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Going the Extra Mile to Achieve and Maintain Compliance with the Stage II Disinfection By-Product Rule: A Comprehensive Case Study

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ABSTRACT

There are many water systems in New England which confidently and smoothly achieved compliance with the Stage II Disinfectants and Disinfection Byproducts Rule (DBPR) when it was promulgated. However, many water utilities with surface water supply sources have recently been struggling with compliance and experiencing elevated trihalomethane (THM) and haloacetic acid (HAA) distribution system sampling results. There are numerous factors which can contribute to increases in the formation of disinfection byproducts (DBPs) including: source water quality, treatment chemistry, distribution system operations, or other seasonal related phenomenon. Although each public water system has a unique set of source, treatment, distribution, and operational circumstances, there are many similarities and common experiences which can be useful for other water systems to consider and be aware of when assessing and evaluating their own compliance with the DBPR (McGuire, M.J., et. al., 2014). The purpose of this paper is to present a case study involving a New England water system using chlorine for disinfection and their efforts to evaluate, achieve, and maintain compliance with the Stage II DBPR.

Introduction and Background

In order for the public water system which is the subject of this case study to remain anonymous, they will be referred to as Utility A. Since Utility A began sampling for the Stage II DBPR in the 4th Quarter of 2013, total trihalomethane (TTHM) sampling results were above the Maximum Contaminant Level (MCL) of 80 µg/L at several Stage II sampling sites. A summary of locational running annual average (LRAA) THM results for Utility A's five (5) Stage II sampling sites is presented in Figure 1. Since the first full annual period of 4 consecutive quarterly sampling events (3rd quarter of 2014), Utility A exceeded the LRAA THM limit of 80 µg/L in 6 of the first 7 quarters for at least one of their 5 Stage II sampling sites. As a result, Utility A commissioned a study of disinfection by-products (DBPs), specifically THMs, to provide recommendations for the control and reduction of these regulated contaminants.

For water systems which use chlorine for disinfection, the formation of THMs fundamentally results from the reaction between natural organic matter (NOM) and chlorine. In most cases, once the reaction begins, there are generally five (5) primary factors which affect and impact the formation of THMs, as generally described below:

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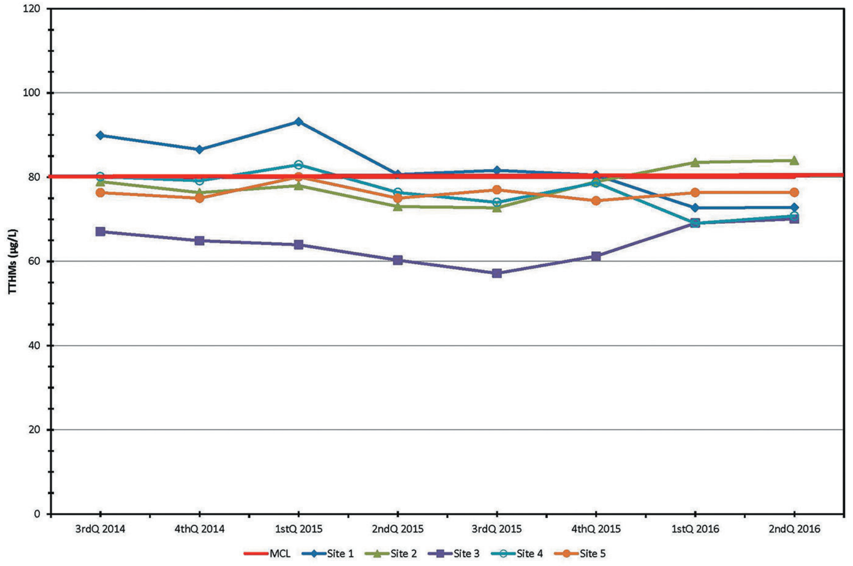
Figure 1
Stage II LRAA THM Sampling Results



1. **NOM** – since NOM is one of the two key ingredients to the formation of THMs, higher levels of NOM present in water will generally produce greater levels of THMs. However, some components of NOM found in drinking water are more reactive than others (Barrett, S.E., et. al., 2000). Therefore, one key to controlling the formation of THMs is to minimize the levels of reactive NOM, or THM precursor material, in the treated water prior to the addition of chlorine.
2. **Chlorine** – although an excellent disinfectant, chlorine will react with NOM to form THMs. Generally, with all other things being equal, higher concentrations of chlorine will result in greater levels of THMs being formed.
3. **Time** – the reaction between chlorine and NOM to form THMs takes time. Generally, with all other things being equal, THM levels will increase with increasing reaction time. The more time that chlorine has to react with NOM, the more THMs will be produced (as long as there is sufficient chlorine and NOM present).
4. **pH** – the reaction between chlorine and NOM is also affected by pH. Generally, with all other things being equal, THM levels are typically higher in water samples with greater pH levels.
5. **Temperature** – water temperature can affect the kinetics of the reaction between chlorine and NOM. Generally, with all other things being equal, THM levels will increase with increasing temperature. Distribution system THM levels are typically higher in warm summer months than in cold winter months.

Scope & Objectives

With a focus on the practical implications and fundamental impacts of THM formation in Utility A's water system, this case study sought to identify the causes for elevated THM levels in the distribution system and make recommendations for their control and reduction. To assist in the development and completion of an appropriate scope of work, this study included the collection and review of existing available water quality information, operating records, and engineering reports, including a Water System Master Plan, a Pilot Treatability Study, facility Record Drawings, Operation & Maintenance Manuals and treatment facility operation and maintenance reports.

The following discreet tasks were completed as part of this case study:

- An evaluation of existing source water quality, treatment and operations of Utility A's two water treatment plants (WTP), referred to as WTP1 and WTP2.
- Completion of a bench scale ozone treatability study.
- Simulated distribution system (SDS) THM testing to investigate the effects of water age, pH, source water blending and ozone on the formation of THMs.

- Desk-top evaluation of the application of distribution system flushing and water main looping to reduce water age.
- Desk-top evaluation of storage tank aeration for the removal of THMs.
- Hydraulic modeling to complete the following assessment of distribution system hydraulics:
    - Water Aging Study – determination of the average water age for various water supply and storage scenarios at numerous distribution system locations, including Utility A's 5 Stage II DBP sampling sites.
    - Source Blending Study – determination of the amount of water from each source present at various locations in the distribution system, including Utility A's 5 Stage II DBP sampling sites.

Water System Description

Utility A's water system consists of over 188 miles of distribution system piping, 6 pressure zones, 7 water storage tanks, 6 booster pumping stations, 6 pressure reducing stations, 2 water treatment facilities, and an emergency groundwater supply pump station. A summary of pertinent storage tank information is presented in Table 1. All of the water storage tanks except two (WTP1 Tank and Tank C) have passive mixing systems.

Table 1. Distribution System Storage.

Storage Tank	Reported Volume (MG)	Reported Overflow Elevation[1] (USGS)
WTP[1] Tank	0.64	149 ft
WTP[2] Tank	1.0	155 ft
Tank A	2.4	374 ft
Tank B	0.4	374 ft
Tank C	5.0	80 ft
Tank D	0.275	190 ft
Tank E	0.37	299 ft

Tank elevations offset by a common factor for anonymity.

WTP1 was constructed in the late 1990s and has a reported hydraulic capacity of 4.0 MGD. The facility makes use of two (2) Advent package treatment units manufactured by Infilco-Degremont (IDI). Each package treatment unit consists of coagulation, non-buoyant media up-flow clarification, and multi-media filtration, with a hydraulic capacity of 2.0 MGD (each unit). The up-flow clarifiers have a design loading rate of 10 gallons per minute (gpm) per square foot (sf) and the multi-media filters have a design loading rate of 5 gpm/sf. Over the years several chemicals have been used for coagulation including: alum, aluminum chlorohydrate (ACH), and polymer. Sodium hypochlorite is used for disinfection, sodium hydroxide is used for pH adjustment, sodium fluoride is used for fluoridation, and phosphate is used for corrosion control. Plans are currently underway to replace the up-flow clarifiers with dissolved air flotation (DAF).

WTP2 is a conventional water treatment facility with a reported hydraulic capacity of 12.5 million gallons per day (MGD) and treats water from a surface water reservoir. The physical/chemical treatment systems include: the use of alum for coagulation; rapid mixing; mechanical flocculation; sedimentation; gravity mixed media filtration; chlorine for disinfection (the chlorine gas system is being converted to sodium hypochlorite); sodium hydroxide for pH adjustment; sodium fluoride for fluoridation; and phosphate for corrosion control.

Results and Findings

Source Water Quality

A summary of pertinent source water quality information for Utility A's two surface water supplies is presented in Table 2. A review and evaluation of the information included in Table 2 suggests that both of Utility A's surface water supplies can be described as being of high quality, exhibiting low levels of turbidity, alkalinity, NOM, iron, and manganese. However, the results of supplemental phytoplankton sampling not included herein indicate that both reservoirs are susceptible to episodes of algae blooms and other general phytoplankton phenomena. In addition, both reservoirs make use of diffused air circulation systems to maintain aerobic conditions in the vicinity of the intakes.

Table 2. Source Water Summary[1].

Water Quality Parameter	Average	Range
Reservoir 1, WTP1		
Temperature (oC)	14	2-30
pH (standard units)	6.8	6.2-7.7
Alkalinity (mg/L as $CaCO_3$)	6.2	1-11
Turbidity (NTU)	0.9	0.2-2.4
TOC (mg/L)	3.5	0.7-5.7
Iron (mg/L)	0.1	ND-0.7
Manganese (mg/L)	0.03	ND-0.3
Reservoir 2, WTP2		
Temperature (oC)	13.5	2-28
pH (standard units)	6.7	6.2-7.5
Alkalinity (mg/L as $CaCO_3$)	5.4	3-8

Figure 2
Treated Water TOC Results: 2013 - 2015

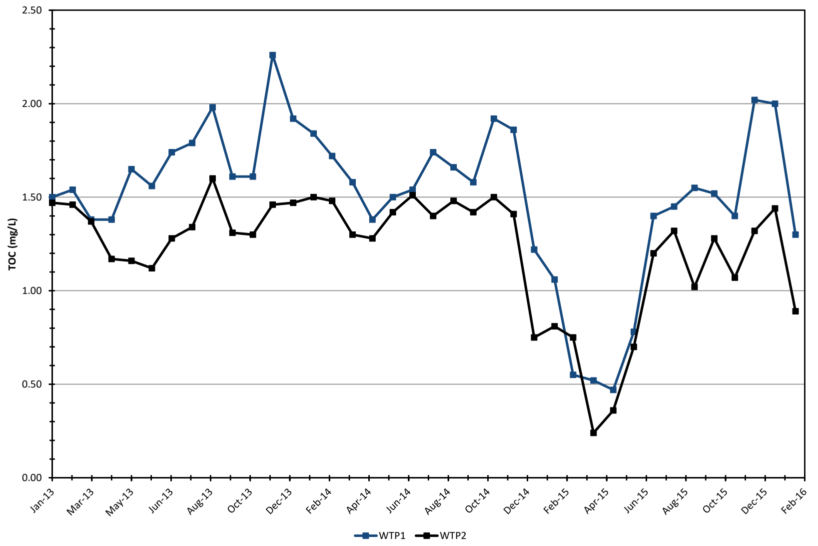


Figure 3
WTP TOC Removal Results: 2013 - 2015

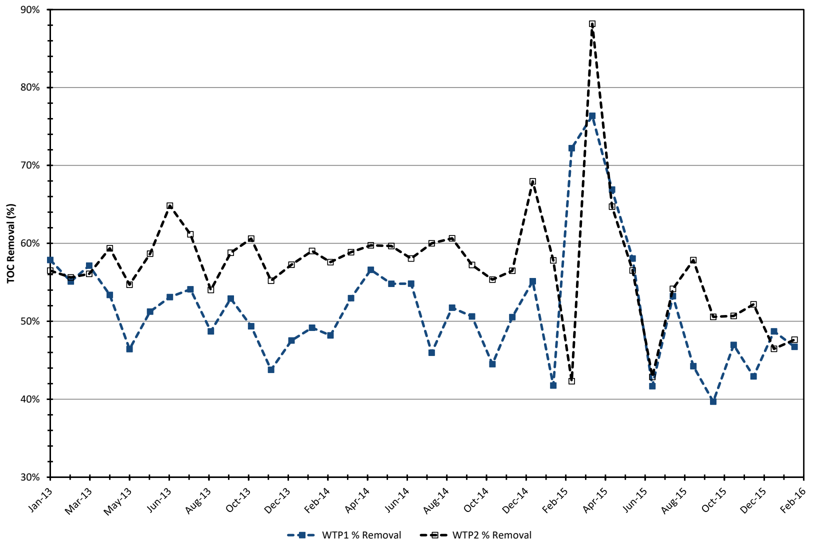


Table 2 (continued)

Water Quality Parameter	Average	Range
Turbidity (NTU)	1	0.4-3.1
TOC (mg/L)	3.3	1.1-5.3
Iron (mg/L)	0.2	ND-0.6
Manganese (mg/L)	0.016	ND-0.1

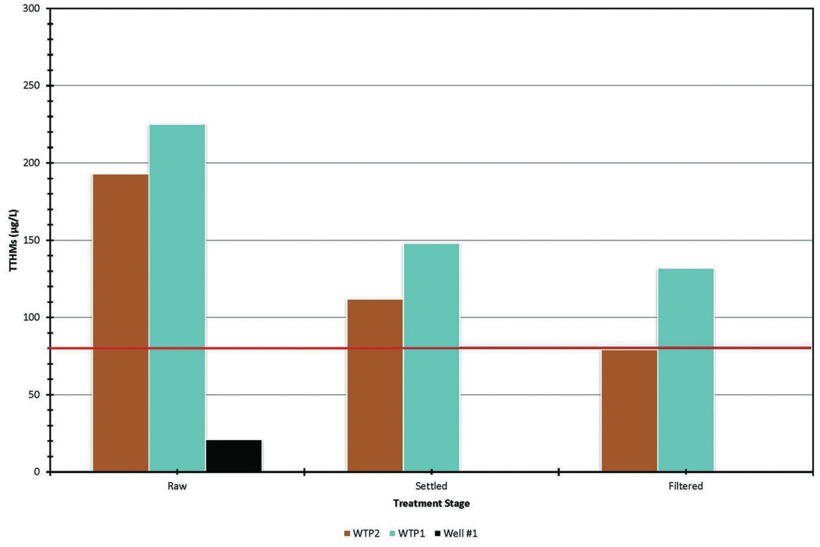
[1] *Source water sampling completed by Utility A for the period 2011-2015.*

In addition to their two surface water supply sources,Utility A has an existing groundwater supply well (Well #1), which is classified for emergency use. There is limited existing available water quality information for Well #1. The well facilities include a small concrete pump station and sodium hypochlorite chemical feed system. Chlorine is manually fed and there are minimal automated controls. Well #1 has historically been used sparingly, typically between a few days and up to two weeks, at a withdrawal rate between 500 and 700 gpm.

Existing Treatment Performance

One means of examining the performance of a WTP for the removal of THM precursor material is

Figure 4
7-Day THMFP Results



to review treated water total organic carbon (TOC) levels. Stage I of the DBPR includes minimum TOC removal requirements for surface water treatment facilities based on source water quality (TOC and alkalinity). For the average raw water alkalinity and TOC levels associated with WTP1 and WTP2, both facilities must achieve a TOC removal of at least 35% (unless the finished water TOC < 2.0 mg/L or the raw water TOC < 2.0 mg/L). Treated water TOC levels for each WTP are presented graphically in Figure 2. The TOC removal levels achieved at both facilities are presented graphically in Figure 3. A review and evaluation of the treated water TOC information presented in Figures 2 and 3 indicates that the finished water TOC levels are typically lower and TOC removals are typically higher at WTP2, compared to WTP1. Although both WTPs achieve TOC removals well above the required 35% under the DDBR, the average TOC removals achieved at WTP2 are consistently greater than those achieved at WTP1. The average TOC removal for WTP2 is approximately 60%, resulting in an average finished water TOC level of approximately 1.0 mg/L. In comparison, the average TOC removal for WTP1 is approximately 50%, with an average finished water TOC level of approximately 1.5 mg/L.

As previously discussed, Utility A is planning to retrofit WTP1 with DAF clarification. Discussions with the operations staff of WTP1 suggest that coagulant dosages are restricted based on the physical performance and limitations of the up-flow clarifiers. Although increasing the coagulant dose could result in lower TOC levels at WTP1, the ability of the up-flow clarifiers to handle the additional solids loading is limited. DAF clarifiers have been shown to have the ability to handle much higher solids loads than up-flow clarifiers. Therefore, once WTP1 is retrofitted with DAF, and coagulant dosages are increased, it is expected that greater removals of TOC can be achieved, which could result in lower THM levels.

TOC is a gross measure of the amount or level of NOM in water. However, TOC levels alone do not indicate the reactiveness of the NOM present to form THMs when chlorine is added (Reckhow, D.A., 2019). One way to assess the relative reactiveness of a water's TOC is to complete a THM formation potential (THMFP) test. The protocol for a THMFP test is typically established to maximize the formation of THMs under a reaction time of seven days (7-day THMFP). For this case study, both 7-day and 14-day THMFP tests were completed for Utility A's three source water supplies (Reservoir 1, Reservoir 2, and Well #1), including raw water, settled water, and filtered water from the treatment facilities. Water samples were collected on October 6, 2015 and October 14, 2015. The test conditions for THMFP samples included a chlorine dose of 12.5 mg/L, a reaction pH of 7.5, a reaction temperature of 21°C, and reaction times of 7-days and 14-days. The samples were collected, prepared, and stored in 250 mL amber glass jars (and in the dark), with no headspace.

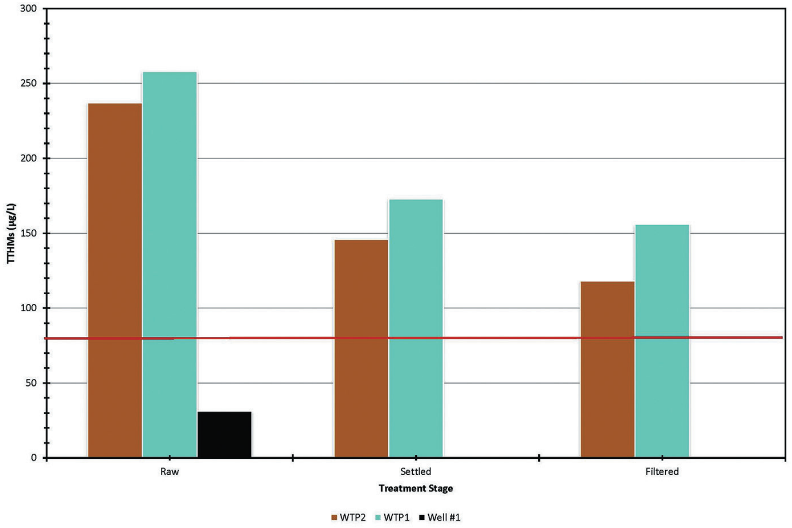


Figure 5
14-Day THMFP Results

The 7-day THMFP test results are presented graphically in Figure 4 and the 14-day THMFP results are presented graphically in Figure 5. A review and evaluation of the THMFP results indicates that chlorine reactive NOM (precursory material to the formation of THMs) is removed as the water advances through the treatment systems. There is a greater reduction in THMFP at WTP2 compared to WTP1. In addition, there is a greater reduction of THMFP between the settled water and filtered water at WTP2 (~29%) compared with WTP1 (~11%). The THMFP results shown on Figure 4 suggest that finished water from WTP2 could be expected to result in distribution system THM levels less than the MCL of 80 µg/L at a water age of 7 days. However, filtered water 7-day THMFP results from WTP1 and filtered water 14-day THMFP results from both surface water treatment plants were above 80 µg/L. Lastly, according to the information presented in Figures 4 and 5, water from Well #1 is not susceptible to the formation of elevated levels of THMs, even after a 14-day reaction period. The water sample collected from Well #1 exhibited a 14-day THMFP level of 31 µg/L.

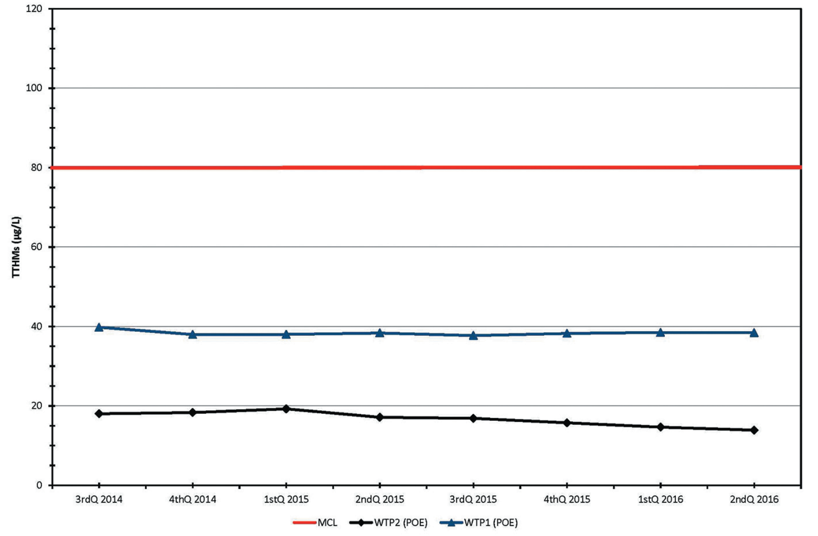
The measured chlorine residuals for each THMFP sample are presented in Table 3. An evaluation of the information presented in Table 3 suggests that there was sufficient chlorine remaining in each sample to continue the reaction. In addition, a comparison of the chlorine residuals indicates that the higher the level of treatment received at the WTP, the greater the chlorine residual. It also appears that the filtered water from WTP2 exhibited the lowest chlorine demand, indicating that the NOM from this location was the least reactive with chlorine, and hence resulted in the lowest reported THMFP levels.

Table 3. THMFP Chlorine Residuals.

Sample Location	7-Day Residual (mg/L)	14-Day Residual (mg/L)
Reservoir 1		
Raw	7.2	5.0
Settled	8.0	5.2
Filtered	8.3	6.0
Reservoir 2		
Raw	7.9	4.3
Settled	8.5	4.7
Filtered	8.6	8.2

As stated previously, one of the most common ways to express and measure the NOM component of drinking water is using TOC. However, as previously mentioned, TOC does not describe a water's reactiveness with chlorine and the resulting potential formation of THMs. One simple water quality parameter commonly used to qualify NOM is measuring absorbance of ultraviolet light at a wavelength of 254 nanometers (UV-254) (Edzwald, J.K., et. al., 1985). The aromatic structure of aquatic fulvic and humic acids is absorbed by UV-light,

Figure 6
WTP Finished Water THMs



and is indirectly and selectively quantified by UV-254. By calculating the ratio of UV-254 to TOC (dissolved organic carbon should be used for compliance calculations) the term specific ultraviolet light absorbance (SUVA) can be estimated. SUVA provides a simple way to characterize the nature and/or composition of the NOM present in water. Raw waters with an SUVA close to 2 suggest a mixture of lower molecular weight humic, aromatic, and aliphatic compounds which are readily removed by coagulation (Pernitsky, D.J. and Edzwald, J.K., 2006). Generally, the lower the SUVA, the less reactive the NOM is with chlorine, which should result in the formation of lower THMs.

TOC, UV-254, and SUVA results for the THMFP samples are presented in Table 4. A review of the information presented in Table 4 indicates that the raw water NOM characteristics between Reservoir 1 and Reservoir 2 are very similar. However, the results also indicate that WTP2 is more efficient at removing NOM (also refer to Figures 2 and 3). The TOC, UV-254, and SUVA of WTP2 filter effluent are all lower than the reported values for WTP1. These data also support the THMFP results presented previously in Figures 4 and 5. Collectively, the NOM fraction remaining in the filtered water at WTP2 is less reactive with chlorine and results in lower levels of THMs. LRAA THM results for Utility A's two WTPs are presented in Figure 6. A review of the information presented in Figure 6 corroborates the NOM and THMFP findings discussed previously. The THMs produced at WTP2 (~20 µg/L) are approximately 50% lower than levels reported for WTP1 (~40 µg/L).

Table 4. NOM Results for THMFP Samples.

Sample Location	TOC (mg/L)	UV-254 (1/cm)	SUVA
WTP1			
Raw	3.0	0.071	2.37
Settled	2.3	0.035	1.52
Filtered	2.1	0.032	1.52
WTP2			
Raw	3.0	0.073	2.43
Settled	1.8	0.035	1.94
Filtered	1.4	0.018	1.29

Supplemental Treatment and THM Reaction Factors

Considerations Evaluated

Based on the five previously identified factors which affect the formation of THMs, the following control strategies become apparent:

1. **NOM** – optimize the removal or oxidation of NOM to minimize the fraction remaining and/or render it less reactive with chlorine. Both lower levels of NOM and less reactive NOM will result in lower THM levels.
   Comment: Based on the TOC and supplemental information for both WTPs, the existing systems appear to be operated close to

optimal conditions for the removal of NOM. In addition, in 2014 Utility A investigated the application of potassium permanganate (a series of bench scale jar tests) for enhanced NOM removal. The results of the study indicated no significant reduction in NOM as measured by UV-254 and TOC results.

This case study includes an evaluation of the application of ozone after filtration to simulate intermediate ozonation. Ozone has been demonstrated to destroy the aromatic structure of NOM, rendering it less reactive to chlorine and the formation of THMs. The application of intermediate ozonation (applying ozone after clarification but before filtration) will result in lower applied dosages (less ozone demand after coagulation/clarification) compared with pre-ozonation (ozonating the raw water) and could allow for enhanced NOM removal in the filtration stage. Ozone has been shown to oxidize NOM and render it more readily assimilable to biological uptake. The promotion of biological filtration can increase the overall removal of NOM, leaving less to react with chlorine.

2. **Chlorine** – lower applied chlorine dosages will result in lower THMs. However, if chlorine dosages cannot be lowered, and none of the other 5 factors can be adjusted, then an alternative disinfectant to chlorine could be implemented. Alternative disinfectants include ozone, chloramines, and chlorine dioxide.

   Comment: Utility A completed an alternative disinfectant study for WTP2 in 2014. The scope of the study evaluated and compared the use of chlorine gas, sodium hypochlorite, ozone, chlorine dioxide, chloramines, and UV light for primary disinfection. Based on the results of the study, it was recommended to replace the chlorine gas system with sodium hypochlorite at WTP2. The application of alternative disinfectants was not found to be favorable.
3. **Time** – minimizing the reaction time, or water age, will result in the production of fewer THMs. Alternative ways of reducing water age include modifying storage, looping dead end water mains, and implementing a distribution system flushing program.

   Comment: This case study included the completion of simulated distribution system (SDS)-THM tests for various water samples for the following reaction times: 1, 3, 7, 14 and 21 days. The reaction times were selected based on the results of a hydraulic study completed in 2012 which indicated water ages up to 21 days. Utility A retained the services of a consulting engineer to update their hydraulic distribution system model and complete a revised water age study. Partial results of the 2016 water age study are presented herein.

   Based on a review of water distribution system maps, there are no obvious water main looping opportunities to reduce the water age of Utility A's current Stage II DBP sample sites, therefore this alternative was not evaluated further. Although distribution system flushing can result in lowering overall water ages, the flow rate, duration, frequency, and location for hydrant flushing or the installation of bleeders were beyond the scope of this case study.
4. **pH** – lower pH levels typically result in lower levels of THMs.

   Comment: SDS-THM tests for various water samples were completed to examine the impacts of pH on THM formation. Finished water point-of-entry (POE) pH and alkalinity information were also evaluated.
5. **Temperature** – water temperature can affect the reaction kinetics between chlorine and NOM whereby warmer water temperatures result in higher levels of THMs.

   Comment: Temperature is one parameter where water systems have the least operational control. Water temperatures change seasonally with the weather pattern. One way to positively affect water temperature in the distribution system is to provide mixing systems in water storage tanks. Mixing systems can keep water relatively cooler in the summer and warmer in the winter. All but one of Utility A's distribution system storage tanks includes a mixing system. In addition, the only water storage tank without a mixing system (Tank C) is scheduled to be replaced. Although this study did not specifically examine the effects of temperature on THMs, all SDS and THMFP tests were completed at a reaction temperature of 21°C (room temperature), which is slightly cooler than maximum reported distribution system temperatures of 25°C.

Based on the existing Stage II THM sampling results and an evaluation of existing treatment performance, some form of supplemental treatment or modification of the factors which affect the formation of THMs is required to reduce

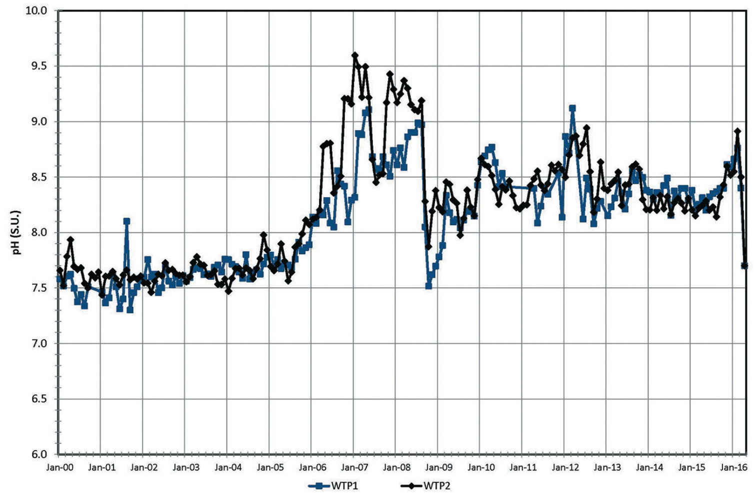


Figure 7
Average Monthly Finished Water POE pH

distribution levels below the MCL. As such, a series of SDS-THM tests were completed to examine the impacts of the following reaction factors on the formation of THMs in Utility A's distribution system:

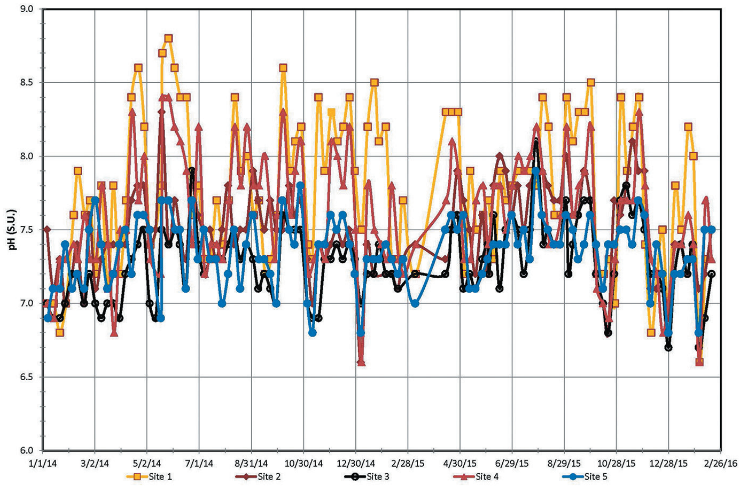
- **Ozone** – an applied ozone dose of 1 mg/L and 2 mg/L to render the NOM present less reactive with chlorine.
- **pH** – investigate the impacts of a lower target POE pH of 7.5, compared with the current target POE pH of 8.5.
- **Water Age** – investigate the formation of THMs for various water ages representative of the Utility A water system.
- **Source Blending with the Well #1** – examine the effects of water age and blending with the use of Well #1 to reduce distribution system THMs.

Methods, Procedures, and Preliminary Findings

Raw water, settled water, filter effluent, and finished water samples from each of Utility A's WTPs were collected on October 6, 2015 (Round #1). An initial round of SDS samples were prepared on site and transported to an office laboratory for storage and subsequent testing. The SDS samples were prepared (chemically adjusted as needed), then stored in 250 mL amber glass jars (and in the dark), with no headspace at a temperature of 21°C. SDS samples were held for 1, 3, 7, 14, and 21 days prior to testing. After the prescribed holding times, SDS samples were tested for THMs, pH, chlorine, and temperature. All water quality parameters with the exception of TOC, THMs, and bromide were tested either in the field or at the office laboratory using bench top equipment and analyzers. TOC, THM, and bromide samples were sent to an independent certified laboratory for testing and analysis.

The objective of SDS testing is to simulate distribution system physical and chemical conditions as closely as possible under controlled conditions. This includes target water quality, temperature, and holding time. The majority of SDS samples were collected from finished water from each WTP. This approach ensured that actual POE finished water quality would be used for testing purposes. While at Utility A's WTP facilities on October 6, 2015, it was determined that the target POE pH for each facility was in the range of pH 8.5 to 8.8. Therefore, two target SDS pH levels were selected for testing: pH 8.5 and pH 7.5. A pH of 7.5 was chosen because it is the optimal pH for corrosion control when using a phosphate inhibitor and it also represents a lower pH than current levels, making it suitable for investigating the effects of pH on the production of THMs. Historic monthly average finished water POE pH levels from both of Utility A's WTPs for the period January 2000 through February 2016 are presented in Figure 7. A review of the information shown on Figure 7 indicates that recent average POE pH levels are in the range of 8.5 to 8.8, while historic pH levels from 2000 to 2004 were in the range of 7.3 to 7.8 (which is more typical of water systems where phosphate is applied for corrosion control).

Figure 8
Distribution System pH Levels



Raw, settled, and filter effluent samples were collected and tested for THMFP as described previously. Finished water samples from each WTP were collected for SDS testing. The pH of the finished water was adjusted using caustic and/or hydrochloric acid to achieve two target pH levels: 7.5 and 8.5. All other finished water parameters were unadjusted (chlorine, fluoride, phosphate) and matched whatever levels were produced at each WTP at the time of sampling. The measured chlorine residual at WTP2 and WTP1 at the time of Round #1 SDS sampling was 1.5 mg/L and 1.6 mg/L, respectively.

While completing in-house laboratory analyses of the 1-day SDS samples, the measured pH results were inconsistent and erratic, compared with the adjusted pH levels at the time the samples were prepared (pH 7.5 and 8.5). As a result, supplemental testing was conducted and it was determined that the alkalinity of the SDS samples was less than 2 mg/L as $CaCO_3$. As a result, historic distribution system pH information was collected and reviewed. It was determined that pH levels within the distribution system were not very stable. A graph of existing available weekly pH data for the period January 2014 through February 2016, from 5 routine bacteria sampling sites in close proximity to Utility A's Stage 2 sampling sites, is presented in Figure 8. A review of the information presented in Figure 8 indicates inconsistent distribution system pH levels in the range of pH 6.7 to 8.7. Although not a focus of this study, it can be important for some water systems to avoid swings in distribution system pH (and chlorine residuals) due to the possible effects of oxidation reduction potential (ORP) which can lead to the oxidation of accumulated legacy manganese within a distribution system, resulting in episodes of discolored water (Horsley, S. and Chamberlain, K., 2019).

Based on the SDS alkalinity measurements and reported distribution system pH results (Figure 8), it was suspected that there was little buffer intensity (β) associated with Utility A's finished water. Buffer intensity is the measure of a water's ability to resist changes in pH, and is affected by pH, alkalinity, and temperature. Theoretical buffer intensity curves for various pH and alkalinity values are presented in Figures 9, 10, and 11 for water temperatures of 5°C, 15°C, and 25°C, respectively. A review of the information shown on Figures 9 through 11 indicates that water typically has the lowest theoretical buffer intensity at pH levels near 8.5, for all alkalinity and temperature levels. At any given pH, the lower the alkalinity, the lower the buffer intensity. Therefore, after evaluating the information presented in Figures 8 through 11, the observed variability in distribution system pH levels is not surprising. By adjusting the alkalinity to 25 mg/L as $CaCO_3$ and the pH to 7.5, the buffer intensity increases by nearly an order of magnitude, compared with the current calculated level for Utility A's finished water (0.01 x103 mol/L). Increasing the buffer intensity of Utility A's finished water would increase the ability to resist changes in pH within the distribution system.

Figure 9
Affects of pH and Alkalinity on Buffer Intensity
Temperature = 5°C

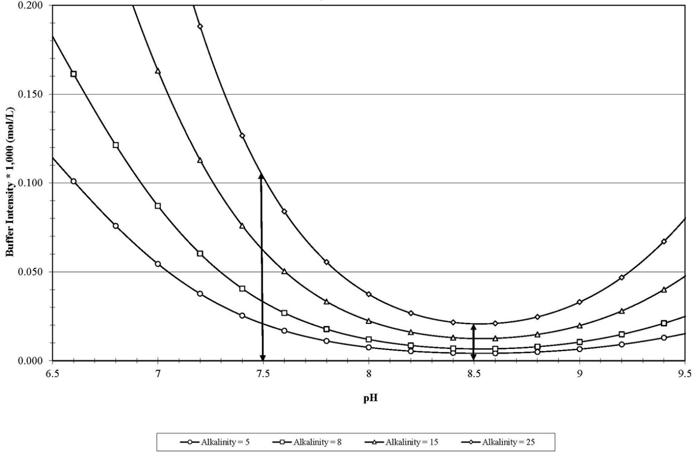


Figure 10
Affects of pH and Alkalinity on Buffer Intensity
Temperature = 15°C

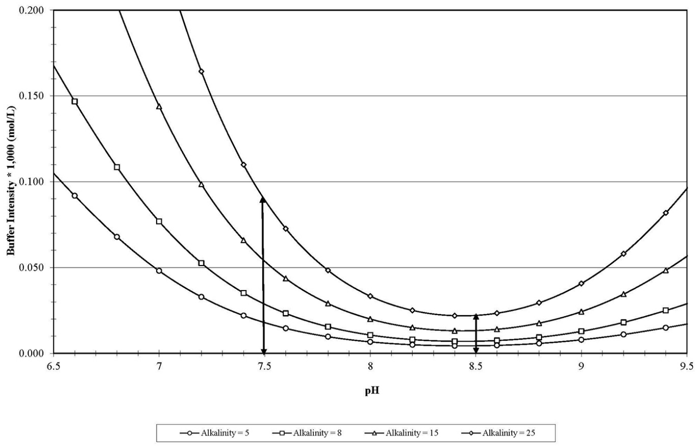


Figure 11
Affects of pH and Alkalinity on Buffer Intensity
Temperature = 25°C

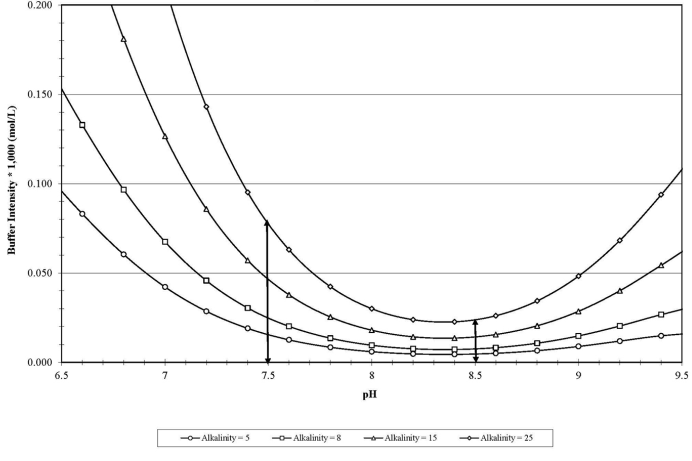


Figure 12
WTP2 SDS-THM Results: pH Effects

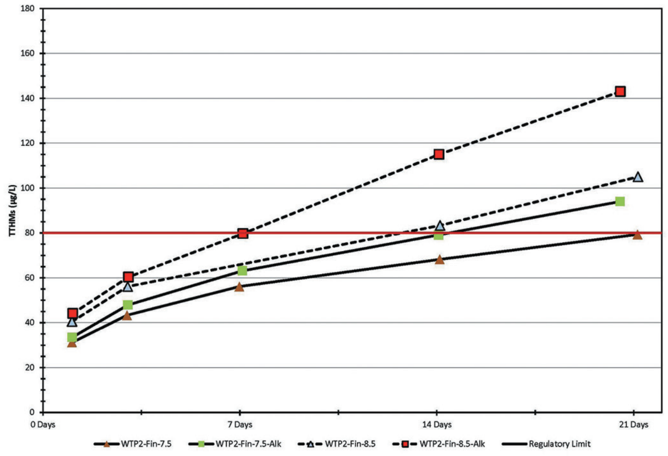


Figure 13
WTP1 SDS-THM Results: pH Effects

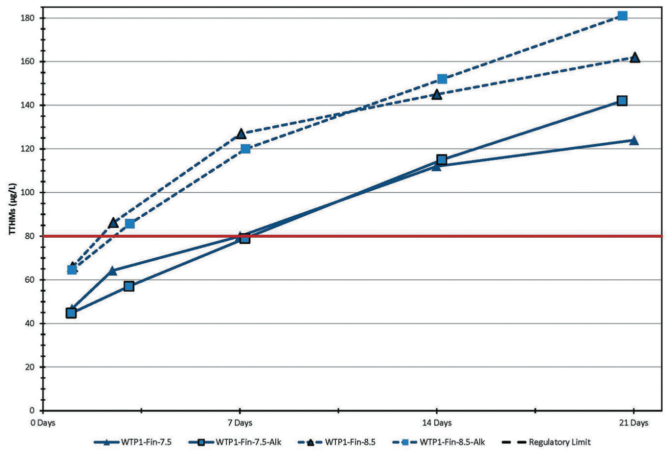


Figure 14
Well and Blended SDS-THM Results: pH Effects

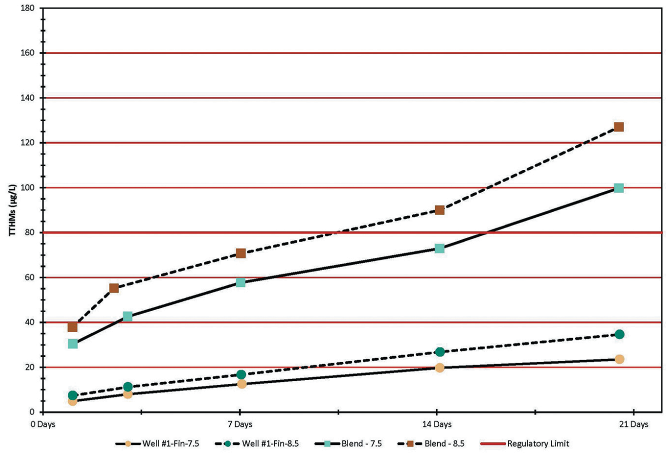
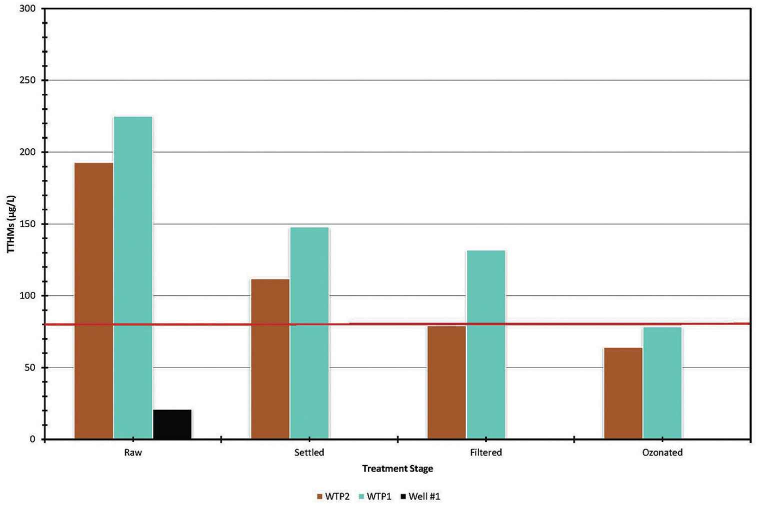


Figure 15
7-Day THMFP Results



Due to the pH and alkalinity results from the initial round of SDS sampling, a second round of SDS sampling was completed on October 14, 2015 (Round #2). Raw water samples from WTP1 and WTP2 were collected for bromide testing, raw water from Well #1 was collected for THMFP and source water blending SDS testing, filter effluent from WTP1 and WTP2 was collected for ozonation and SDS testing, and finished water was collected from each WTP for SDS testing. The blended SDS samples consisted of the following proportions of water from each source: WTP2 60%, WTP1 20%, and Well #1 20%.

The alkalinity of all Round #2 SDS samples (except Well #1) was adjusted using sodium bicarbonate to achieve a target alkalinity of approximately 25 mg/L (as $CaCO_3$). The pH of all SDS samples was adjusted using caustic and/or hydrochloric acid to achieve two target pH levels: 7.5 and 8.5. THMFP, blended SDS, and finished water SDS samples were prepared on site at each WTP and then transported to an office laboratory for storage and subsequent testing. All finished water parameters were unadjusted (chlorine, fluoride, phosphate) and matched whatever levels were produced at each WTP at the time of sampling. The measured chlorine residual at WTP1 and WTP2 at the time of Round #2 SDS sampling was 1.8 mg/L and 1.75 mg/L, respectively.

Filter effluent samples were transported to the University of Massachusetts Environmental Engineering Research Laboratory facility for bench scale ozone dosing and subsequent SDS sample preparation. The ozonated SDS samples did not include the addition of fluoride or phosphate. Chlorine was added to the ozone SDS samples to achieve a target chlorine residual of 1.75 mg/L for WTP2 filter effluent samples and 1.8 mg/L for WTP1 filter effluent samples, to match levels measured at the WTPs. All Round #2 SDS samples were stored and tested as previously described for Round #1.

Results and Discussion

Bromide levels from the two samples analyzed were reported to be non-detect. SDS-THM results for non-ozonated samples and two different pH levels (7.5 and 8.5) from WTP1, WTP2, and Well #1 are presented graphically in Figures 12, 13, and 14, respectively. A review of the information in these 3 figures clearly demonstrates that lower THM levels are achieved at a reaction pH of 7.5, compared to a reaction pH of 8.5. SDS-THM levels were 30% lower at pH 7.5 for WTP1 samples and 25% lower at pH 7.5 for WTP2 samples. At a reaction pH of 8.5, SDS-THM levels exceeded 80 μg/L after only 7 days of holding time for WTP2 samples and after only 1 day of holding time for WTP1 samples. In comparison, at a reaction pH of 7.5, SDS-THM levels exceeded 80 μg/L after 14 days of holding time for WTP2 samples and after 7 days of holding time for WTP1 samples. SDS-THM levels were also consistently higher in WTP1 samples compared to WTP2 samples,

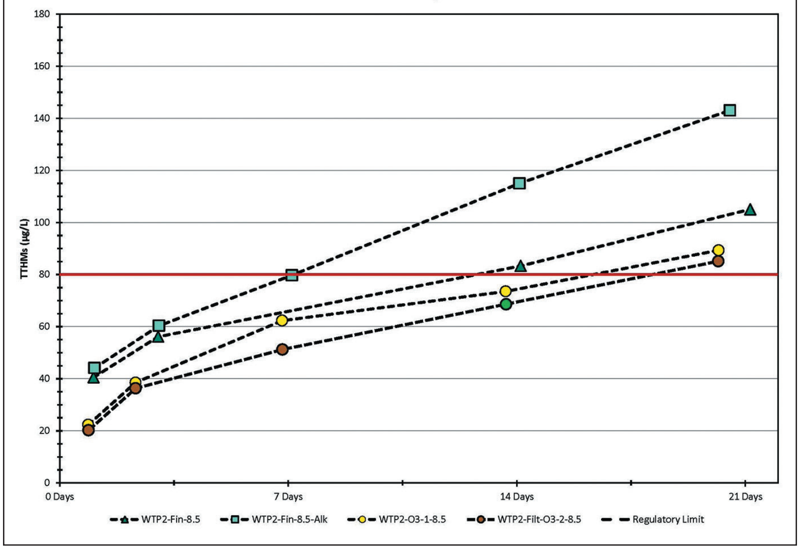


Figure 16
WTP2 SDS-THM Results: pH 8.5 and Ozone

similar to the trend of THMFP observations made previously. Well #1 SDS-THM results were all less than 40 µg/L, even after 21 days of reaction time. However, the blended water SDS samples exhibited similar THM levels and trends as the WTP2 finished water SDS samples.

Filter effluent samples were adjusted to a pH of 7.5 and ozonated at two dosages (1 mg/L and 2 mg/L) to examine the effects of ozone on reducing the formation of THMs. 7-Day THMFP results for raw water, settled water, filter effluent, and ozonated filter effluent from each WTP are presented graphically in Figure 15. A review of the information shown on Figure 15 suggests that the use of ozone reduced filter effluent THMFP levels by as much as 41% at WTP1 and 19% at WTP2. In addition, ozonated filter effluent 7-Day THMFP results were less than 80 µg/L at both WTPs, and lowest for WTP2 (64 µg/L).

SDS sample results of finished water and ozonated filter effluent from WTP2 at pH 8.5 and pH 7.5 are presented graphically in Figure 16 and Figure 17, respectively. SDS sample results of finished water and ozonated filter effluent from WTP1 at pH 8.5 and pH 7.5 are presented graphically in Figure 18 and Figure 19, respectively. A review and comparison of the information presented in these four figures indicates that at each WTP, ozonated filter effluent SDS-THM levels were always less than their paired non-ozonated SDS-THM levels. Ozonated WTP2 filter effluent SDS-THMs were 30% to 50% lower than non-ozonated SDS-THMs for both pH conditions. The effects of pH and ozone on WTP1 SDS-THM results were slightly different. Reductions in SDS-THM levels were greater at a pH of 7.5 compared to a reaction pH of 8.5. WTP1 filter effluent ozonated SDS-THMs were 40% to 60% lower than non-ozonated samples tested at a pH of 7.5 and 30% to 45% lower than non-ozonated samples tested at a pH of 8.5. The differences in SDS-THM levels between ozonated and non-ozonated samples were greater with increasing SDS reaction times.

A review of all the information presented in Figures 12 through 19 indicates that none of the SDS water treatment scenarios conducted at a reaction pH of 8.5 were able to achieve THM levels less than 80 µg/L at a SDS holding time of 21 days, with the exception of water from Well #1. However, there were several treatment scenarios conducted at a reaction pH of 7.5 which resulted in SDS-THM levels less than 80 µg/L, including:

- Water from the Well #1;
- One of the two WTP2 finished water samples (Round #1, unadjusted alkalinity);
- Both ozonated filter effluent samples from WTP2; and,
- The 2 mg/L ozonated filter effluent sample from WTP1.

Water Age and Blending

Utility A updated their hydraulic distribution system model and completed a revised water age study. The water age hydraulic analysis was

Figure 17
WTP2 SDS-THM Results: pH 7.5 and Ozone

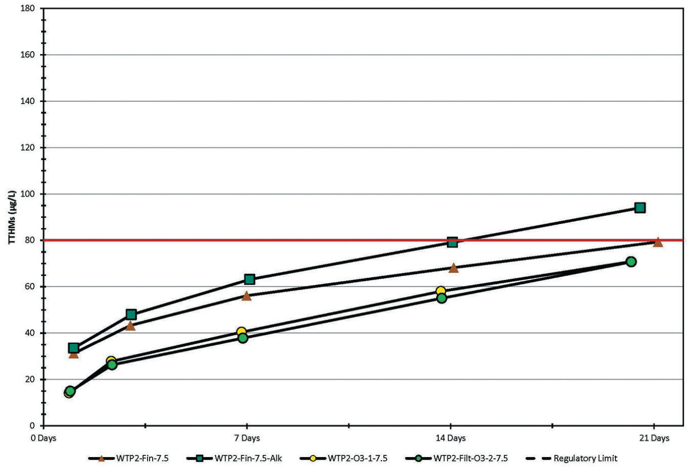


Figure 18
WTP1 SDS-THM Results: pH 8.5 and Ozone

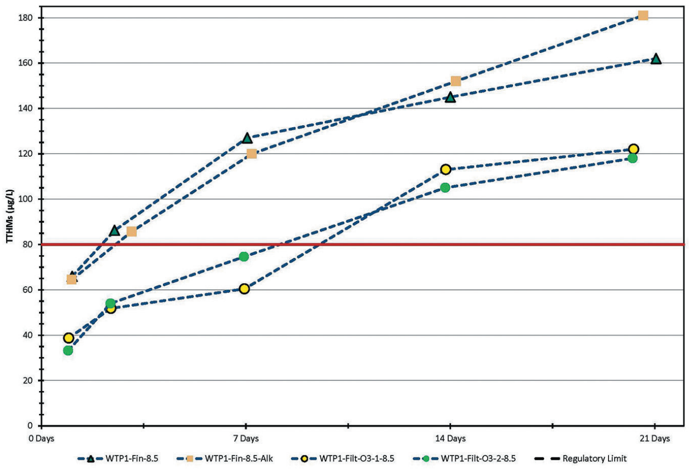


Figure 19
WTP1 SDS-THM Results: pH 7.5 and Ozone

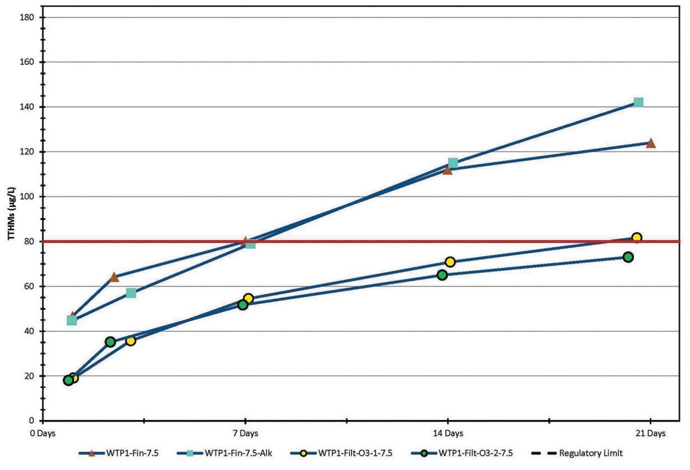


Table 5. Water Age Modeling Results (Days).

Stage II Sample Site	Pressure Zone	Existing System	Existing System with Well #1	New Tank C	Well #1 and New Tank C
Site 1	Tank A	24.2	24.1	24.3	24.2
Site 2	Low Service	0.9	1.0	0.9	0.9
Site 3	Low Service	1.4	2.4	1.6	1.9
Site 4	Low Service	1.9	2.1	2.3	2.1
Site 5	Low Service	4.3	4.3	6.1	6.1

completed under average day conditions and an extended period duration of 600 hours (25 days). The analysis considered the existing water system, the effects of pumping Well #1, the effects of the proposed new Tank C, and the effects of pumping Well #1 with the new Tank C. The average water age of each Stage II THM sampling site (Sites 1 through 5) for the above referenced conditions is presented in Table 5. A review of the information presented in Table 5 indicates that the water age at Site 1 is extreme, exceeding 24 days. The Stage II sample site with the second oldest water age is the Site 5, however a water age of 4 days is not considered excessive. An evaluation of the information presented in Table 5 also suggests that operating Well #1 and/or implementing the proposed new Tank C will have little impact on the water age of Utility A's Stage II sample sites, with the exception of Site 5. It appears that the proposed Tank C will increase the water age at Site 5 by approximately 2 days. In addition, it is anticipated that the average water age of other locations in the low service zone, downstream of Tank C and the WTPs, will increase since the existing tank does not move, and therefore does not currently contribute to the age of the water in the low service pressure zone. However, once a new tank is installed and operated properly off of the hydraulic grade line, the hydraulic detention time of the tank will add to the overall age of the water down stream of the tank.

A review and evaluation of the water age information provided in Table 5 and the SDS-THM information presented in Figures 12 and 13 is meaningful. It is important to consider again the effects of pH on SDS-THMs in light of calculated State II sample site water ages. At a reaction pH of 8.5, SDS-THM levels exceeded 80 μg/L after 7 days for WTP2 samples and after only 1 day for WTP1 samples. In comparison, at a reaction pH of 7.5, SDS-THM levels exceeded 80 μg/L after 14 days for WTP2 samples and after 7 days of WTP1 samples. Given the water ages presented in Table 5 and the SDS-THM results presented in Figures 12 and 13, it is anticipated that Utility A should be able to comply with the LRAA THM limits at all Stage II sites (except Site 1) by simply adjusting the POE target pH to 7.5, and maintaining this pH in the distribution system.

As previously discussed, there does not appear to be any obvious water main looping opportunities to reduce the water age of Utility A's current Stage II DBP sample sites. In addition, although distribution system flushing and the use of bleeders have been shown to reduce water age and distribution system THMs in other water systems, the examination of the impacts of water main looping and system flushing on water age was not modeled as part of this study, and therefore a definitive assessment of the impacts of looping and distribution system flushing was not completed. However, as stated previously, since THMs increase with increasing reaction times, any reduction in water age should result in lower distribution system THM levels.

In addition to water age, Utility A also completed hydraulic modeling runs to estimate the ratio of source water from each of Utility A's supplies at each Stage II sample site. These source water tracing modeling analyses were completed under average day conditions and for an extended duration of 48 hours. The source water tracing model scenarios evaluated the existing water system, the effects of pumping Well #1, the effects of the proposed new Tank C, and the effects of pumping Well #1 with the new Tank C. The average ratios of each source associated with Utility A's Stage II THM sampling sites for the above referenced conditions are presented in Table 6. A review of the information presented in Table 6 indicates that Site 1 and Site 4 consist of water predominately from WTP2 and that water from Site 2 and Site 3 is predominantly associated with water from WTP1. The information also

Table 6. Source Water Tracing Results for Stage II Sites.

Stage II Sample Sites	Existing System			Existing System with Well #1			New Tank C			Well #1 and New Tank C		
	WTP1	WTP2	Well #1	WTP1	WTP2	Well #1	WTP1	WTP2	Well #1	WTP1	WTP2	Well #1
Site 1	0%	100%	0%	0%	45%	54%	0%	100%	0%	0%	72%	28%
Site 2	100%	0%	0%	100%	0%	0%	100%	0%	0%	100%	0%	0%
Site 3	91%	9%	0%	89%	6%	5%	84%	16%	0%	88%	9%	3%
Site 4	0%	100%	0%	0%	42%	57%	0%	88%	0%	0%	69%	26%
Site 5	24%	76%	0%	18%	36%	45%	23%	76%	0%	16%	60%	23%

suggests that the proposed new Tank C would not significantly impact the source water ratios at Utility A's Stage II sites, but that operating Well #1 would significantly impact the blend of source water at Site 1, Site 4, and Site 5. When both the new Tank C and Well #1 are considered together, the change in source water blending ratios are not as significant at these three sites, but are still impacted. Under this scenario, water from Site 1, Site 4, and Site 5 would be between 23% and 28% composed of water from Well #1.

Distribution Treatment Options

Besides trying to adjust and optimize the 5 basic factors which contribute to the formation of THMs, an alternative approach for the reduction of distribution system THMs is to remove them after they have been formed. A distribution system THM removal technology which has been shown to be effective for the removal of THMs is aeration. There are three basic types of aeration that can be installed in water distribution storage tanks:

- Spray aeration
- Surface aeration
- Diffused bubble aeration

The removal of THMs by means of aeration is based on the application of Henry's Law. Each of the tank aeration options can be modeled using physical information about the tank and water quality, and then designed for target THM removals. There are several established tank aeration systems which have been in service for more than 5 years. Each system is designed individually for the tank where it is proposed to be installed. Performance can vary based on the design of the system; however documented typical THM removals have been reported between 40% and 90%. In addition, the amount of energy consumption can vary based on the type of system and the specific application.

Another distribution system alternative for aeration is horizontal in-line diffused aeration (HILDA). The application of HILDA for the reduction of distribution system THMs was investigated and developed at the University of New Hampshire (McCowan, M., 2015). Although successful pilot scale applications have been tested and documented, there have been no full system case studies completed. One potential benefit of HILDA is that it could provide THM reductions using aeration for sample sites that are not in proximity to a water storage tank.

Candidate or target sites for the application of tank aeration to reduce THMs require that the majority of the water obtained at the sample site originates at the target storage tank being treated. In addition, based on Henry's Law Constants, chlorinated THMs are more readily removed by aeration then brominated species. Therefore, ideal candidate sites for in-tank aeration for THM removal should be dominated by chloroform, and not bromoform. A review of the individual THM speciation results from all THMFP and SDS-THM samples completed in this study indicates that the composition of THMs generated from water samples obtained from WTP1 and WTP2 are between 70% and 90% chloroform. In contrast, the percentage of chloroform associated with the THMs generated from samples of water from Well #1 is between 15% and 30% chloroform.

Utility A Stage II sample sites that have water ages in excess of 5 days, obtain their water from WTP1, and are located downstream of a storage tank (the sample site obtained water from the subject tank) could benefit from in-tank aeration. Based on water age (refer to Table 5) and reported Stage II THM sample results (refer to Figure 1) Site 1 would likely benefit from in-tank aeration at Tank A. Supplemental modeling results of the Utility A system indicate that approximately 90% of the water at Site 1 is fed from Tank A. Therefore,

Table 7. Qualitative Impacts on Distribution System THM Levels.

	Site 1	Site 2	Site 3	Site 4	Site 5
1. **Lower the Target POE pH to 7.5 at both WTPs (includes alkalinity adjustment)**	Expected 25% reduction	Expected 30% reduction	Expected 25% reduction	Expected 25% reduction	Expected 25% reduction
2. **Implement Ozone at WTP1**	No change	Expected 30% reduction	Expected 30% reduction	No change	Expected 10% reduction
3. **Optimize Coagulation for NOM Removal at WTP1**	No change	Potential 5% reduction	Potential 5% reduction	No change	Potential reduction
4. **Implement Ozone at WTP2**	Expected 15% reduction	No change	No change	Expected 15% reduction	Potential 10% reduction
5. **Operating the Well #1 (Source Blending)**	No significant change	No change	No change	No significant change	No significant change
6. **Distribution System Tank Aeration (indicate target water storage tank)**	Expected 50% reduction (Tank A)	Not considered	Not considered	Not considered	Expected 25% reduction (New Tank C)
7. **New Tank C (Water Age)**	No significant change	No significant change	No significant change	No significant change	Marginal potential increase

implementation of a tank mixing system in Tank A could result in a 25% to 80% reduction in THM levels at Site 1, depending on the system design and operation. In addition, based on water age information (Table 5) and source tracing information (Table 6), it is highly anticipated that Site 5 could also benefit from in-tank aeration in the proposed new Tank C.

Summary of Alternatives

After reviewing the results and findings of this study, and considering the work completed by others (both previously and concurrently with this study), the following alternatives were identified for Utility A to consider for the control and reduction of distribution system THMs:

1. Lower the target POE pH to 7.5 at both WTPs. However, for this strategy to be fully effective, distribution system pH levels need to be stabilized. Therefore, this alternative includes the installation of alkalinity adjustment at both WTPs to achieve a target POE alkalinity of 25 mg/L as $CaCO_3$.
2. Install intermediate ozone at WTP1.
3. Optimize coagulation at WTP1 for NOM removal.
4. Install intermediate ozone at WTP2.
5. Operate Well #1 to achieve source water blending.
6. Install in-tank aeration. At a minimum, target Tank A and the proposed new Tank C.

A summary of the potential quantitative changes to distribution system THMs for Utility A's Stage II sample sites for the six alternatives developed in this study is presented in Table 7. Table 7 also includes the potential impacts of the proposed new Tank C on distribution system THM levels at Utility A's Stage II sites. A review of the information provided in Table 7 suggests that lowering the target POE pH level to 7.5 will have the greatest overall impact on distribution system THM levels. Not only will this alternative help to reduce THM levels at Utility A's Stage II sites, THM levels are anticipated to be reduced in the entire distribution system. In addition, supplementing the finished water alkalinity will increase the buffer intensity and help to stabilize water quality for the entire water system. A stable distribution system pH of 7.5 will benefit overall water quality in several ways, including: optimizing the control of tap water lead and copper levels using phosphate; helping to control the potential for distribution system regrowth; creating a more effective condition for secondary disinfection with chlorine, thus potentially enhancing compliance with the Total Coliform Rule (TCR); and, creating an environment for more stable distribution system water quality which

Table 8. Estimate of Probable Capital Costs.

Alternative	Capital Cost Estimate
1. **Lower the Target POE pH to 7.5 at both WTPs (includes alkalinity adjustment)**	WTP 2: $1,525,000 WTP 1: $65,000
2. **Implement Ozone at WTP1**	$2,525,000
3. **Optimize Coagulation for NOM Removal at WTP1**	$3,800,000[1]
4. **Implement Ozone at WTP2**	$5,000,000
5. **Operate Well #1 (source blending)**	$190,000
6. **Distribution System Tank Aeration (per tank)**	$350,000

[1] *Represents cost estimate for DAF upgrade at WTP1.*

could reduce episodes of aesthetically displeasing water and customer complaints resulting from legacy manganese and changes in oxidation reduction potential (ORP).

The use of ozone at one or more WTP facilities showed a consistent benefit for reducing THM levels, and would be effective for that portion of the distribution system served by the water supply source being ozonated. Although Well #1 exhibited very low THM levels, even up to 21 days of reaction time, once the water is blended with the other sources, the effectiveness achieved by dilution diminishes based on the overall blending ratio achieved. Other regulatory and water quality impacts associated with changing the status of Well #1 from emergency to active were not considered herein, but should be identified if this alternative is implemented. Distribution system tank aeration has a high potential for lowering distribution system THM levels at target sites. However, in order to achieve reductions in THM levels, the target sites must be supplied by water from the tank being treated. Based on an analysis of water age alone, the effect of the proposed new Tank C on Utility A Stage II sample sites should be minimal, with the exception of the Site 5. Without in-tank aeration at the proposed new Tank C, THM levels at Site 5 could increase due to water age.

Estimates of probable capital costs for each THM reduction and control alternative were

Table 9. Capital Cost Components.

Alternative	Included in Capital Cost Estimate
1. **Lower the Target POE pH to 7.5 at both WTPs (includes alkalinity adjustment)**	Site work including restoration; yard piping; sodium bicarbonate silo; chemical feed, mixing, and handling equipment; process piping; instrumentation & SCADA; electrical; contingencies; engineering.
2. **Implement Ozone at WTP1**	Site work including restoration; yard piping; building addition; contactor; liquid oxygen system; ozone generation and feed systems; process piping; instrumentation & SCADA; electrical; contingencies; engineering.
3. **Optimize Coagulation for NOM Removal at WTP1**	Cost estimate prepared by others for the proposed DAF upgrade to WTP1. Includes DAF and new chemical feed systems.
4. **Implement Ozone at WTP2**	Site work including restoration; yard piping; building addition; contactor; liquid oxygen system; ozone generation and feed systems; process piping; instrumentation & SCADA; electrical; contingencies; engineering.
5. **Operating the Well #1 (source blending)**	Miscellaneous building improvements; chlorine feed, storage, and handling system; caustic feed, storage, and handling system; process piping; instrumentation & SCADA; electrical; contingencies; engineering.
6. **Distribution System Tank Aeration (per tank)**	Miscellaneous site work; tank modification and restoration; aeration system equipment; process piping; instrumentation & SCADA; electrical; contingencies; engineering.

prepared, and are presented in Table 8. Based on the maturity level of the project definitions, these cost estimates should be considered to be between Class 5 and Class 4 (AACE Classification System), and have an expected accuracy between -25% and +50%. Site work, equipment, and construction costs were based on recent project bids, equipment quotes, and engineering judgment. Based on the preliminary planning level of these alternatives, capital costs include contingencies in the amount of 25% and engineering in the amount of 25%. The preparation of a capital cost estimate for the proposed new Tank C is considered outside the scope of this study.

A description of the cost components included in the estimate of capital costs for each alternative is presented in Table 9.

Conclusions and Recommendations

After reviewing the results and findings of this study, several conclusions and recommendations are made as summarized below:

Conclusions

1. The water from Reservoir 1 and Reservoir 2 is typical of high quality surface water supplies in New England: low turbidity; low alkalinity; low levels of NOM; trace levels of iron and manganese; and, susceptible to episodes of algae blooms or other general phytoplankton phenomena.
2. WTP2 achieves lower levels of treated/finished NOM that is less reactive with chlorine resulting in lower levels of THMs, compared to the treated/finished water from WTP1.
3. Utility A is planning to retrofit WTP1 with DAF clarification. The implementation of DAF, which is a high rate and robust clarification process, should allow WTP1 to increase applied coagulant dosages, improve the removal of NOM, and reduce the production of THMs in the distribution system.
4. Distribution system pH levels are not stable. The current target POE pH of 8.5 for both WTPs is not optimal for the use of phosphate for corrosion control. In addition, a target POE pH of 8.5 represents the worst case condition for buffer intensity. Based on pH and alkalinity levels, the buffer intensity of Utility A's finished water is extremely low and likely the cause of unstable distribution system pH levels, which could also contribute to episodes of discolored water.
5. Lowering the target POE pH from 8.5 to 7.5 will result in lower levels of distribution system THMs. SDS-THM levels were 30% lower at pH 7.5 for WTP1 samples and 25% lower at pH 7.5 for WTP2 samples, compared with SDS-THM levels reported for with a reaction pH of 8.5.
6. At a reaction pH of 7.5, SDS-THMs from WTP2 were greater than 80 μg/L after 14 days of holding time and after 7 days of holding time for WTP1.
7. Based on water age information presented in Table 5 and SDS-THM results presented in Figures 12 and 13, it is anticipated that Utility A should be able to comply with the LRAA THM limits at all Stage II sites (except Site 1) by simply adjusting the POE target pH to 7.5, and maintaining this pH in the distribution system.
8. A target POE pH of 7.5 is optimal for corrosion control programs that utilize phosphate inhibitors.
9. The use of ozone significantly reduced measured THMFP levels and SDS-THM levels.
10. The application of ozone reduced filter effluent THMFP levels by as much as 41% at WTP1 and 19% at WTP2.
11. Ozonated WTP 2 filter effluent SDS-THMs were 30% to 50% lower than non-ozonated SDS-THMs for both pH conditions evaluated. For the WTP 1 filter effluent ozonated SDS samples, THMs were 40% to 60% lower than non-ozonated samples evaluated at a pH of 7.5 and 30% to 45% lower than non-ozonated samples evaluated at a pH of 8.5.
12. SDS-THM levels for ozonated samples were incrementally lower for the higher ozone dose (2 mg/L).
13. Well #1 SDS-THM results were all less than 40 μg/L, even after 21 days of reaction time.
14. None of the SDS water treatment scenarios conducted at a reaction pH of 8.5 achieved THM levels less than 80 μg/L at a SDS holding time of 21 days (except the Well #1 sample).
15. There were several treatment scenarios conducted at a reaction pH of 7.5 and a SDS reaction time of 21 days which achieved SDS-THM levels less than 80 μg/L, including:
    - Water from Well #1;
    - One of the two WTP2 finished water samples (Round #1, unadjusted alkalinity);

  - Both ozonated filter effluent samples from WTP2; and,
  - The 2 mg/L ozonated filter effluent sample from WTP1.

16. With the exception of Site 1, all of Utility A's Stage II sample sites have estimated average water ages of 6 days or less (including the scenario with the proposed new Tank C). The estimated water age of the Site 1 site is excessive, greater than 24 days.
17. The application of water main looping and distribution system flushing on water age are best evaluated using Utility A's distribution system hydraulic model.
18. Site 1 and Site 4 consist of water predominately from WTP2. Water at Site 2 and Site 3 is predominantly from WTP1. Water from Site 5 is reported to be approximately 75% from WTP2 and 25% from WTP1.
19. The implementation of in-tank aeration to Tank A would likely significantly reduce THM levels at Site 1. In addition, the implementation of in-tank aeration at the proposed new Tank C would likely lower THM levels at Site 5.
20. Considering the THMFP and SDS-THM results collectively with the information provided in Tables 5 and 6 suggests that the following factors are likely affecting compliance with the DDBR at Utility A's Stage II samplings Sites:
    - Site 1 – Water age and distribution system pH
    - Site 2 – Water from WTP1 and distribution system pH
    - Site 3 – Currently in compliance
    - Site 4 – Distribution system pH
    - Site 5 – Water age and water from WTP1

Recommendations

In consideration of the results presented herein, including water quality, water age, source water blending, and the complexities of the Utility A supply and distribution system, the following recommendations are made:

1. Adopt a new target POE pH level of 7.5 and adjust the finished water alkalinity to approximately 25 mg/L (as $CaCO_3$). This will result in lower distribution system pH levels and improve overall water quality including corrosion control. It is unclear if lowering the target POE pH to 7.5 will result in adequately stable distribution system water quality, however by simply adjusting the target pH from 8.5 to 7.5 the buffer intensity of the finished water will be 4 to 6 times greater than the existing buffer intensity.
2. Implement in-tank aeration at Tank A. This should result in significant reductions of THM levels at Site 1. Based on the potential long lead time for implementing recommendation #1, the installation of in-tank aeration at Tank A should be undertaken as soon as possible.
3. Depending on the implementation schedule for the proposed new Tank C with respect to recommendation #1, the need for in-tank aeration at this site may or may not be required. However, in-take aeration at this tank will likely result in lower THM levels at Site 5.
4. Activation of Well #1 to create source water blending to lower THM levels at Utility A's Stage II sites does not appear to be a viable option.
5. Increasing the coagulant dose at WTP1 would result in greater removals of NOM, which would likely contribute to lower distribution system THM levels. An examination of the maximum practical and achievable coagulant dose for the existing WTP1 should be undertaken to investigate if coagulant dosages can be increased either year round or seasonally. In addition, the treated water pH after coagulant addition should be adjusted as necessary to optimize NOM removal. For most aluminum based coagulants, a reaction pH of 6.2 works best for NOM removal in warm water and a reaction pH of 6.8 is recommended under cold water conditions (Edzwald, J.K. and Kaminski, G.S., 2009).
6. It is clear that if ozone is implemented at either WTP then distribution system THM levels will be reduced. However, what is not confidently apparent is the need for ozonation at this time. The impacts of lowering the target POE pH to 7.5, optimizing NOM removal at WTP1, and installing in-tank aeration may be enough for Utility A to achieve compliance with the DDBR and achieve LRAA THM levels less than 80 µg/L. It can however be confidently stated that the implementation of ozone treatment at Utility A's WTPs will result in distribution system LRAA THM levels less than 80 µg/L.

Strategic Implementation Plan

In consideration of the conclusions and recommendations and after discussions with Utility

A, the following strategic implementation plan was developed:

1. Lower the target POE pH to 7.5 at both WTPs. This should be done gradually in increments over the course of 4 to 6 weeks to minimize potential disruptions in water quality. As discussed above, this target POE pH will result in more stable water quality due to increased buffer intensity, will lower distribution system THMs, and result in optimal conditions for tap water corrosion control with the use of a phosphate corrosion inhibitor.
2. During and after lowering the target POE pH continue to monitor distribution system pH levels at routine coliform bacteria monitoring sites. The pH data at each site should be graphed and statistically analyzed for a 3 month period before and after the pH change. Review the information and make a determination if alkalinity adjustment is warranted. If POE alkalinity adjustment is required and recommended to maintain stable distribution system pH levels, then seek funding for alkalinity adjustment systems at each WTP and implement the design, permitting, procurement, and construction.
3. Optimize coagulation conditions at WTP1 as soon as possible. This includes coagulant dose and pH. Begin monitoring UV-254 (raw, clarified, filtered) at WTP1 at least once a day (every 4 hours is recommended). Establish a target filtered water UV-254 level and adjust the coagulant dose and pH to maintain the target level. Typical target filtered UV-254 levels for the control of THMs is in the range of 0.030 and 0.045 (1/cm).
4. Seek funding for the design, permitting, procurement, and construction of an active aeration system for the Tank A. This task should be implemented as soon as possible.
5. Continue to monitor Stage II distribution system THMs. Once the distribution system pH has been lowered, WTP1 coagulation is optimized, and the Tank A aeration system has been installed, review THM sampling data for one year. If LRAA THMs are still above the MCL, then review specific site details to determine if aeration at the proposed Tank C is a viable alternative. If not, begin making plans to implement ozone at one or both WTPs.

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