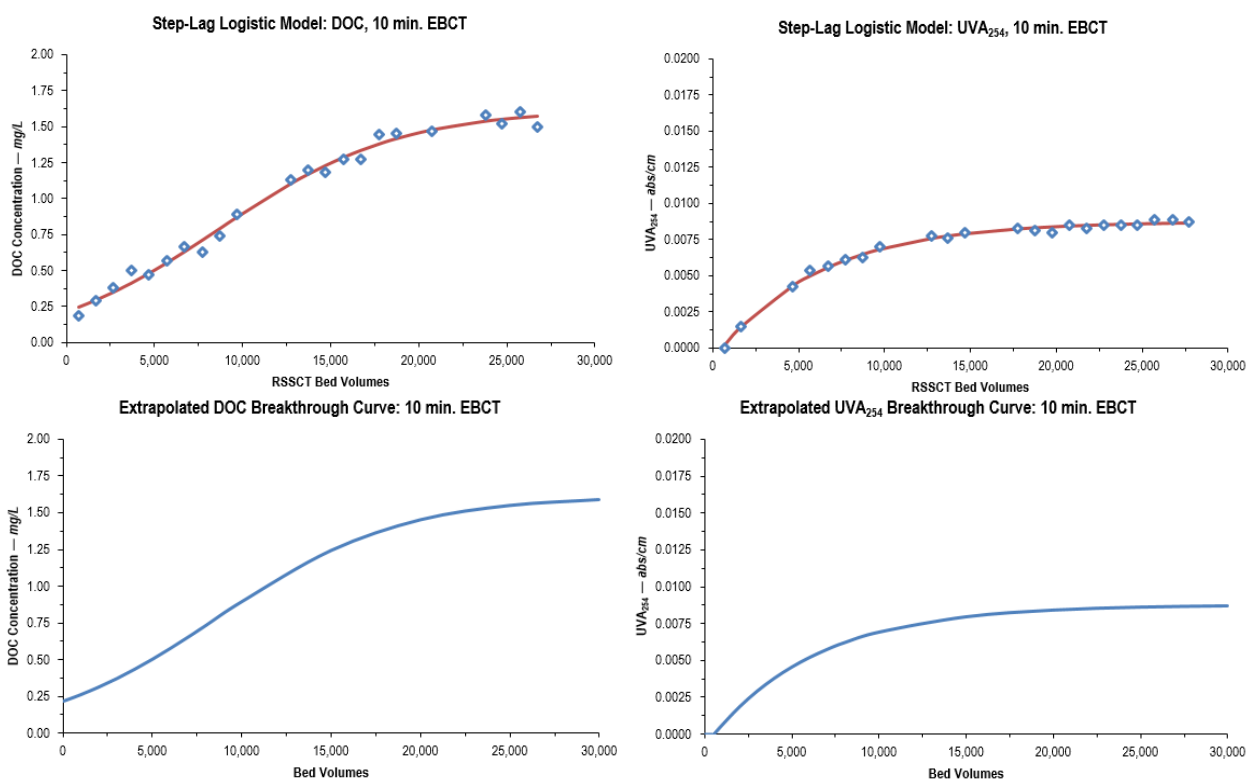

Figure 29. 10 min EBCT Step-Lag Logistic Model applied to (left) DOC, and (right) UVA_{254}.

Table 26. 10 min EBCT Step-Lag Logistic Model variables determined experimentally.

Variable	DOC Curve	UVA_{254} Curve
A (Asymptote)	1.66	7.37
A_0 (Step applied to curve)	-0.04	-7.37
B	5.45	0.0013
D	0.20	0.16
R^2	**0.9982**	**0.9994**

SUVA measurements have shown a good correlation with the aromaticity and hydrophobicity of the organics present in water. The column influent water had a calculated SUVA of 0.74 L/mg-m, and an initial DOC concentration of 2.0 mg/L. SUVA values of <2 indicates that a DOC is mostly non-humics, low hydrophobicity and low molecular weight organics. Higher values of SUVA indicate higher levels of hydrophobic organics and higher molecular weights. In this case, the influent SUVA value is indicating that the organics present are primarily composed of low molecular weight hydrophilic compounds, thus making them very difficult to remove. The hydrophilic nature of these organics is apparent in the RSSCT results from the very early DOC seepage observed at the beginning of the test.

Additional analysis of selected column effluents included 56 CEC compounds, 1,4-dioxane, PFOS+PFOA, and 17β-estradiol, at 10,350 and 20,376 bed volumes. Table 27 summarizes the results of these analysis. The GAC effluent samples removed virtually all remaining CECs; most notably, sucralose (non detection) and PFOA (which has largely been recalcitrant up to this step in the treatment train).

Table 27. Column 1 RSSCT effluent remaining CECs.

Sample Information					
Sample Description		Untreated	RSSCT Influent	10,350 BVs	20,376 BVs
Eurofins Selected Contaminants of Emerging Concern (CEC) Analysis					
1,4-Dioxane	ng/L	270	<70 U	n/a	130
17β-estradiol	ng/L	0.45	<0.4 U	<0.4 U	<0.4 U
Perfluorooctanoic acid (PFOA)	ng/L	12	14	<3 U	<3 U
Perfluorooctanesulfonic acid (PFOS)	ng/L	<2.5 U	<2.5 U	<3 U	<3 U
Eurofins Contaminants of Emerging Concern (CEC) Analysis					
4-nonylphenol – semi quantitative	ng/L	2,000	<100 U	510	940
Azithromycin	ng/L	550	<20 U	260	120
Total CECs	ng/L	23,675	7,271	770	1,060

NOTE: The CECs listed are only those with positive detections in RSSCT effluents, for the full list of compounds detected in the untreated water and RSSCT influent (Post BAC/MF Ozonated) see *Table 20*.
J = Estimated value below reporting limit.
U = Not detected at specified detection limit.

Column 2

The 15 minute EBCT column was evaluated over 30,758 BV total. *Table 28* shows the results for the various analyses performed at different bed volumes throughout the test.

Table 28. Column 2 RSSCT results.

Bed Volumes **RSSCT**	UVA_{254} abs/cm	DOC mg/L	SUVA L/mg-m	Cumulative DOC Loading mg/mg media	Cumulative DOC Adsorbed mg/mg media	Applied DOC Loading kBV*mg/L
454	0.0011	<0.20 U	0.72	0.00	0.00	0.91
1,105	0.0023	0.23 J	0.97	0.00	0.00	2.21
1,773	0.0009	0.30 J	0.29	0.01	0.01	3.55
2,449	0.0018	<0.20 U	0.91	0.01	0.01	4.90
3,119	0.0025	<0.20 U	1.38	0.01	0.01	6.24
3,788	0.0033	0.22 J	1.50	0.01	0.01	7.58
4,467	0.0033	0.26 J	1.26	0.02	0.01	8.93
5,139	0.0029	<0.20 U	1.76	0.02	0.02	10.3
5,816	0.0038	0.38 J	0.98	0.02	0.02	11.6
6,466	0.0048	0.48 J	0.99	0.02	0.02	12.9
7,146	0.0050	1.01	0.49	0.03	0.02	14.3
7,800	0.0073	0.82	0.88	0.03	0.02	15.6
8,477	0.0053	0.81	0.65	0.03	0.02	17.0
9,136	0.0055	0.86	0.64	0.03	0.03	18.3
9,800	0.0060	0.87	0.69	0.04	0.03	19.6
10,496	0.0066	1.04	0.64	0.04	0.03	21.0
11,143	0.0073	1.00	0.73	0.04	0.03	22.3
11,821	0.0076	1.32	0.58	0.04	0.03	23.6
12,502	0.0063	1.30	0.48	0.04	0.03	25.0
13,155	0.0064	1.21	0.53	0.05	0.03	26.3
13,836	0.0065	1.18	0.55	0.05	0.03	27.7
14,506	0.0066	1.28	0.52	0.05	0.03	29.0
15,190	0.0065	1.37	0.48	0.05	0.03	30.4
15,856	0.0068	1.33	0.51	0.06	0.04	31.7
16,488	0.0070	1.34	0.52	0.06	0.04	33.0
17,159	0.0075	1.38	0.55	0.06	0.04	34.3
17,833	0.0078	1.33	0.58	0.06	0.04	35.7
18,496	0.0073	1.11	0.65	0.07	0.04	37.0
19,170	0.0075	1.22	0.61	0.07	0.04	38.3
19,831	0.0075	1.22	0.61	0.07	0.04	39.7
20,537	0.0079	1.27	0.62	0.07	0.04	41.1
21,197	0.0078	1.31	0.59	0.08	0.04	42.4
21,852	0.0078	1.35	0.57	0.08	0.04	43.7
22,528	0.0080	1.29	0.62	0.08	0.04	45.1
23,232	0.0068	1.11	0.61	0.08	0.04	46.5
23,893	0.0068	1.06	0.64	0.09	0.05	47.8
24,519	0.0075	1.04	0.72	0.09	0.05	49.0
25,246	0.0078	1.09	0.71	0.09	0.05	50.5
25,863	0.0085	1.12	0.76	0.09	0.05	51.7
26,531	0.0078	1.05	0.74	0.09	0.05	53.1
27,194	0.0080	1.16	0.69	0.10	0.05	54.4
27,859	0.0080	0.93	0.86	0.10	0.05	55.7
28,533	0.0078	1.12	0.69	0.10	0.05	57.1
29,200	0.0075	1.07	0.70	0.10	0.05	58.4
29,873	0.0080	1.05	0.77	0.11	0.06	59.7
30,758	0.0080	1.02	0.78	0.11	0.06	61.5

The DOC concentration after 11,821 BVs reached an asymptote at approximately 1.32 mg/L, or 66 percent of the influent. The DOC concentration in the effluent did not climb any higher than this asymptote. The UVA_{254} behaved similarly, and at this point was determined to be 0.076 abs/cm or 51 percent of the measured influent UVA_{254}. *Figure 30* depicts graphical representations of the organics breakthrough results (DOC and UVA_{254}) over the course of the test.

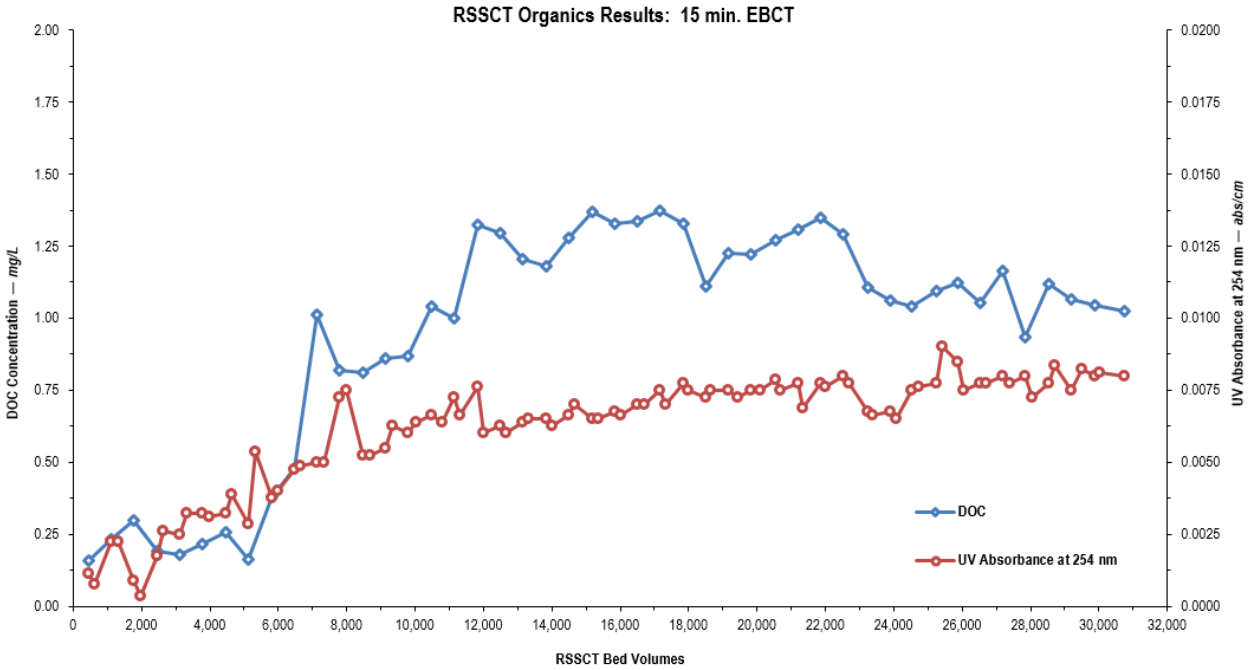

Figure 30. 15 min EBCT RSSCT Test results for organics breakthrough.

Using selected data generated from the RSSCT, the DOC and UVA_{254} results were used to develop the *Step-Lag Logistic Model*, for a better curve fit of the organics breakthrough. Following the same process as with column 1, *Figure 31* displays the results of the Step-Lag Logistic Model, with an R^2 value determined to be 0.9987 and 0.9984 for DOC and UVA_{254}, respectively. The R^2 values show very strong curve fits were developed for the Step-Lag Logistic Model based on the RSSCT data generated during the bench-scale testing effort. *Table 29* summarizes the results of the experimentally determined values listed in *Equation 1*.

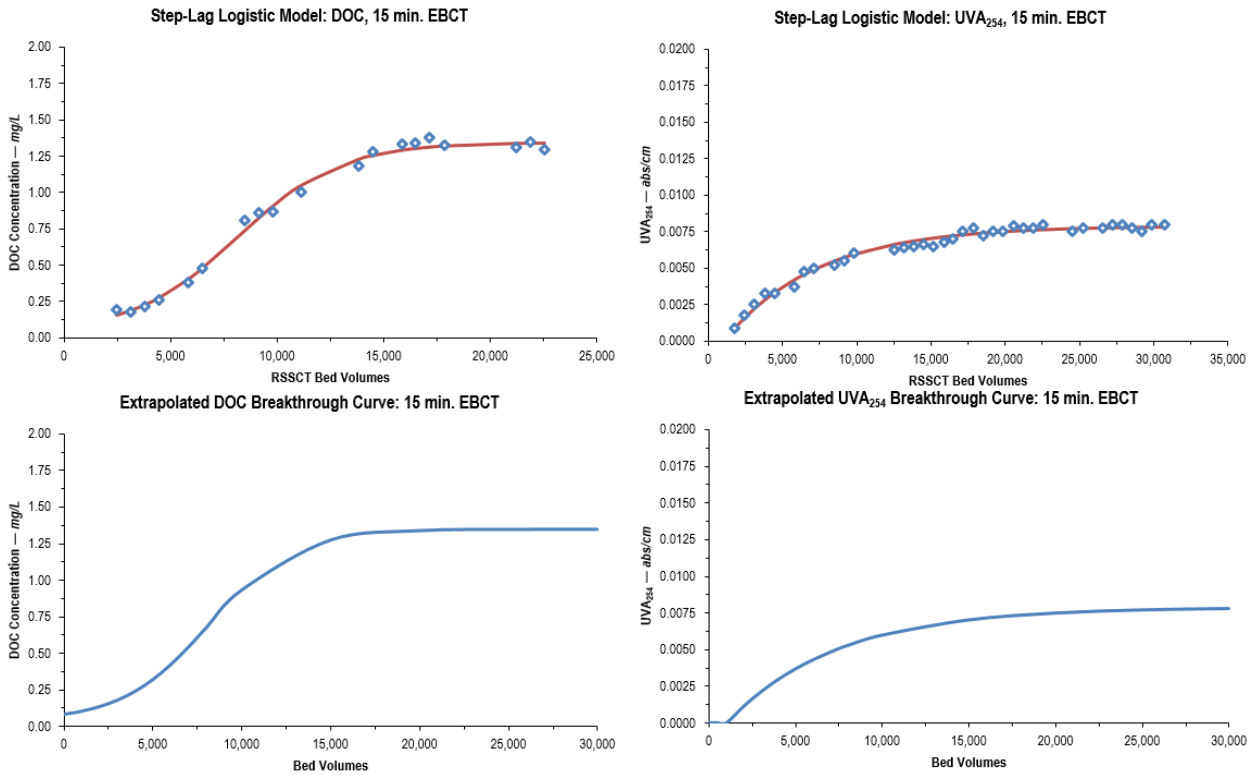

Figure 31. 15 min EBCT Step-Lag Logistic Model applied to (left) DOC, and (right) UVA_{254}.

Table 29. 15 min EBCT Step-Lag Logistic Model variables determined experimentally.

Variable	DOC Curve	UVA_{254} Curve
A (Asymptote)	1.31	11.5
A_0 (Step applied to curve)	0.04	-11.5
B	28.2	0.0008
D	0.41	0.16
R^2	**0.9987**	**0.9984**

Similar to column 1, the hydrophilic nature of the organics resulted in very early DOC seepage in column 2. The increased EBCT resulted in improved organics removal in the beginning, however the breakthrough curve was much steeper than observed with column 1.

Additional analysis of selected column effluents included 56 CEC compounds, 1,4-dioxane, PFOS+PFOA, 17β-estradiol, EEM/TF, VOCs and SOCs at 9,590 BV, 20,323 BV and 30,400 BV. *Table 30* summarizes the results of these analysis. The GAC effluent samples removed virtually all remaining CECs; most notably, sucralose (non-detection) and PFOA (which has largely been recalcitrant up to this step in the treatment train). Overall, total CEC reduction was improved with a 15 min. EBCT compared to a 10 min. EBCT (column 1). *Figure 32* displays the EEM heat maps for all upstream treatment processes as well as the column effluent samples at approximately 10k, 20k and 30k BVs which shows complete removal of organics in the humic acid-like and soluble microbial by-product-like regions, and low levels of organics in the aromatic proteins and fulvic acid-like regions.

Table 30. Column 2 RSSCT effluent remaining CECs.

Sample Information						
Sample Description		Untreated	RSSCT Influent	9,590 BVs	20,323 BVs	30,400 BVs
ASL VOC Analysis						
Chloroform	µg/L	0.19 J	n/a	n/a	n/a	<0.15 U
Acetone	µg/L	<0.50 U	n/a	n/a	n/a	2.09
*Non-detect on all other volatile compounds; see analytical report for details.						
University of Arizona, Snyder Labs Total Fluorescence (TF) Analysis						
UVA_{254}	abs/cm	0.0820	0.0180	0.0056	0.0089	0.0087
UVT_{254}	%	82.8	95.9	98.7	98.0	98.0
Total Fluorescence	R.U.nm^2	103,887	8,782	10,970	8,357	11,821
Eurofins Selected Contaminants of Emerging Concern (CEC) Analysis						
1,4-Dioxane	ng/L	270	<70 U	n/a	120	n/a
17β-estradiol	ng/L	0.45	<0.4 U	<0.4 U	<0.4 U	n/a
Perfluorooctanoic acid (PFOA)	ng/L	12	14	<3 U	<3 U	n/a
Perfluorooctanesulfonic acid (PFOS)	ng/L	<2.5 U	<2.5 U	<3 U	<3 U	n/a
Eurofins Contaminants of Emerging Concern (CEC) Analysis						
4-nonylphenol – semi quantitative	ng/L	2,000	<100 U	400	420	n/a
Azithromycin	ng/L	550	<20 U	69	29	n/a
Total CECs	ng/L	23,675	7,271	469	449	n/a
Eurofins Synthetic Organic Carbon (SOC) Analysis						
*Non-detect on all Synthetic Organic Carbon compounds; see analytical report for details.						

NOTE: The CECs listed are only those with positive detections in RSSCT effluents, for the full list of compounds detected in the untreated water and RSSCT influent (Post BAC/MF Ozonated) see *Table 20*.
J = Estimated value below reporting limit.
U = Not detected at specified detection limit.

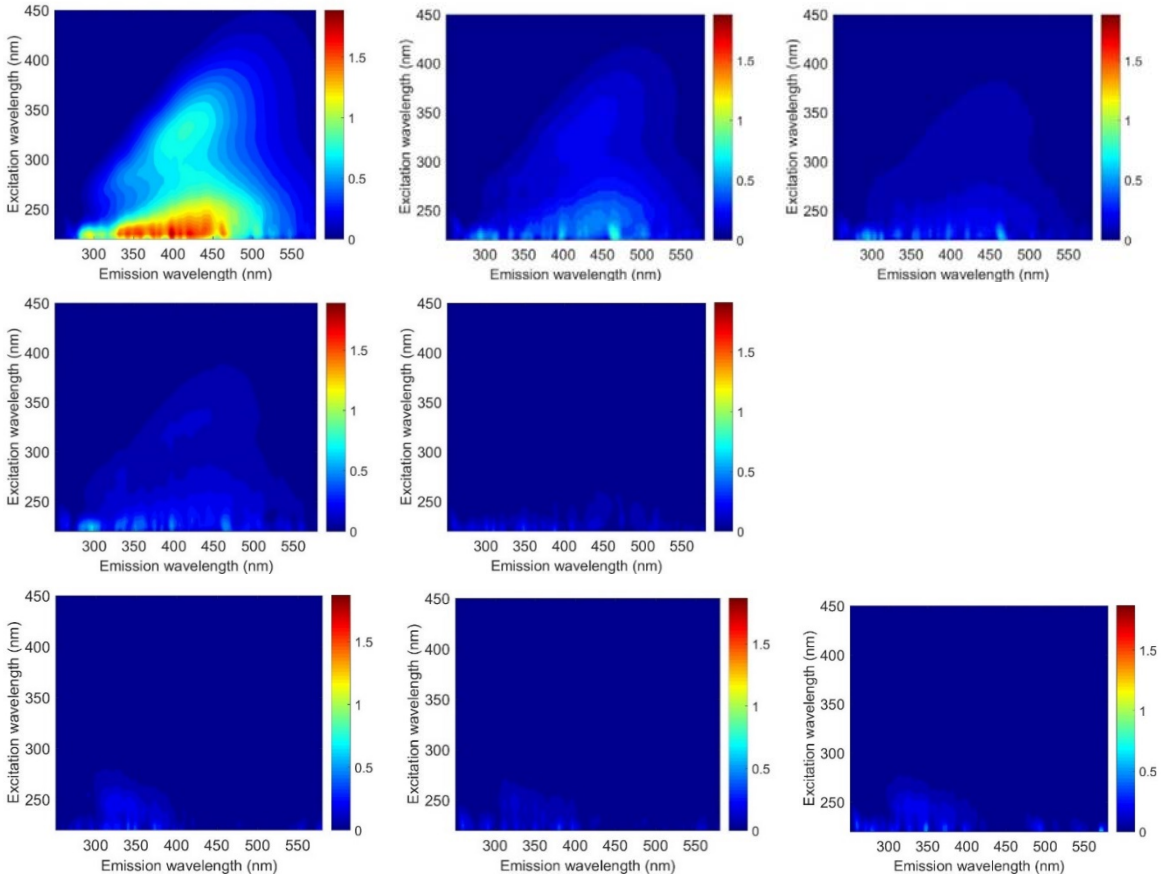

Figure 32. Exitation Emission Matrix heat map for (top-left) untreated blend water, (top-middle) pre-ozonated with 2.0 mg/L O_3, (top-right) 60 mg/L ferric chloride treated at ambient pH, (middle-left) 7.0 min EBCT BAC Effluent, (middle-right) Post-BAC/MF Ozonation, (bottom-left) GAC after 10 kBV, (bottom-middle) GAC after 20 kBV, and (bottom-right) GAC after 30 kBV (ALL EEM heat maps normalized to untreated water; Snyder labs, University of Arizona).

Column 3

The 20 minute EBCT column was evaluated over 23,426 BV total. *Table 31* shows the results for the various analyses performed at different bed volumes throughout the test.

Table 31. Column 3 RSSCT results.

Bed Volumes **RSSCT**	UVA_{254} abs/cm	DOC mg/L	SUVA L/mg-m	Cumulative DOC Loading mg/mg media	Cumulative DOC Adsorbed mg/mg media	Applied DOC Loading kBV*mg/L
341	0.0009	<0.20 U	1.25	0.00	0.00	0.68
829	0.0016	0.21 J	0.79	0.00	0.00	1.66
1,330	0.0000	0.23 J	n/a	0.00	0.00	2.66
1,837	0.0020	<0.20 U	1.01	0.01	0.01	3.67
2,340	0.0023	<0.20 U	2.00	0.01	0.01	4.68
2,841	0.0023	<0.20 U	2.03	0.01	0.01	5.68
3,350	0.0028	<0.20 U	2.04	0.01	0.01	6.70
3,854	0.0045	0.27 J	1.67	0.01	0.01	7.71
4,362	0.0025	0.16 J	1.55	0.02	0.01	8.72
4,850	0.0033	0.23 J	1.42	0.02	0.02	9.70
5,359	0.0036	0.48 J	0.76	0.02	0.02	10.7
5,850	0.0031	0.79	0.40	0.02	0.02	11.7

Table 31. Column 3 RSSCT results.

Bed Volumes **RSSCT**	UVA_{254} abs/cm	DOC mg/L	SUVA L/mg-m	Cumulative DOC Loading mg/mg media	Cumulative DOC Adsorbed mg/mg media	Applied DOC Loading kBV*mg/L
6,358	0.0044	0.59	0.74	0.02	0.02	12.7
6,852	0.0050	0.59	0.85	0.02	0.02	13.7
7,350	0.0050	0.66	0.76	0.03	0.02	14.7
7,872	0.0053	0.81	0.65	0.03	0.02	15.7
8,357	0.0056	0.81	0.69	0.03	0.02	16.7
8,866	0.0053	1.14	0.46	0.03	0.02	17.7
9,376	0.0046	1.18	0.39	0.03	0.03	18.8
9,866	0.0053	1.26	0.42	0.04	0.03	19.7
10,377	0.0050	1.05	0.48	0.04	0.03	20.8
10,879	0.0053	1.04	0.51	0.04	0.03	21.8
11,392	0.0053	1.06	0.50	0.04	0.03	22.8
11,892	0.0054	1.12	0.48	0.04	0.03	23.8
12,366	0.0058	1.15	0.50	0.04	0.03	24.7
12,869	0.0060	1.07	0.56	0.05	0.03	25.7
13,374	0.0065	1.14	0.57	0.05	0.03	26.7
13,872	0.0061	0.97	0.63	0.05	0.03	27.7
14,378	0.0063	1.02	0.61	0.05	0.03	28.8
14,873	0.0063	1.00	0.62	0.05	0.03	29.7
15,403	0.0066	1.00	0.66	0.06	0.04	30.8
15,897	0.0063	1.03	0.61	0.06	0.04	31.8
16,389	0.0069	1.21	0.57	0.06	0.04	32.8
16,896	0.0070	1.00	0.70	0.06	0.04	33.8
17,424	0.0064	1.00	0.64	0.06	0.04	34.8
17,920	0.0080	0.98	0.82	0.06	0.04	35.8
18,390	0.0069	1.00	0.69	0.07	0.04	36.8
18,935	0.0078	1.04	0.75	0.07	0.04	37.9
19,397	0.0085	0.93	0.92	0.07	0.04	38.8
19,898	0.0068	0.98	0.69	0.07	0.04	39.8
20,395	0.0068	0.89	0.75	0.07	0.04	40.8
20,894	0.0070	1.05	0.67	0.07	0.05	41.8
21,400	0.0075	0.99	0.75	0.08	0.05	42.8
21,900	0.0068	0.89	0.76	0.08	0.05	43.8
22,404	0.0071	0.92	0.77	0.08	0.05	44.8
22,952	0.0069	0.96	0.72	0.08	0.05	45.9
23,408	0.0076	0.94	0.81	0.08	0.05	46.8

The DOC concentration after 8,866 BVs reached an asymptote at approximately 1.14 mg/L, or 57 percent of the influent. The DOC concentration in the effluent did not climb any higher than this asymptote. The UVA_{254} results at this point was determined to be 0.053 abs/cm or 35 percent of the measured influent UVA_{254}. *Figure 33* depicts graphical representations of the organics breakthrough results (DOC and UVA_{254}) over the course of the test.

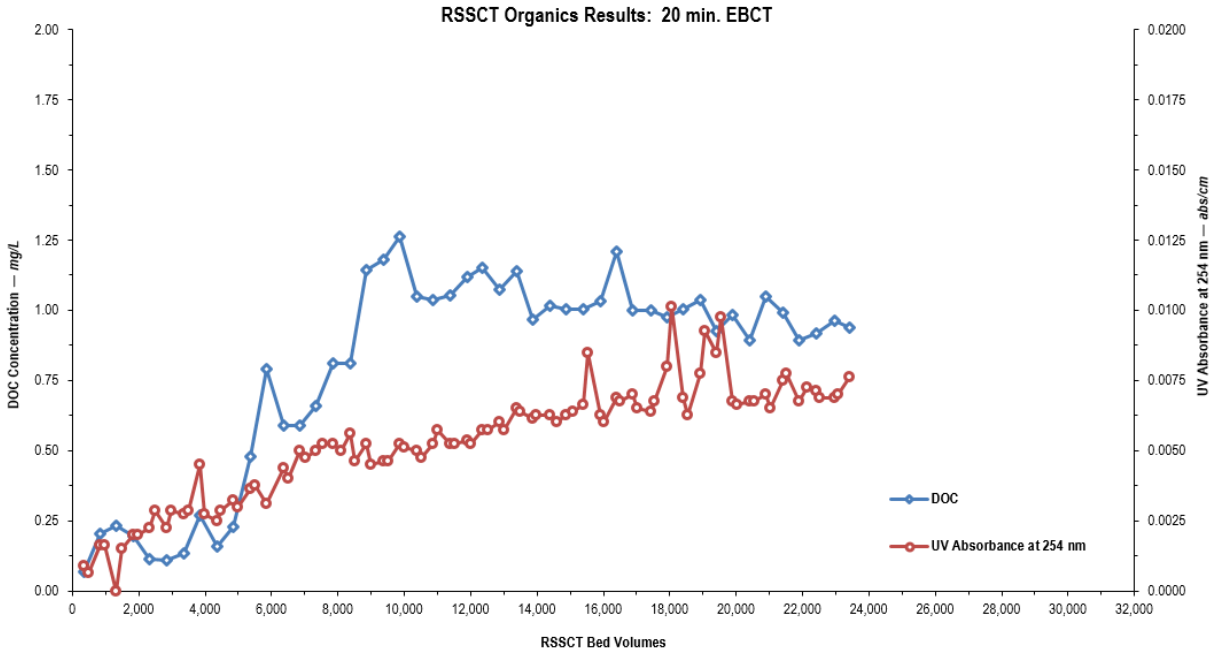

Figure 33. 20 min EBCT RSSCT Test results for organics breakthrough.

Using selected data generated from the RSSCT, the DOC and UVA_{254} results were used to develop the *Step-Lag Logistic Model*, for a better curve fit of the organics breakthrough. Following the same process as with column 1, *Figure 34* displays the results of the Step-Lag Logistic Model, with an R^2 values determined to be 0.9972 and 0.9968 for DOC and UVA_{254}, respectively. The R^2 values show very strong curve fits were developed with the Step-Lag Logistic Model based on the RSSCT data generated during the bench-scale testing effort. *Table 32* summarizes the results of the experimentally determined values listed in *Equation 1*.

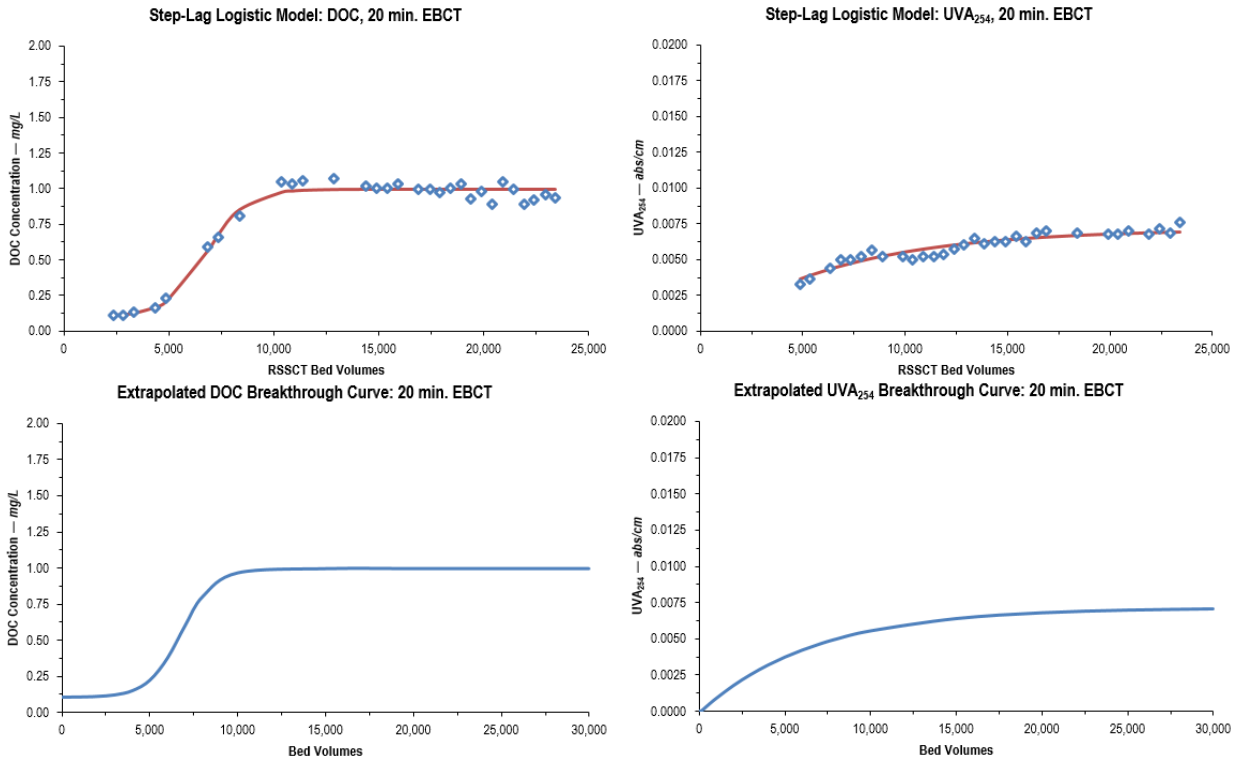

Figure 34. 20 min EBCT Step-Lag Logistic Model applied to (left) DOC, and (right) UVA_{254}.

Table 32. 20 min EBCT Step-Lag Logistic Model variables determined experimentally.

Variable	DOC Curve	UVA254 Curve
A (Asymptote)	0.89	6.49
A_0 (Step applied to curve)	0.11	-6.48
B	1,218	0.0011
D	1.05	0.15
R^2	**0.9972**	**0.9968**

Similar to column 1 and 2, the hydrophilic nature of the organics resulted in very early DOC seepage as observed at the beginning of the test. The increased EBCT resulted in improved organics removal in the beginning, however the breakthrough curve was much steeper than observed with columns 1 and 2, and ended with a lower asymptote than column 2.

Additional analysis of selected column effluents included 56 CEC compounds, 1,4-dioxane, PFOS+PFOA, and 17β-estradiol, at 10,188 and 20,209 bed volumes. Table 33 summarizes the results of these analyses. The GAC effluent samples removed virtually all remaining CECs; most notably, sucralose (non-detection) and PFOA (which has largely been recalcitrant up to this step in the treatment train). Overall, the total CEC reduction was improved for a 20 min. EBCT compared to both 10 and 15 min. EBCTs.

Table 33. Column 3 RSSCT effluent remaining CECs.

Sample Information					
Sample Description		Untreated	RSSCT Influent	10,188 BVs	20,209 BVs
Eurofins Selected Contaminants of Emerging Concern (CEC) Analysis					
1,4-Dioxane	ng/L	270	<70 U	n/a	120
17β-estradiol	ng/L	0.45	<0.4 U	<0.4 U	<0.4 U
Perfluorooctanoic acid (PFOA)	ng/L	12	14	<3 U	<2.5 U
Perfluorooctanesulfonic acid (PFOS)	ng/L	<2.5 U	<2.5 U	<3 U	<2.5 U
Eurofins Contaminants of Emerging Concern (CEC) Analysis					
4-nonylphenol – semi quantitative	ng/L	2,000	<100 U	<100 U	<100 U
Azithromycin	ng/L	550	<20 U	40	20
Total CECs	ng/L	23,675	7,271	40	20

NOTE: The CECs listed are only those with positive detections in RSSCT effluents, for the full list of compounds detected in the untreated water and RSSCT influent (Post BAC/MF Ozonated) see Table 20.
J = Estimated value below reporting limit.
U = Not detected at specified detection limit.

Section 8.8 – Comparison of the EBCT Performances

Side-by-side comparisons of all 3 empty bed contact times for DOC, UVA_{254}, and the extrapolated Step-Lag Logistic Curves are depicted graphically in *Figure 35*.

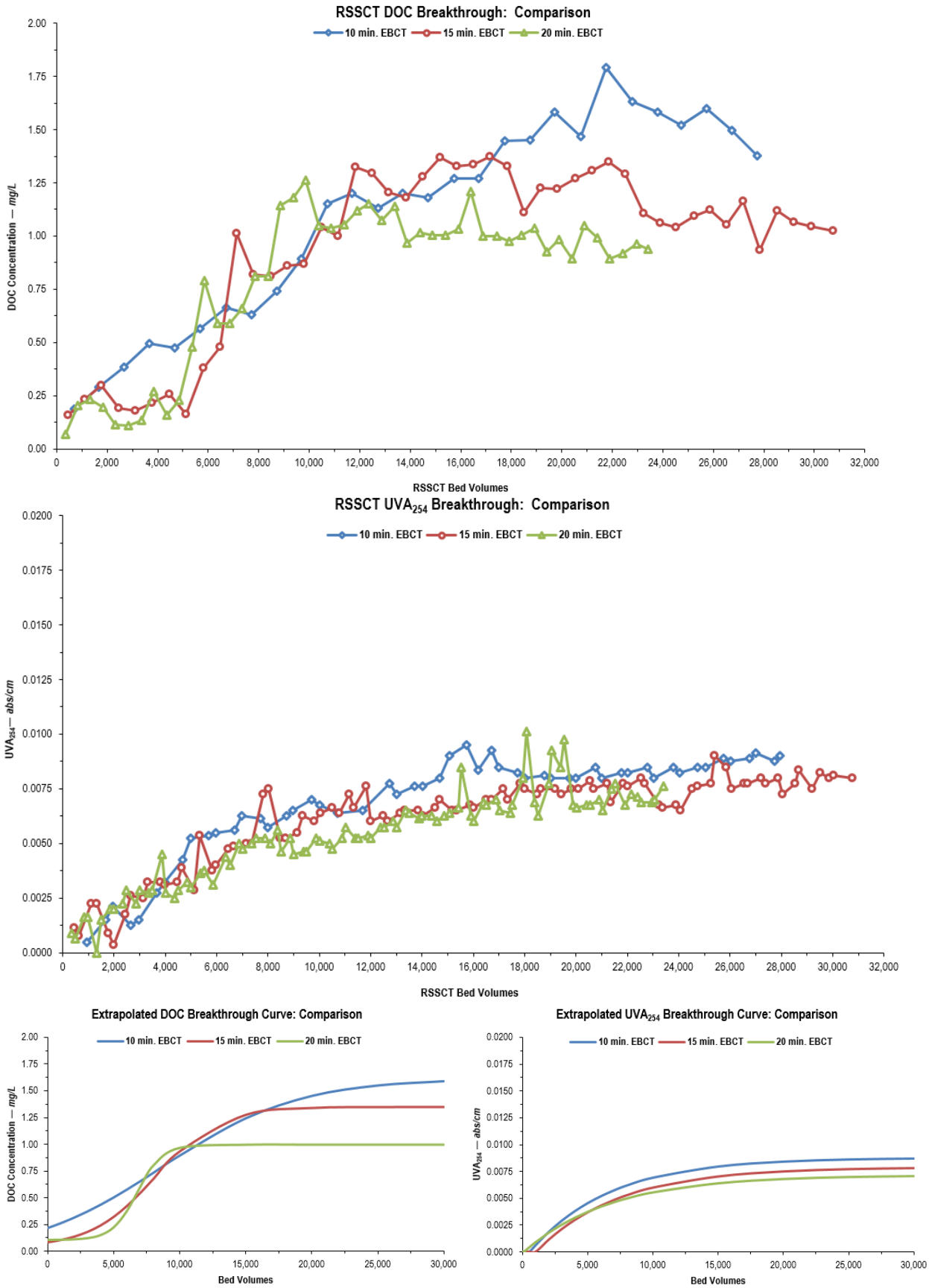

Figure 35. Side-by-side comparisons for all three EBCTs.

Section 9.0 – Correlation Between UVA_{254} and DOC

The data gathered for each concurrent pair of DOC and UVA_{254} points were used to develop various correlation plots for the purposes of predicting DOC concentrations in this blended source water with UVA_{254} alone.

In total there were three separate correlation plots developed: the first includes all data pairs throughout all treatment steps, the second includes only the data pairs obtained from jar testing (following pre-ozonation), and the third includes only data pairs obtained from the RSSCT column effluents.

Figure 36 depicts the correlation plot developed for all data pairs created throughout all treatment steps.

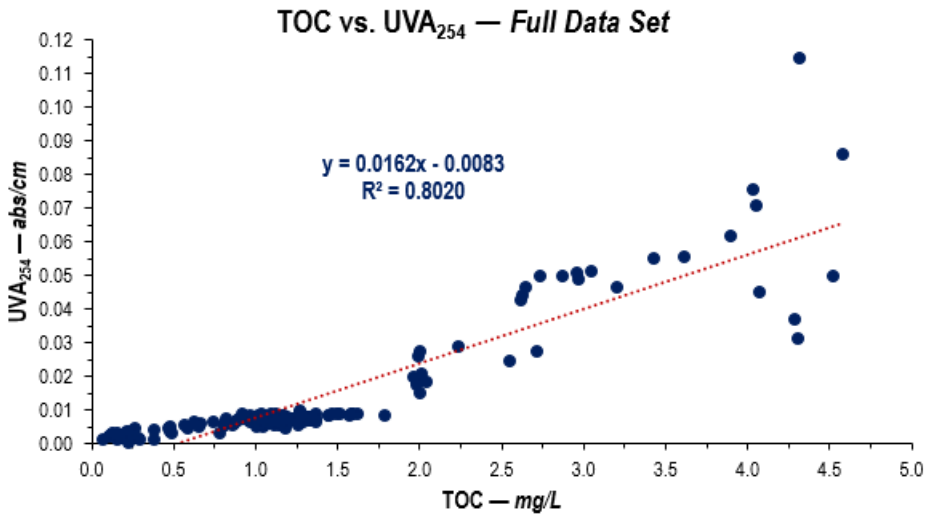

Figure 36. TOC vs. UVA_{254} correlation plot for full data set gathered throughout entire bench-scale testing effort.

The full data set correlation plot has an R^2 value of 0.8020, which indicates that a good correlation between UV_{254} and TOC exists for all treatment processes; this linear regression can be used as a good indicator or predictor of DOC and/or TOC concentrations.

Figure 37 depicts the correlation plot developed for only the data pairs created during the jar testing phase of testing.

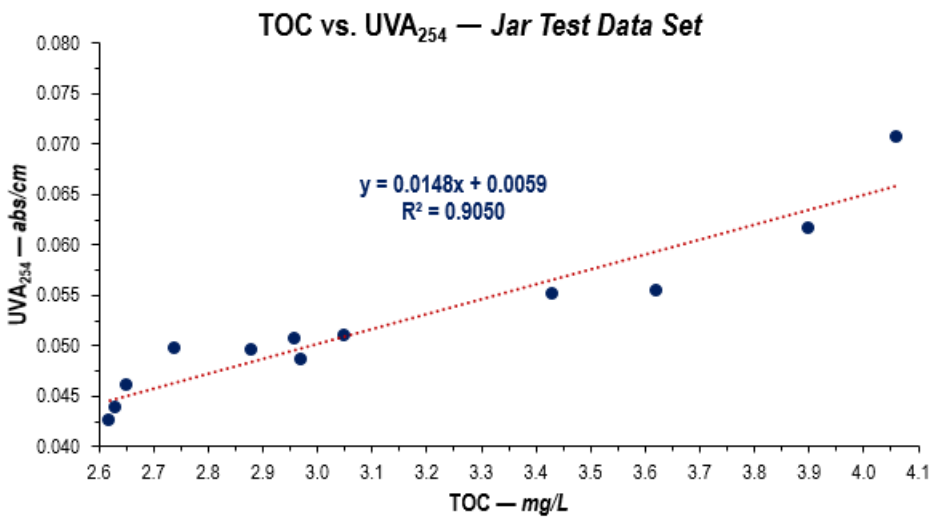

Figure 37. TOC vs. UVA_{254} correlation plot for jar test data set only.

The Jar Testing correlation plot has an R2 value of 0.9050, which indicates that a strong correlation between UV254 and TOC exists for this treatment; this linear regression can be used as a good indicator or predictor of DOC and/or TOC concentrations following ferric chloride treatment.

Figure 38 depicts the correlation plot developed for only the data pairs created during the RSSCT phase of testing.

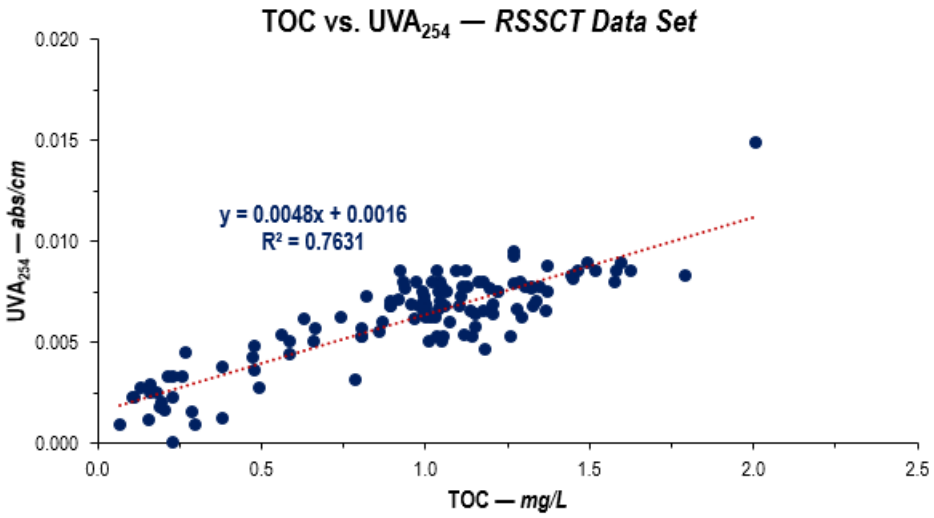

Figure 38. TOC vs. UVA_{254} correlation plot for RSSCT data set only.

The RSSCT correlation plot has an R^2 value of 0.7631, which indicates that a good correlation between UV_{254} and TOC exists for GAC treatment; this linear regression can be used as a good indicator or predictor of DOC and/or TOC concentrations following GAC treatment.

Section 10.0 – Chlorine Disinfection

Column 2 effluent (15 min. EBCT) at approximately 10,000 bed volumes was used to conduct a series of chlorination and chloramination tests to study the formation of TTHMs and HAA5s during final disinfection. In order to ensure enough volume of water was available, several larger samples were composited, and the average EBCT calculated based on the RSSCT data. The sample water used corresponds to 9,590 bed volumes.

The PCWPF treats finished water with sodium hypochlorite to achieve a free chlorine residual to provide 4-log of virus disinfection. Typical free chlorine residual is greater than 0.5 mg/L. Testing was conducted on the selected column effluent sample to measure chlorine demand at 0.8 mg/L, 1.2 mg/L, and 2.0 mg/L residuals. Ammonia was measured on the post-GAC water; tests were conducted at ambient pH (~8.0). Demands were measured at 30-minute and 60-minute reaction times, which correspond to detention times in the chlorine contact basin (CCB) at 3 and 6 mgd flow rates. TTHMs and HAA5 was also measured to determine DBP production at 30-minute and 60-minute reaction times.

In total, there were 5 initial chlorine demand tests. The conditions for each of these 5 tests are summarized below in *Table 34*.

Table 34. Initial chlorine testing conditions.

Sample ID	Chlorine Dose mg/L as Cl_2	Free Residual mg/L as Cl_2	Free Demand mg/L as Cl_2	Total Residual mg/L as Cl_2	Temp. °C	Measured pH Units	Start Time date/time	Take-Off Time date/time	Reaction Time h:m
CR-CLD-0.8-30min	1.40	1.08	0.32	1.26	22.0	8.1	7/20/16 15:08	7/20/16 15:09	0:01
		0.79	0.61	0.93	22.0	8.1		7/20/16 15:39	0:31
CR-CLD-0.8-60min	1.50	1.15	0.35	1.35	22.3	8.1	7/20/16 14:53	7/20/16 14:54	0:01
		0.78	0.72	0.95	22.0	8.1		7/20/16 15:53	1:00
CR-CLD-1.2-30min	1.90	1.48	0.42	1.60	22.0	8.1	7/20/16 15:17	7/20/16 15:18	0:01
		1.23	0.67	1.41	22.0	8.1		7/20/16 15:48	0:31
CR-CLD-1.2-60min	2.00	1.53	0.47	1.81	22.2	8.1	7/20/16 15:01	7/20/16 15:02	0:01
		1.23	0.77	1.41	22.0	8.1		7/20/16 16:01	1:00
CR-CLD-2.8-60min	2.80	2.40	0.40	2.60	-	-	7/22/16 14:40	7/22/16 14:41	0:01
		1.98	0.82	2.14	19.1	8.2		7/22/16 15:46	1:06

The TTHM formation for these 5 tests were low, ranging between 1.6 to 3.2 µg/L in total. Additionally, the HAA5 concentrations were also low ranging between 1.5 to 6.5 µg/L. These results are summarized below in *Table 35*, while *Figures 39* and *40* depict the total TTHMs and HAA5s as well as each individual species analyzed side-by-side for comparison.

Table 35. DBP results from initial chlorine demand testing.

Sample ID	TTHMs µg/L	HAA5s µg/L	HAA6s µg/L
CR-CLD-0.8-30min	1.63	6.53	7.18
CR-CLD-0.8-60min	2.53	1.54	2.27
CR-CLD-1.2-30min	1.84	6.46	7.19
CR-CLD-1.2-60min	2.51	2.53	3.36
CR-CLD-2.8-60min	3.16	2.21	3.17
Stage 1 D/DBPR	**80.0**	**60.0**	**n/a**

For full speciation of THMs and HAAs see analytical reports, Treatability Excel Summaries and/or *Figures 43 and 44*
D/DBPR = Stage 1 Disinfectants/Disinfection Byproducts Rule

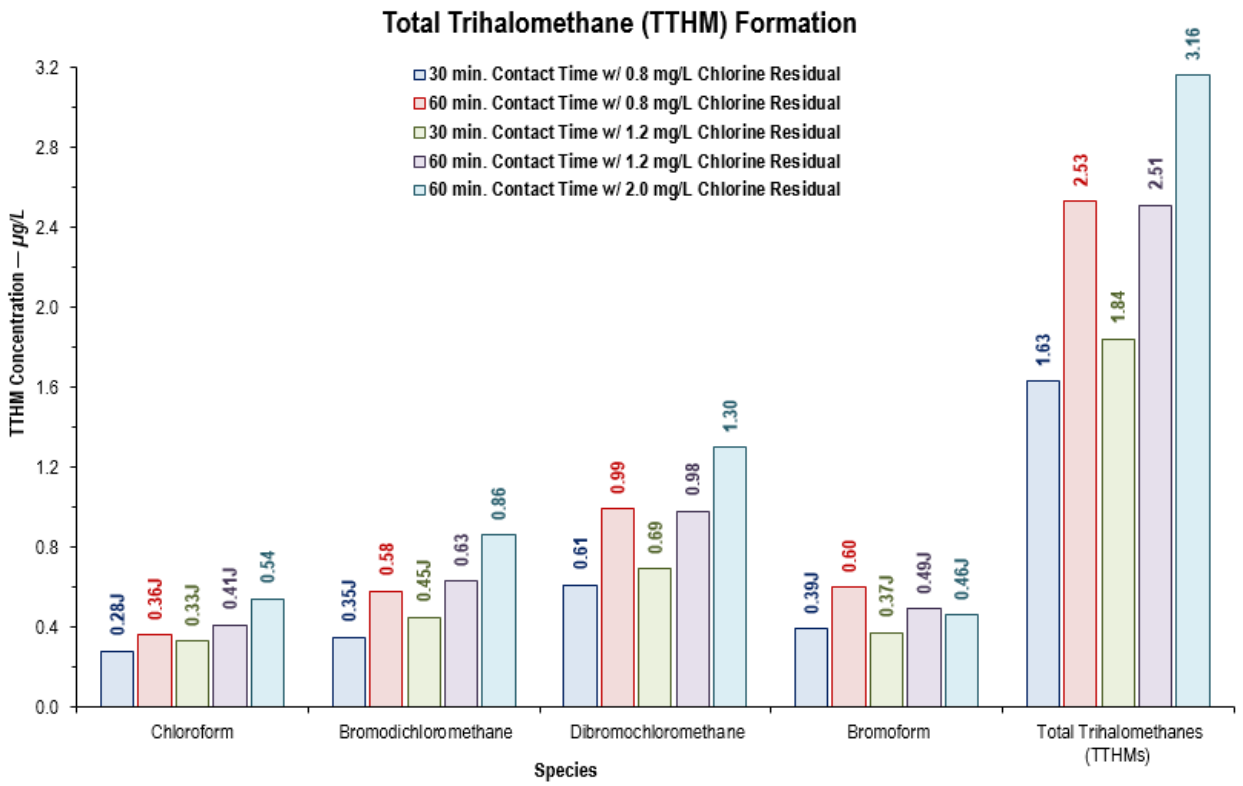

Figure 39. TTHM results for the initial chlorine demand testing.

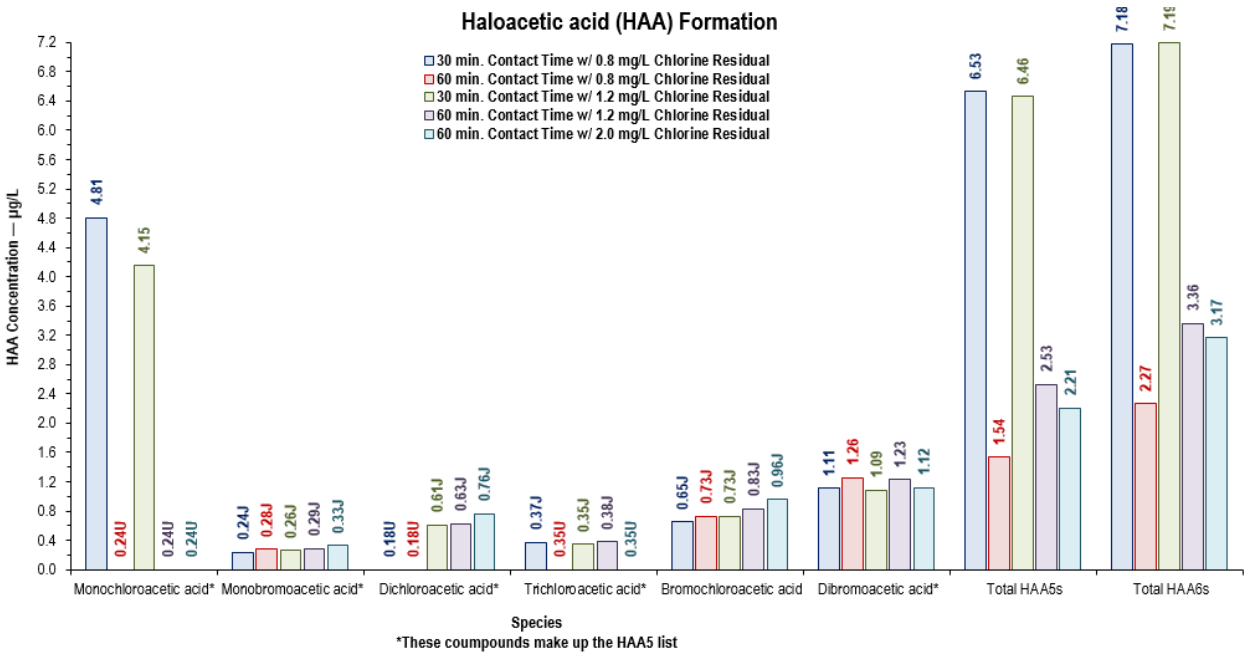

Figure 40. HAA results for the initial chlorine demand testing.

Based on the initial chlorine testing, a dose of 2.8 mg/L as Cl_2 (highest dose; worst case scenario) was selected for the chloramination testing. Three additional tests were set up with an initial chlorine dose of 2.8 mg/L as Cl_2 at ambient pH (8.0) and room temperature, with variable chlorine to ammonia ratios applied. The Free chlorine, total chlorine, monochloramine, free ammonia, temperature, pH, TTHM (SDS1 only) and HAA5s (SDS1 only) were monitored at 1 day, 7 days, 15 days, and 20 days of contact

time. Additionally, nitrosamines were analyzed at days 7 and 20, while excitation emission matrix, total fluorescence and UVA_{254} was analyzed at day 7 (SDS1 only). The testing conditions are summarized in *Table 36*. Note that SDS1 is most representative of current finished water chlorine to ammonia ratio and the other SDS conditions were evaluated to provide perspective on current and future distribution system conditions.

Table 36. Testing conditions for the chloramination Simulated Distribution System (SDS) test.

Test Conditions	Units	SDS1	SDS2	SDS3
Chlorine Dose Applied	mg/L as Cl_2	2.8	2.8	2.8
Ammonia Dose Applied	mg/L as N	0.80	0.70	0.56
Cl_2 : NH_3^+-N Ratio		3.5 : 1	4.0 : 1	5.0 : 1
Temperature	°C	≈20	≈20	≈20
pH	s.u.	8.0	8.0	8.0
Reaction Times	days	1, 7, 15, 20	1, 7, 15, 20	1, 7, 15, 20

Immediately after the samples were dosed with chlorine and ammonia to form chloramines, aliquots were collected and analyze for final water quality parameters including turbidity, conductivity, alkalinity, hardness, and total dissolved solids. The results of the final water quality can be found in Table 37.

Table 37. Final water quality, as determined immediately following chloramination.

Test Conditions	Units	SDS1	SDS2	SDS3
Conductivity	µS/cm	617	619	618
Total Dissolved Solids	mg/L	325	343	372
Alkalinity	mg/L as $CaCO_3$	64.8	64.8	65.5
Calcium	µg/L	50,300	52,400	50,900
Magnesium	µg/L	6,890	7,170	6,950
Hardness, Ca	mg/L as $CaCO_3$	126	131	127
Hardness, Mg	mg/L as $CaCO_3$	28.4	29.5	28.6
Hardness, total	mg/L as $CaCO_3$	154	160	156

Over the course of 20 days, the total chlorine and monochloramine decay was slow and stable for all three tests. At the 5:1 chlorine to ammonia ratio, the observed decay was fastest- most likely due to the formation of less stable chloramine species like dichloramines, which typically begin forming at chlorine to ammonia ratios above 4:1. At the 3.5 and 4.0 to 1 chlorine to ammonia ratios, the decay was almost identical, which is to be expected. At a 4:1 chlorine to ammonia ratio and below, monochloramines, which are the most stable species of chloramines, are the dominant species present. Figure 41 illustrates the total chlorine and monochloramine decay for all 3 tests over the full 20 day incubation period, while Table 38 summarizes the test data acquired.

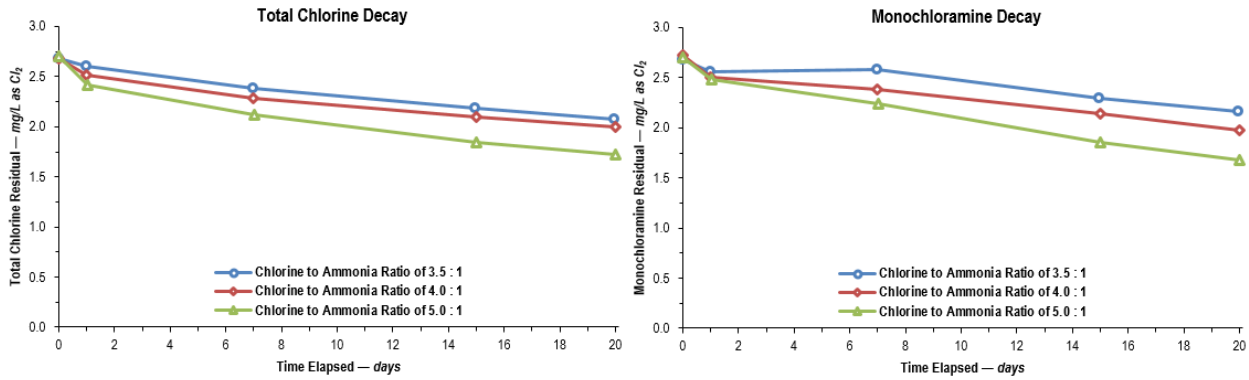

Figure 41. Total chlorine and monochloramine decay results for the chloramination testing.

Table 38. Demand/Decay results for chloramination testing.

Sample ID	Reaction Time days	Cl_2:NH_3^+-N ratio	Total Cl_2 Residual mg/L as Cl_2	NH_2Cl Residual mg/L as Cl_2	Free Cl_2 Residual mg/L as Cl_2	Free NH_3^+ Residual mg/L as N	pH s.u.	Temp. °C
CR-SDS1	0.0	3.5 : 1	2.68	2.68	<0.08 U	0.24	8.0	21.5
	1.0		2.60	2.56	<0.08 U	0.28	8.0	19.8
	7.0		2.38	2.58	<0.08 U	0.28	8.4	20.7
	15.0		2.18	2.30	<0.08 U	0.12	8.3	20.5
	20.0		2.08	2.16	<0.08 U	0.18	8.4	20.4
CR-SDS2	0.0	4.0 : 1	2.68	2.72	<0.08 U	0.14	8.1	21.5
	1.0		2.52	2.50	<0.08 U	0.18	8.1	19.8
	7.0		2.28	2.38	<0.08 U	0.12	8.5	20.7
	15.0		2.10	2.14	<0.08 U	0.12	8.5	20.5
	20.0		2.00	1.98	<0.08 U	0.13	8.4	20.4
CR-SDS3	0.0	5.0 : 1	2.70	2.70	<0.08 U	<0.04 U	8.0	21.5
	1.0		2.42	2.48	<0.08 U	<0.04 U	8.1	19.8
	7.0		2.12	2.24	<0.08 U	0.09	8.6	20.7
	15.0		1.84	1.86	<0.08 U	0.10	8.5	20.5
	20.0		1.72	1.68	<0.08 U	0.10	8.4	20.4

Using the chlorine decay data obtained in the chloramination testing, a pseudo-first-order linearization was developed for all three tests. Linearization serves as a data quality check and can be used to determine the tests' specific decay rate constants and half-lives. Chlorine decay follows second-order reaction kinetics, and a true linearization of the decay is very complicated and requires additional knowledge of parameters such as DOC concentrations at the various reaction points. In lieu of a second-order linearization, a pseudo-first-order linearization offers a very close approximation. The chlorine residual is taken as a reciprocal and plotted versus the reaction time. Using the 1, 7, 15 and 20 day reaction times, the pseudo-first-order linearization results are represented graphically in *Figure 42*. The total chlorine and monochloramine linearizations all have very strong R^2 values, indicating that the data quality is high (accurate chlorine/chloramine measurements, based on data following expected trends). Based on these linearizations, the rate constants, K, can be determined from the slope of each line, while the half-life can be calculated by taking the reciprocal of K*[initial chlorine dose]. These values are summarized below in *Table 39*.

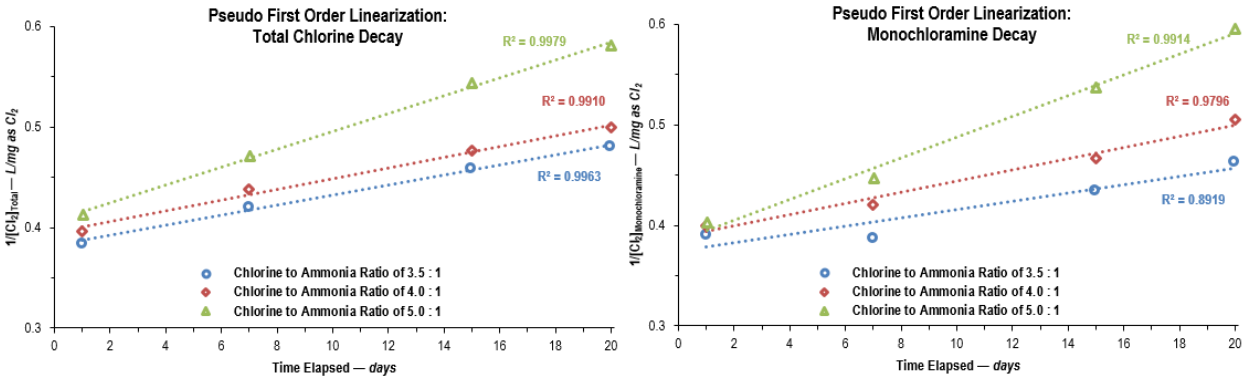

Figure 42. Pseudo first order linearization of total chlorine and monochloramine decay results for the chloramination testing. NOTE: Psuedo first order linearizations are specific to these test conditions (i.e., chlorine dose, temperature, pH, organics concentration, etc…) and should not be used as a predictive tool.

Table 39. Pseudo first order linearization results for chloramination testing.

Sample ID	Cl_2:NH_3^+-N ratio	Total Cl_2 Rate Constant (K) L/mg*day	Total Cl_2 Half-life ($t_{1/2}$) day^{-1}	Total Cl_2 R^2	NH_2Cl Rate Constant (K) L/mg*day	NH_2Cl Half-life ($t_{1/2}$) day^{-1}	NH_2Cl R^2
CR-SDS1	3.5 : 1	0.0050	70.9	0.9963	0.0041	87.4	0.8919
CR-SDS2	4.0 : 1	0.0053	66.9	0.9910	0.0056	64.2	0.9796
CR-SDS3	5.0 : 1	0.0089	40.2	0.9979	0.0103	34.7	0.9914

It is important to note that these linearizations are specific to these test conditions and should not be used as a predictor at full-scale. If the chlorine dose, organics concentration, pH and/or temperature were to change from these specific conditions, the decay kinetics would also change accordingly.

Over the course of 20 days, TTHMs were analyzed for SDS1 only (3.5:1 Cl2:NH3+-N ratio), and the formation was minimal. In total, TTHMs were not detected until day 7, and between day 7 and 20 the TTHM concentrations were estimated values (J-flags) between 0.15 and 0.50 µg/L increasing linearly over time. The estimated TTHM results were comprised of only one species, chloroform, while the other three species were not detected (less than 0.15 µg/L). Figure 43 and Table 40 summarizes these results.

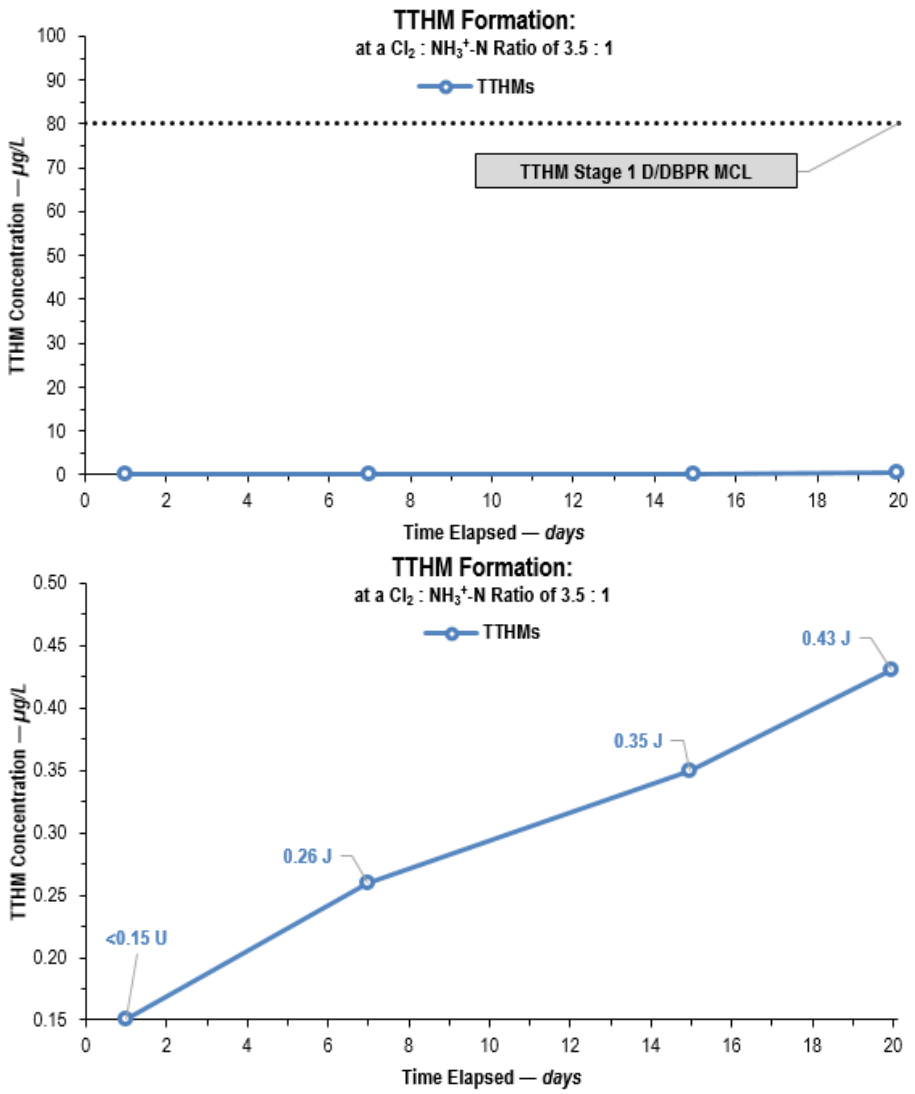

Figure 43. TTHM results over the course of 20 days during the chloramination testing.

HAA5 formation over the course of 20 days was minimal, and only saw one positive detection at day 20 for SDS1 (3.5:1 Cl2:NH3+-N ratio; only test monitored for HAA5 formation). In total, HAA5 concentrations at day 20 were measured as 1.75 µg/L for dichloroacetic acid, and 1.13 µg/L for Bromochloroacetic acid (HAA6 compound). These results are summarized below in Figure 44 and Table 40.

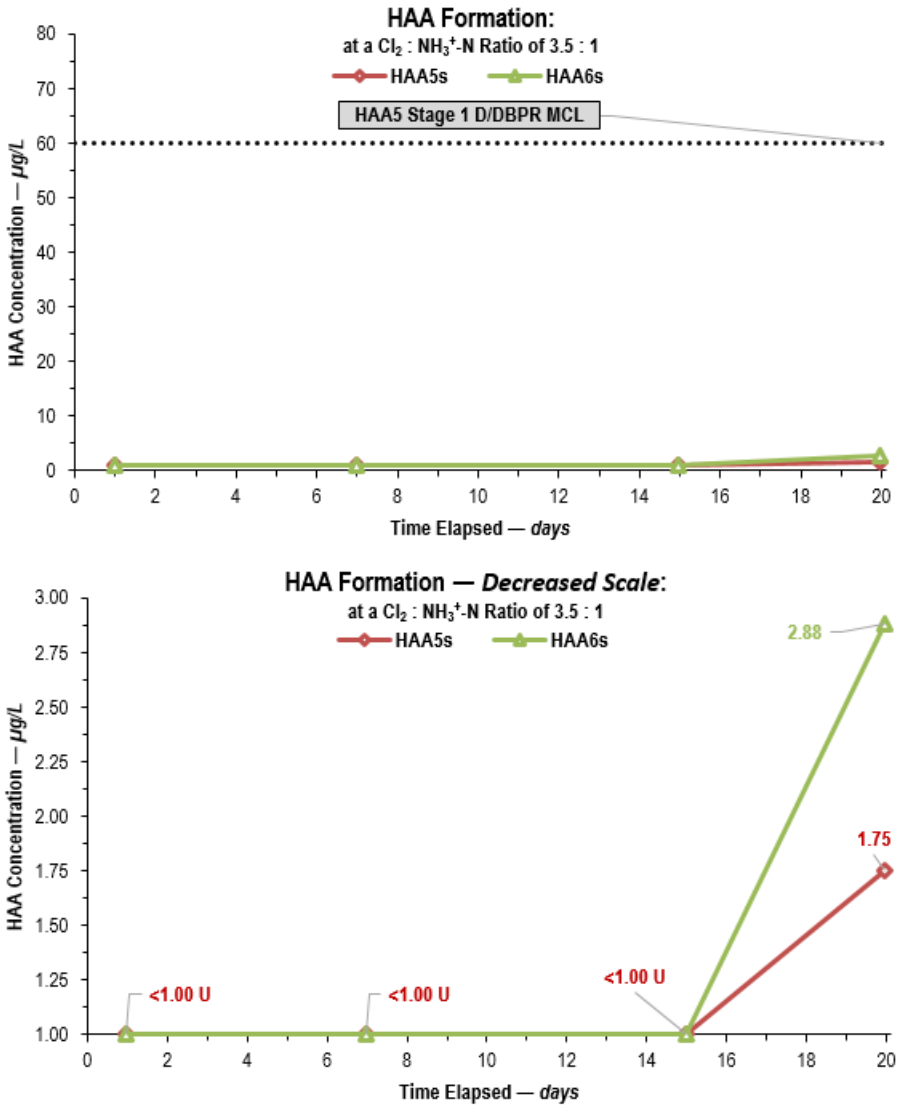

Figure 44. HAA results over the course of 20 days during the chloramination testing.

Nitrosamine formation was monitored at days 7 and 20 for all three SDS tests, and higher chlorine to ammonia ratios yielded slightly higher concentrations. *Figure 45* below displays these results on a total nitrosamine basis. No current federal regulations exist for nitrosamines, and the *California Department of Health Services* has established a notification level of 10 ng/L for three individual nitrosamine species: N-Nitrosodiethylamine (NDEA), N-Nitroso-dimethylamine (NDMA), and N-Nitrosodi-n-propylamine (NDPA). While total nitrosamine formation was at or slightly above 10 ng/L by day 7 in SDS 2 and 3, and above 10 ng/L by day 20 in SDS 1, these individual species all remained below the California notification level. Specifically, only two of the eight species were detected throughout the test, which included NDMA and N-Nitrosodibutylamine (NDBA). NDBA, does not have an established notification level by the state of California, however, it too remained below 10 ng/L. The three species with established notification levels are displayed in *Figure 46* below. In *Figure 47* below, a *near*-linear trend is apparent for NDMA formation versus the chlorine to ammonia ratio applied. Numerical results for NDMA and total nitrosamines can be found summarized in *Table 40*.

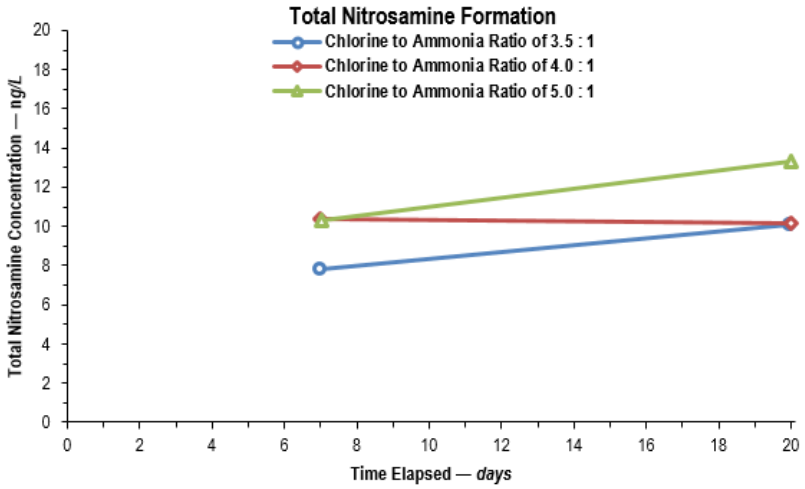

Figure 45. Nitrosamine results over the course of 20 days during the chloramination testing.

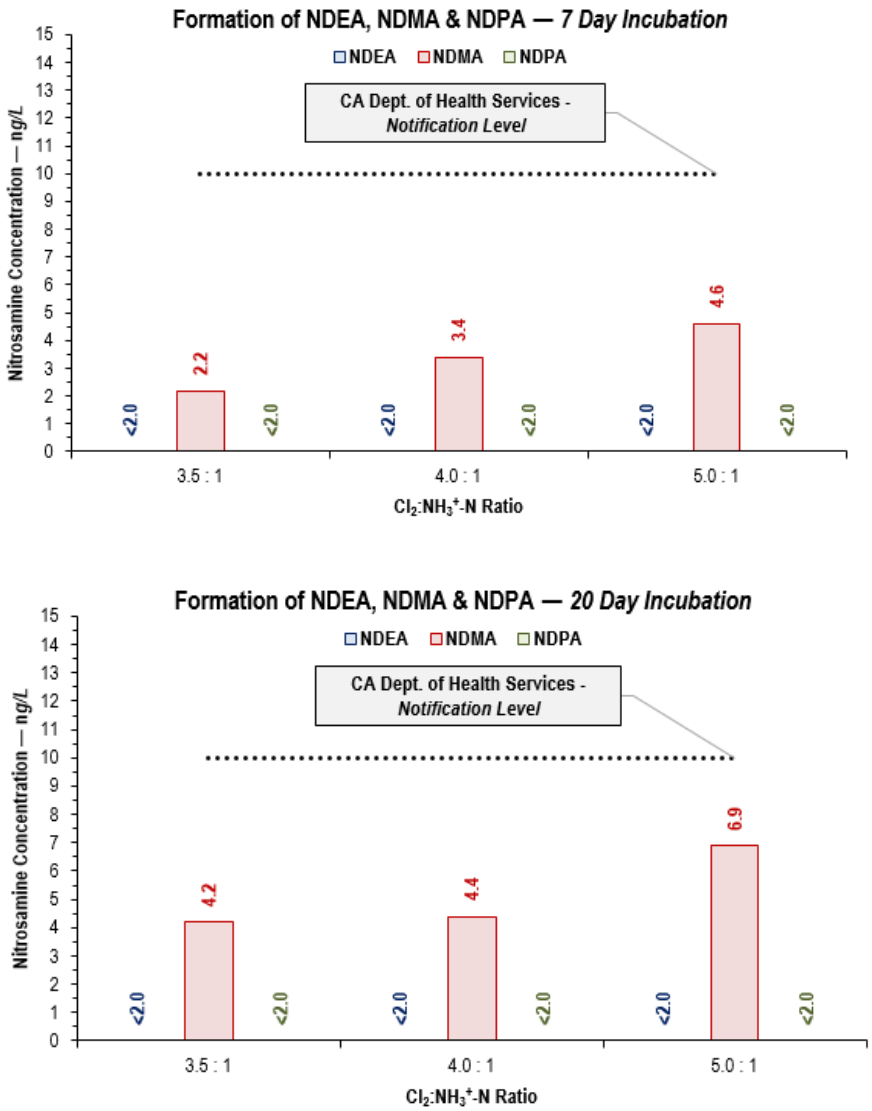

Figure 46. Three nitrosamine species with established notification levels by the California Department of Health Services (top) at 7 days, and (bottom) at 20 days.

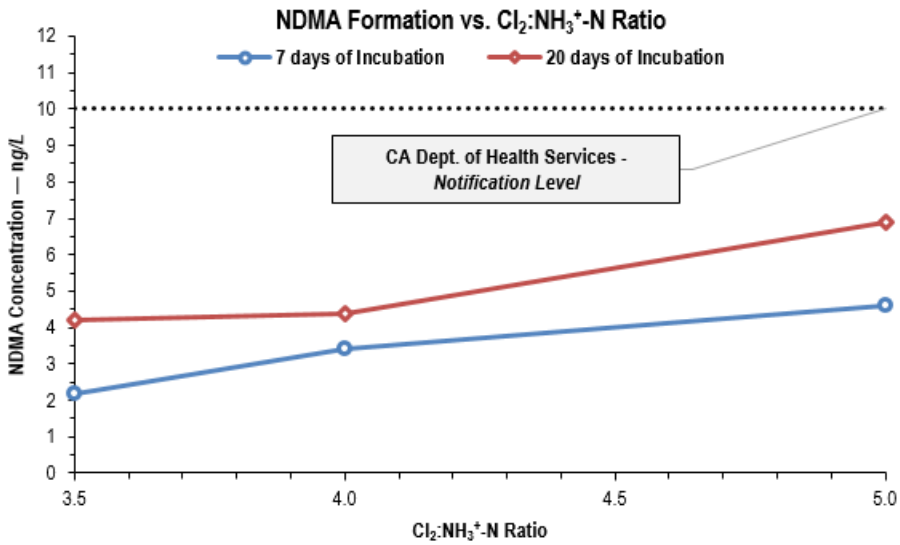

Figure 47. NDMA formation vs. chlorine to ammonia ratio during the chloramination testing.

Table 40. DBP results for chloramination testing. NOTE: THMs and HAAs only analyzed for SDS1, and nitrosamines only analyzed on days 7 and 15.

Sample ID	Reaction Time days	Cl_2 : NH_3^+-N ratio	Total Cl_2 Residual mg/L as Cl_2	TTHMs µg/L	HAA5s µg/L	HAA6s µg/L	NDMA ng/L	Total Nitrosamines ng/L
CR-SDS1	0.0	3.5 : 1	2.68	n/a	n/a	n/a	n/a	n/a
	1.0		2.60	<0.15 U	<1.00 U	<1.00 U	n/a	n/a
	7.0		2.38	0.26 J	<1.00 U	<1.00 U	2.2	7.8
	15.0		2.18	0.35 J	<1.00 U	<1.00 U	n/a	n/a
	20.0		2.08	0.43 J	1.75	2.88	4.2	10.1
CR-SDS2	0.0	4.0 : 1	2.68	n/a	n/a	n/a	n/a	n/a
	1.0		2.52	n/a	n/a	n/a	n/a	n/a
	7.0		2.28	n/a	n/a	n/a	3.4	10.4
	15.0		2.10	n/a	n/a	n/a	n/a	n/a
	20.0		2.00	n/a	n/a	n/a	4.4	10.2
CR-SDS3	0.0	5.0 : 1	2.70	n/a	n/a	n/a	n/a	n/a
	1.0		2.42	n/a	n/a	n/a	n/a	n/a
	7.0		2.12	n/a	n/a	n/a	4.6	10.3
	15.0		1.84	n/a	n/a	n/a	n/a	n/a
	20.0		1.72	n/a	n/a	n/a	6.9	13.3
Stage 1 D/DBPR			**4.00$^{\alpha}$**	**80.0**	**60.0**	**n/a**	**10***	**n/a**

For full speciation of THMs, HAAs, and nitrosamines see analytical reports and/or Treatability Excel Summaries
D/DBPR = Stage 1 Disinfectants/Disinfection Byproducts Rule
α = Stage 1 Disinfectants/Disinfection Byproducts Rule (D/DBPR) Maximum Residual Disinfectant Level (MRDL)
* = No regulation established; *California Department of Health Services* notification level of 10 ng/L for NDEA, NDMA & NDPA

Additionally, the TF and EEM was analyzed on a single sample from SDS1 after 7 days of incubation. The TF was recorded as 7,243 R.U. nm^2, which was the lowest recorded TF throughout all of the bench-scale treatment evaluations (raw water recorded as 103,887 R.U.nm^2 while the 15 min. EBCT RSSCT effluent

at approximately 10 kBVs was recorded as 10,970 R.U. nm^2). *Figure 46* depicts side-by-side comparisons of all EEM heat maps across all treatment processes evaluated, which indicate that chloramination further reduced the organics present in the aromatic protein region.

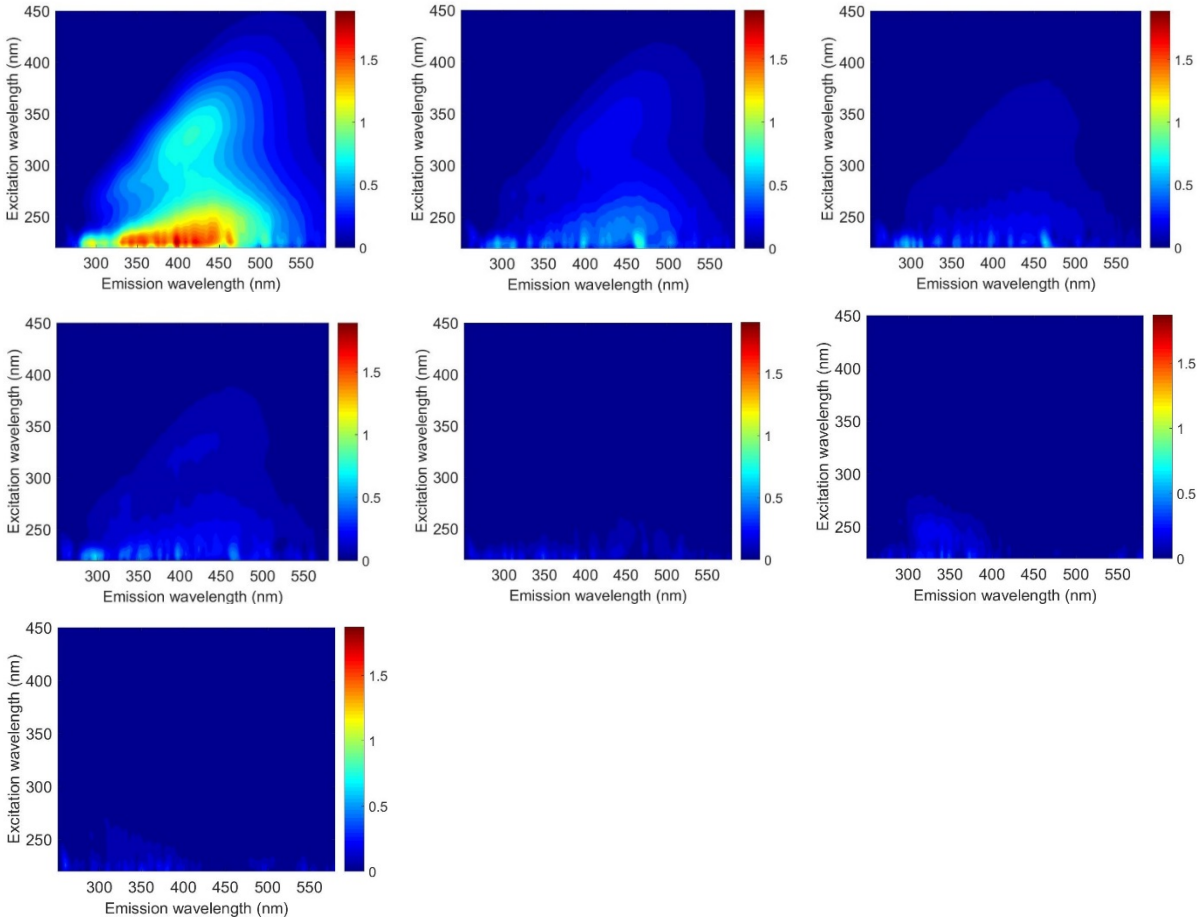

Figure 48. Exitation Emission Matrix heat map for (top-left) untreated blend water, (top-middle) pre-ozonated with 2.0 mg/L O_3, (top-right) 60 mg/L ferric chloride treated at ambient pH, (middle-left) 7.0 min EBCT BAC Effluent, (middle-middle) Post-BAC/MF Ozonation, (middle-right) GAC after 10 kBV, and (bottom-left) after 7 days incubation with chloramines at a 3.5:1 Cl_2:NH_3^+-N ratio (ALL EEM heat maps normalized to untreated water; Snyder labs, University of Arizona).

Section 12.0 – References

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