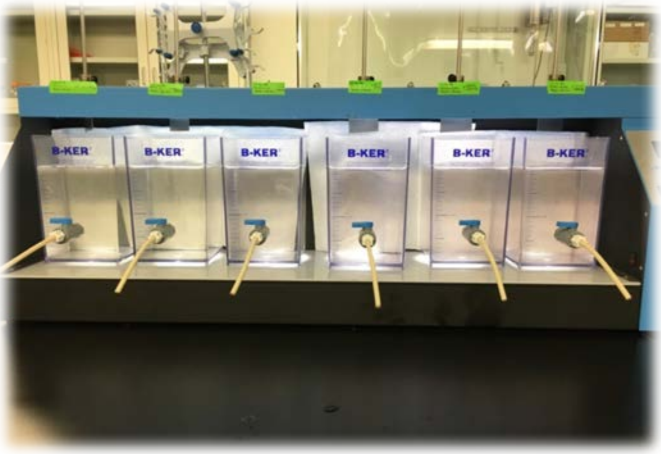
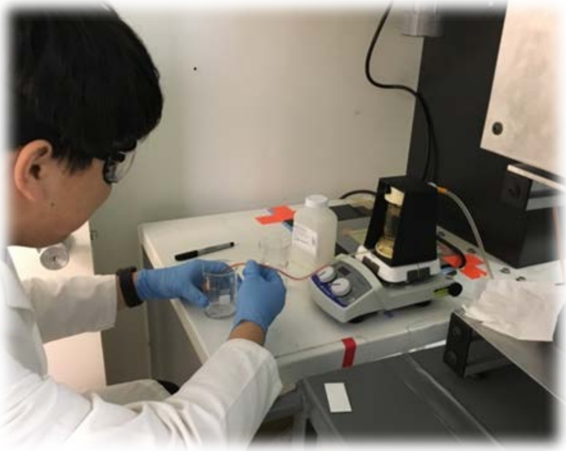
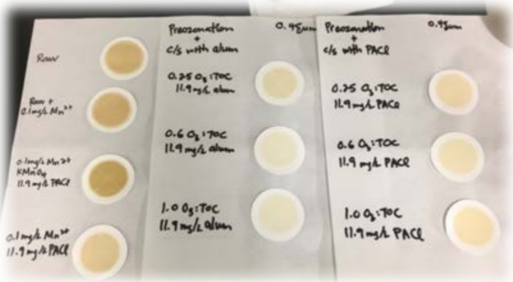
# Stanislaus Regional Water Authority
# Water Supply Project
# Bench Test Results – TM 1
# November 2016 through February 2017







*Prepared for:*

***Stanislaus Regional Water Authority***

SRWA
STANISLAUS REGIONAL WATER AUTHORITY

*October 2017*

Trussell
TECHNOLOGIES INC

WEST YOST
ASSOCIATES
*Consulting Engineers*

# Table of Contents

## List of Tables

## List of Figures

# TECHNICAL MEMORANDUM

Stanislaus Regional Water Authority Water Supply Project
Bench Test Results - TM 1

**Draft Date:** September 12, 2017
**Final Date:** October 18, 2017

**To:** Stanislaus Regional Water Authority (SRWA)

**Authors:** Emily Owens-Bennett, P.E. (Trussell Technologies)
Elaine W. Howe, P.E. (Trussell Technologies)
Israel Monroy (Trussell Technologies)

**Reviewers:** R. Rhodes Trussell, Ph.D., P.E. (Trussell Technologies)
Andy Smith, P.E. (West Yost Associates)
Whitney Sandelin, P.E. (West Yost Associates)

**Subject:** Bench Test Results – TM 1

---

## 1 EXECUTIVE SUMMARY

The Stanislaus Regional Water Authority (SRWA), a joint powers authority between the Cities of Turlock and Ceres, is pursuing a new water supply project to provide treated surface water from the Tuolumne River as a supplement to their existing groundwater supplies. Candidate treatment options for the project are being evaluated through a one-year bench testing program (November 2016 – October 2017), using samples collected from the Tuolumne River as part of a parallel source water quality monitoring campaign. The bench-scale tests were designed to evaluate enhanced coagulation, ozone demand of both the raw water and coagulated/settled water, disinfection by-product (DBP) formation associated with free chlorine and combined chlorine, as well as techniques for removal of manganese from the raw water. Of particular concern in selecting appropriate treatment is the impact of seasonal water quality changes, thus the bench testing includes one year of 1) monthly ozone demand assessment and 2) quarterly manganese removal evaluation.

This first bench testing technical memorandum (TM 1) summarizes the objectives and methodology for each of the test conditions, as well as results and conclusions from testing conducted on samples taken between November 2016 and February 2017. A subsequent TM (TM 2) will address a full year of testing in order to support more detailed treatment plant design criteria and will be prepared after the entire one-year bench testing program is complete.

Important treatment questions were developed for each bench testing category, to shape the test conditions and support treatment decision making. These critical treatment questions provide a summary of the November 2016 through February 2017 bench testing drivers, as follows:

**Enhanced Coagulation**

- Can the required total organic carbon (TOC) removal be achieved through coagulation? What percentage TOC removal is realistically attainable?
- Will pH reduction be required to achieve target TOC removals?
- How seasonably variable are the TOC and alkalinity of the source water? What, if any, is the impact on TOC removal requirements per the Stage 1 Disinfectants and Disinfection Byproducts Rule (D/DBP Rule) and ability to achieve required removal via enhanced coagulation?

**Ozone Demand**

- What ozone dose is required to meet the ozone demand?
- How does ozone demand of the raw water (preozonation) compare with ozone demand of coagulated/settled water (intermediate ozonation)?
- What is the seasonal variability of the ozone demand?
- Will bromate be formed with ozonation?

**DBP Formation**

- Are the DBPs (i.e., TTHM and $HAA_5$) a concern for this source water?
- Can the use of enhanced coagulation enable SRWA to meet DBP regulations? What level of TTHM and $HAA_5$ will form?
- In order to meet the MCLs for TTHM and $HAA_5$, will chloramines be required, rather than free chlorine, to maintain a disinfectant residual in the distribution system?
- When ozonation is included in the treatment train (preozonation or intermediate ozonation), does it impact the DBP formation?
- How does DBP formation vary with seasonal changes in water quality?
- What level of TOC removal is required for the finished water to be below 80% of the DBP MCLs—a treatment goal of the SRWA TAC?

**Manganese Removal**

- Is manganese likely to be present in the source water and, if so, in what form?
- If soluble manganese is present in the raw water, how can it be removed?
- How can the use of ozonation be optimized (preozonation and intermediate ozonation) to improve manganese removal?
- Which treatment trains allow for removal of manganese?

Salient findings that can be drawn from the initial four months (November 2016 through February 2017) of bench testing are the following:

- Although ferric chloride was initially identified as the preferred coagulant for turbidity and TOC removal, it was later rejected because of the amount of manganous ion

($Mn^{2+}$, a soluble ionic form of manganese) the bulk chemical was found to contain, which is not desirable. The coagulant for the full-scale design has not be selected, however, and further discussion of manganese removal will be provided in TM2.

- All three coagulants—alum, ferric, and PACl—were able to meet the TOC removal targets per the Stage 1 D/DBP Rule. On a mmol/L basis, all three coagulants performed similar for both turbidity and TOC removal. However, when the dose was converted to mg/L, a lower ferric dose was needed to achieve the target turbidity and TOC removal compared to alum and PACl, with alum and PACl performing almost identically. Also, ferric chloride was not as prone to turbidity increases due to particle restabilization or some other mechanism, as was alum and PACl.
- Reduction of pH during coagulation improved TOC removal, however it was possible to achieve the required TOC removal per Stage 1 D/DBP Rule with coagulation alone, without lowering the pH.
- Under "wet weather" conditions, significant TOC removal will be required to stay below the DBP MCLs if free chlorine is used for final disinfection. Direct filtration and membrane filtration will likely produce DBPs in excess of the MCLs unless chloramines are used for secondary disinfection since the maximum coagulant dose with these treatment processes is roughly 5 mg/L, and a higher coagulant dose is required under storm water conditions to remove the required amount of DBP precursor material.
- Simulated distribution system (SDS) DBP testing results indicated intermediate ozonation resulted in lower levels of DBPs with free chlorine disinfection, compared with DBP formation in non-ozonated samples.
- Increased ozone demand correlated with increased TOC concentrations in the waters being treated.
- Ozone decay was more rapid in warm water, as compared with cold water. Considering these reaction kinetics, the monthly testing is being conducted using warmer water conditions (20-22ºC).
- Bromate formation is not expected to be an issue if either preozonation or intermediate ozonation are used with this water, due to low bromide concentrations measured in the raw water.

## 2 INTRODUCTION

This technical memorandum (TM) is the first of two reports summarizing findings from the bench testing. This TM (TM 1) addresses testing conducted on samples taken between November 2016 and February 2017 in order to support early decision-making. The second TM (TM 2) will address a full year of testing in order to support more detailed treatment plant design criteria and will be prepared after the entire year of the bench testing program is complete.

The Stanislaus Regional Water Authority (SRWA), a joint powers authority between the Cities of Turlock and Ceres, is pursuing a new water supply project to provide treated surface water from the Tuolumne River as a supplement to their existing groundwater supplies. To inform treatment train selection, a source water quality monitoring campaign was initiated in October 2016. The monitoring program was designed to provide data on water quality parameters with State and Federal drinking water regulatory limits, pesticides of local concern, as well as other key parameters used to assess treatability. To provide some indication of seasonable variability in the source water, all of the monitoring parameters are being analyzed on a quarterly basis, with more frequent analysis (monthly or twice monthly) for some of the physical, chemical, and microbiological parameters that drive treatment selection.

In tandem with the source water sampling, the candidate treatment options are being further evaluated through a series of bench tests using source water collected from the Tuolumne River during the monitoring sampling events. The bench-scale tests were designed to evaluate enhanced coagulation, ozone demand of both the raw water and coagulated/settled water, disinfection by-product (DBP) formation associated with free chlorine and combined chlorine, as well as techniques for removal of manganese from the raw water. Of particular concern in selecting appropriate treatment is the impact of seasonal water quality changes, thus the bench testing includes one year of 1) monthly ozone demand assessment and 2) quarterly manganese removal evaluation.

# 3 TESTING OVERVIEW FOR TM 1

Four rounds of bench testing were completed using Tuolumne River samples collected between late November 2016 and mid-February 2017. The following list provides the sample collection dates and general sampling conditions along with a brief description of the testing objectives. The reported flow values are measured from the La Grange flow gauge station, upstream of the monitoring site.

- November 28, 2016 – lower flow (170 $ft^3/s$)
    - Ozone demand, enhanced coagulation, DBP formation tests
- December 12, 2016 – lower flow (170 $ft^3/s$)
    - Ozone demand, manganese removal
- January 9, 2017 – storm flow with releases from Don Pedro Dam (7,000 $ft^3/s$)
    - Ozone demand, enhanced coagulation
- February 13, 2017 – storm flow with releases from Don Pedro Dam (10,000 $ft^3/s$)
    - Ozone demand, DBP formation tests

Each of the test objectives listed above are listed in further detail in the subsequent subsections. The experimental methods are described in Appendix A.

## 3.1 Enhanced Coagulation

The D/DBP Rule requires water treatment systems that treat water that has an average TOC concentration greater than 2 mg/L to practice enhanced coagulation in order to minimize the public's exposure to potentially carcinogenic DBPs. The required TOC removal depends on both source water TOC and alkalinity, as indicated in Table 3-1, below.

Table 3-1. TOC removal required by the Stage 1 D/DBP Rule

| Source Water TOC (mg/L) | Source Water Alkalinity (mg/L as $CaCO_3$) | | |
|---|---|---|---|
| | 0-60 | >60-120 | >120 |
| >2.0 – 4.0 | 35% | 25% | 15% |
| >4.0 – 8.0 | 45% | 35% | 25% |
| >8.0 | 50% | 40% | 30% |

Raw water quality data were previously collected adjacent to the proposed intake location by Turlock Irrigation District (TID) between May 2006 and October 2008, as part of TID's Watershed Sanitary Survey. As part of this TID source water monitoring program, 47 samples were analyzed for TOC with a mean value of 3.3 mg/L and a median value of 3.0 mg/L. The alkalinity was measured 40 times, with a mean and median value of 37 mg/L as $CaCO_3$. Based on these data, the new water treatment plant (WTP) would be required to remove at least 35% of the source water TOC through the treatment train. The treated water in the distribution system must also meet maximum contaminant levels (MCLs) for specific DBPs; of particular importance for this project are the MCL for total trihalomethanes (TTHMs) set at 0.080 mg/L and the MCL for the sum of five haloacetic acids ($HAA_5$) set at 0.060 mg/L. Both of these MCLs are applied to the sampling point in the distribution system with the highest running annual average concentration.

With regard to TOC, important questions that arise regarding treatment of Tuolumne River water include:

- Can the required TOC removal be achieved through coagulation? What percentage TOC removal is realistically attainable?
- Will pH reduction be required to achieve target TOC removals?
- How seasonably variable are the TOC and alkalinity of the source water? What, if any, is the impact on TOC removal requirements per D/DBP Rule and ability to achieve required removal via enhanced coagulation?

Enhanced coagulation is achieved through the addition of sufficient coagulant to remove DBP precursor material (i.e., TOC) during conventional treatment. For some waters, reducing the pH of coagulation allows effective precursor removal at lower coagulant doses. The D/DBP Rule does not require enhanced coagulation for direct filtration because only very small coagulant doses (typically < 5 mg/L) can be used with direct filtration. Regardless of whether enhanced coagulation is practiced, the finished water in the distribution system must be compliant with the DBP MCLs. Three commonly used drinking water coagulants – aluminum sulfate (alum), ferric chloride (ferric), or polyaluminum chloride (PACl) – were tested to assess which was is better for TOC removal. The initial round of bench testing (November 2016 sample) included jar tests with acid addition to lower the coagulation pH for an assessment of additional TOC removal for an equivalent coagulant dose.

Because TOC removal requirements increase with greater concentrations of organic carbon in the source water (Table 3-1), the enhanced coagulation assessment was completed on water from two different sampling dates representing different seasonal conditions (late November and mid-January). Heavy rainfall in December, January, and February resulted in elevated flow in the Tuolumne River due to the release of water from the Don Pedro Dam, upstream of the source water sampling site. The rainfall produced poor water quality at the Tuolumne River with increased TOC levels in excess of 4 mg/L. Since TOC removal changes above 4 mg/L (Table 3-1), additional jar testing was conducted to understand the effectiveness of different coagulants (alum, PACl, and ferric chloride) at ambient pH, for turbidity and TOC removal during worst-case conditions.

## 3.2 Ozone Demand

Ozone is being considered as a potential treatment process for the project due to its ability to 1) break down large organic molecules (e.g., TOC, synthetic organic chemicals (SOCs), pesticides), 2) address algae by-products and related taste and odor (T&O) compounds, and 3) achieve primary disinfection with reduced DBP formation compared with the use of free chlorine.

With regard to ozone, important questions that arise regarding treatment of Tuolumne River water include:

- What ozone dose is required to meet the ozone demand?
- How does ozone demand of the raw water (preozonation) compare with ozone demand of coagulated/settled water (intermediate ozonation)?
- What is the seasonal variability of the ozone demand?
- Will bromate be formed with ozonation?

Ozone demand, and consequently the required ozone dose, can vary with changes in source water quality (e.g., TOC, turbidity, reduced iron and manganese, nitrite, etc.). Particulate matter (measured as turbidity) can be particularly variable when the source water is a river. Stormwater inputs and other runoff (e.g., agricultural tailwater) within the watershed can result in spikes of turbidity that may affect chemical (e.g., coagulant, ozone) demand and the dosing required to achieve treatment goals. To better understand the temporal variability of ozone demand, monthly tests are being conducted for one calendar year (November 2016 – October 2017) on both the raw source water (preozonation) and the source water that has been jar tested with an optimum coagulant dose to replicate coagulated/settled (CS) water (intermediate ozonation). Each test involves the following test conditions, with ozone dosing based on a ratio of ozone-to-TOC ($O_3$:TOC) of the water being treated:

- Raw source water: 0.6 $O_3$:TOC
- Raw source water: 1.0 $O_3$:TOC
- CS water: 0.6 $O_3$:TOC
- CS water: 1.0 $O_3$:TOC

The results of the initial ozone demand bench tests (November 2016) are presented in this TM, however the full results of the monthly ozone demand bench tests will be included in TM2, following completion of the bench testing activities in October 2017.

## 3.3 SDS DBP Tests

Simulated distribution system disinfection byproduct (SDS DBP) testing is used to assess the concentrations of DBPs that would be expected to form following treatment over a specified hold time, representative of the time in the distribution system. Different treatment conditions and hold times can be compared using this test method. Typically, DBP formation is correlated with TOC concentrations, as TOC is the precursor material for these compounds.

With regard to the DBPs of free chlorine, important questions that arise regarding treatment of Tuolumne River water include:

- Are the DBPs (i.e., TTHMs and $HAA_5$) a concern for this source water?
- Can the use of enhanced coagulation enable SRWA to meet DBP Regulations? What level of THMs and $HAA_5$ will form?
- In order to meet the MCLs for TTHM and $HAA_5$, will chloramines be required, rather than free chlorine, to maintain a disinfectant residual in the distribution system?
- When ozonation is included in the treatment train (preozonation or intermediate ozonation), does it impact the DBP formation?
- How does DBP formation vary with seasonal changes in water quality?
- What level of TOC removal is required for the finished water to be below 80 percent of the DBP MCLs—a treatment goal of the SRWA TAC?

Disinfection of the treated water with both free and combined chlorine (chloramines) were evaluated during two rounds of SDS DBP testing. The initial round of testing was conducted in November 2016, when the raw water was representative of "dry weather" conditions with low turbidity (≤2 NTU) and low TOC concentration (<2 mg/L). For the second round of testing in February 2017, the raw water was representative of "wet weather" conditions with higher turbidity (5-10 NTU) and higher TOC (3-4.5 mg/L).

### 3.4 Manganese Removal

Historical measurements of total manganese at the project infiltration gallery site range from <0.010 to 0.110 mg/L, with only two of the 94 samples exceeded the Secondary Maximum Contaminant Level (sMCL) of 0.05 mg/L under Title 22 of the California Code of Regulations (California State Water Resources Control Board, 2016). Measurements of the dissolved fraction of manganese were not available in the historical dataset. Manganese removal is important largely because of the potential for aesthetically unpleasant colored water in the distribution system, as well as potential health impacts. Soluble manganese in the water supply can cause colored water, staining, and buildup on the distribution system pipe walls.

Currently, manganese has only a secondary MCL and no primary MCL. However, manganese has been included on the latest Contaminant Candidate List (CCL4) and Unregulated Contaminant Monitoring Rule (UCMR4) lists because of potential neurological effects in children and infants. Therefore, a Primary MCL may be forthcoming in the future for this constituent.

Removal of manganese in water treatment is particularly difficult when soluble manganese is present, typically under anaerobic or anoxic conditions. While data suggest the Tuolumne River is well oxygenated, it is unknown if the infiltration gallery intake may provide anoxic conditions under which manganese can be reduced into a soluble form or whether the infiltration gallery may pull groundwater that contains soluble manganese. It is not uncommon for manganese to appear in a water supply, which was once thought to be manganese free. The most reliable method for removing manganese is to carry a chlorine residual through a granular media filter that has been conditioned to form a manganese dioxide layer on its surface, but this treatment strategy, which requires the use of a high free chlorine residual, has become less viable in recent years as DBP regulations have become more strict. Ozone is a stronger oxidant, but results on manganese removal via ozonation are more mixed.

Considering the historic measurement of manganese in the source water, as well as the potential implications for the water supply, an assessment of manganese removal has been included in the bench testing. Seasonal changes in the source water quality are also a concern for understanding the occurrence and removal of manganese through treatment. For this reason, manganese removal testing is being conducted on a quarterly basis for one calendar year (December 2016, plus March, June, and September 2017).

With regard to manganese, important questions that arise regarding treatment of Tuolumne River water include:

- Is manganese likely to be present in the source water and, if so, in what form?
- If soluble manganese is present in the raw water, how can it be removed?
- How can the use of ozonation be optimized (preozonation and intermediate ozonation) to improve manganese removal?
- Which treatment trains allow for removal of manganese?

Full results from the quarterly manganese removal testing will be addressed in the Bench Test Results TM 2.

# 4 RAW WATER QUALITY RESULTS

FishBio has been contracted to collect the samples for the source water quality monitoring campaign, along with field measurements of select raw water quality parameters. Upon receipt of the water samples in the Trussell Tech Lab, water quality measurements also were completed for each batch of sample used in the bench tests. Raw water quality results are presented in Appendix B (Table B-1 through Table B-4) according to sample date and separate sample cubitainer used for individual jar tests. The raw water quality, particularly the turbidity, TOC, and DOC, changed significantly between the December 2016 and January 2017 sampling events. Winter storms brought heavy rains to the area from late December through February. The Tuolumne River flows swelled from approximately 170 $ft^3/s$ in November and early December to 7,000 $ft^3/s$ in early January and 10,000 $ft^3/s$ by mid-February, as depicted in the Figure 4-1 photo taken January 5, 2017. As seen in the figure, the recent flows are the highest since 1997, when flow exceeded 50,000 $ft^3/s$. The high storm flows were exacerbated by releases from the upstream Don Pedro Dam, as indicted in Figure 4-2.

**Figure 4-1. Photo of flooded Tuolumne River near infiltration gallery and source water sampling location, January 5, 2017**

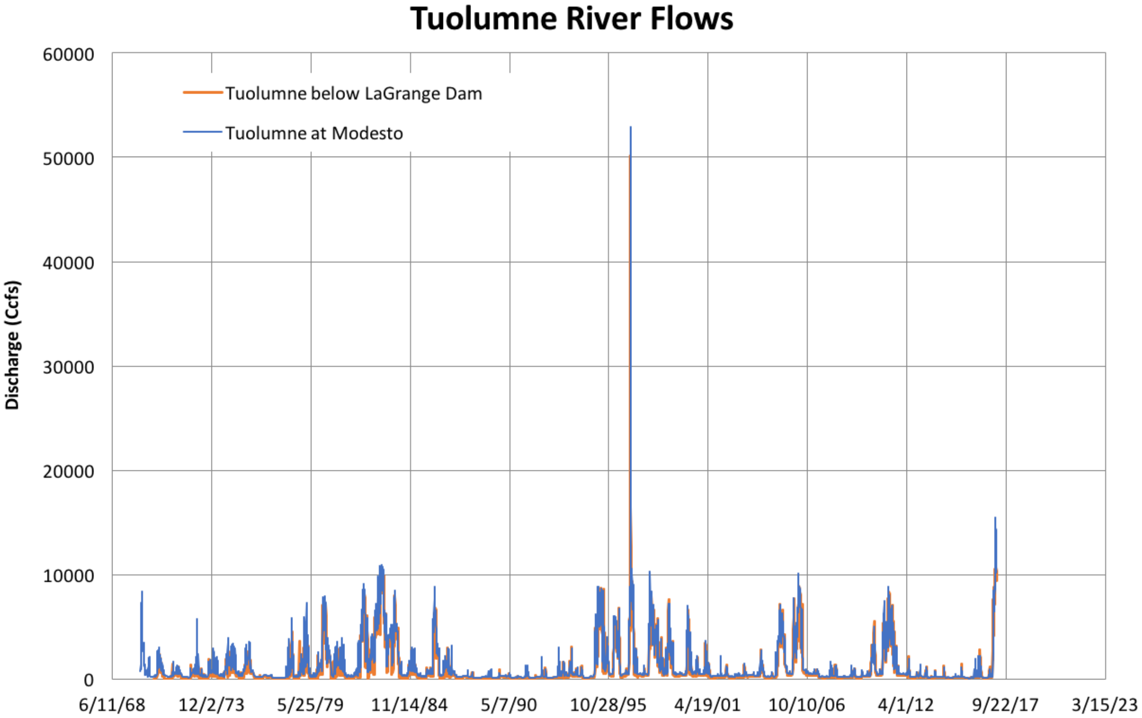


**Figure 4-2. Historical stream flows on the Tuolumne River upstream and downstream of the Infiltration Gallery**

The bench testing program was designed to understand seasonal changes in the source water and the corresponding impact on treatment. The raw water quality results for January and February 2017 are representative of heavy rains and high flood conditions in the Tuolumne River, resulting in elevated TOC and turbidity. The impacts of this storm water quality on enhanced coagulation, ozone demand, and SDS DBP formation provide important information for design consideration and are discussed in the following sections.

# 5 ENHANCED COAGULATION JAR TEST RESULTS

Enhanced coagulation jar testing was first conducted using the Tuolumne River sample collected on November 28, 2016. Additional, testing was completed on samples collected January 9, 2017, under high flow conditions related to winter storm runoff. Raw water quality measured in conjunction with enhanced coagulation jar testing is summarized in Appendix B Table B-1 (November 28, 2016 sample) and Table B-3 (January 9, 2017 sample).

## 5.1 Jar Testing Results

Jar testing for enhanced coagulation was conducted using water samples collected on November 28, 2016 and January 9, 2017, to account for varying source water quality. Additional jar tests were completed to prepare water for the monthly ozone demand testing. All water quality results related to the jar testing are presented in Appendix C.

### 5.1.1 November 28, 2016 Sample (Jar Tests 1A-6A)

The first three sets of jar tests during the initial round of bench testing were designed to evaluate the effectiveness of three coagulants— alum, ferric chloride, and PACl—at ambient pH, for both turbidity removal and TOC removal. Jar Test 1A evaluated six alum doses, Jar Test 2A evaluated six ferric doses, and Jar Test 3A evaluated five PACl doses and an additional alum dose (0.101 mM $Al^{3+}$). The removal of TOC, turbidity, and reduction of UV-254 were compared among the doses of each coagulant, as well as between the various coagulants tested. Results from the first three jar tests were used to select an optimum coagulant type and dose for Jar Test 4A, in order to prepare water for the SDS DBP testing (Section 7). The effect of pH on coagulation was tested using acid addition in combination with Jar Test 5A. A subsequent test, Jar Test 6A, was also added to compare two lower doses of PACl (0.007 and 0.017 mM $Al^{3+}$). The results are shown in Table C-1 through Table C-5 in Appendix C and summarized in the following discussion.

#### 5.1.1.1 Turbidity and TOC Removal

The coagulant doses tested were based on an equal millimolar (mM) metal ion (either $Fe^{3+}$ or $Al^{3+}$) basis, which ranged from 0.007 mM to 0.101 mM. Both alum and ferric chloride act as strong acids and consume alkalinity. One mg/L alum consumes 0.50 mg/L of alkalinity as $CaCO_3$, and one mg/L ferric consumes 0.92 mg/L of alkalinity as $CaCO_3$ per mg/L. This reduction in pH and alkalinity is apparent in the data presented in Table C-1 and Table C-2.

Polyaluminum chloride (PACl) is a hydrolyzed polymeric aluminum chain with the following general formula $Al_a(OH)_b(Cl)_c(SO_4)_d$. Because it contains hydroxide anions, PACl is able to neutralize the acidic behavior of the aluminum ions, and thus produces very little change in pH or alkalinity. The degree of acid neutralization is measured by the chemical's basicity. Testing involving PACl was completed using a proprietary blend from Kemira Cheimcals, Inc. called PAX-18, with a basicity of 43.5%. Its neutralization ability is illustrated by the data in Table C-3, which shows less reduction in pH and alkalinity at higher PACl doses, as compared with equivalent mM doses of alum or ferric chloride.

The ability of the three different coagulants to reduce turbidity is illustrated in Figure 5-1 and Figure 5-2. Figure 5-1 demonstrates the coagulant dose on a mM basis to compare the performance of turbidity removal based on the metal ions active in the three coagulants. Figure 5-2 demonstrates the coagulant dose in mg/L to compare the removal of turbidity for the different coagulant doses. Both figures have a modified turbidity removal graph for ferric chloride to account for the one outlier value. The increase in settled water turbidity at the very low coagulant doses is likely attributed to floc carry-over during sampling.

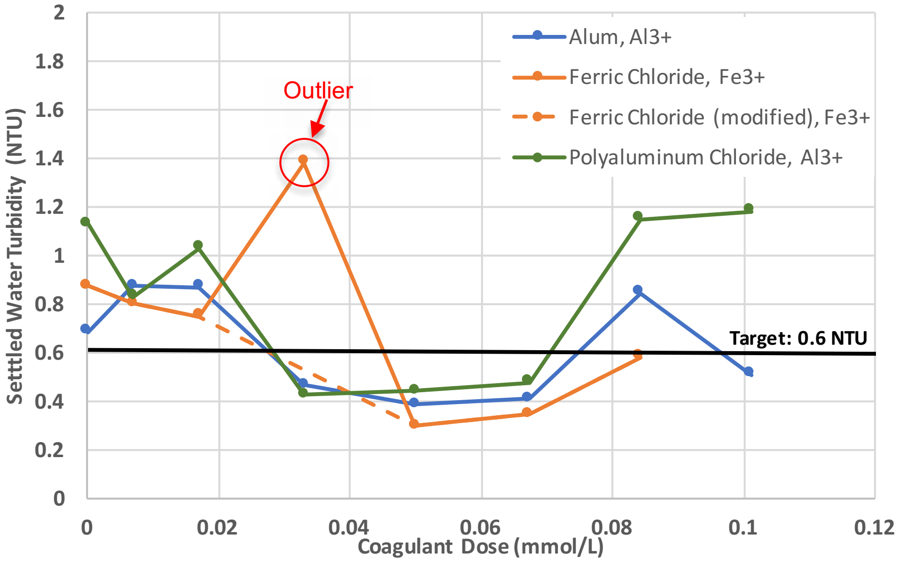


**Figure 5-1. Settled water turbidity as a function of coagulant type and mmol/L dose (November 2016).**

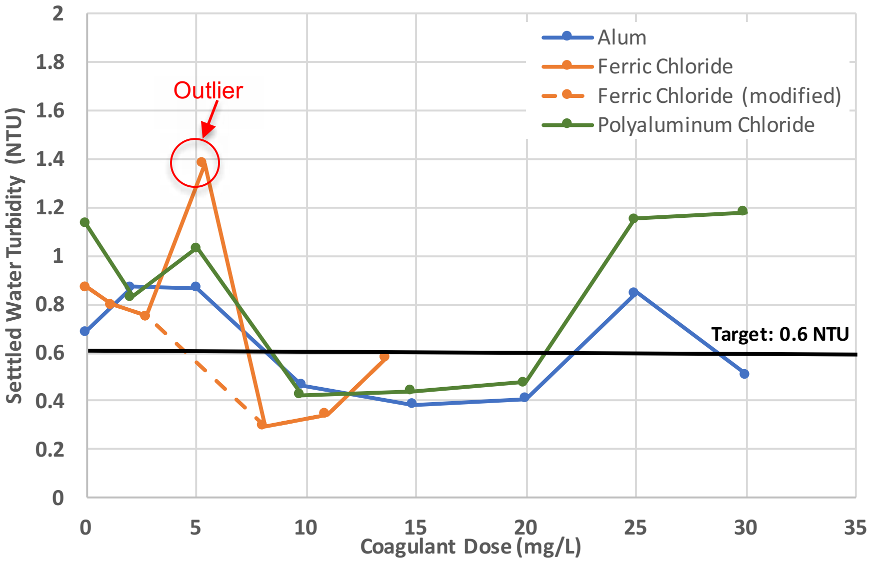


**Figure 5-2. Settled water turbidity as a function of coagulant type and mg/L dose (November 2016).**

The dose required to achieve a settled water turbidity of 0.6 NTU was used to compare jar test results, based on the low turbidity of the raw water (less than 2 NTU). On an equal molar basis, all three coagulants performed similarly for turbidity removal—with slightly better performance by ferric—until the point where the coagulant was over-dosed and the settled water turbidity increased. Ferric chloride produced a settled water turbidity less than 0.6 NTU over a wide range of doses and was not as prone to turbidity increases due to "peptization" – stabilization of precipitated colloidal material through the addition of an electrolyte, as were both alum and PACl. The correlation of turbidity removal with coagulant dose can be used to assess the production of sludge, and is discussed further in Section 5.1.2.1.

The ability of the three different coagulants to remove TOC is shown in Figure 5-3; the average TOC value is used to calculate the 35% TOC removal target provided in this figure, whereas removals associated with the individual jar tests are provided in Appendix C (Table C-1, Table C-2, and Table C-3). Routine monitoring of the SRWA source water quality began October 30, 2016. Monthly monitoring results for November and December yielded an average TOC of 2.05 mg/L and an average alkalinity of 26 mg/L as $CaCO_3$. Per the D/DBP Rule, the required TOC removal was 35%. As indicated by the data in Figure 5-3, the dose required to achieve the target 35% TOC removal (without pH adjustment) was approximately 9 mg/L or greater for ferric chloride, approximately 15 mg/L for PACl, and approximately 18 mg/L for alum. For the three coagulants, the overall removal trend for DOC is consistent (see Appendix C Figure C-1), while increases in TOC were observed at the higher doses for alum and PACl, possibly due to floc carry-over during the sampling process.

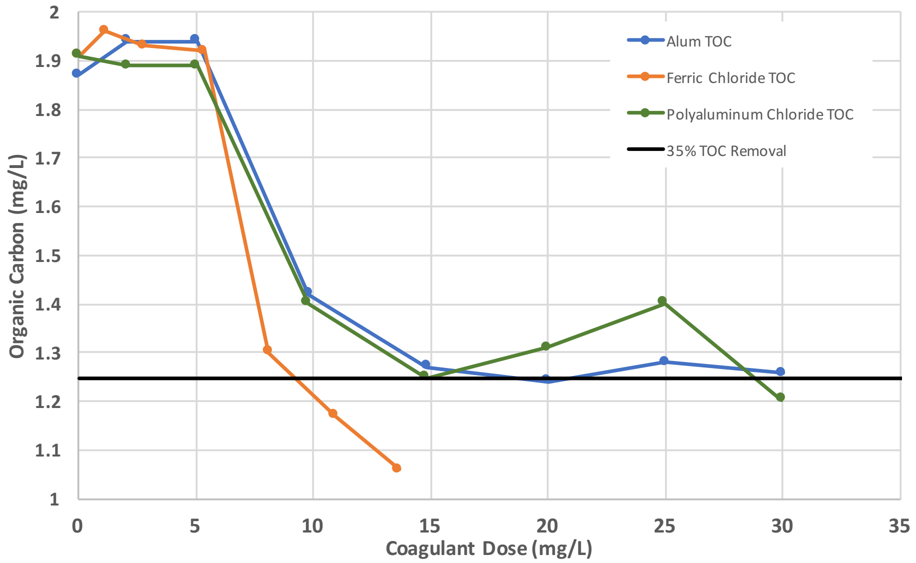


**Figure 5-3. TOC after coagulation as a function of coagulant type and mg/L dose (November 2016). Note: The removal target for TOC is calculated based on an average raw water concentration of 1.92 mg/L.**

### 5.1.1.2 Effect of pH on Coagulation

Another objective of the enhanced coagulation bench testing was to evaluate the effect of reducing the pH of coagulation on TOC removal. For most waters, greater TOC removal can be achieved at a lower pH with the same coagulant dose. The optimum ferric chloride and alum doses selected for further testing at a reduced pH were determined based on performance of Jar Tests 1A and 2A. Because PACl has acid neutralizing capabilities, it was not appropriate for reduced pH testing. Ferric chloride doses of 5.4 and 8.1 mg/L were tested at a target coagulation pH of 6.0, and the dose of 5.4 mg/L was also tested at a target pH of 6.5. Concurrently, alum doses of 9.8 and 14.9 mg/L were tested at a target coagulation pH of 6.0, and a dose of 9.8 mg/L was likewise tested at a target pH of 6.5. Hydrochloric acid (1 N) was used for pH adjustment and added to each jar prior to coagulant addition.

The full jar test results from this test are provided in Appendix C (Table C-5). TOC removal is summarized for ferric chloride and alum dosed at 0.033 mmol/L for the coagulation pHs tested in Figure 5-4; PACl results from this same 0.033 mmol/L dose and ambient pH are provided for comparison. For the ferric chloride dose of 5.4 mg/L, reducing the coagulation pH increased TOC removal from 0%[1] at ambient pH to 20% at pH 6.55 and 36% at pH 6.05. The ferric chloride dose of 8.1 mg/L increased TOC removal from 32% at ambient pH to 47% at pH 6.12. For the alum dose of 9.8 mg/L, TOC removal increased from 24% at ambient pH to 29% at pH 6.6. When the coagulation pH was reduced to 6.1, the TOC removal decreased to 10%[2], likely due to incorporation of floc in the TOC sample; the corresponding DOC removal increased from 28% at ambient pH to 34% at pH 6.1. A similar decrease in TOC removal was observed in conjunction with the alum dose of 14.9 mg/L, also thought to be due to floc carry-over in the settled water TOC sample. TOC removal for this dose was 32% at ambient pH and measured at 0% at pH 6.11[3]. DOC removal correlated with the settled water pH for both alum and ferric dosed at 0.033 mmol/L and is provided in Appendix C (Figure C-2). ***In general, lowering the pH of coagulation resulted in increased TOC removal, as compared with equivalent coagulant doses at ambient pH. However, the TOC removal at ambient pH was sufficient to meet removal requirements (per Stage 1 D/DBP Rule) for this source water.***

---

[1] At ambient pH, TOC of the settled water associated with the 5.4 mg/L ferric chloride dose was measured as 1.92 mg/L as compared to 1.91 mg/L measured in the raw water.

[2] There was likely an error in the TOC measurement. The corresponding DOC removal increased from 28% at ambient pH to 34% at pH 6.1 and the filtered UV-254 dropped from 0.026 at ambient pH to 0.017 at pH 6.1.

[3] The settled water TOC measured for the alum dose of 14.9 mg/L at pH 6.11 was 1.94 mg/L as compared to the 1.92 mg/L measured in the raw water. The corresponding DOC removal exhibited a lower decrease from 33% at ambient pH to 31% at pH 6.11 and the filtered UV-254 dropped from 0.023 at ambient pH to 0.015 at pH 6.11.

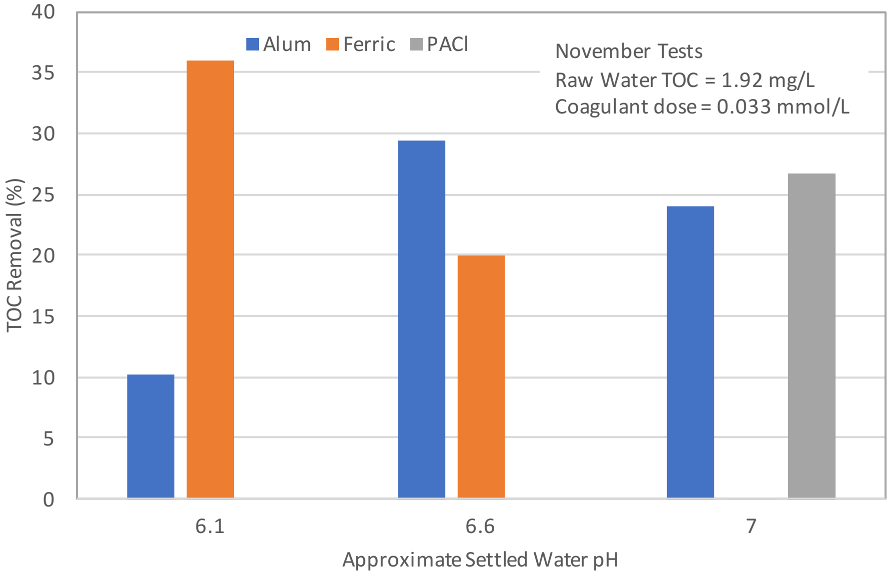


**Figure 5-4. TOC removal as a function of coagulation pH for coagulant doses of 0.033 mmol/L.**

### 5.1.2 January 9, 2017 Sample (Jar Tests 1B-4B)

As shown in the raw water data for January 2017 (Appendix B, Table B-3), the higher flow conditions associated with this sample yielded significantly higher source water turbidity and TOC values. Based on the TOC values measured at the Trussell Tech Lab, the raw water exceeded 4.0 mg/L TOC and 45% TOC removal would be required based on the Stage 1 D/DBP Rule. Four jar tests (1B-4B) were completed to understand turbidity, TOC, and DOC removal for this water using the same three coagulants (alum, ferric, and PACl) dosed over a similar range used for the November 2016 sample (lower raw water TOC and turbidity).

#### 5.1.2.1 Turbidity and TOC Removal

Results from January 2017 enhanced coagulation jar testing are provided in Appendix C (Table C-6, Table C-7, and Table C-8), according to the coagulant used (alum, ferric chloride, and PACl, respectively). Similar coagulant dose ranges were tested during the November 2016 bench testing, using millimolar (mM) metal ion (either $Fe^{3+}$ or $Al^{3+}$) doses from 0.007 mM to 0.101 mM.

As with the previous enhanced coagulation testing, the performance of the three different coagulants is compared on the basis of turbidity removal (mmol/L coagulant dose in Figure 5-5; mg/L coagulant dose in Figure 5-6) and TOC removal (mg/L coagulant dose in Figure 5-7). Due to the high initial turbidity of the raw water, the dose required to achieve a settled water turbidity of 2 NTU was used to compare jar test results. This target was achieved for all three coagulants (Figure 5-5 and Figure 5-6). The testing with PACl and alum yielded lower settled water turbidity in the dose range of 0.049 to 0.067 mmol/L, however the lowest settled water turbidity result was observed for a ferric dose of 0.084 mmol/L.

Consistent with the November 2016 testing, ferric yielded the lowest settled water turbidity on a mg/L basis, indicating that less sludge would be produced per volume of water treated with ferric. Estimates of annual sludge production were made for all three coagulants, assuming a one-to-one ratio of TSS to turbidity, winter water quality representative of the January 2017 sample, as well as optimum coagulant doses determined based on 35% TOC removal (15 mg/L for both alum and PACl and 12 mg/L for ferric). As expected, sludge production associated with the use of ferric is expected to be lower with approximately 4.4 x $10^5$ pounds of sludge per year, compared with an estimated 4.8 x $10^5$ pounds of sludge per year associated with alum or PACl.

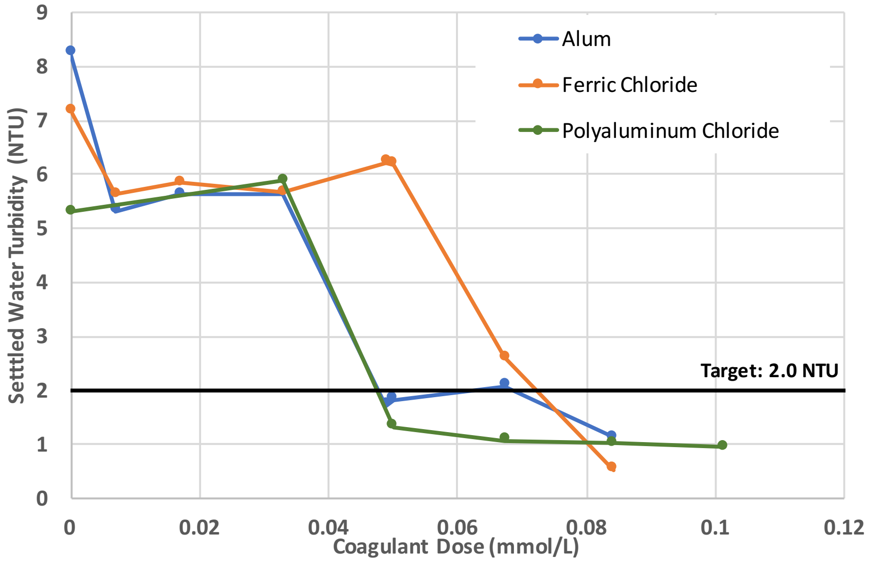


**Figure 5-5. Settled water turbidity as a function of coagulant type and mmol/L dose (January 2017).**

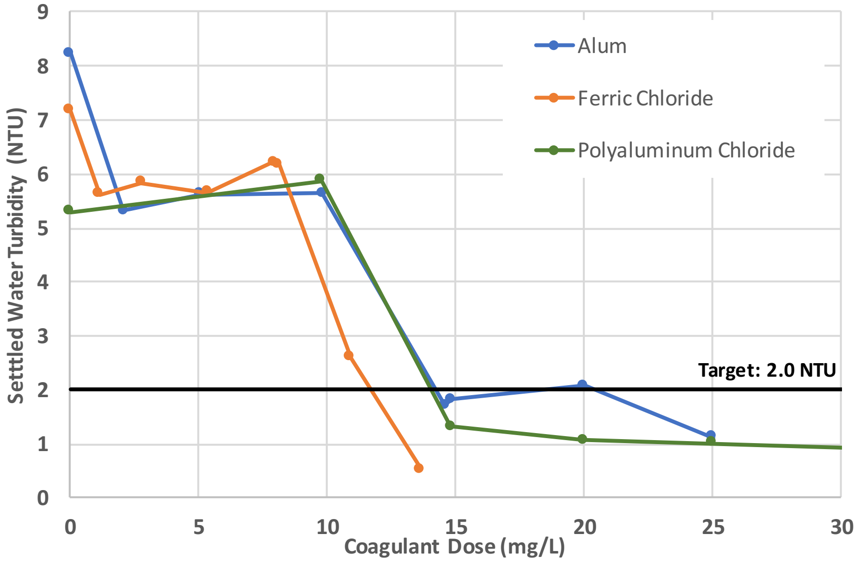


**Figure 5-6. Settled water turbidity as a function of coagulant type and mg/L dose (January 2017).**

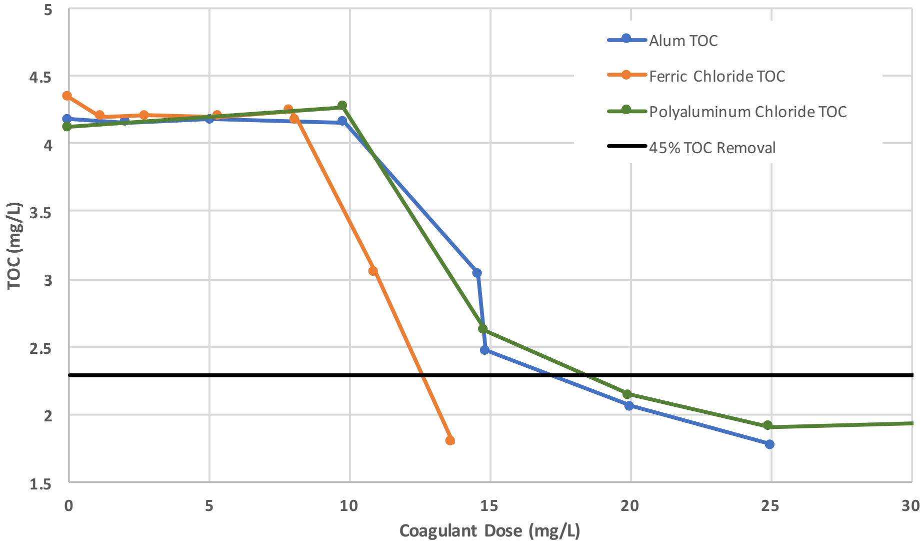


**Figure 5-7. TOC after coagulation as a function of coagulant type and mg/L dose (January 2017). Note: The removal target for TOC is calculated based on an average raw water concentration of 4.18 mg/L.**

Higher TOC removal (45% versus 35%) is required per the Stage 1 D/DBP Rule (Table 2-1) to address the elevated raw water TOC related to the storm water flows in January 2017, however all three coagulants achieved the 45% removal target. Similar to turbidity removal, ferric achieved greater removal of TOC with a lower mg/L dose. DOC removal for the three coagulants is provided in Appendix C (Figure C-3).

## 5.2 Conclusions

### Can the required TOC removal be achieved through coagulation? What percentage TOC removal is realistically attainable?

Results from November and January enhanced coagulation testing indicate that the Stage 1 D/DBP Rule TOC removal requirements can be achieved. The November water samples contained low TOC (<2 mg/L), putting them just under the TOC threshold requiring removal (Table 3-1), however 35% TOC removal was realized for all three coagulants tested. Stormwater flows in January resulted in elevated TOC in the raw water (>4 mg/L), however the target 45% TOC removal was realized using enhanced coagulation – again, with all three coagulants tested.

### Will pH reduction be required to achieve target TOC removals?

While lowering the pH of coagulation yielded improved TOC and DOC removal as compared with equivalent coagulant doses at ambient pH, the DOC removal at ambient pH was sufficient to meet removal requirements (per Stage 1 D/DBP Rule) for this source water.

### How seasonably variable are the TOC and alkalinity of the source water? What, if any, is the impact on TOC removal requirements per D/DBP Rule and ability to achieve required removal via enhanced coagulation?

Overall source water monitoring results from October 2016 through February 2017 indicate that TOC varied between 2.0 and 3.9 mg/L and alkalinity varied between 16 and 26 mg/L as $CaCO_3$. Water quality results associated with bench testing completed during this same time frame were similar, with TOC values ranging from 1.9 to 4.2 mg/L and alkalinity values ranging between 20 and 28 mg/L as $CaCO_3$. Based on these values, the corresponding TOC removal requirements per Stage 1 D/DBP Rule would be expected to vary between no removal and 45%. Bench scale testing associated with the November 2016 and January 2017 water qualities indicate that enhanced coagulation can be used to effectively address the target, despite the seasonal variability in water quality.

# 6 OZONE DEMAND TESTING RESULTS

## 6.1 Ozone Demand

Ozone is a fast reacting disinfectant/oxidant that typically decays rapidly in water. The decay profile in natural waters can be characterized by a more rapid initial decay due to the initial ozone demand exerted by reacting constituents in the water, followed by a slower first-order decay profile (Rakness 2005; U.S. EPA 2010). The initial ozone demand of the water is a function of many parameters including pH, alkalinity, temperature, and natural organic matter (NOM) concentration. The NOM concentration (measured as TOC) has a large influence on the ozone demand of the water, due to its reaction with ozone. Thus, the higher the TOC concentration in the water, the greater the ozone demand. For this reason, ozone testing typically involves dosing ozone as a function of the raw water TOC concentration (e.g., 0.6 or 1.0 mg/L $O_3$ is added per mg/L TOC measured in the raw water). Dosing ratios of 0.6 and 1.0 O3:TOC are commonly used as a starting place in establishing a dosing ratio that will provide an ozone residual after approximately 4 to 6 minutes, to be representative of the hydraulic detention time of a typical ozone contactor. Maintaining an ozone residual through this timeframe is important for establishing an ozone decay rate and for assessing the ozone dose needed for disinfection credit.

The solution ozone test (SOT) was used to establish decay curves for ozonated raw water samples, as well as ozonated clarified water (prepared by jar testing) for each of the bench test sampling events (November 2016 – February 2017). From these SOT data, initial ozone demand and ozone decay coefficients (after meeting the initial ozone demand) were calculated for both raw water and clarified waters. The results are discussed in the following sections.

### 6.1.1 Ozone Demand of Raw Water

Using water from the November bench test sampling event, ozone decay curves were established at two temperatures (7ºC and 22ºC) to represent seasonal high and low water temperatures. For both temperature conditions, ozone was dosed at ozone-to-raw water TOC ratios of 0.6 and 1.0. The resultant ozone decay curves are presented in Figure 6-1. The November results highlight the impact of temperature on reaction kinetics between ozone and the reacting material, with faster ozone decay occurring at the warmer temperature (22ºC), for an equivalent ozone dose. Considering this, subsequent ozone demand tests were done at the warmer temperature which provides a more conservative estimate of the ozone demand. Raw water ozone decay curves from the December, January, and February samples are also presented in Figure 6-1.

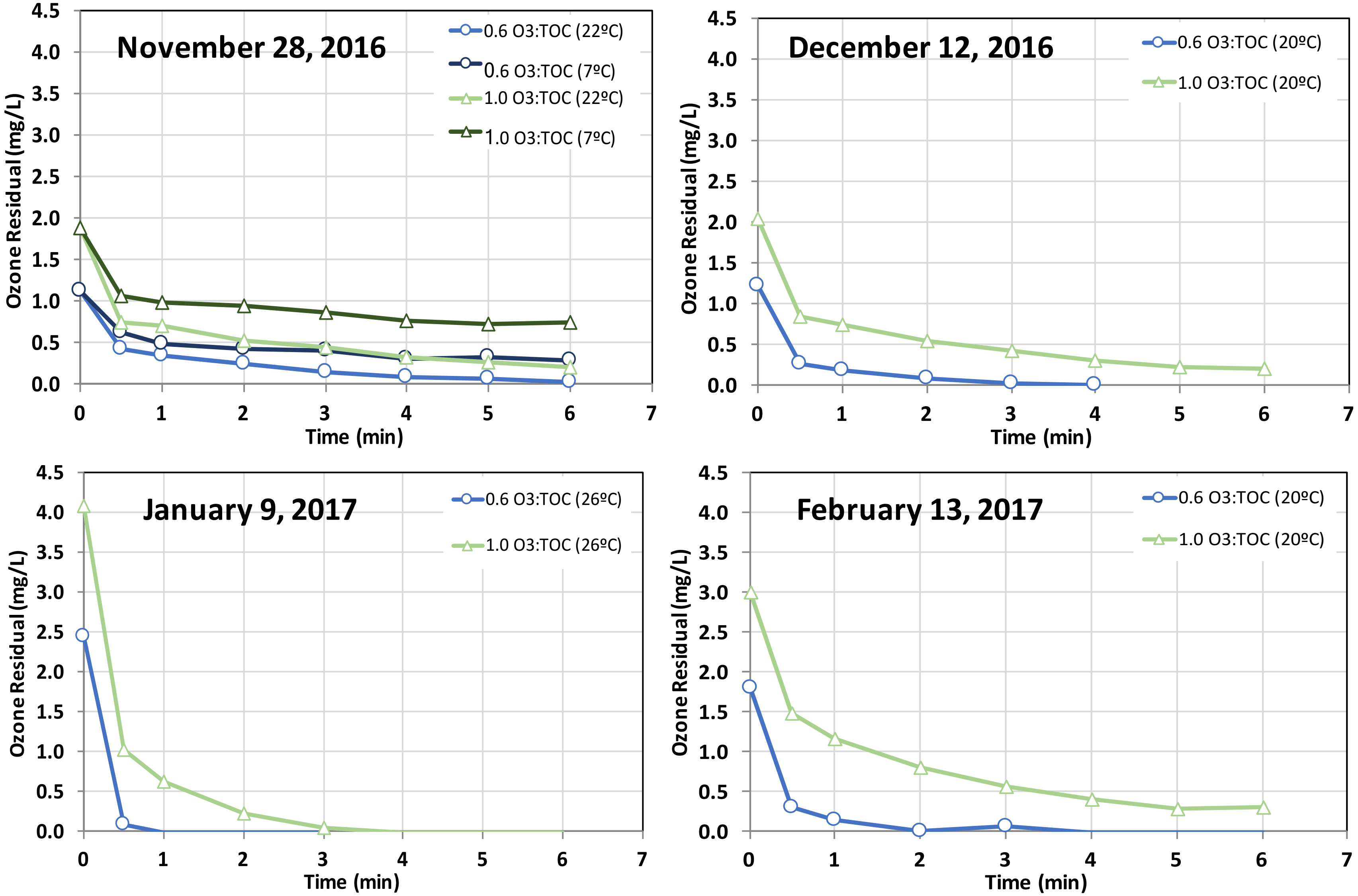


**Figure 6-1. Raw water ozone decay curves for November, December, January, and February samples.**

A discussion of first-order ozone decay and determination of the ozone demand is provided in Appendix D. Rakness (2005) considered the ozone demand of a water to be the difference between the transferred dose and the ozone concentration after 60 seconds of reaction time. This characterization of ozone demand is relevant for designing an appropriate ozone contactor for the project. The ozone demand of the raw water at room temperature (20-26ºC) was plotted as a function of ozone dose and O3:TOC dosing ratio in Figure 6-2 for the samples from November, December, January, and February. The regression equations shown in Figure 6-2 can be used to calculate the 60-second ozone demand for any ozone dose using O3:TOC of 0.6 or 1.0. ***For all tests, the 60-second ozone demand increased with increasing TOC concentrations (and thus, with increasing transferred ozone dose).***

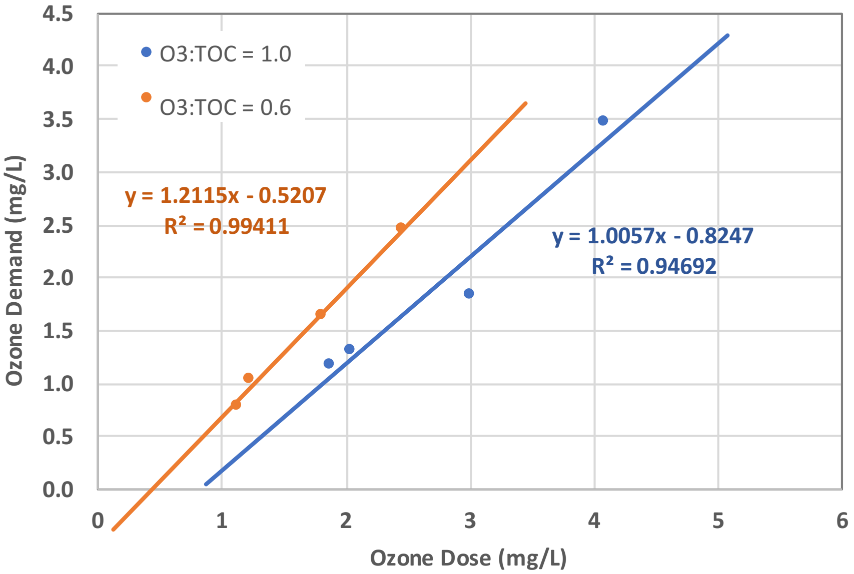


**Figure 6-2. Ozone demand after 60 seconds as a function of ozone dose in raw water for November, December, January, and February samples.**

### 6.1.2 Ozone Demand of Clarified Water

As discussed in Section 5, coagulant doses were optimized in the November enhanced coagulation bench testing using ferric, alum, and PACl. Using the selected coagulant and optimum dose to achieve the percent TOC removal required by the D/DBP Rule, clarified water was prepared for assessment of ozone decay with ferric chloride at a dose of 7.9 mg/L. The November tests were done under warm (22ºC) and cold (7ºC) water conditions, whereas subsequent monthly testing was conducted using only the warm/room temperature condition. It was intended that the optimized coagulant and dose would be used for all monthly ozone demand testing of the clarified water. However, bench testing related to manganese removal showed that ferric chloride can be a source of manganese so the decision was made to use alum or PACl for subsequent jar tests to prepare CS water for ozone demand testing. The coagulant type and dose used to prepare CS water for ozone demand testing are specified in Table 6-1, along with the clarified water TOC. Ozone decay curves for all clarified water samples are presented for the four testing events in Figure 6-3.

.

**Table 6-1. Coagulant type and dose for clarified (CS) water preparation, as well as CS water TOC used in ozone demand testing.**

| Month | Coagulant | Coagulant Dose (mg/L) | Average Raw Water TOC (mg/L) | CS Water TOC (mg/L) | TOC Removal (%) |
|---|---|---|---|---|---|
| Nov-16 | Ferric | 7.9 | 1.92 | 1.21 | 37.0 |
| Dec-16 | Ferric | 7.9 | 2 | 1.29 | 35.5 |
| Jan-17 | Ferric | 7.9 | 4.18 | 4.24 | -1.4 |
|  | Alum | 14.6 |  | 3.04 | 27.3 |
| Feb-17 | Alum | 14.6 | 3.07 | 1.8 | 41.4 |
|  | PACl | 14.5 |  | 1.88 | 38.8 |

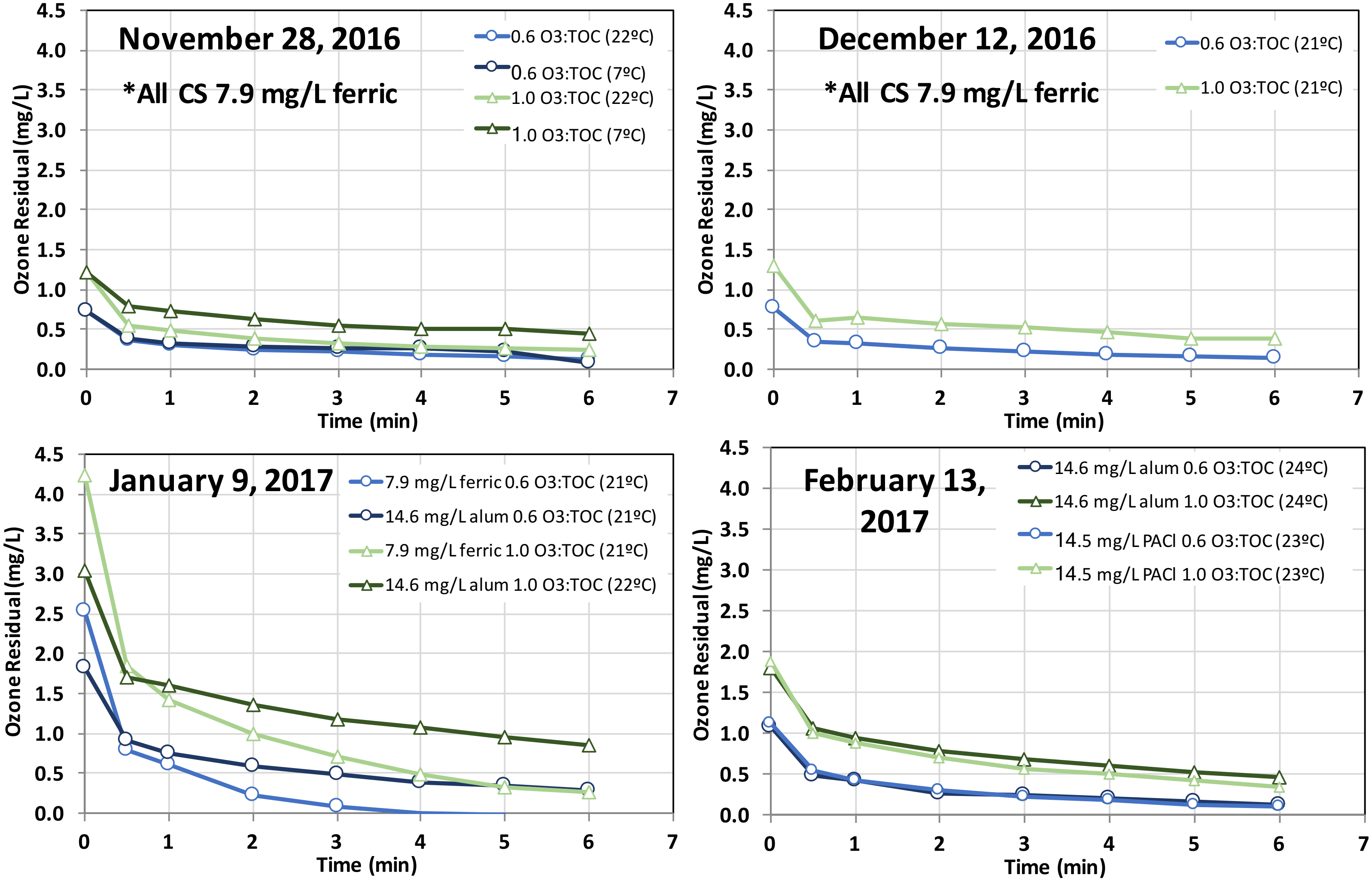


**Figure 6-3. Clarified water ozone decay curves for November, December, January, and February samples. Coagulants and doses used to prepare clarified water are specified for each test.**

From Figure 6-3, it is clear that the high TOC CS water (Table 6-1) in January yielded a larger initial drop in ozone residual within the first minute of the decay test. As with the raw water decay curves (Figure 6-1), the ozone decay is more rapid in the warmer water (Figure 6-3, November), however this difference is less pronounced at lower ozone doses (O3:TOC ratio of 0.6 vs. 1.0, then CS water vs. raw).

The 60-second ozone demand (Appendix D, Table D-2) of the clarified water at room temperature (21-24ºC) was plotted as a function of ozone dose and O3:TOC dosing ratio in Figure 6-4 for the samples from November, December, January, and February. The regression equations shown in Figure 6-4 can be used to calculate the clarified water ozone demand for any ozone dose using O3:TOC of 0.6 or 1.0.

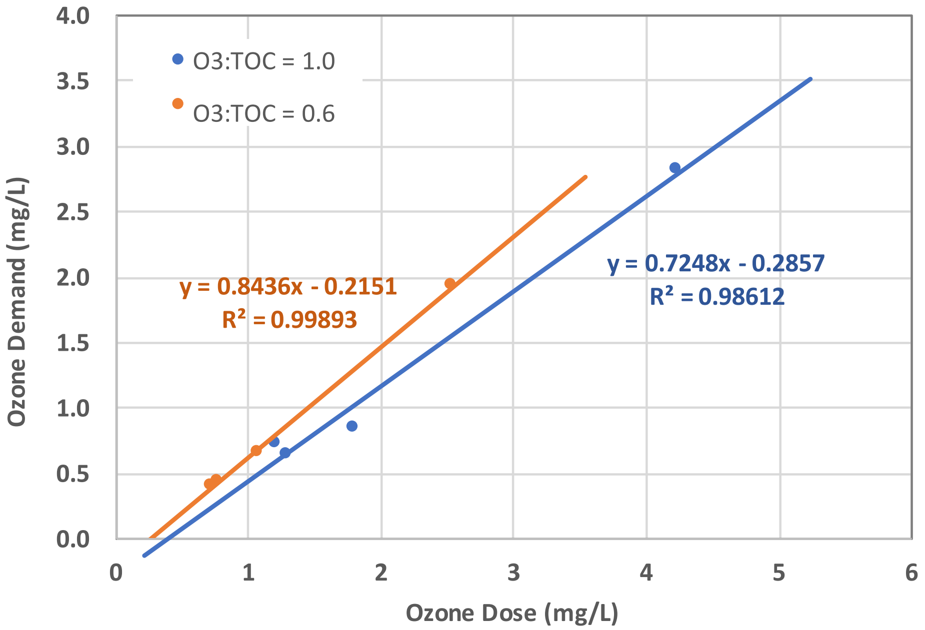


**Figure 6-4. Ozone demand after 60 seconds as a function of ozone dose in clarified water for November, December, January, and February samples.**

## 6.2 Bromate Formation

Along with ozone demand, the monthly ozone bench testing included an assessment of bromate formation as a function of ozone dose. Bromate is a disinfection by-product that can be formed when bromide is ozonated and has a MCL of 0.010 mg/L. All of the ozonated samples of raw water and clarified water from the monthly ozone decay tests were analyzed for bromate. The results are summarized in Table 6-2. Bromide was detected in two of the four raw water samples analyzed, however bromate was either non-detect (ND) or detected at the reporting limit for all ozonated samples, regardless of the O3:TOC dosing ratio.

**Table 6-2. Summary of raw water bromide and ozonated water bromate results associated with monthly ozone decay testing, November 2016 – February 2017.**

| Sampling Date | Raw Water Bromide (µg/L) | Preozonation | | Intermediate Ozonation | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | CS 7.9 mg/L ferric | | CS 14.6 mg/L alum | | CS 14.5 mg/L PACl | |
| | | 0.6 O3:TOC | 1.0 O3:TOC | 0.6 O3:TOC | 1.0 O3:TOC | 0.6 O3:TOC | 1.0 O3:TOC | 0.6 O3:TOC | 1.0 O3:TOC |
| | | Bromate Concentration in Ozonated Water (µg/L) | | | | | | | |
| 11/28/16 | 8.00 | ND (1) | 1.00 | ND (1) | ND (1) | | | | |
| 12/12/16 | 8.60 | ND (1) | ND (1) | ND (1) | ND (1) | | | | |
| 01/09/17 | ND (5) | ND(10)[1] | ND(10)[1] | ND(10)[1] | ND (1) | ND(10)[1] | ND(10)[1] | | |
| 2/13/17 | ND (5) | ND (1) | ND (1) | | | ND (1) | ND (1) | ND (1) | ND (1) |

[1] Eurofins Flag D1 – Sample required dilution due to matrix.

## 6.3 Conclusions

### What ozone dose is required to meet the ozone demand?

The ozone dose was correlated with ozone demand based on bench testing of raw and clarified water associated with monthly source water samples collected from November through February. Figure 6-2 correlates ozone dose and demand of the raw water using dose ratios of 0.6 and 1.0 for O3:TOC. This same relationship is provided for the clarified water in Figure 6-4.

### How does ozone demand of the raw water (preozonation) compare with ozone demand of coagulated/settled water (intermediate ozonation)?

Ozone demand of the raw water was higher than that of the coagulated/settled water, unless the TOC of the water prior to being ozonated was higher (January 2017 coagulated/settled water prepared using ferric).

### What is the seasonal variability of the ozone demand?

The winter water quality represented by the January and February 2017 samples was characterized by higher turbidity (6.5-8.2 NTU vs. <1.5 NTU for November and December 2016) and TOC (≥3 mg/L vs. ≤2 mg/L for November and December 2016). The increase in turbidity and TOC for the winter water samples yielded increased ozone demand in both the raw and coagulated source water, as compared with the ozone demand of these waters measured under dry weather conditions (November and December 2016).

### Will bromate be formed with ozonation?

Results to-date indicate that bromate formation is not expected to be an issue related to either preozonation (raw water) or intermediate ozonation (clarified water), regardless of the O3:TOC dosing ratio.

# 7 SDS DBP FORMATION

SDS DBP testing was completed using various treated water scenarios produced from the November 2016 (dry weather flows) and February 2017 (storm water flows) samples. Details of the SDS setup protocol are provided in Appendix A. All SDS DBP test conditions with intermediate ozonation involved the use of CS water ozonated using an O3:TOC dosing ratio of 1.0. The process used to determine the appropriate chlorine doses for the SDS DBP tests is discussed in Appendix E. As discussed in describing the SDS DBP setup protocol (Appendix A), all chloraminated test conditions included 1 hour of free chlorine contact time prior to ammonia addition to represent full-scale operation where inactivation of ammonia oxidizing bacteria is required to produce a stable chloraminated water for the distribution system.

### 7.1 Round 1 SDS DBP Test Results – November 2016 sample

The CS water for the November SDS DBP tests was prepared using jar testing (Jar Test 4A results provided in Appendix C, Table C-1) with optimum treatment conditions – ferric chloride at a dose of 7.9 mg/L and ambient pH – determined via enhanced coagulation testing (Appendix C, Jar Tests 1A-3A). An average of 40% TOC removal was achieved in the CS water. The free chlorine and chloramine doses selected for SDS DBP testing (Appendix E) were 2 mg/L and 3.25 mg/L, respectively.

Results of the SDS tests are provided in Table 7-1, Table 7-2, and Figure 7-1. THMs and $HAA_5$ formed under both disinfection scenarios—free chlorine and chloramines—were well below the TTHM MCL of 0.080 mg/L and the $HAA_5$ MCL of 0.060 mg/L. In general, greater concentrations of THMs formed than $HAA_5$. Comparing the 48-hour DBP results, the CS-Free Chlorine sample had the greatest concentration of both THMs and $HAA_5$, followed by CS-O3-Free Chlorine, then CS-Chloramine, and CS-O3-Chloramine had the least. The addition of ammonia was shown to significantly arrest the formation of both THMs and $HAA_5$. Note that DBP concentrations were not measured after the 1-hr of free chlorine contact time prior to ammonia addition for the CS-Chloramine and CS-O3-Chloramine samples. However, assuming the DBP formation following one hour of free chlorine contact time would have been comparable for chlorine doses of 2 mg/L (CS-Free Chlorine) and 3.25 mg/L (CS-Chloramine), 67% of the THMs and 78% of the $HAA_5$ in the 48 hour CS-Chloramine sample formed in the first 60 minutes. By comparison, the initial hour of free chlorine contact time accounted for only 36% of the THMs and 35% of the $HAA_5$ ultimately formed after 48 hours in the CS-Free Chlorine sample. Ozonation helped to mitigate DBP formation, but to a lesser degree than ammonia addition (i.e., chloramination). The concentrations of brominated DBPs were very low, confirming the very low level of bromide measured in this source water.

### Table 7-1. November 2016 SDS DBP test results using free and combined chlorine.

| Parameter | One Hour Free Chlorine Hold Time | | 48 Hours Hold Time | | | |
|---|---|---|---|---|---|---|
| | CS - Free Chlorine SDS Test | CS - O3 - Free Chlorine | CS - Free Chlorine SDS Test | CS - Chloramine SDS Test | CS - O3 - Free Chlorine | CS - O3 - Chloramine |
| | DBP Concentration | DBP Concentration (µg/L) | DBP Concentration | DBP Concentration | DBP Concentration (µg/L) | DBP Concentration (µg/L) |
| Raw Water TOC (mg/L) | 2.03 | | | | | |
| Average Settled Water TOC (mg/L) | 1.21 | | | | | |
| Coagulant | Ferric chloride | | | | | |
| Coagulant Dose (mg/L) | 7.9 | | | | | |
| **Total Trihalomethanes (TTHMs)** | **11** | **3.1** | **31** | **17** | **27** | **7.1** |
| - Chloroform (CHCl3) | 9.1 | 2.3 | 27 | 14 | 22 | 5.7 |
| - Bromodichloromethane (CHBrCl2) | 2 | 0.83 | 4.1 | 2.5 | 3.9 | 1.4 |
| - Dibromochloromethane (CHBr2Cl) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | 0.87 | ND (0.5) |
| - Bromoform (CHBr3) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) |
| **Total Haloacetic Acids (HAA5)** | **8.3** | **ND (2.0)** | **24** | **11** | **15** | **3.6** |
| - Monochloroacetic Acid (MCAA) | ND (2.0) | ND (2.0) | ND (2.0) | ND (2.0) | ND (2.0) | ND (2.0) |
| - Dichloroacetic Acid (DCAA) | 4.7 | 1.5 | 11 | 5.7 | 8.4 | 2.5 |
| - Trichloroacetic Acid (TCAA) | 3.6 | ND (1.0) | 13 | 4.9 | 7.0 | 1.1 |
| - Monobromoacetic Acid (MBAA) | ND (1.0) | ND (1.0) | ND (1.0) | ND (1.0) | ND (1.0) | ND (1.0) |
| - Dibromoacetic Acid (DBAA) | ND (1.0) | ND (1.0) | ND (1.0) | ND (1.0) | ND (1.0) | ND (1.0) |
| NDMA | - | - | - | - | - | ND (0.002) |
| pH at End of Hold Time* | - | - | 7.79 | 7.77 | 7.78 | 7.78 |
| Holding Time | 1 hour | 1 hour | 48 hours | 48 hours | 48 hours | 48 hours |
| Chlorine Dose | 2.0 mg/L | 2.0 mg/L | 2.0 mg/L | 3.25 mg/L | 2.0 mg/L | 3.25 mg/L |
| Chlorine Residual at End of Hold Time** | 1.34 mg/L | 1.47 mg/L | 0.60 mg/L | 2.24 mg/L | 0.54 mg/L | 2.22 mg/L |

*A phosphate buffer was added to each SDS sample prior to chlorine/chloramine addition, to maintain a fished water pH of approximately 7.8.

**The target residual concentrations after the 48 hour hold time for free chlorine and chloramines were 0.4 mg/L and 2.0 mg/L, respectively.

**Table 7-2. Chlorine and chloramine residuals for November 2016 SDS DBP testing. Note: All CS samples prepared using 7.9 mg/L ferric.**

| Test Condition | Free Chlorine or Chloramine Dose (mg/L as $Cl_2$) | Target Chlorine or Chloramine Residual After 48 Hours (mg/L) | Measurement of Residual Chlorine or Chloramine for Corresponding Target Elapsed Hold Time (mg/L) | |
|---|---|---|---|---|
| | | | 1 Hour | 48 Hours |
| CS - Free Cl2 | 2 | 0.4 | 1.34 | 0.60 |
| CS - Chloramine | 3.25 | 2.0 | - | 2.2 |
| CS - O3 - Free Cl2 | 2 | 0.4 | 1.47 | 0.54 |
| CS - O3 - Chloramine | 3.25 | 2.0 | - | 2.2 |

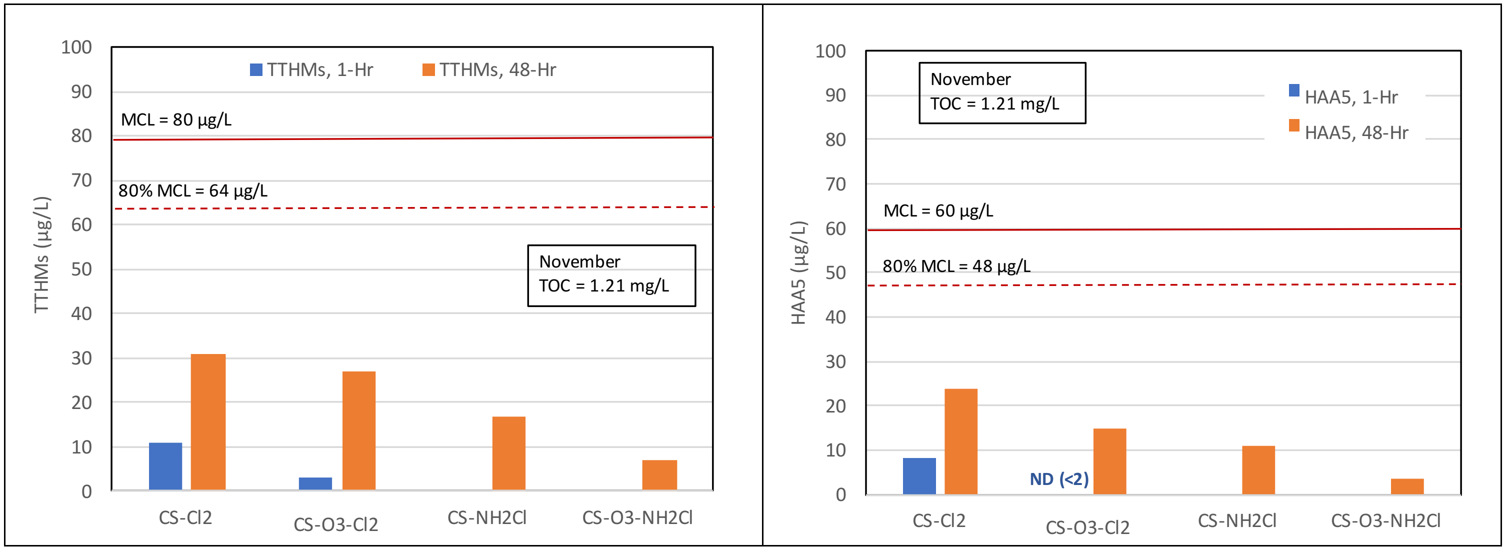


**Figure 7-1. November SDS DBP test results representing enhanced coagulation with low TOC raw water quality.**

## 7.2 Round 2 SDS DBP Test Results – February 2017 sample

Additional SDS DBP testing was completed using the February 2017 sample, due to the water quality changes associated with the winter storm water flows. Ferric chloride was used as the coagulant for the first round of SDS DBP testing in November 2016. Subsequent testing revealed that ferric chloride can be a source of manganese, and since similar performance was observed (i.e., turbidity and TOC removal) for all three coagulants (Section 5.1), the coagulant used to prepare the CS water for the Round 2 SDS DBP testing was switched to alum. Round 2 SDS DBP testing included CS water samples prepared via jar tests (Jar Tests 1D and 2D, Appendix C) using two doses of alum, 5.1 mg/L and 9.8 mg/L, to compare DBP formation following two different levels of TOC removal (TOC is the precursor material that reacts with chlorine to form DBPs). The lower dose of 5.1 mg/L is representative of the upper limit of coagulant dose that should be used with direct filtration or membrane filtration. Organic carbon (TOC and DOC) was not removed using this low coagulant dose in conjunction with the February winter storm water samples. The 9.8 mg/L alum dose is representative of an enhanced coagulation dose associated with conventional treatment, providing a conservative degree of organic carbon removal (approximately 25%) so as not to skew DBP formation on the low side. When treated with the 9.8 mg/L alum dose, average TOC removal was 11% and average DOC removal was 25% for the Round 2 samples. The settled water TOC was likely high due to unsettled floc, however the settled water DOC was more in line with expected values.

The free chlorine and chloramine doses selected for Round 2 SDS DBP testing were 2.75 mg/L and 3.25 mg/L, respectively, for the CS water prepared with 5.1 mg/L alum; doses of 2.5 mg/L and 3.0 mg/L, respectively, were selected for the CS water prepared with 9.8 mg/L alum (see Appendix E for details). Results of the SDS tests are provided in Table 7-3, Table 7-4, and Table 7-5, as well as Figure 7-2 and Figure 7-3.

**Table 7-3. Round 2 SDS DBP test results using free and combined chlorine for samples prepared using 5.1 mg/L alum, February 2017.**

| Parameter | One Hour Free Chlorine Hold Time | | 48 Hours Target Hold Time | | 96 Hours Target Hold Time | |
|---|---|---|---|---|---|---|
| | CS - Free Chlorine SDS Test | CS - Chloramine SDS Test | CS - Free Chlorine SDS Test | CS - Chloramine SDS Test | CS - Free Chlorine SDS Test | CS - Chloramine SDS Test |
| | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) |
| Raw Water TOC (mg/L) | 3.07 | | | | | |
| Average Settled Water TOC (mg/L) | 3.33 | | | | | |
| Coagulant | Alum | | | | | |
| Coagulant Dose (mg/L) | 5.1 | | | | | |
| **Total Trihalomethanes (TTHMs)** | **28** | **30** | **90** | **40** | **79** | **37** |
| - Chloroform (CHCl3) | 27 | 29 | 88 | 39 | 77 | 36 |
| - Bromodichloromethane (CHBrCl2) | 1.3 | 1.4 | 2.1 | 1.2 | 2 | 1.2 |
| - Dibromochloromethane (CHBr2Cl) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) |
| - Bromoform (CHBr3) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) |
| **Total Haloacetic Acids (HAA5)** | **38** | **33** | **114** | **46** | **91** | **47** |
| - Monochloroacetic Acid (MCAA) | ND (2) | ND (2) | ND (2) | ND (2) | 3.5 | ND (2) |
| - Dichloroacetic Acid (DCAA) | 20 | 16 | 48 | 24 | 41 | 25 |
| - Trichloroacetic Acid (TCAA) | 18 | 17 | 66 | 22 | 46 | 22 |
| - Monobromoacetic Acid (MBAA) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) |
| - Dibromoacetic Acid (DBAA) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) |
| Holding Time (hours) | 1 | 1 | 45.6 | 46.1 | 92.5 | 94.1 |
| Chlorine Dose | 2.75 mg/L | 3.25 mg/L | 2.75 mg/L | 3.25 mg/L | 2.75 mg/L | 3.25 mg/L |
| Chlorine Residual at End of Hold Time | 1.82 mg/L | 1.76 mg/L | 0.42 mg/L | 1.85 mg/L | 0.14 mg/L | 1.83 mg/L |

Notes:

1. A phosphate buffer was added to each SDS sample prior to chlorine/chloramine addition, to maintain a finished water pH of approximately 7.8.
2. The target residual concentrations after the 48 hour hold time for free chlorine and chloramines were 0.4 mg/L and 2.0 mg/L, respectively.

**Table 7-4. Round 2 SDS DBP test results using free and combined chlorine for samples prepared using 9.8 mg/L alum, February 2017.**

| Parameter | One Hour Free Chlorine Hold Time | | 48 Hours Target Hold Time | | | | 96 Hours Target Hold Time | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | CS - Free Chlorine SDS Test | CS - O3 - Free Chlorine SDS Test | CS - Free Chlorine SDS Test | CS - Chloramine SDS Test | CS - O3 - Free Chlorine SDS Test | CS - O3 - Chloramine SDS Test | CS - Free Chlorine SDS Test | CS - Chloramine SDS Test | CS - O3 - Free Chlorine SDS Test | CS - O3 - Chloramine SDS Test |
| | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) | DBP Concentration (µg/L) |
| Raw Water TOC (mg/L) | 3.07 | | | | | | | | | |
| Average Settled Water TOC (mg/L) | 2.76 | | | | | | | | | |
| Coagulant | Alum | | | | | | | | | |
| Coagulant Dose (mg/L) | 9.8 | | | | | | | | | |
| **Total Trihalomethanes (TTHMs)** | **16.2** | **10** | **55** | **22** | **41** | **15** | **49** | **20** | **49** | **14** |
| - Chloroform (CHCl3) | 15 | 9.1 | 53 | 21 | 39 | 14 | 47 | 19 | 47 | 13 |
| - Bromodichloromethane (CHBrCl2) | 1.2 | 1.2 | 2 | 1.1 | 2 | 1.1 | 1.8 | 1 | 2.2 | 1.1 |
| - Dibromochloromethane (CHBr2Cl) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) |
| - Bromoform (CHBr3) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) | ND (0.5) |
| **Total Haloacetic Acids (HAA5)** | **15.1** | **12** | **47** | **18** | **37** | **12** | **52** | **20** | **53** | **13** |
| - Monochloroacetic Acid (MCAA) | ND (2) | ND (2) | ND (2) | ND (2) | ND (2) | ND (2) | ND (2) | ND (2) | ND (2) | ND (2) |
| - Dichloroacetic Acid (DCAA) | 7.3 | 6.9 | 21 | 9 | 20 | 6.8 | 24 | 11 | 26 | 7.6 |
| - Trichloroacetic Acid (TCAA) | 7.8 | 5.2 | 26 | 8.5 | 17 | 5.6 | 28 | 8.8 | 27 | 5.6 |
| - Monobromoacetic Acid (MBAA) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) |
| - Dibromoacetic Acid (DBAA) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) | ND (1) |
| Holding Time (hours) | 1 | 1 | 48.1 | 48.4 | 44.5 | 44.8 | 96.5 | 96.7 | 92.8 | 93.1 |
| Chlorine Dose | 2.5 mg/L | 2.5 mg/L | 2.5 mg/L | 3 mg/L | 2.5 mg/L | 3 mg/L | 2.5 mg/L | 3 mg/L | 2.5 mg/L | 3 mg/L |
| Chlorine Residual at End of Hold Time | 2.02 mg/L | 1.82 mg/L | 1.05 mg/L | 2.12 mg/L | 0.91 mg/L | 2.04 mg/L | 0.83 mg/L | 1.94 mg/L | 0.63 mg/L | 1.78 mg/L |

Notes:

1. Ozone was dosed using an ozone-to-TOC ratio of 1.0.
2. A phosphate buffer was added to each SDS sample prior to chlorine/chloramine addition, to maintain a finished water pH of approximately 7.8.
3. The target residual concentrations after the 48 hour hold time for free chlorine and chloramines were 0.4 mg/L and 2.0 mg/L, respectively.

**Table 7-5. Chlorine and chloramine residuals for Round 2 SDS DBP testing, February 2017.**

| Test Condition | Free Chlorine or Chloramine Dose (mg/L as $Cl_2$) | Target Chlorine or Chloramine Residual After 48 Hours (mg/L) | Measurement of Residual Chlorine or Chloramine For Corresponding Target Elapsed Hold Time (mg/L) | | |
|---|---|---|---|---|---|
| | | | 1 Hour | 48 Hours | 96 Hours |
| CS[a] - Free Cl2 | 2.75 | 0.4 | 1.8 | 0.42 | 0.14 |
| CS[a] - Chloramine | 3.25 | 2.0 | 1.8 | 1.9 | 1.8 |
| CS[b] - Free Cl2 | 2.5 | 0.4 | 2.0 | 1.1 | 0.83 |
| CS[b] - Chloramine | 3 | 2.0 | - | 2.1 | 1.9 |
| CS[b] - O3 - Free Cl2 | 2.5 | 0.4 | 1.8 | 0.91 | 0.63 |
| CS[b] - O3 - Chloramine | 3 | 2.0 | - | 2.0 | 1.8 |

[a] CS samples prepared using 5.1 mg/L alum are representative of direct or membrane filtration.

[b] CS samples prepared using 9.8 mg/L alum are representative of enhanced coagulation with conventional treatment.

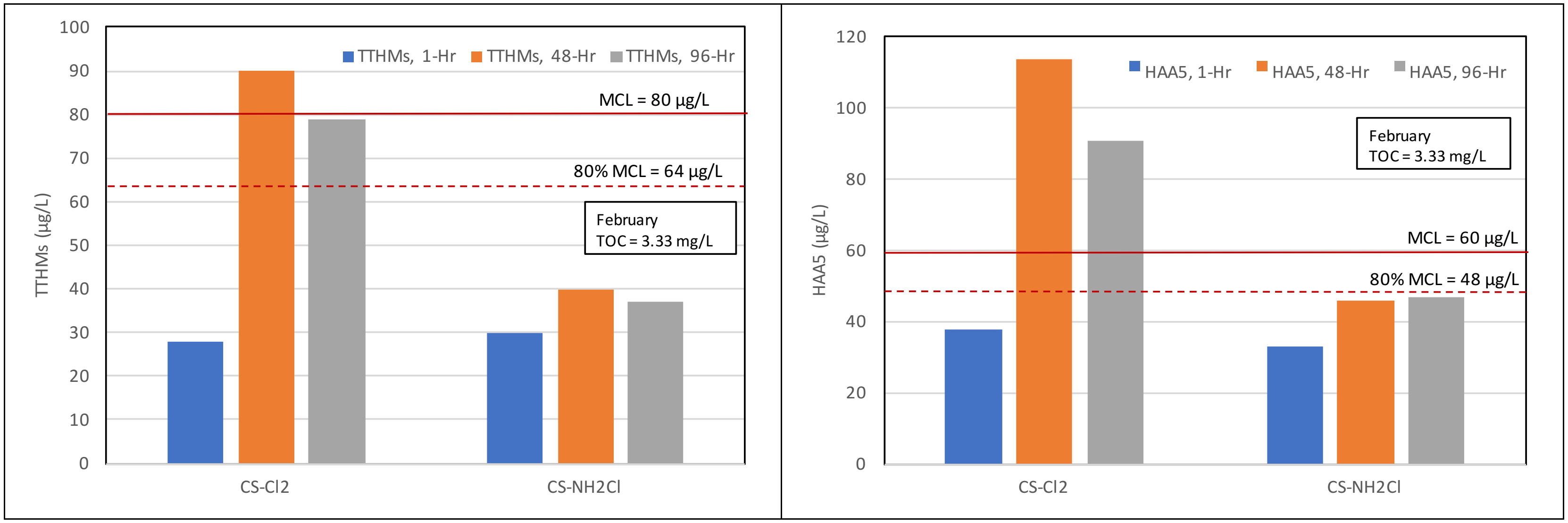


**Figure 7-2. Round 2 SDS DBP test results representing direct filtration equivalent low coagulant dose (5.1 mg/L alum) with high TOC raw water quality, February 2017. *Note: Listed TOC value is based on the average of all 5.1 mg/L alum jar test results.**

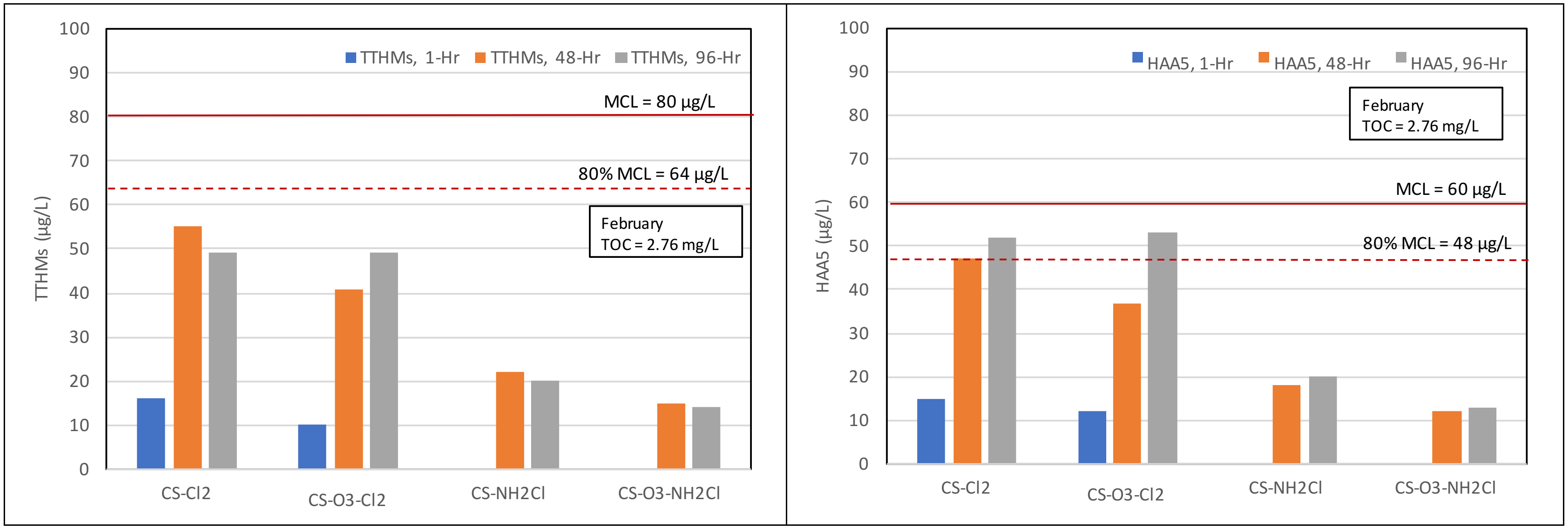


**Figure 7-3. Round 2 SDS DBP test results representing enhanced coagulation (9.8 mg/L alum) with high TOC raw water quality, February 2017. *Note: Listed TOC value is based on the average of all 9.8 mg/L alum jar test results.**

***A significant finding from the SDS DBP testing using water coagulated with an alum dose of 5.1 mg/L and free chlorine was that direct filtration and membrane filtration would not be expected to provide sufficient removal of DBP precursor material from the winter storm water to sufficiently limit DBP formation for compliance with the DBP MCLs***. After a 48 hour hold time (Figure 7-2), the TTHM and $HAA_5$ concentrations exceeded their respective MCLs in the SDS tests with free chlorine. Chloramination of this same water yielded significantly lower DBPs after the 48 and 96 hour hold times, but the HAA levels were close to the desired limit of 48 µg/L, or 80% of the MCL. Round 2 testing included measurement of the DBPs in the 'chloraminated' sample after 1 hour of free chlorine contact time (prior to ammonia addition) to check for any differences associated with the higher free chlorine dose (3 mg/L as $Cl_2$ in the CS-Chloramines, as compared to 2.5 mg/L as $Cl_2$ in the CS-Free Chlorine). The DBP formation after one hour of free chlorine contact time was comparable for both doses, as the higher dose yielded a 7% increase in TTHM and a 13% decrease in $HAA_5$ concentration. Once ammonia was added to the sample, DBP formation was significantly less in the 48 and 96 hour chloraminated samples than in the free chlorinated samples. The majority of the DBP formation (76% of the TTHM and 72% of the $HAA_5$ concentration) associated with the 48 hour CS-Chloramine sample is attributed to the initial one hour of free chlorine contact time. Three of the four SDS DBP results with the 5.1 mg/L alum dose (all but the $HAA_5$ value for CS-Chloramines) had greater DBP formation after 48 hours, with a subsequent reduction in DBP concentration after 96 hours. The lower DBP concentrations in the 96 hour samples compared with the 48 hour samples are counter to what was expected and may be the results of sample setup procedure rather than a true reduction. Subsequent testing could be performed to substantiate or reject this finding.

Lower DBP formation occurred in conjunction with the Round 2 SDS samples coagulated with a dose of 9.8 mg/L alum (Table 7-4 and Figure 7-3). These test conditions, representative of enhanced coagulation, yielded DBP concentrations below the MCLs for TTHM and $HAA_5$ after both 48 and 96 hours of hold time. The TTHM concentrations associated with these samples at all hold times were less than 80% of the MCL value, whereas the HAA5 concentrations exceeded the 80% threshold after 96 hours of hold time in the two samples with free chlorine (CS-Free Chlorine and CS-O3-Free Chlorine). Consistent with Round 1 results, chloramines formed lower DBP concentrations than free chlorine. Likewise, intermediate ozonation (i.e., after clarification) was found to be beneficial for both disinfectants, resulting in lower TTHM and $HAA_5$.

Although the winter water (February 2017) enhanced coagulation and SDS DBP formation tests indicated a low potential for $HAA_5$ to exceed the 80% MCL treatment goal, experience and a review of literature indicates that additional TOC removal can be expected through biofiltration (i.e., ozone followed by granular activated carbon (GAC)/sand filtration), providing further reduction of DBP precursor material prior to final disinfection with free chlorine. Westerhoff, et al. (2005) conducted a review of full-scale water treatment plants utilizing ozone/biofiltration and found a median TOC removal of 19% (through ozone and biofiltration). One limitation of the bench tests conducted for SRWA is that biofiltration cannot be easily evaluated at the bench scale. ***Based on these bench tests we can conclude low potential to exceed the DBP treatment goals with free chlorine, and if we extrapolate to consider additional TOC removal through ozone/biofiltration we can conclude very low potential to exceed DBP treatment goals with free chlorine final disinfection during winter storm event conditions. The winter water quality has higher TOC than the non-storm event***

***"normal" water. Therefore, as long as the treatment train selected for SRWA's new water treatment plant allows for enhanced coagulation and includes ozonation followed by GAC/sand biofiltration, free chlorine (rather than chloramines) is acceptable for final disinfection and residual maintenance in the distribution system.***

## 7.3 Conclusions

### Are the DBPs (i.e., TTHM and $HAA_5$) a concern for this source water?

Yes, formation of TTHM and $HAA_5$ was identified in conjunction with winter water quality (February 2017 sample) and a limited coagulant dose representative of membrane filtration combined with free chlorine disinfection. The use of enhanced coagulation provided significant reduction in chlorination DBP formation, however $HAA_5$ may still be a concern – particularly when using free chlorine and longer detention times in the distribution system. In addition to enhanced coagulation, it is recommended that the treatment train include intermediate ozonation followed by GAC/sand biofiltration for further removal of TOC (DBP precursor material).

### Can the use of enhanced coagulation enable SRWA to meet DBP Regulations? What level of TTHM and $HAA_5$ will form?

Enhanced coagulation was more effective in removing precursor material (i.e., TOC) and limiting the formation of chlorination DBPs. The 9.8 mg/L alum dose applied to the winter water quality in combination with free chlorination yielded $HAA_5$ formation in excess of the target limit (48 µg/L, or 80% of the MCL) for hold times of 96 hours. While the WTP might increase the coagulant dose to achieve improved removal of DBP precursor material, the high formation of $HAA_5$ that was demonstrated during testing, combined with its lower MCL value are a potential compliance concern; thus, the addition of intermediate ozonation followed by GAC/sand biofiltration is recommended. The formation of TTHM was not found to be an issue with enhanced coagulation of the winter water.

### In order to meet the MCLs for TTHM and $HAA_5$, will chloramines be required, rather than free chlorine, to maintain a disinfectant residual in the distribution system?

As discussed above, enhanced coagulation was found to be effective in reducing TTHM formation to less than 80% of the MCL for all test conditions. The $HAA_5$ target (80% of the MCL) – on the other hand – was not achieved with enhanced coagulation of the winter water in combination with free chlorine at the 96 hour hold time. The use of chloramines, in lieu of free chlorine, with this same water was found to mitigate chlorination DBP formation to levels below the $HAA_5$ target. Results associated with the low coagulant dose (5.1 mg/L alum) representative of membrane filtration demonstrate that chloramines would be required; DBP formation associated with free chlorine exceeded the targets for both TTHM and $HAA_5$, whereas the results using chloramine were below the same targets. See above for additional discussion of limiting DBPs through the use of intermediate ozonation followed by GAC/sand biofiltration.

### When ozonation is included in the treatment train (preozonation or intermediate ozonation), does it impact the DBP formation?

In general, DBP formation was slightly lower when intermediate ozonation was included, regardless of disinfection with free chlorine or chloramines. This was not found to be true at the 96 hour hold time. This impact was not as significant as the difference in formation associated with the disinfectant used (free chlorine vs. chloramines). No SDS DBP testing was completed using preozonated water.

**How does DBP formation vary with seasonal changes in water quality?**
Changes in water quality associated with the winter storm water (February 2017) resulted in greater DBP formation. The use of enhanced coagulation served to mitigate this, for the most part (see discussion, above), however if free chlorine is used, $HAA_5$ may still be a concern with longer detention times in the distribution system.

**What level of TOC removal is required for the finished water to be below 80% of the DBP MCLs—a treatment goal of the SRWA TAC?**
Bench testing results indicate that by achieving the required TOC removal per the Enhanced Coagulation part of the Stage 1 D/DBP Rule and using free chlorine for final disinfection, DBP formation in the distribution system should be below both the MCLs for TTHM and $HAA_5$ and the treatment goals (i.e., 80% of the MCL). For this source water (low alkalinity), 35% TOC removal is required for TOC levels between 2 and 4 mg/L, and 45% TOC removal is required when the TOC is between 4 and 8 mg/L.

# 8 MANGANESE REMOVAL TESTING RESULTS

## 8.1 Round 1 Manganese Removal Test Results – December 2016 sample

The first of four rounds of manganese removal testing was completed using the December 2016 source water sample. The initial source water sampling campaign results for total and dissolved manganese were analyzed from the November 14, 2016 sample, with values of 15 µg/L and ND with a reporting limit of 2 µg/L, respectively. Manganese has a secondary MCL value of 50 µg/L (0.05 mg/L). Although the source water values were low, additional potential sources of manganese for SRWA's treatment plant may include: a) manganese as a component of a ferric chloride coagulant (if used); b) reduction of particulate manganese through the infiltration gallery or an unanticipated contribution by groundwater to infiltration gallery influent; or c) dissolved manganese in the decant stream from sludge storage basins and drying beds. Considering these factors, all raw water used in testing was spiked with 0.3 mg/L $Mn^{2+}$ to understand potential manganese removal mechanisms.

Testing focused on assessing a) the potential for ozonation to form colloidal $MnO_2$ which passes through treatment, b) the effectiveness of potassium permanganate for oxidizing $Mn^{2+}$ to $MnO_2$ and subsequent removal through clarification, c) the importance of reaction time for permanganate oxidation, and d) the preferred location for ozonation—pre- or intermediate—for particulate and colloidal $MnO_2$ removal. Results from the first round of manganese removal testing (full data set presented in Appendix F) will inform subsequent rounds to build an understanding of manganese speciation and removal through various treatment processes.

From the December tests, preliminary findings included:

- Coagulation alone does not remove soluble manganese; permanganate is needed. Also, the contact time is important for permanganate oxidation of $Mn^{2+}$. Two contact times, 1 minute and 5 minutes, were tested for round one. These findings are illustrated in Figure 8-1.

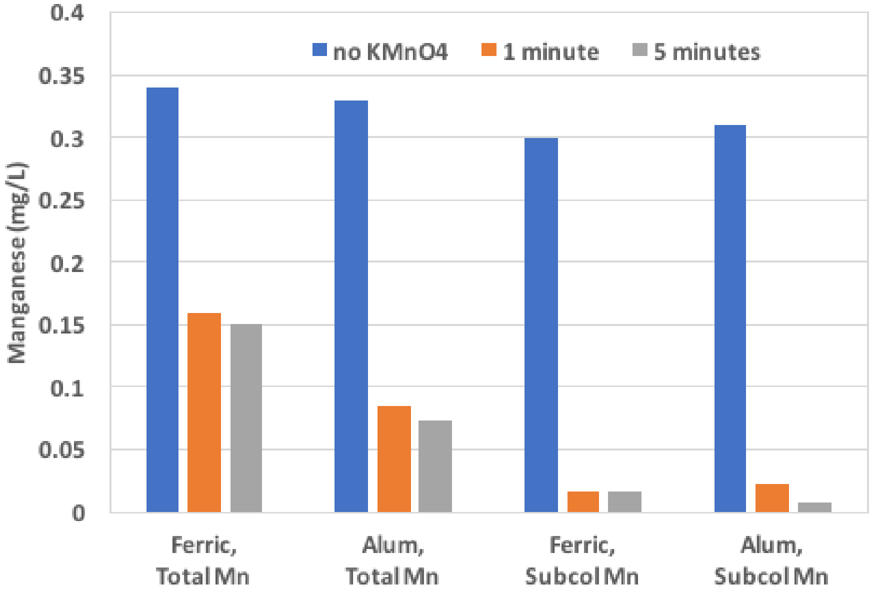


**Figure 8-1. Impact of permanganate oxidation and contact time (1 vs. 5 minutes) on total and subcolloidal (< 30,000 Dalton particle size) manganese removal for December 2016 bench testing. Note: raw water was spiked with 0.3 mg/L Mn for each test.**

- Higher manganese removals were observed at higher ozone doses (i.e., higher O3:TOC) in conjunction with pre-ozonation, as depicted in Figure 8-2.

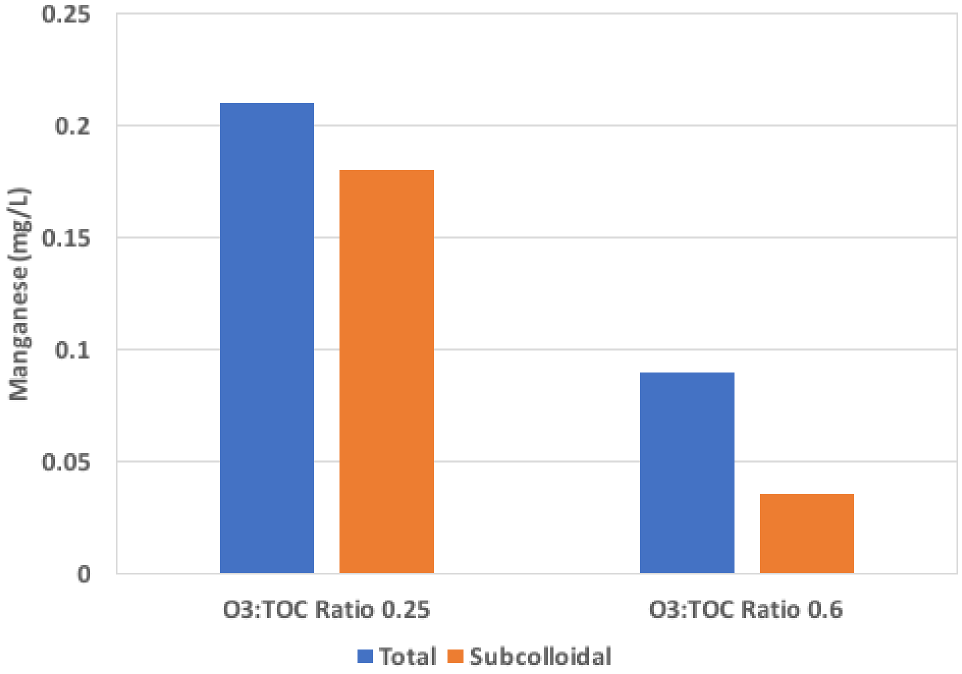


**Figure 8-2. Impact of pre-ozonation dose on total and subcolloidal (< 30,000 Dalton particle size) manganese removal for December 2016 bench testing. Note: raw water was spiked with 0.3 mg/L Mn for each test.**

## 8.2 Conclusions

### Is manganese likely to be present in the source water and, if so, in what form?

Source water monitoring results from October 2016 through February 2017 indicate that low levels of total manganese are present (range: 14–28 µg/L), however of this total manganese, little-to-none was found to be dissolved (range: ND with a reporting limit of 2 µg/L – 4.4 µg/L). Nevertheless, the possibility that manganese may occur in the future cannot easily be dismissed.

### If soluble manganese is present in the raw water, how can it be removed?

Although not expected to be significant in the source water, soluble manganese may be a concern for SRWA's treatment plant due to the following potential sources: a) manganese as a component of a ferric chloride coagulant (if used); b) reduction of particulate manganese through the infiltration gallery or an unanticipated contribution by groundwater to infiltration gallery influent; or c) dissolved manganese in the decant stream from sludge storage basins and drying beds. If present, preliminary results indicate that permanganate oxidation combined with coagulation/settling provides some degree of removal – although further testing is required to optimize the dose and contact time required. Preozonation followed by clarification/settling also provided significant manganese removal in conjunction with a higher ozone dose (0.6 vs. 0.25 O3:TOC) – again, further testing is required to optimize the ozone dose and corresponding manganese removal.

### How can the use of ozonation be optimized (preozonation and intermediate ozonation) to improve manganese removal?

As stated above, preozonation followed by clarification/settling provided significant manganese removal when the higher ozone dose (0.6 vs. 0.25 O3:TOC ratio) was applied. The impact of manganese removal associated with intermediate ozonation was less conclusive. As part of the subsequent rounds of bench testing, it is recommended to characterize the manganese speciation (total, filtered through 0.45 µm filter, filtered through 30,000 Dalton filter) following each treatment step (e.g., permanganate oxidation, clarification/settling, and intermediate ozonation).

### Which treatment trains allow for removal of manganese?

Further testing is recommended to more conclusively answer this question.

# 9 CONCLUSIONS

Conclusions that can be drawn from the initial four months of bench testing are the following:

- Although ferric chloride was initially identified as the preferred coagulant for turbidity and TOC removal, it was later rejected because the ferric stock solution was found to contain 0.4% manganese, which is not desirable. The coagulant for the full-scale design has not been selected, however, and further discussion of manganese removal will be provided in TM2.
- All three coagulants—alum, ferric, and PACl—were able to meet the TOC removal targets per the Stage 1 D/DBP Rule. On a mmol/L basis, all three coagulants performed similarly for both turbidity and TOC removal. However, when the dose was converted to mg/L, a lower ferric dose was needed to achieve the target turbidity and TOC removal compared to alum and PACl, with alum and PACl performing

almost identically. Also, ferric chloride was not as prone to turbidity increases due to particle restabilization or some other mechanism, as was alum and PACl.

- Reduction of pH during coagulation improved TOC removal, however it was possible to achieve the required TOC removal per Stage 1 D/DBP Rule with coagulation alone, without lowering the pH.
- Under "wet weather" conditions, significant TOC removal will be required to stay below the DBP MCLs if free chlorine is used for final disinfection. Direct filtration and membrane filtration will likely produce DBPs in excess of the MCLs unless chloramines are used for secondary disinfection since the maximum coagulant dose with these treatment processes is roughly 5 mg/L, and a higher coagulant dose is required under storm water conditions to remove the required amount of DBP precursor material.
- SDS DBP testing results indicated intermediate ozonation resulted in lower levels of DBPs with free chlorine disinfection, compared with DBP formation in non-ozonated samples.
- Increased ozone demand correlated with increased TOC concentrations in the waters being treated.
- Ozone decay was more rapid in warm water, as compared with cold water. Considering these reaction kinetics, the monthly testing is being conducted using warmer water conditions (20-22ºC).
- Bromate formation is not expected to be an issue if either preozonation or intermediate ozonation are used with this water, due to low bromide concentrations measured in the raw water.

# 10 REFERENCES

A.W.W.A. (2011). Operational Control of Coagulation and Filtration Processes. Denver, CO, American Water Works Association.

California State Board Division of Drinking Water (2016 (updated)). Title 22 Code of Regulations. Sacramento.

Kawamura, S. (2000). Integrated Design and Operation of Water Treatment Facilities, John Wiley & Sons, Inc.

Rakness, K.L. (2005). Ozone in Drinking Water Treatment: Process Design, Operation, and Optimization. AWWA, Denver CO.

U.S. EPA (2010). Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual. Office of Water.

Westerhoff, P., Summers, R.S., Chowdhury, Z., Kommineni, S. (2005). Ozone-Enhanced Biofiltration for Geosmin and MIB Removal. Awwa Research Foundation and American Water Works Association.

# A APPENDIX A – EXPERIMENTAL METHODS AND MATERIALS

## A.1 Source Water Collection

Samples of Tuolumne River water were collected by staff from FishBio, concurrently with the source water monitoring samples near the infiltration gallery site indicated in Figure A-1. A pole-mounted Kemmerer water sampler was used, pulling water from the middle of the water column at the time of sampling. The water samples were transferred into 5-gallon cubitainers and packed in coolers filled with ice packs. Field measurements made at the time of sample collection included: turbidity, pH, temperature, conductivity, and dissolved oxygen concentration. The filled coolers were shipped to the Trussell Technologies Laboratory (TT Lab) in Pasadena, CA via FedEx for next morning delivery. Upon receipt, the cubitainers of water were placed in the refrigerator until testing. Prior to each of the bench tests, the water was removed from the refrigerator and allowed to warm to the desired testing temperatures.

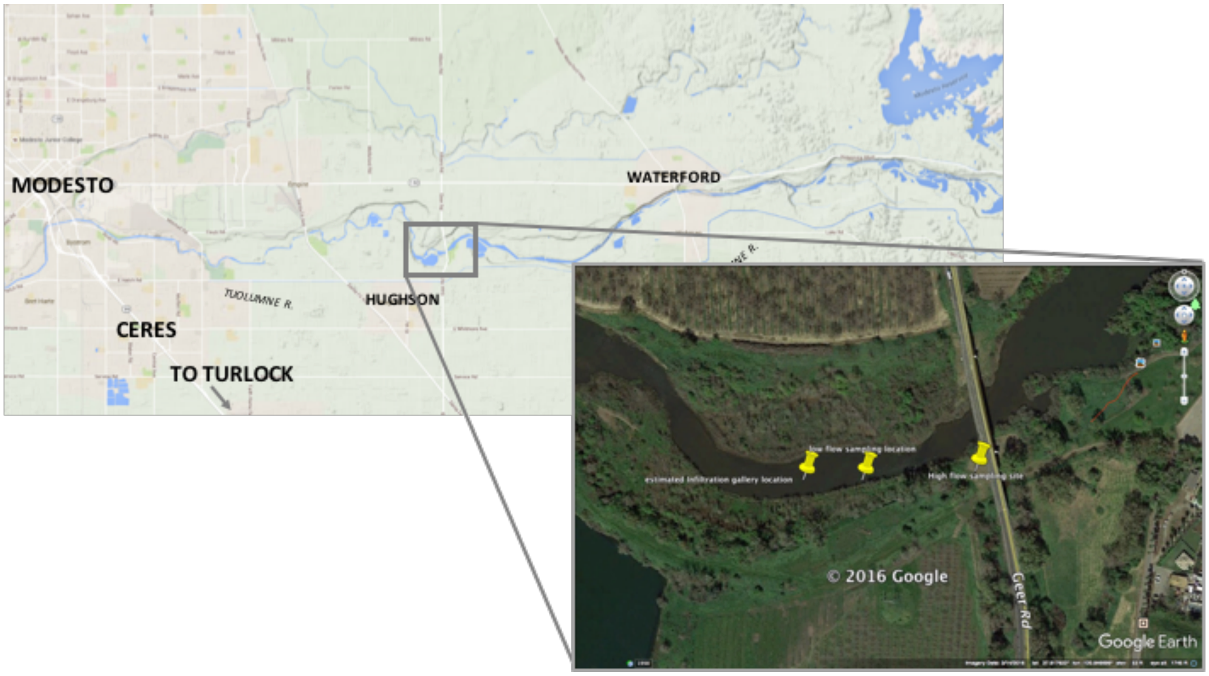


**Figure A-1. Tuolumne River source water monitoring locations (high and low flow conditions), east of Modesto, CA**

The sample collection date and water volume collected by FishBio and shipped to the TT Lab for bench testing rounds 1 through 4, are specified as follows:

- Round 1: November 28, 2016 – 30 gallons
- Round 2: December 12, 2016 – 30 gallons
- Round 3: January 9, 2017 – 10 gallons
- Round 4: February 13, 2017 – 15 gallons

## A.2 Coagulants

Three different coagulants—alum, ferric, and PACl—were evaluated during the initial round of enhanced coagulation jar tests. Kemira Chemicals, Inc. provided samples of these three chemicals. A 0.05M stock solution of each coagulant was prepared for dosing the jars.

Specifications of each coagulant along with the volume of each bulk chemical used to make the stock solutions are shown in Table A-1. Samples of each stock solution, diluted to approximately 5 mg/L metal ion (e.g., 5 mg/L $Fe^{3+}$), were sent to Eurofins Labs for aluminum or iron analysis, to confirm the concentration of the stock solutions. Measured stock concentrations, shown in Table A-1, confirmed the solutions were prepared correctly and were approximately equal to the desired concentrations.

**Table A-1. Coagulant specifications.**

| Property | Ferric Chloride | Alum | Polyaluminum Chloride |
|---|---|---|---|
| Chemical Formula | $FeCl_3$ | $Al_2(SO_4)_3 \bullet 14H_2O$ | PAX-18<br>Formula Unknown |
| Specific Gravity | 1.452 | 1.332 | 1.373 |
| % as $Al_2O_3$ | -- | 8.18 | 17.20 |
| % as Alum | -- | -- | -- |
| % as Ferric Chloride | 41.31 | -- | -- |
| mL of Bulk Chemical in 500-mL of Solution | 6.76 | 11.70 | 5.40 |
| Estimated Stock Concentration | 0.05 mol $Fe^{3+}$/L | 0.05 mol $Al^{3+}$/L | 0.05 mol $Al^{3+}$/L |
| Measured Stock Concentration | 0.048 mol $Fe^{3+}$/L | 0.047 mol $Al^{3+}$/L | 0.047 mol $Al^{3+}$/L |

## A.3 Jar Test Procedures

Prior to starting the jar tests, the water was taken out of the refrigerator and allowed to warm to approximately the same temperature as when collected. The raw water was analyzed for pH, temperature, turbidity, alkalinity, dissolved UV-254, TOC, dissolved organic carbon (DOC), total and dissolved manganese (Mn), as well as N-Nitrosodimethylamine (NDMA). The reason for measuring NDMA on the raw water, since NDMA is typically considered a by-product of disinfection—was to document if there was a background concentration present in the Tuolumne River water.

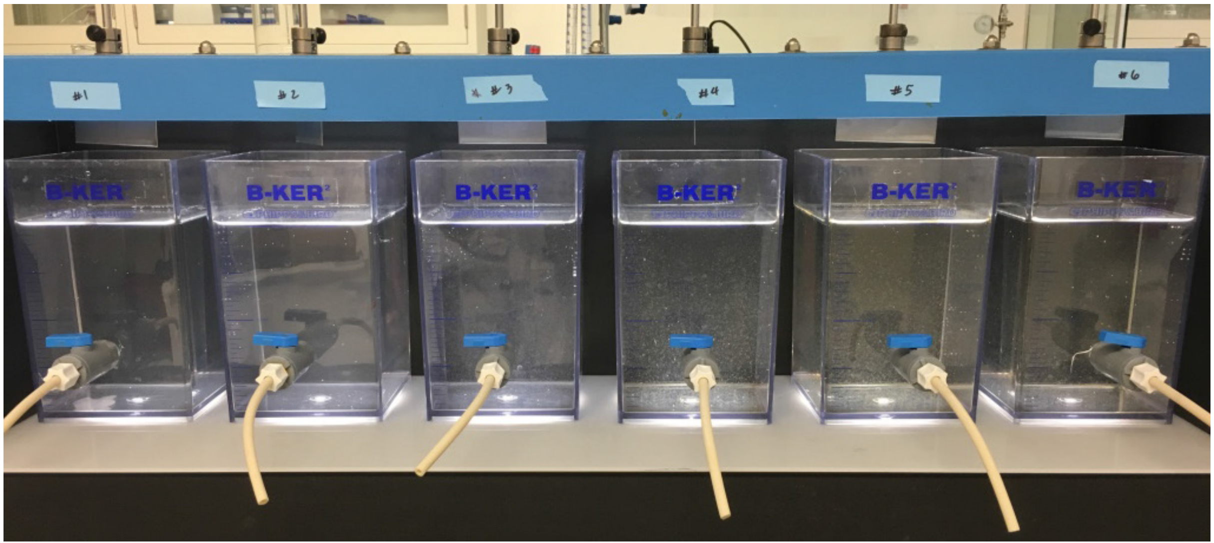


**Figure A-2. Phipps & Bird jar testing apparatus with B-KER$^2$ jars.**

The procedures used for the jar tests followed generally accepted procedures as described in (Kawamura, 2000) and (AWWA, 2011), using square 'gator' jars—which Phipps & Bird calls the B-KER$^2$—depicted in Figure A-2. The mixing regime for all tests included rapid mix followed by four steps of tapered flocculation. The relationship between velocity gradient (G) and impeller speed for the Phipps & Bird mixer with B-KER$^2$ is shown in Figure A-3. The maximum speed of the mixer was used for rapid mix, for 1 minute. The velocity gradients used during tapered flocculation were 55, 40, 25, and 15 sec$^{-1}$, which correspond to mixing speeds of 55, 45, 33, and 22 rpm, respectively. Each step of tapered flocculation had a duration of 7.5 minutes, for a total flocculation time of 30 minutes. Following coagulation, the water was allowed to settle for 30 minutes prior to sample collection. The sampling point is the same in all jars, and is located 10 centimeters below the water surface.

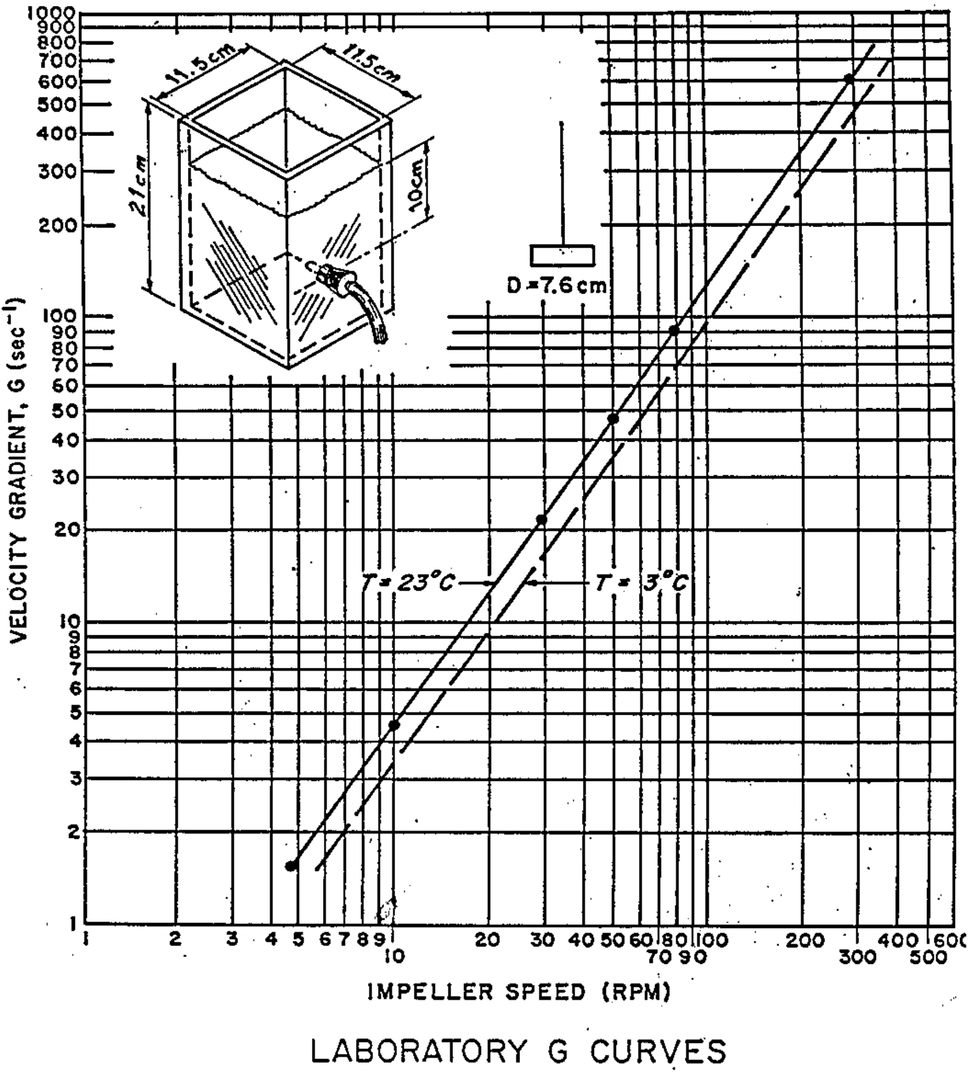


**Figure A-3. G curves for Phipps & Bird 7.6-cm paddles and 2-liter B-KER$^2$ (AWWA, 2011)**

## A.4 Solution Ozone Test

A modification of the solution ozone test (SOT) described by Rakness (2005) was used for bench scale ozone dosing and assessment of ozone demand. In brief, a stock ozone solution was prepared by bubbling ozone through deionized (DI) water. Oxygen was used as the feed gas for the ozone generator. Dry ice was packed around a custom-made ozone stock solution vessel to maintain a water temperature just below zero degrees Celsius for better gas transfer as ozone was bubbled in through a ceramic diffuser. The equipment setup for the SOT is shown in Figure A-4. The resulting ozone stock solutions used for the SOT tests had very high ozone concentrations, up to 90 mg/L of dissolved ozone. The SOT procedure delivers ozone in the form of an aqueous solution, rather than as a gas stream bubbled through the test sample. As a result, the applied ozone dose is the same as the transferred ozone dose, and ozone gas transfer efficiency is not a factor in determining ozone dose.

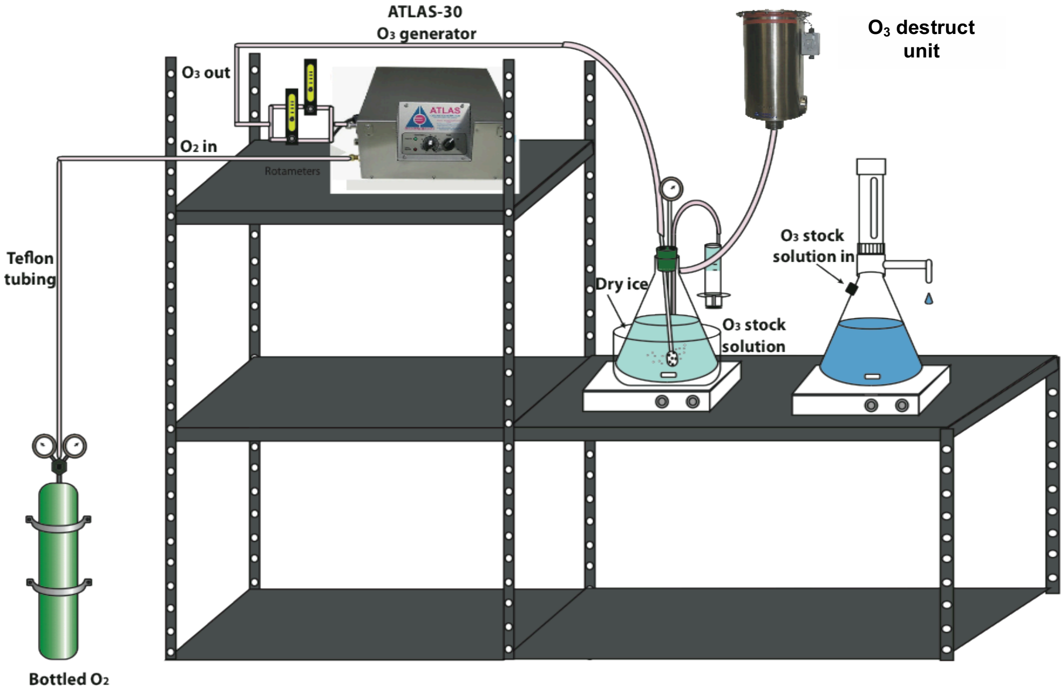


Figure A-4. SOT apparatus

After bubbling ozone into the chilled DI water for at least 10 minutes to make the concentrated ozone solution, an aliquot of the ozone stock solution was removed, using a glass syringe, for measuring the ozone concentration. The gravimetric indigo standard method (Rakness, 2005) was used for ozone analysis. The ozone stock solution was gradually added to a known volume (50 mL) of indigo solution using the syringe, and the blue color of the indigo solution faded as it reacted with the ozone. Once the blue color was almost gone, the mass of the sample was measured for gravimetric determination of the ozonated solution volume dispensed into the indigo solution, and the residual indigo concentration was measured at 600 nanometers (nm) using the spectrophotometer. The ozone concentration of the stock solution was calculated from these measurements.

## A.5 Ozone Decay

The ozone demand and decay coefficients of the water were determined using ozone decay curves. Once the concentration of the ozone stock solution was measured (Section 3.2), a known volume of the ozone stock solution was added to a known volume of sample, typically dosed as a ratio of ozone-to-TOC (e.g., 0.6 mg/L $O_3$ for each 1.0 mg/L TOC in the sample), and stirred for about 10 seconds. The ozone residual was measured at the following time intervals (each in terms of time elapsed after the ozone dose was added): 30 seconds, then 1, 2, 3, 4, 5, and 6 minutes. The residual ozone was measured at each time interval by withdrawing an aliquot of the ozonated sample (using a dispenser system) into a small vial containing indigo solution and using the gravimetric indigo standard method described in Section A.4.

## A.6 SDS DBP Test Procedures

To simulate DBP formation of various treated water conditions, the jar coagulated and settled (CS) water (procedures described in Section A.3) was dosed with a phosphate buffer to stabilize the pH, then dosed with free chlorine or chloramine to achieve a final target disinfection residual. The sample was held at room temperature for the timeframe of interest. An additional measure used to approximate filtration step can be achieved by filtering the jar tested water through a 0.45-µm membrane filter.

Both free chlorine and chloramine disinfection were used with the SDS test conditions. All SDS DBP samples were spiked with free chlorine for the initial one hour of hold time. The one hour of free chlorine contact represents the disinfection necessary to provide at least 0.5-log *Giardia* inactivation and to simulate post-filtration chlorination to control heterotrophic plate count bacteria and ammonia oxidizing bacteria present in a biofilter. Residual chlorine was measured in the after 55 minutes of hold time in the ‘chloraminated’ samples, then ammonia was added using a 4-to-1 chlorine-to-ammonia ($NH_3$-N) ratio to form chloramines.

Prior to setting up the SDS sample bottles, chlorine decay was assessed over a 24-hour period to inform dose selection for the SDS testing. The chlorine or chloramine residuals were measured for each test condition after various time intervals to establish decay curves. The residual chlorine or chloramine was plotted against the elapsed contact time and used to observe the initial chlorine or chloramine demand of the waters (e.g., drop in residual between 0 and 4 hours of elapsed time) and to characterize the subsequent – more gradual – chlorine or chloramine decay. A final chlorine residual between 0.5 and 1.0 mg/L at the end of the hold time was targeted for all samples treated with free chlorine, and the chloraminated sample target was approximately 2.0 mg/L. Using this information, chlorine and chloramine doses were selected for use in the SDS tests.

The SDS testing was completed in amber glass bottles, adding the sample, phosphate buffer, then chlorine (chloramine samples included ammonia addition after 1 hour of free chlorine contact). Once the desired hold time was achieved, the sample was transferred into amber glass vials provided by Eurofins Lab for the analysis of TTHM and $HAA_5$. Each of the sample collection bottles contained sufficient quenching agent for up to 4 mg/L as $Cl_2$.

It is significant to note that the samples used for the February SDS tests were filtered through a 0.45 µm membrane filter prior to being dosed with phosphate buffer and chlorine/chloramine, however the corresponding decay assessment was completed without filtering the samples. The November SDS samples were not filtered prior to setup. Higher concentrations of DBPs were measured in conjunction with the February SDS samples than with the November SDS samples, and this is likely related to the sample water quality (turbidity and TOC), rather than due to the impact of filtering.

## A.7 Analytical Methods

Eurofins Eaton Analytical Lab analyzed samples for TTHM, $HAA_5$, NDMA, total and dissolved manganese, iron, aluminum, bromide, and bromate. All other analyses were performed on-site at the TT Lab in Pasadena. The analytical methods implemented are shown in Table A-2. Samples for DOC and UV-254 analysis were filtered through a 0.45-µm membrane filter prior to analysis.

**Table A-2. Analytical methods used during the jar tests.**

| Parameter | Method | Lab | Comments |
|---|---|---|---|
| pH | SM 4500-H+ | TT | Hach IntelliCAL Standard pH probe |
| Temperature | | TT | Digital thermometer |
| Turbidity | SM 2130 | TT | HACH 2100AN |
| UV-254 | SM 5910 B | TT | HACH DR5000. Samples were filtered using 0.45-µm filter before analysis. |
| Alkalinity | SM 2320 | TT | Titration with 0.002N HCl |
| TOC | SM 5310C | TT | GE Sievers 5310C |
| DOC | SM 5310C | TT | GE Sievers 5310C. Sample filtered through a 0.45-µm filter. |
| SDS DBP | SM 5710C | TT | Sample filtered through a 0.45-µm Gelman Supor 450 (PES) membrane filter prior to setup for Round 4 only |
| TTHM | EPA 551.1 | Eurofins | |
| $HAA_5$ | SM 6251B | Eurofins | |
| NDMA | EPA 521 | Eurofins | |
| Free Chlorine | HACH 8021 (DPD Method) | TT | HACH DR900 |
| Ammonia | EPA 350.1 | TT | HACH DR900 |

# B APPENDIX B – RAW WATER QUALITY DATA

**Table B-1. Raw water quality measurements from November 28, 2016 samples.**

| Water Quality Parameter | Field Measurements* | Jar Test #1A | Jar Test #2A | Jar Test #3A | Jar Test #4A | Jar Test** #5A | Jar Test** #6A |
|---|---|---|---|---|---|---|---|
| Conductivity (µS/cm) | 65 (F) | - | - | - | - | - | - |
| Dissolved Oxygen (mg/L) | 10.9 (F) | - | - | - | - | - | - |
| Turbidity (NTU) | 1.19 (F) | 0.69 | 0.87 | 1.13 | 1.30 | 1.04 | 1.33 |
| pH | *** | 7.40 | 7.21 | 7.32 | - | 7.16 | 7.41 |
| Alkalinity (mg/L as CaCO3) | - | 24 | 26 | 27 | - | 26 | 26 |
| UV-254, filtered ($cm^{-1}$)**** | - | 0.050 | 0.053 | 0.049 | - | 0.049 | 0.048 |
| TOC (mg/L) | - | 1.87 | 1.91 | 1.91 | 2.03 | 1.92 | 1.89 |
| DOC (mg/L) | - | 1.92 | 1.95 | 1.91 | - | 1.82 | 1.86 |
| Temperature (°C) | 11.0 (F) | 14.2 | 14.5 | 15.5 | 16.7 | 16.7 | 15.5 |
| Total Manganese (µg/L) | - | - | - | - | 12 | - | - |
| Bromide (ug/L) | - | - | - | - | - | 8.0 | 8.0 |

*Source water monitoring results from field measurements by FishBio (F) or Eurofins Eaton Analytical (E)

**Same cubitainer of water used to perform Test 5A and Test 6A

***Invalid pH measurement by Fishbio

****All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis

**Table B-2. Raw water quality measurements from December 12, 2016 samples.**

| Water Quality Parameter | Field Measurements* | Cubitainer #1 | Cubitainer #2 | Cubitainer #3 | Cubitainer #4 – 12/14/16 | Cubitainer #4 – 12/15/16 |
|---|---|---|---|---|---|---|
| Conductivity (µS/cm) | 67.5 (F) | - | - | - | - | - |
| Dissolved Oxygen (mg/L) | 10.2 (F) | - | - | - | - | - |
| Turbidity (NTU) | 1.51 (F) | 1.39 | 1.43 | 1.19 | 1.13 | 1.04 |
| pH | *** | 7.45 | 7.45 | 7.21 | 7.31 | 7.16 |
| Alkalinity (mg/L as CaCO3) | - | 26 | 28 | 28 | 28 | 26 |

| Water Quality Parameter | Field Measurements* | Cubitainer #1 | Cubitainer #2 | Cubitainer #3 | Cubitainer #4 – 12/14/16 | Cubitainer #4 – 12/15/16 |
|---|---|---|---|---|---|---|
| UV-254, filtered (cm$^{-1}$)**** | - | 0.052 | 0.052 | 0.053 | 0.053 | 0.049 |
| TOC (mg/L) | - | 2.04 | 2.00 | 2.00 | 1.96 | - |
| DOC (mg/L) | - | 2.03 | 1.91 | 1.92 | 1.94 | - |
| Temperature (°C) | 11.9 (F) | - | - | - | - | - |
| Total Manganese (µg/L) | 14 (E) | 14 | - | - | - | - |
| Dissolved Manganese (µg/L) | 4.4 (E) | 5.4 | - | - | - | - |
| Bromide (ug/L) | - | 8.6 | - | - | - | - |

*Source water monitoring results from field measurements by FishBio (F) or Eurofins Eaton Analytical (E)

**Same cubitainer of water used to perform Test 5A and Test 6A

***Invalid pH measurement by Fishbio

****All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis

**Table B-3. Raw water quality measurements from January 9, 2017 samples.**

| Water Quality Parameter | Field Measurements* | Jar Test #1B** | Jar Test #2B | Jar Test #3B** | Jar Test #4B |
|---|---|---|---|---|---|
| Conductivity (µS/cm) | 59.3 (F) | - | - | - | - |
| Dissolved Oxygen (mg/L) | 9.81 (F) | - | - | - | - |
| Turbidity (NTU) | 7.63 (F) | 5.25 | 8.24 | 7.17 | 5.30 |
| pH | 7.4 (F) | 7.25 | 7.16 | 7.20 | 7.28 |
| Alkalinity (mg/L as CaCO3) | 22 (E) | 22 | 21.6 | 21.6 | 23.4 |
| UV-254, filtered (cm$^{-1}$)*** | 0.117 (E) | 0.116 | 0.116 | 0.119 | 0.114 |
| TOC (mg/L) | 3.5 (E) | 4.08 | 4.18 | 4.34 | 4.12 |
| DOC (mg/L) | - | 4.02 | 3.98 | 4.03 | 3.98 |
| Temperature (°C) | 11.8 (F) | - | - | - | - |
| Total Manganese (µg/L) | 28 (E) | 36 | - | - | - |
| Dissolved Manganese (µg/L) | ND (2)**** (E) | 4.3 | - | - | - |
| Bromide (ug/L) | - | ND (5) | - | - | - |

*Source water monitoring results from field measurements by FishBio (F) or Eurofins Eaton Analytical (E)

**Same cubitainer of water used to perform Test 1B and Test 3B

***All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis

****ND indicates the parameter was Non Detect at a concentration greater than or equal to the analytical reporting limit, which is indicated in parentheses.

### Table B-4. Raw water quality measurements from February 13, 2017 samples

| Water Quality Parameter | Field Measurements* | Jar Test #1C | Jar Test #2C |
|---|---|---|---|
| Conductivity (µS/cm) | 51 (F) | - | - |
| Dissolved Oxygen (mg/L) | 10.93 (F) | - | - |
| Turbidity (NTU) | 7.74 (F) | 6.56 | 6.5 |
| pH | 7.9 (F) | 7.26 | 7.01 |
| Alkalinity (mg/L as CaCO3) | 18 (E) | 20 | 20 |
| UV-254, filtered ($cm^{-1}$)** | 0.086 (E) | 0.084 | 0.086 |
| TOC (mg/L) | 7.3 (E) | 3.00 | 3.13 |
| DOC (mg/L) | 2.8 (E) | 2.90 | 3.04 |
| Temperature (°C) | 10.1 (F) | - | - |
| Total Manganese (µg/L) | 13 (E) | - | - |
| Dissolved Manganese (µg/L) | ND (2)*** (E) | | |
| Bromide (ug/L) | - | ND (5) | - |

*Source water monitoring results from field measurements by FishBio (F) or Eurofins Eaton Analytical (E)

**All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis

***ND indicates the parameter was Non Detect at a concentration greater than or equal to the analytical reporting limit, which is indicated in parentheses.

# C APPENDIX C – JAR TEST DATA

## C.1 November 28, 2016 Sample (Jar Tests 1A-6A)

**Table C-1. Results of Jar Test 1A using alum with no pH adjustment.**

| | | | Settled Water Quality | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Jar | Alum Dose (mM $Al^{3+}$) | Alum Dose (mg/L as $Al_2(SO_4)_3 \bullet 14H_2O$) | Turbidity (NTU) | pH (units) | Alkalinity (mg/L as $CaCO_3$) | UV-254* ($cm^{-1}$) | TOC (mg/L) | TOC Removal (%) | DOC (mg/L) | DOC Removal (%) |
| 0 | 0 | 0 | 0.685 | 7.40 | 24 | 0.050 | 1.87 | | 1.92 | |
| 1 | 0.007 | 2.1 | 0.872 | 7.30 | 25 | 0.052 | 1.94 | 0** | 1.97 | 0** |
| 2 | 0.017 | 5.1 | 0.868 | 7.20 | 23 | 0.039 | 1.94 | 0** | 1.79 | 6.8 |
| 3 | 0.033 | 9.8 | 0.465 | 7.01 | 20 | 0.026 | 1.42 | 24.1 | 1.39 | 27.6 |
| 4 | 0.050 | 14.9 | 0.387 | 6.87 | 19 | 0.023 | 1.27 | 32.1 | 1.29 | 32.8 |
| 5 | 0.067 | 20.0 | 0.410 | 6.65 | 16 | 0.020 | 1.24 | 33.7 | 1.26 | 34.4 |
| 6 | 0.084 | 25.0 | 0.846 | 6.60 | 14 | 0.020 | 1.28 | 31.6 | 1.18 | 38.5 |
| 7*** | 0.101 | 30.0 | 0.508 | 6.40 | 12 | 0.017 | 1.26 | 34.2*** | 1.11 | 41.7 |

*All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis.

** Removal is listed as zero if the measured value in the settled water was less than the raw water value.

***An extra dose of 30 mg/L alum was evaluated as part of jar test 3A. The raw water TOC associated with jar test 3A was 1.91 mg/L.

**Table C-2. Results of Jar Test 2A using ferric chloride with no pH adjustment.**

| | | | Settled Water Quality | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Jar | Ferric Chloride Dose (mM $Fe^{3+}$) | Ferric Chloride Dose (mg/L as $FeCl_3$) | Turbidity (NTU) | pH (units) | Alkalinity (mg/L as $CaCO_3$) | UV-254* ($cm^{-1}$) | TOC (mg/L) | TOC Removal (%) | DOC (mg/L) | DOC Removal (%) |
| 0 | 0 | 0 | 0.872 | 7.21 | 26 | 0.053 | 1.91 | | 1.95 | |
| 1 | 0.007 | 1.1 | 0.8 | 7.25 | 25 | 0.071 | 1.96 | 0** | 1.98 | 0** |
| 2 | 0.017 | 2.8 | 0.75 | 7.04 | 24 | 0.102 | 1.93 | 0** | 1.94 | 0.5 |
| 3 | 0.033 | 5.4 | 1.38 | 6.82 | 21 | 0.048 | 1.92 | 0** | 1.82 | 6.7 |
| 4 | 0.050 | 8.1 | 0.297 | 6.64 | 19 | 0.027 | 1.3 | 31.9 | 1.35 | 30.8 |
| 5 | 0.067 | 10.9 | 0.345 | 6.52 | 15 | 0.025 | 1.17 | 38.7 | 1.2 | 38.5 |
| 6 | 0.084 | 13.6 | 0.58 | 6.44 | 13 | 0.021 | 1.06 | 44.5 | 1.19 | 39.0 |

*All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis.

** Removal is listed as zero if the measured value in the settled water was less than the raw water value.

**Table C-3. Results of Jar Test 3A using polyaluminum chloride (PAX-18) with no pH adjustment.**

| | | | Settled Water Quality | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Jar** | **PACl Dose (mM $Al^{3+}$)** | **PACl Dose (mg/L as PACl)** | **Turbidity (NTU)** | **pH (units)** | **Alkalinity (mg/L as $CaCO_3$)** | **UV-254* ($cm^{-1}$)** | **TOC (mg/L)** | **TOC Removal (%)** | **DOC (mg/L)** | **DOC Removal (%)** |
| 0 | 0 | 0 | 1.13 | 7.32 | 27 | 0.049 | 1.91 | | 1.91 | |
| 1** | 0.007 | 2.1 | 0.83 | 7.42 | 26 | 0.046 | 1.89 | 0** | 1.82 | 2.15 |
| 2** | 0.017 | 5.0 | 1.03 | 7.35 | 24 | 0.033 | 1.89 | 0** | 1.56 | 16.13 |
| 3 | 0.033 | 9.8 | 0.424 | 7.06 | 25 | 0.024 | 1.40 | 26.7 | 1.40 | 26.7 |
| 4 | 0.050 | 14.8 | 0.442 | 7.03 | 21 | 0.020 | 1.25 | 34.7 | 1.26 | 34.2 |
| 5 | 0.067 | 19.9 | 0.477 | 6.98 | 21 | 0.019 | 1.31 | 31.4 | 1.25 | 34.7 |
| 6 | 0.084 | 24.9 | 1.15 | 6.89 | 19 | 0.021 | 1.40 | 26.7 | 1.31 | 31.4 |
| 7 | 0.101 | 29.9 | 1.18 | 6.80 | 19 | 0.017 | 1.20 | 37.0 | 1.18 | 38.4 |

*All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis.

**Extra doses (2.1 and 5.0 mg/L PACl) were evaluated as part of jar test 6A. The raw water TOC associated with jar test 6A was 1.89 mg/L.

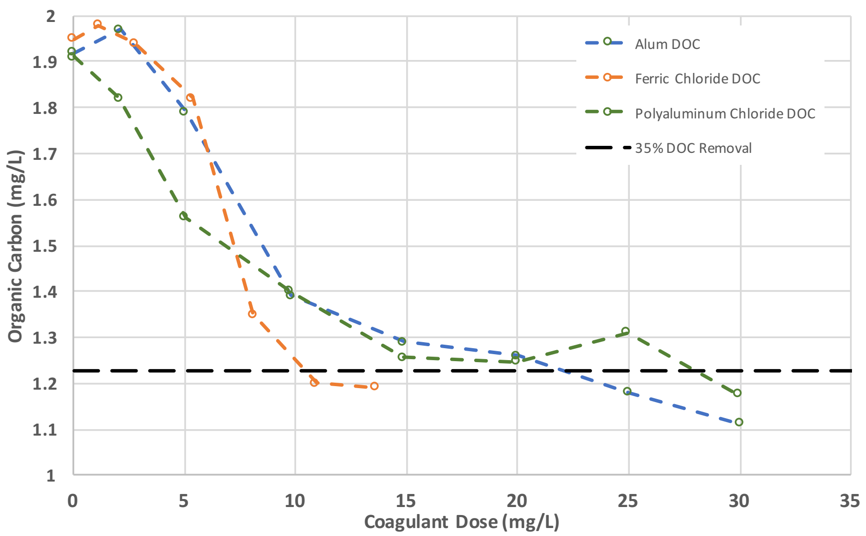


**Figure C-1. DOC after coagulation as a function of coagulant type and mg/L dose (November 2016 sample). Note: The removal target for DOC is calculated based on an average raw water concentrations of 1.89 mg/L.**

**Table C-4. Results from Jar Test 4A preparing water for the intermediate ozone demand tests, chlorine demand test and SDS DBP test.**

| Jar | Ferric Chloride Dose (mM $Fe^{3+}$) | Ferric Chloride Dose (mg/L as $FeCl_3$) | Settled Water Quality | | |
|---|---|---|---|---|---|
| | | | Turbidity (NTU) | TOC (mg/L) | TOC Removal (%) |
| 0 | 0 | 0 | 1.3 | 2.03 | |
| 1 | 0.049 | 7.9 | 0.193 | 1.19 | 41.2 |
| 2 | 0.049 | 7.9 | 0.345 | 1.18 | 41.6 |
| 3 | 0.049 | 7.9 | 0.35 | 1.18 | 42.1 |
| 4 | 0.049 | 7.9 | 0.4 | 1.26 | 38.1 |
| 5 | 0.049 | 7.9 | 0.724 | 1.22 | 39.9 |
| 6 | 0.049 | 7.9 | 0.403 | 1.26 | 38.1 |

**Table C-5. Results of Jar Test 5A evaluating the effect of pH adjustment on coagulant dose and TOC removal, using alum and ferric.**

| Jar | Coagulant | Coagulant Dose (mM $Al^{3+}$ or $Fe^{3+}$) | Alum Dose (mg/L as $Al_2(SO_4)_3 \bullet 14 H_2O$) | Settled Water Quality | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Turbidity (NTU) | pH (units) | Alkalinity (mg/L as $CaCO_3$) | UV-254* ($cm^{-1}$) | TOC (mg/L) | TOC Removal (%) | DOC (mg/L) | DOC Removal (%) |
| 0 | none | 0 | 0 | 1.04 | 7.16 | 26 | 0.049 | 1.92 | | 1.82 | |
| 1 | alum | 0.033 | 9.8 | 1.1 | 6.10 | 8 | 0.017 | 1.73 | 10.2 | 1.20 | 33.9 |
| 2 | alum | 0.050 | 14.9 | 1.15 | 6.11 | 8 | 0.015 | 1.94 | 0** | 1.26 | 31.0 |
| 3 | alum | 0.033 | 9.8 | 0.443 | 6.60 | 14 | 0.020 | 1.36 | 29.4 | 1.32 | 27.5 |
| 4 | ferric chloride | 0.033 | 5.4 | 0.445 | 6.05 | 8 | 0.018 | 1.23 | 36.0 | 1.21 | 33.4 |
| 5 | ferric chloride | 0.050 | 8.1 | 0.304 | 6.12 | 8 | 0.014 | 1.02 | 46.7 | 1.07 | 41.3 |
| 6 | ferric chloride | 0.033 | 5.4 | 0.812 | 6.55 | 14 | 0.030 | 1.54 | 20.0 | 1.36 | 25.0 |

*All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis.

** Removal is listed as zero if the measured value in the settled water was less than the raw water value.

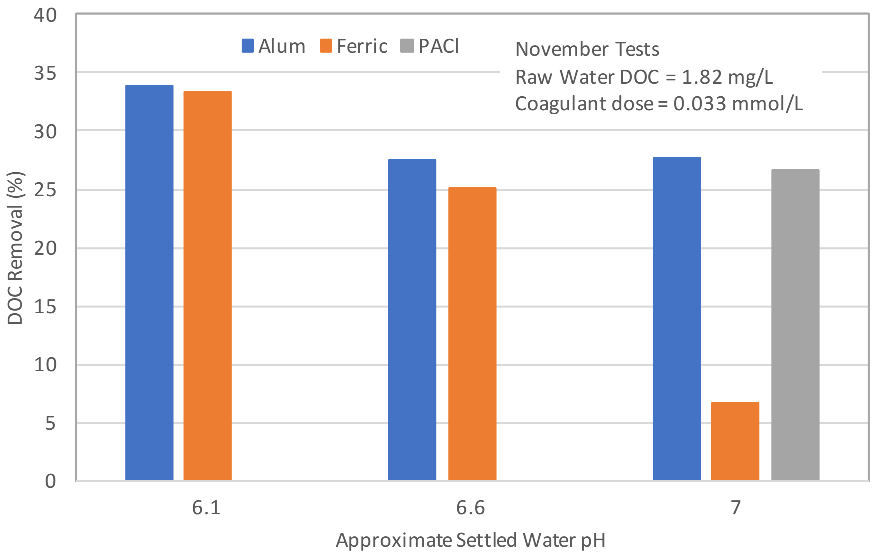


Figure C-2. DOC removal as a function of coagulation pH for coagulant doses of 0.033 mmol/L (November 2016).

## C.2 January 9, 2017 Sample (Jar Tests 1B-3B)

Table C-6. Results of Jar Test 1B using alum with no pH adjustment.

| Jar | Alum Dose (mM $Al^{3+}$) | Alum Dose (mg/L as $Al_2(SO_4)_3{\bullet}14H_2O$) | Settled Water Quality Turbidity (NTU) | pH (units) | Alkalinity (mg/L as $CaCO_3$) | UV-254* ($cm^{-1}$) | TOC (mg/L) | TOC Removal (%) | DOC (mg/L) | DOC Removal (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 8.24 | 7.16 | 21.6 | 0.116 | 4.18 | | 3.98 | |
| 1 | 0.007 | 2.1 | 5.32 | 7.06 | 20.2 | 0.116 | 4.16 | 0.5 | 3.96 | 0.5 |
| 2 | 0.017 | 5.1 | 5.63 | 6.93 | 18.8 | 0.114 | 4.18 | 0.0 | 4.00 | -0.5 |
| 3 | 0.033 | 9.8 | 5.64 | 6.76 | 16.6 | 0.084 | 4.16 | 0.5 | 3.22 | 19.1 |
| 4** | 0.049 | 14.6 | 1.71 | - | - | 0.038 | 3.04 | 25.5 | 2.32 | 42.3 |
| 5 | 0.050 | 14.9 | 1.83 | 6.65 | 14.6 | 0.047 | 2.47 | 40.9 | 2.28 | 42.7 |
| 6 | 0.067 | 20.0 | 2.08 | 6.60 | 11.8 | 0.035 | 2.06 | 50.7 | 1.95 | 51.0 |
| 7 | 0.084 | 25.0 | 1.13 | 6.39 | 10.2 | 0.030 | 1.78 | 57.4 | 1.77 | 55.5 |

*All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis.

**An extra dose of 14.6 mg/L alum was evaluated as part of jar test 1B. The raw water TOC associated with jar test 1B was 4.08 mg/L.

## Table C-7. Results of Jar Test 2B using alum with no pH adjustment.

| | | | Settled Water Quality | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Jar** | **Ferric Chloride Dose (mM Fe$^{3+}$)** | **Ferric Chloride Dose (mg/L as FeCl$_3$)** | **Turbidity (NTU)** | **pH (units)** | **Alkalinity (mg/L as CaCO$_3$)** | **UV-254* (cm$^{-1}$)** | **TOC (mg/L)** | **TOC Removal (%)** | **DOC (mg/L)** | **DOC Removal (%)** |
| 0 | 0 | 0 | 7.17 | 7.20 | 21.6 | 0.119 | 4.34 | | 4.03 | |
| 1 | 0.007 | 1.1 | 5.62 | 7.18 | 19.6 | 0.140 | 4.20 | 3.2 | 4.03 | -0.1 |
| 2 | 0.017 | 2.8 | 5.84 | 7.00 | 19.8 | 0.169 | 4.21 | 3.0 | 4.00 | 0.7 |
| 3 | 0.033 | 5.4 | 5.65 | 6.81 | 13.6 | 0.174 | 4.20 | 3.2 | 3.60 | 10.6 |
| 4** | 0.049 | 7.9 | 6.22 | - | - | 0.087 | 4.24 | 0*** | 2.80 | 30.3 |
| 5 | 0.050 | 8.1 | 6.19 | 6.60 | 13.2 | 0.207 | 4.18 | 3.7 | 3.50 | 13.1 |
| 6 | 0.067 | 10.9 | 2.60 | 6.42 | 11.2 | 0.061 | 3.05 | 29.7 | 2.21 | 45.1 |
| 7 | 0.084 | 13.6 | 0.53 | 6.21 | 9.0 | 0.033 | 1.80 | 58.5 | 1.76 | 56.3 |

*All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis.
**An extra dose of 7.9 mg/L ferric was evaluated as part of jar test 1B. The raw water TOC associated with jar test 1B was 4.08 mg/L.
***Removal is listed as zero if the measured value in the settled water was less than the raw water value.

## Table C-8. Results of Jar Test 3B using alum with no pH adjustment.

| | | | Settled Water Quality | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Jar** | **PACl Dose (mM Al$^{3+}$)** | **PACl Dose (mg/L as PACl)** | **Turbidity (NTU)** | **pH (units)** | **Alkalinity (mg/L as CaCO$_3$)** | **UV-254* (cm$^{-1}$)** | **TOC (mg/L)** | **TOC Removal (%)** | **DOC (mg/L)** | **DOC Removal (%)** |
| 0 | 0 | 0 | 5.3 | 7.28 | 23.4 | 0.114 | 4.12 | | 3.98 | |
| 1 | 0.033 | 9.8 | 5.88 | 7.06 | 18.4 | 0.087 | 4.27 | -3.6 | 3.42 | 14.1 |
| 2 | 0.05 | 14.8 | 1.32 | 6.81 | 16.8 | 0.048 | 2.62 | 36.4 | 2.44 | 38.7 |
| 3 | 0.067 | 19.9 | 1.07 | 6.62 | 15.4 | 0.037 | 2.15 | 47.8 | 2.07 | 48.0 |
| 4 | 0.084 | 24.9 | 1.01 | 6.47 | 14.0 | 0.031 | 1.91 | 53.6 | 1.84 | 53.8 |
| 5 | 0.101 | 30.0 | 0.94 | 6.37 | 13.2 | 0.027 | 1.94 | 52.9 | 1.70 | 57.3 |

*All UV-254 samples were filtered using a 0.45 µm membrane filter prior to analysis.

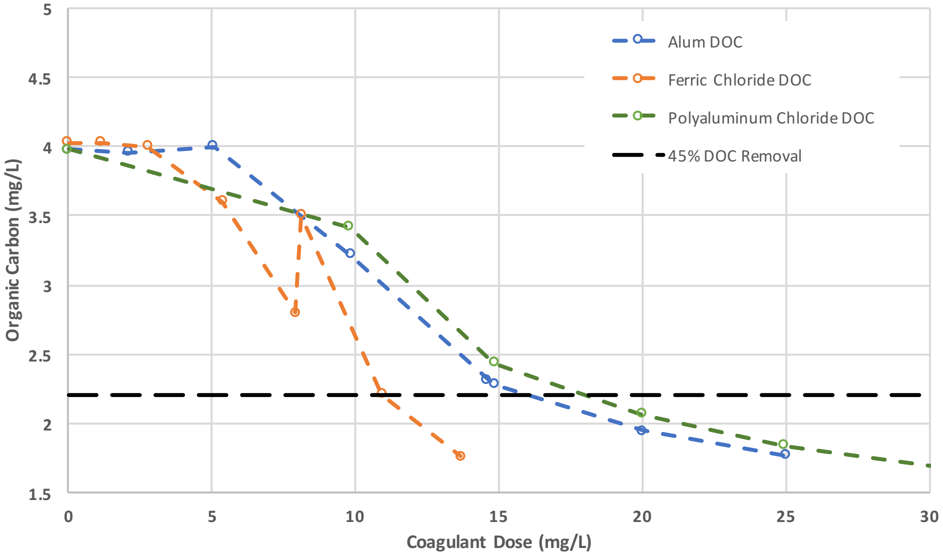


**Figure C-3. DOC after coagulation as a function of coagulant type and mg/L dose (January 2017). Note: The removal target for DOC is calculated based on an average raw water concentration of 4.0 mg/L.**

**Table C-9. Results using alum from Jar Tests 1D and 2D preparing water for the chlorine demand test and SDS DBP tests (February 2017).**

| Jar | Alum Dose (mM $Al^{3+}$) | Alum Dose (mg/L as $Al_2(SO_4)_3 \bullet 14H_2O$) | Settled Water Quality | | | | |
|---|---|---|---|---|---|---|---|
| | | | Turbidity (NTU) | TOC (mg/L) | TOC Removal (%) | DOC (mg/L) | DOC Removal (%) |
| 1D-0 | 0 | 0 | 6.56 | 3.0 | | 2.9 | |
| 1D-1 | 0.017 | 5.1 | 5.72 | 3.36 | 0* | 3.08 | 0* |
| 1D-2 | 0.017 | 5.1 | 5.93 | 3.3 | 0* | 3.08 | 0* |
| 1D-3 | 0.017 | 5.1 | 5.77 | 3.39 | 0* | 3.15 | 0* |
| 1D-4 | 0.033 | 9.8 | 3.81 | 3.18 | 0* | 2.35 | 19.0 |
| 2D-0 | 0 | 0 | 6.5 | 3.13 | | 3.04 | |
| 2D-1 | 0.033 | 9.8 | 2.58 | 3.07 | 1.9 | 2.38 | 21.7 |
| 2D-2 | 0.033 | 9.8 | 2.7 | 2.68 | 14.4 | 2.23 | 26.6 |
| 2D-3 | 0.033 | 9.8 | 2.2 | 2.62 | 16.3 | 2.26 | 25.7 |
| 2D-4 | 0.033 | 9.8 | 2.32 | 2.48 | 20.8 | 2.15 | 29.3 |
| 2D-5 | 0.033 | 9.8 | 2.02 | 2.5 | 20.1 | 2.15 | 29.3 |
| 2D-6 | 0.017 | 5.1 | 5.89 | 3.27 | 0* | 3.03 | 0.3 |

*Removal is listed as zero if the measured value in the settled water was less than the raw water value.

# D APPENDIX D – OZONE DEMAND FROM DECAY CURVES

The initial ozone demand of the water can be calculated from the first-order decay equation, as discussed below. The initial ozone demand is defined as ozone dose minus the calculated initial ozone concentration, $C_0$. The equation for first-order decay is:

$$\frac{dC}{dt} = -kC \qquad \text{(Eqn D-1)}$$

Through integration, this equation becomes:

$$\ln\left(\frac{C}{C_0}\right) = -kt \qquad \text{(Eqn D-2)}$$

which, in the linearized form, is:

$$\ln(C) = -kt + \ln(C_0) \qquad \text{(Eqn D-3)}$$

where: $C_0$ = initial ozone concentration (mg/L)
$C$ = residual ozone concentration (mg/L)
$k$ = ozone decay coefficient ($\text{min}^{-1}$)
$t$ = reaction time (min)

The first-order decay equation can also be written as:

$$C = C_0 e^{-kt} \qquad \text{(Eqn D-4)}$$

## D.1 Raw Water Ozone Demand

Ln(C) versus reaction time is plotted for the raw water dosed with 0.6 and 1.0 O3:TOC in Figure D-1 for the November, December, January, and February bench tests. The residual ozone concentrations measured at 60 seconds and beyond were used in developing these regression lines. The data associated with the 0.6 ozone-to-TOC ratio doses from the December, January, and February samples was too limited to calculate initial demand and decay coefficients because the ozone dose was not high enough to maintain a residual for a long enough time to collect enough data points for a regression line.

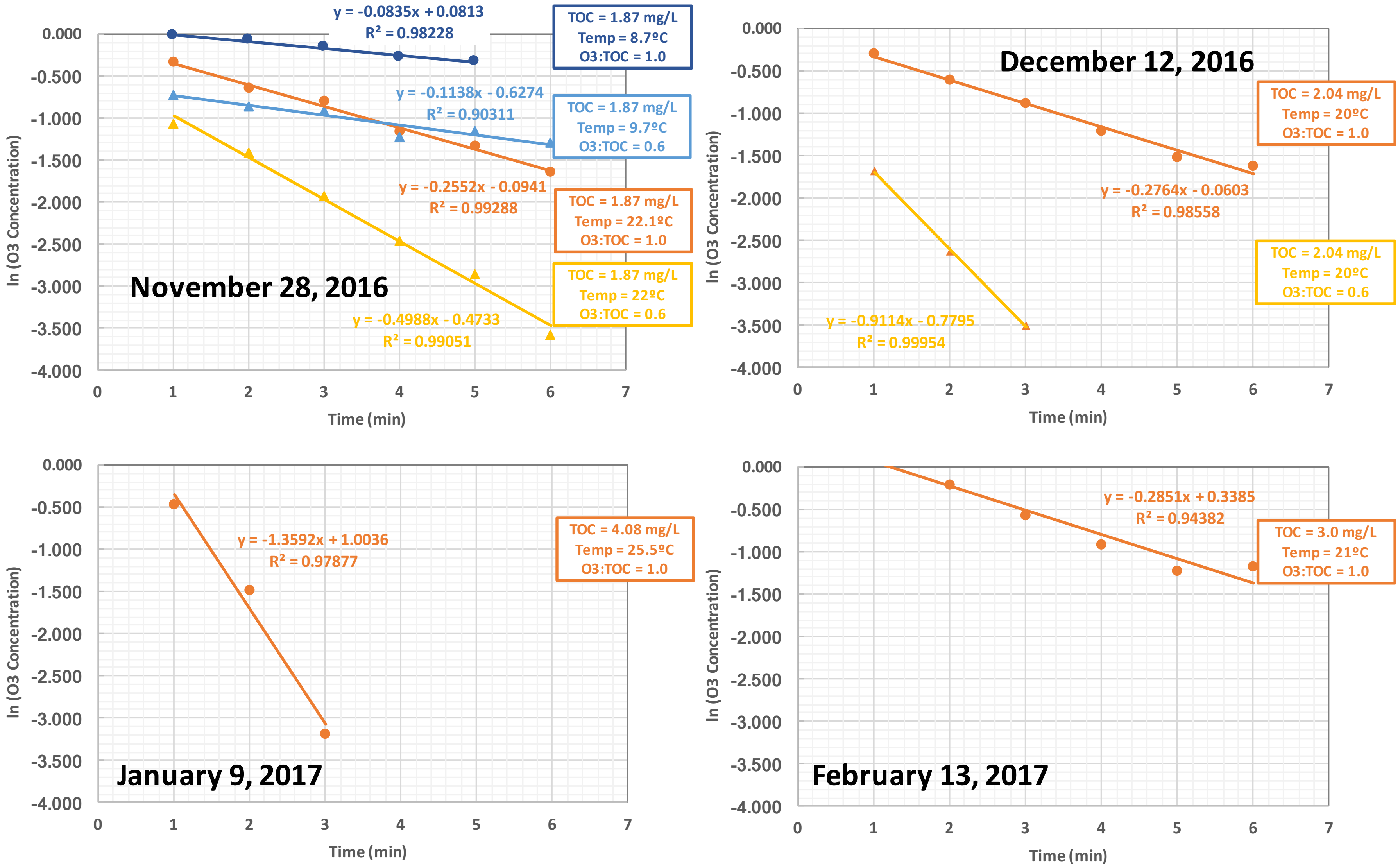


**Figure D-1. Raw water first-order ozone decay for November, December, January, and February samples.**

The slope of the ln(C) versus time regression line (Eqn D-3) is the ozone decay coefficient. From the regression lines shown in Figure D-1, the ozone decay coefficient was calculated for each set of test conditions. These numbers represent the rate of ozone decay after meeting the 60-second demand of the water. A summary of the 60-second ozone demand and ozone decay coefficients from November through February ozone bench tests are presented in Table D-1.

**Table D-1. Initial and 60-second ozone demand of raw Tuolumne River water as a function of ozone dose and water temperature.**

| Target Ozone/TOC Ratio | Transferred Ozone Dose (mg/L) | Water Temp. (°C) | Ozone Decay Coefficient[(A)], *k* ($min^{-1}$) | 60-Sec. Ozone Residual (mg/L) | 60-Sec Ozone Demand (mg/L) |
|---|---|---|---|---|---|
| November 2016 Test Results (TOC = 1.87 mg/L) | | | | | |
| 0.6 | 1.12 | 9.7 | 0.4988 | 0.49 | 0.78 |
| 1 | 1.87 | 8.7 | 0.2552 | 0.98 | 0.89 |
| 0.6 | 1.12 | 22.0 | 0.50 | 0.34 | 0.78 |
| 1 | 1.87 | 22.1 | 0.2552 | 0.71 | 1.16 |
| December 2016 Test Results (TOC = 2.04 mg/L) | | | | | |
| 0.6 | 1.22 | 20.2 | 0.91 | 0.19 | 1.04 |
| 1 | 2.04 | 19.9 | 0.2764 | 0.74 | 1.30 |
| January 2017 Test Results (TOC = 4.08 mg/L) | | | | | |
| 0.6 | 2.45 | 25.9 | n/a [(B)] | 0.00 | 2.45 |
| 1 | 4.08 | 25.5 | 1.3592 | 0.62 | 3.46 |
| February 2017 Test Results (TOC = 3.00 mg/L) | | | | | |
| 0.6 | 1.8 | 21.4 | n/a [(B)] | 0.16 | 1.64 |
| 1 | 3 | 21.2 | 0.2851 | 1.17 | 1.83 |

(A) These ozone decay coefficients are based on ozone residual concentrations measured after one minute or more of reaction time. Thus, the decay coefficients exclude the initial period of rapid decay when the ozone demand of the water is being met.

(B) The ozone dosed was insufficient to exceed the ozone demand and maintain an ozone residual for the 6 minutes of decay testing; no ozone demand values could be calculated.

## D.2 Clarified Water Ozone Demand

As with the raw water, ln(C) versus reaction time is plotted for the clarified water dosed with 0.6 and 1.0 O3:TOC in Figure D-2 for the November, December, January, and February bench tests. In addition to the two ozone doses (0.6 and 1.0 O3:TOC), the plots in Figure D-2 characterize the first-order ozone decay of the waters clarified using different coagulants. Milimolar-per-liter equivalent doses of ferric (November, December, and January), alum (January and February), and PACl (February only) were used to prepare the clarified water.

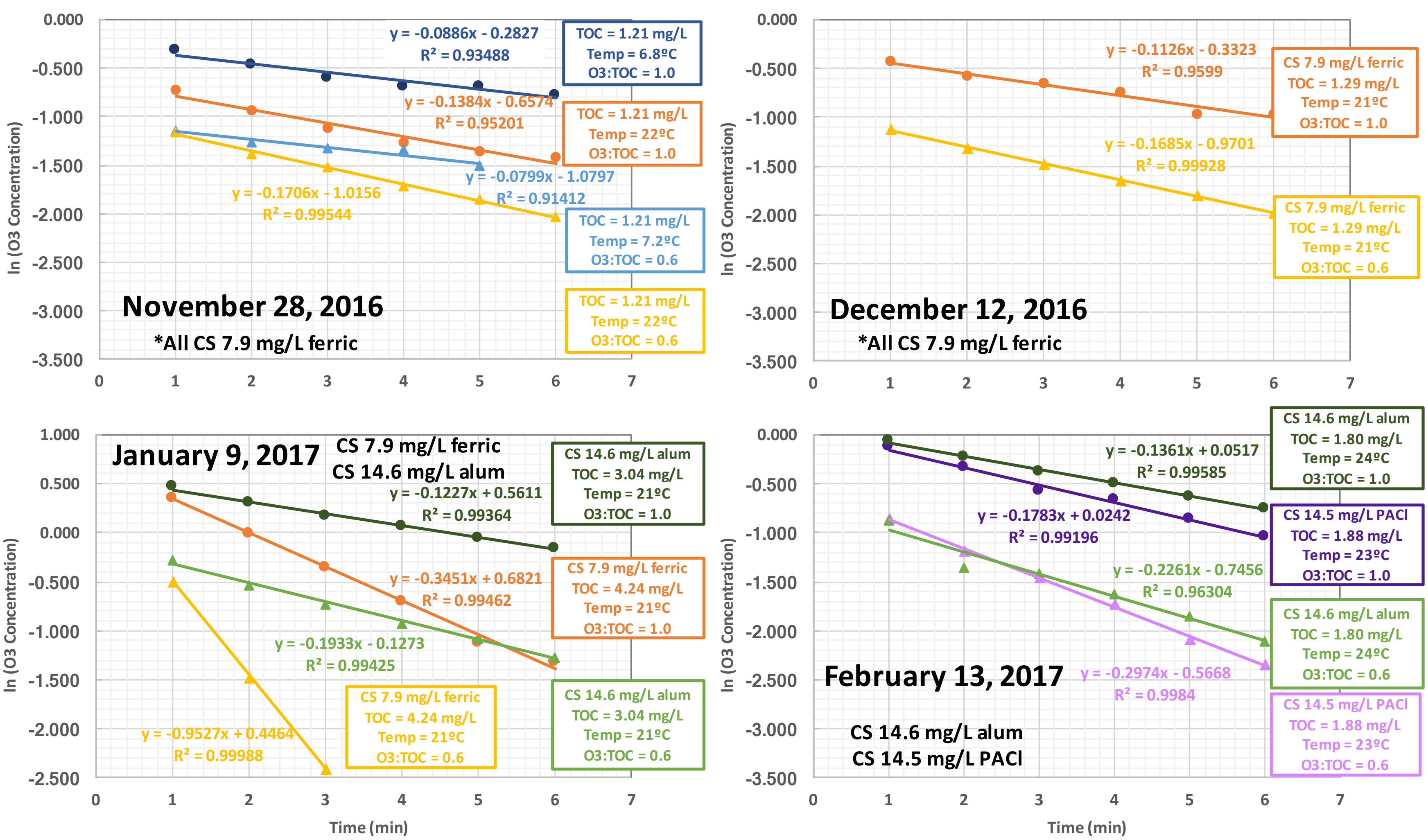


**Figure D-2. Clarified water first-order ozone decay for November, December, January, and February samples. Coagulants and doses used to prepare clarified water are specified for each test.**

The ozone decay coefficient (slope of **Error! Reference source not found.** regression lines) s summarized in Table D-2, along with the 60-second ozone demand. ***The ozone decay coefficient is greater in the warmer vs. cooler water, as well as in water with higher TOC***. Comparing the results in terms of the different coagulants used for the CS waters, there are differences in the ozone decay coefficients (ferric vs. alum in January; alum vs. PACl in February), however this is most likely associated with the TOC of the CS waters – and difference in the TOC removal by the different coagulants –, rather than due to the individual coagulant.

**Table D-2. Initial and 60-second ozone demand of clarified water as a function of ozone dose and water temperature.**

| Target Ozone/TOC Ratio | Transferred Ozone Dose (mg/L) | Water Temp. (°C) | Ozone Decay Coefficient$^{(A)}$, $k$ (min$^{-1}$) | 60-Sec. Ozone Residual (mg/L) | 60-Sec Ozone Demand (mg/L) |
|---|---|---|---|---|---|
| November 2016 Test Results (7.9 mg/L Ferric, CS Water TOC = 1.21 mg/L) | | | | | |
| 0.6 | 0.73 | 7.2 | 0.0799 | 0.32 | 0.78 |
| 1 | 1.21 | 6.8 | 0.0886 | 0.73 | 0.48 |
| 0.6 | 0.73 | 22.1 | 0.171 | 0.31 | 0.41 |
| 1 | 1.21 | 22 | 0.138 | 0.48 | 0.73 |
| December 2016 Test Results (7.9 mg/L Ferric, CS Water TOC = 1.29 mg/L) | | | | | |
| 0.6 | 0.77 | 21.0 | 0.169 | 0.32 | 0.45 |
| 1 | 1.29 | 21.2 | 0.113 | 0.65 | 0.64 |
| January 2017 Test Results (7.9 mg/L Ferric, CS Water TOC = 4.24 mg/L) | | | | | |
| 0.6 | 2.54 | 21 | 0.345 | 1.42 | 2.82 |
| 1 | 4.24 | 20.7 | 0.953 | 0.61 | 1.94 |
| January 2017 Test Results (14.6 mg/L Alum, CS Water TOC = 3.04 mg/L) | | | | | |
| 0.6 | 1.82 | 21.1 | 0.193 | 0.75 | 1.94 |
| 1 | 3.04 | 21.2 | 0.123 | 1.59 | 2.39 |
| February 2017 Test Results (14.6 mg/L Alum, CS Water TOC = 1.80 mg/L) | | | | | |
| 0.6 | 1.08 | 23.5 | 0.226 | 0.42 | 0.66 |
| 1 | 1.80 | 24 | 0.136 | 0.94 | 0.86 |
| February 2017 Test Results (14.5 mg/L PACl, CS Water TOC = 1.88 mg/L) | | | | | |
| 0.6 | 1.13 | 23.4 | 0.297 | 0.43 | 1.00 |
| 1 | 1.88 | 23.3 | 0.178 | 0.88 | 0.70 |

(A) These ozone decay coefficients are based on ozone residual concentrations measured after one minute or more of reaction time. Thus, the decay coefficients exclude the initial period of rapid decay when the ozone demand of the water is being met.

(B) Initial ozone demand is the difference between the transferred ozone dose and $C_o$ determined from the ln(C) versus time regression equations.

# E APPENDIX E – SDS DBP CHLORINE DOSE DETERMINATION

The specifics of the SDS DBP testing varied between the two rounds of sampling, and the details are provided in Table E-1.

**Table E-1. SDS testing parameters**

| Sample Date | Test Condition | Decay Test | | SDSDBP Test | |
|---|---|---|---|---|---|
| | | Free Chlorine or Chloramine Dose (mg/L as $Cl_2$) | Measurement of Residual Chlorine (elapsed hours from dosing) | Free Chlorine or Chloramine Dose (mg/L as $Cl_2$) | Target Hold Times (elapsed hours from dosing) |
| Nov-16 | CS[a] - Free Cl2 | 1.5, 2, 2.5, 3, 4 | 1, 4, 8, 24 | 2 | 1, 48 |
| | CS[a] - Chloramine | 2.5, 3, 3.5 | | 3.25 | 48 |
| | CS[a] - O3 - Free Cl2 | 1, 2 | | 2 | 1, 48 |
| | CS[a] - O3 - Chloramine | n/a | n/a | 3.25 | 48 |
| Feb-17 | CS[b] - Free Cl2 | 1.5, 2, 2.5, 3 | 1,3,22 | 2.75 | 1, 48, 96 |
| | CS[b] - Chloramine | 2.5, 3, 3.5 | | 3.25 | 1, 48, 96 |
| | CS[c] - Free Cl2 | 1.5, 2, 2.5, 3 | | 2.5 | 1, 48, 96 |
| | CS[c] - Chloramine | 2.5, 3, 3.5 | | 3 | 48, 96 |
| | CS[c] - O3 - Free Cl2 | n/a | n/a | 2.5 | 1, 48, 96 |
| | CS[c] - O3 - Chloramine | n/a | n/a | 3 | 48, 96 |

[a] CS samples prepared for November testing using 7.9 mg/L ferric are representative of enhanced coagulation with conventional treatment.

[b] CS samples prepared for February testing using 5.1 mg/L alum are representative of direct or membrane filtration.

[c] CS samples prepared for February testing using 9.8 mg/L alum are representative of enhanced coagulation with conventional treatment.

Notes:

1. Ozone was dosed using an ozone-to-TOC ratio of 1.0.
2. A phosphate buffer was added to each sample prior to chlorine/chloramine addition, targeting finished water pH of approximately 7.8.
3. Chloramine procedure: 1 hour free chlorine contact, chlorine residual measurement after 55 minutes, and addition of ammonia using 4:1 $Cl_2$:$NH_3$-N.
4. Target residual concentrations after the 48 hour hold time for free chlorine and chloramines were 0.4 mg/L and 2.0 mg/L, respectively.

Chlorine decay testing was completed on the buffered, treated water samples used in SDS DBP testing, in order to select the appropriate chlorine doses. The target chlorine and chloramine doses were such that approximately 0.4 mg/L as $Cl_2$ free chlorine residual and approximately 2.0 mg/L as $Cl_2$ of chloramine would remain after 48 hours of hold time, respectively. The 48-hour hold time was selected to represent the detention time of the water in the distribution system. Although the residual chlorine and chloramine targets were determined based on this hold time of 48 hours, the chlorine decay tests were carried out over a 24-hour period. The 24-hour time period was sufficient to characterize the initial demand of each treated water type (approximated by the drop in residual chlorine or chloramines (mg/L as $Cl_2$) within the first 4 hours of reaction time), as well as the more stable decay rate that was established between approximately 4 and 24 hours of reaction time.

## E.1 Round 1 – November 2016 sample

Chlorine decay tests were completed on three of the four treated waters used for SDS DBP testing: CS-Free Chlorine, CS-O3-Free Chlorine, and CS-Chloramine.  It was assumed that the CS-O3-Chloramine test condition would use the same chloramine dose determined via chlorine decay testing of the CS-Chloramine.

Results from the November chlorine demand tests are shown in Table E-2 and Figure E-1, for 1 hour, 4 hour, 8 hour, and 24-hour contact times. Free chlorine and chloramine doses for use in the SDS DBP tests were determined by extrapolating the chlorine decay testing results (Figure E-1). A free chlorine dose of 2 mg/L was selected for both the CS-Free Chlorine and CS-O3-Free Chlorine test conditions. A chloramine dose of 3.25 mg/L was selected for the CS-Chloramine test condition, and was also used for the CS-O3-Chloramine SDS DBP test.

**Table E-2. Chlorine decay test results for November 2016 tests.**

| | Free Chlorine Residual (mg/L) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sampling Time (hr) | CS-Free Cl2 Test 1 | CS-Free Cl2 Test 2 | CS-Free Cl2 Test 3 | CS-Free Cl2 Test 4 | CS-Free Cl2 Test 5 | CS-Chloramine Test 1 | CS-Chloramine Test 2 | CS-Chloramine Test 3 | CS-O3-Free Cl2 Test 1 | CS-O3-Free Cl2 Test 2 |
| 0 | 1.50 | 2.00 | 2.50 | 3.00 | 4.00 | 2.50 | 3.00 | 3.50 | 1.00 | 2.00 |
| 1 | 0.87 | 1.29 | 1.71 | 1.9 | 2.98 | 1.8 | 2.07 | 2.56 | 0.42 | 1.3 |
| 4 | 0.65 | 1.04 | 1.51 | 1.89 | 2.64 | 1.62 | 2.05 | 2.56 | 0.26 | 1.05 |
| 8 | 0.51 | 0.9 | 1.35 | 1.63 | 2.56 | 1.57 | 1.99 | 2.5 | 0.17 | 0.87 |
| 24 | 0.36 | 0.69 | 1.09 | 1.40 | 2.18 | 1.55 | 1.9 | 2.42 | 0.06 | 0.65 |

*Chloraminated samples were exposed to free chlorine for one hour prior to ammonia addition. Residual chlorine was measured at 55 minutes, then ammonia was added using a 4:1 Cl$_2$ to NH$_3$-N ratio.

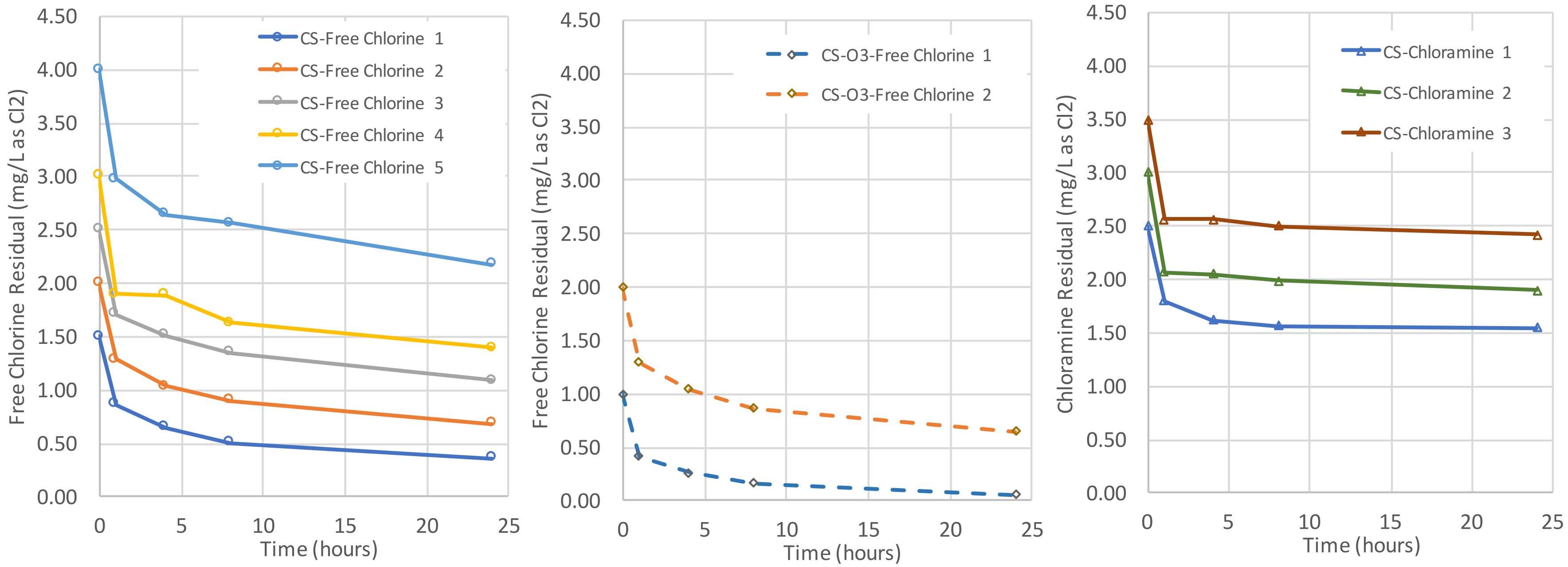


**Figure E-1. Comparison of November 2016 chlorine decay testing results for three treated waters (CS-Free Chlorine, CS-O3-Free Chlorine, and CS-Chloramine).**

## E.2 Round 2 – February 2017 sample

Chlorine decay tests were completed on the CS-Free Chlorine and CS-Chloramine test conditions for both of the alum doses tested (5.1 mg/L and 9.8 mg/L). It was assumed that the test conditions with intermediate ozonation prior to the addition of disinfection would be dosed with the same free chlorine or chloramine dose determined via chlorine decay testing of the non-ozonated conditions.

Results of the associated chlorine decay tests are shown in Table E-3 and Table E-4, as well as Figure E-2 and Figure E-3. Using the chlorine decay testing results associated with the 5.1 mg/L alum CS water (Figure E-2) the selected targets included a free chlorine dose of 2.75 mg/L and a chloramine dose of 3.25 mg/L. The decay results from the 9.8 mg/L alum CS water (Figure E-3), yielded a free chlorine dose of 2.5 mg/L and chloramine dose of 3 mg/L for the SDS testing.

**Table E-3. Chlorine decay test results for February 2017 SDS DBP test samples prepared with 5.1 mg/L alum.**

| | Free Chlorine Residual (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|
| Sampling Time (hr) | CS5.1-Free Cl2 Test 1 | CS5.1-Free Cl2 Test 2 | CS5.1-Free Cl2 Test 3 | CS5.1-Free Cl2 Test 4 | CS5.1-Chloramine Test 1 | CS5.1-Chloramine Test 2 | CS5.1-Chloramine Test 3 |
| 0 | 1.50 | 2.00 | 2.50 | 3.00 | 2.50 | 3.00 | 3.50 |
| 1 | 0.60 | 1.10 | 1.70 | 2.00 | 1.50 | 2.00 | 2.40 |
| 3 | 0.30 | 0.70 | 1.00 | 1.50 | 1.30 | 1.90 | 2.20 |
| 22 | 0.03 | 0.07 | 0.28 | 0.63 | 1.22 | 1.64 | 2.06 |

**Table E-4. Chlorine decay test results for February 2017 SDS DBP test samples prepared with 9.8 mg/L alum.**

| | Free Chlorine Residual (mg/L) | | | | | | |
|---|---|---|---|---|---|---|---|
| Sampling Time (hr) | CS9.8-Free Cl2 Test 1 | CS9.8-Free Cl2 Test 2 | CS9.8-Free Cl2 Test 3 | CS9.8-Free Cl2 Test 4 | CS9.8-Chloramine Test 1 | CS9.8-Chloramine Test 2 | CS9.8-Chloramine Test 3 |
| 0 | 1.50 | 2.00 | 2.50 | 3.00 | 2.50 | 3.00 | 3.50 |
| 1 | 1.00 | 1.10 | 1.70 | 2.20 | 1.60 | 2.20 | 2.60 |
| 3 | 0.70 | 0.80 | 1.20 | 1.80 | 1.30 | 2.00 | 2.50 |
| 22 | 0.09 | 0.18 | 0.50 | 0.81 | 1.19 | 1.86 | 2.37 |

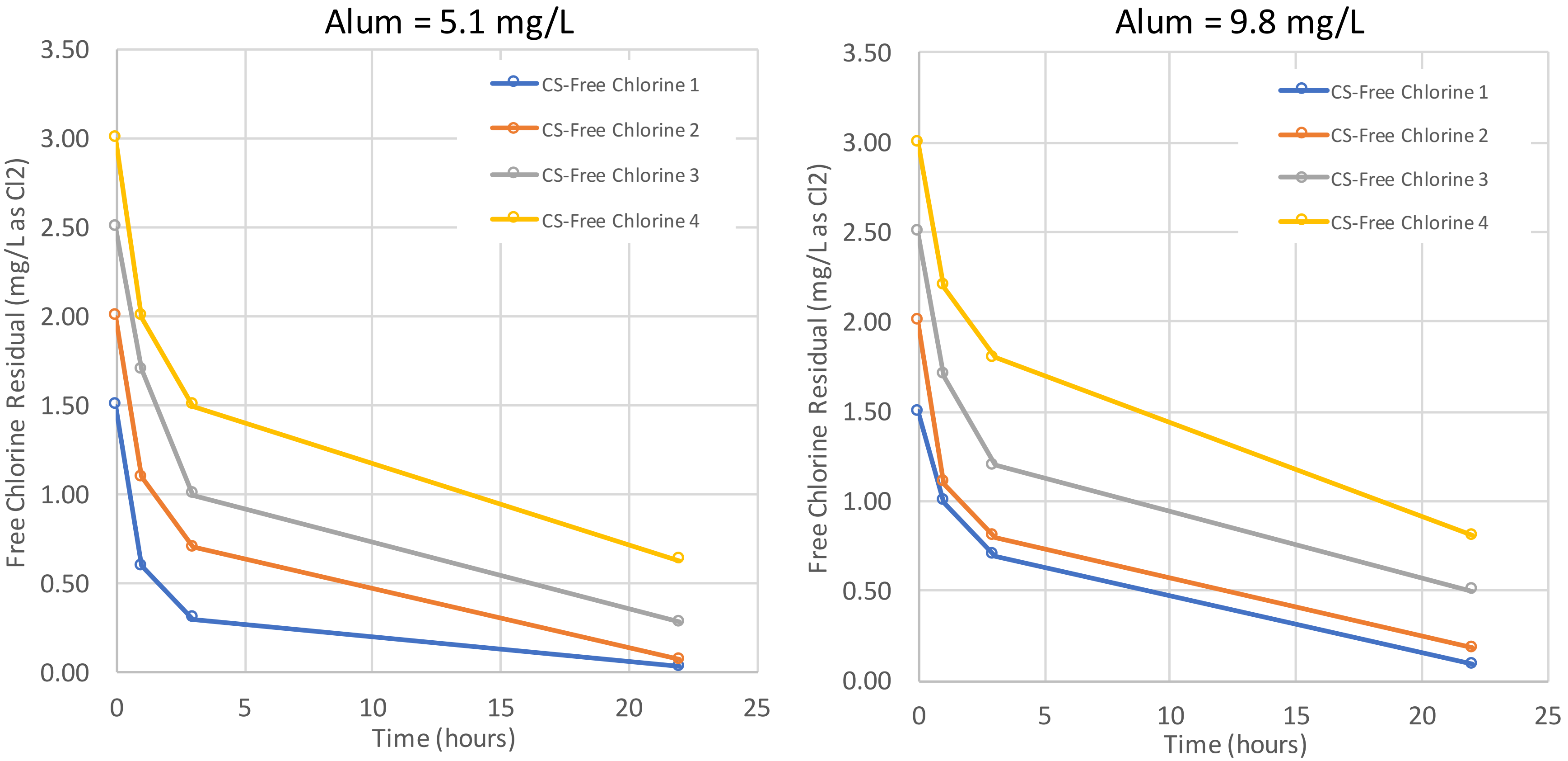


**Figure E-2. Comparison of February free chlorine decay testing results for samples prepared with 5.1 mg/L and 9.8 mg/L alum.**

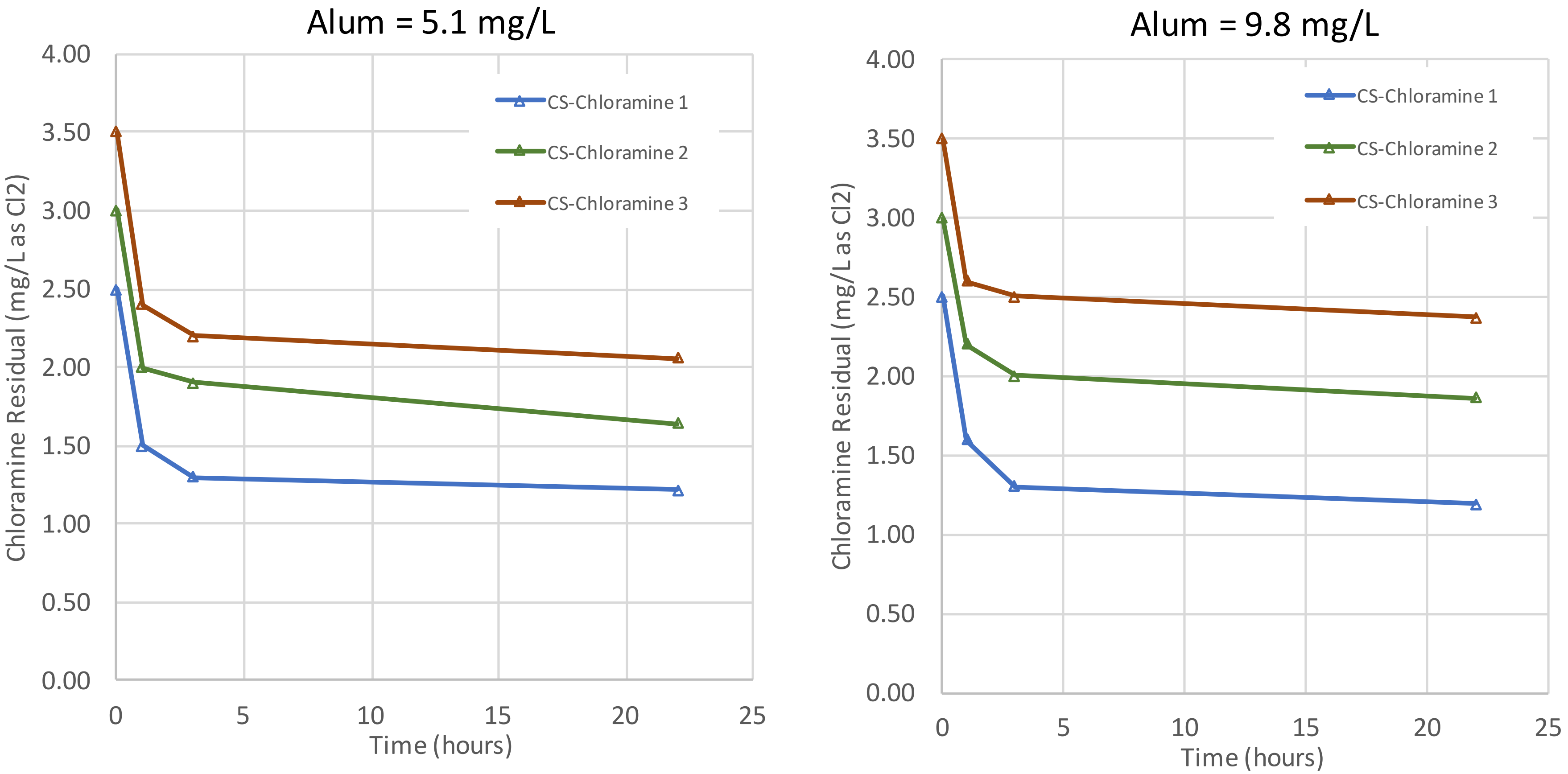


**Figure E-3. Comparison of February chloramine decay testing results for samples prepared with 5.1 mg/L and 9.8 mg/L alum.**

# F APPENDIX F – MANGANESE REMOVAL TESTING DATA

**Table F-1. Results of manganese removal testing with permanganate oxidation and clarification/settling (no ozone), December 2016.**

| | No ozonation tests | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Test Conditions | | | | | | |
| Initial Total Mn - spiked with Mn$^{2+}$ (mg/L) | 0.300 | | | | | |
| Initial Total Mn in raw water (mg/L) | 0.014 | | | | | |
| Oxidant – permanganate* (mg/L) | 0.57 | | | | none | |
| Oxidant Contact Time (min) | 5.00 | 1.00 | 5.00 | 1.00 | 5.00 | 5.00 |
| Coagulant Type | Ferric | Ferric | Alum | Alum | Alum | Ferric |
| Coagulant Dose (mg/L) | 7.90 | 7.90 | 14.60 | 14.60 | 14.60 | 7.90 |
| Clarified Water TOC (mg/L) | 1.47 | | | 1.36 | | |
| Results | | | | | | |
| Clarified Water TOC (mg/L) | 1.47 | 1.51 | 1.36 | 1.36 | 1.32 | 1.45 |
| Final Total Mn (mg/L) | 0.150 | 0.160 | 0.073 | 0.085 | 0.330 | 0.340 |
| Passed 0.45 µm filter | 0.017 | 0.018 | 0.007 | 0.023 | 0.310 | 0.320 |
| Passed 30k Dalton filter | 0.016 | 0.017 | 0.0075 | 0.023 | 0.300 | 0.310 |
| Particulate Mn (mg/L) | 0.133 | 0.142 | 0.066 | 0.062 | 0.020 | 0.020 |
| Colloidal (mg/L)** | 0.0010 | 0.0010 | -0.0001 | 0.0000 | 0.0100 | 0.0100 |
| Dissolved (mg/L) | 0.0160 | 0.0170 | 0.0075 | 0.0230 | 0.3000 | 0.3100 |
| **Manganese Removal (%, total)** | **52.2%** | **49.0%** | **76.8%** | **72.9%** | **-5.1%** | **-8.3%** |

*Permanganate added at 1 x stoichiometric amount required to oxidize Mn(II) to Mn (IV)

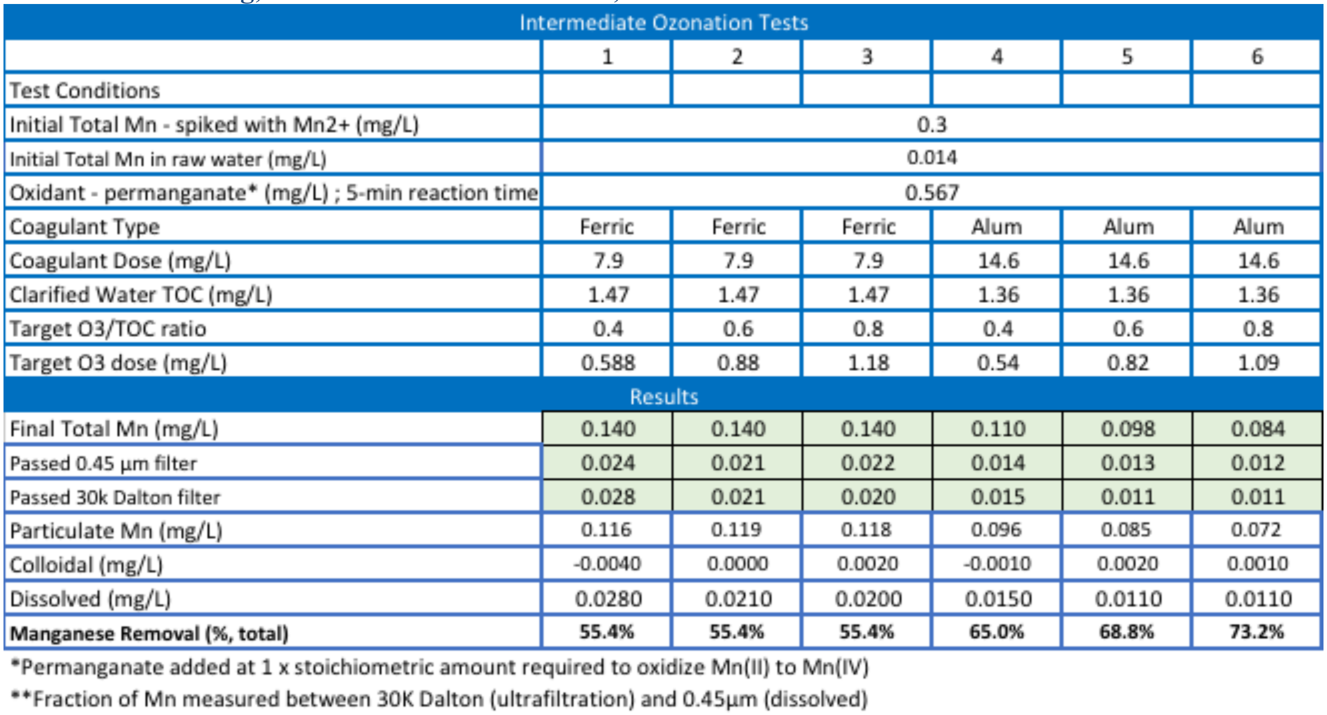
**Fraction of Mn measured between 30K Dalton (ultrafiltration) and 0.45µm (dissolved)

**Table F-2. Results of manganese removal testing with pre-ozonation and clarification/settling (no oxidation), December 2016.**

| | Preozonation Tests | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Test Conditions | | | | | | |
| Initial Total Mn - spiked with Mn2+ (mg/L) | 0.3 | | | | | |
| Initial Total Mn in raw water (mg/L) | 0.014 | | | | | |
| Initial TOC (mg/L) | 2.04 | | | | | |
| Target O3/TOC ratio | 0.25 | 0.25 | 0.25 | 0.6 | 0.6 | 0.6 |
| Target O3 dose (mg/L) | 0.51 | 0.51 | 0.51 | 1.22 | 1.22 | 1.22 |
| Coagulant Type | Ferric | Ferric | Alum | Ferric | Ferric | Alum |
| Coagulant Dose (mg/L) | 7.9 | 6.5 | 14.6 | 7.9 | 6.5 | 14.6 |
| Results | | | | | | |
| Final TOC (mg/L) | 1.39 | 1.84 | 1.27 | 1.42 | 1.86 | 1.29 |
| Final Total Mn (mg/L) | 0.260 | 0.330 | 0.210 | 0.150 | 0.320 | 0.090 |
| Passed 0.45 µm filter | 0.230 | 0.230 | 0.190 | 0.080 | 0.090 | 0.034 |
| Passed 30k Dalton filter | 0.210 | 0.220 | 0.180 | 0.085 | 0.089 | 0.035 |
| Particulate Mn (mg/L) | 0.030 | 0.100 | 0.020 | 0.070 | 0.230 | 0.056 |
| Colloidal (mg/L)* | **0.0200** | **0.0100** | **0.0100** | -0.0050 | 0.0010 | -0.0010 |
| Dissolved (mg/L) | 0.2100 | 0.2200 | 0.1800 | 0.0850 | 0.0890 | 0.0350 |
| **Manganese Removal (%, total)** | **17.2%** | **-5.1%** | **33.1%** | **52.2%** | **-1.9%** | **71.3%** |

*Fraction of Mn measured between 30K Dalton (ultrafiltration) and 0.45µm (dissolved)

### Table F-3. Results of manganese removal testing with permanganate oxidation, clarification/settling, and intermediate ozonation, December 2016.



| Intermediate Ozonation Tests | | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Test Conditions | | | | | | |
| Initial Total Mn - spiked with Mn2+ (mg/L) | 0.3 | | | | | |
| Initial Total Mn in raw water (mg/L) | 0.014 | | | | | |
| Oxidant - permanganate* (mg/L) ; 5-min reaction time | 0.567 | | | | | |
| Coagulant Type | Ferric | Ferric | Ferric | Alum | Alum | Alum |
| Coagulant Dose (mg/L) | 7.9 | 7.9 | 7.9 | 14.6 | 14.6 | 14.6 |
| Clarified Water TOC (mg/L) | 1.47 | 1.47 | 1.47 | 1.36 | 1.36 | 1.36 |
| Target O3/TOC ratio | 0.4 | 0.6 | 0.8 | 0.4 | 0.6 | 0.8 |
| Target O3 dose (mg/L) | 0.588 | 0.88 | 1.18 | 0.54 | 0.82 | 1.09 |
| Results | | | | | | |
| Final Total Mn (mg/L) | 0.140 | 0.140 | 0.140 | 0.110 | 0.098 | 0.084 |
| Passed 0.45 µm filter | 0.024 | 0.021 | 0.022 | 0.014 | 0.013 | 0.012 |
| Passed 30k Dalton filter | 0.028 | 0.021 | 0.020 | 0.015 | 0.011 | 0.011 |
| Particulate Mn (mg/L) | 0.116 | 0.119 | 0.118 | 0.096 | 0.085 | 0.072 |
| Colloidal (mg/L) | -0.0040 | 0.0000 | 0.0020 | -0.0010 | 0.0020 | 0.0010 |
| Dissolved (mg/L) | 0.0280 | 0.0210 | 0.0200 | 0.0150 | 0.0110 | 0.0110 |
| **Manganese Removal (%, total)** | **55.4%** | **55.4%** | **55.4%** | **65.0%** | **68.8%** | **73.2%** |

*Permanganate added at 1 x stoichiometric amount required to oxidize Mn(II) to Mn(IV)

**Fraction of Mn measured between 30K Dalton (ultrafiltration) and 0.45µm (dissolved)