A Model to Identify Future Treatment Needs to Minimize Disinfection Byproduct Formation

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As the largest community-owned utility in Florida, JEA provides water and energy services to nearly 500,000 customers in the greater Jacksonville area. Currently, JEA operates 38 water treatment plants (WTPs), distributing about 120 mil gal per day (mgd) of drinking water to two major grids—North Grid and South Grid—and smaller subgrids.

The Main Street WTP is JEA's largest, located in the heart of downtown Jacksonville. This WTP currently provides 20 mgd average daily flow with a build-out production capacity of approximately 30 mgd. Although the Main Street WTP is located in the North Grid (north of the St. Johns River), it predominantly provides water supply to JEA's South Grid (south of the St. Johns River) through major transmission pipelines underneath the St. Johns River. The current water transfers from the Main Street WTP are, and will be, key to serving future water needs as the South Grid expands to serve new development areas; however, management of water age and control of disinfection byproduct (DBP) formation will be critical for expanding water service in the South Grid.

The Main Street WTP provides treatment of a groundwater supply from 10 Lower Floridan aquifer wells, with an average sulfide concentration of 1.9 mg/L. The existing Main Street WTP includes a two-step sulfide removal process consisting of ozone oxidation followed by cascade tray aeration on top of a ground storage tank (GST). Water from the Main Street WTP is not chlorinated onsite because of potential concerns with DBP formation, specifically total trihalomethanes (TTHMs). Select WTPs in the South Grid receive unchlorinated Main Street water, referred to here as treated water, which is blended with the local groundwater supply prior to disinfection and distribution to customers.

Transmission of treated water from the North Grid to the South Grid occurs via major transmission lines from a project referred to as the total water management plan (TWMP). A planned southside integrated piping system (SIPS) will also convey the water treated by the Main Street WTP to multiple South Grid WTPs, expanding the existing TWMP network. Finished water age (treated water from the Main Street WTP that has been blended with South Grid groundwater, then treated and chlorinated) is measured starting from the point of chlorination at the South Grid WTPs.

Figure 1 presents JEA's current distribution system in the South Grid.

It's anticipated that the Main Street WTP will require additional refurbishment and expansion within the next 10 years. Ahead of plans to expand the Main Street WTP,

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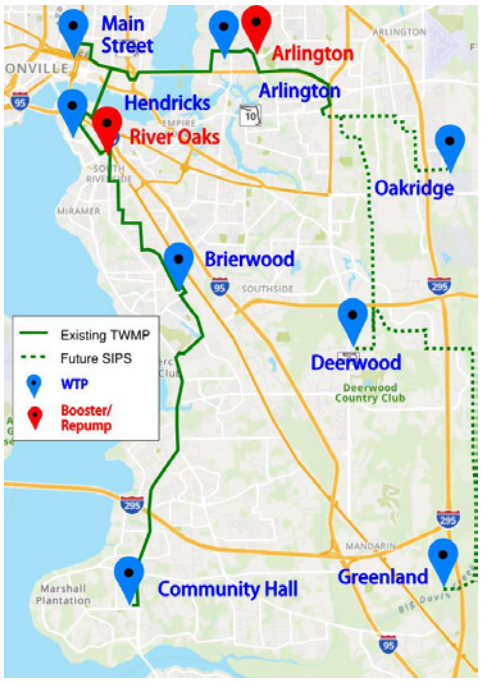

Figure 1. The JEA water distribution system map showing the Main Street Water Treatment Plant and related water treatment plants in the South Grid. This is adapted from the southside integrated piping system, Task Order S1 – Activity 8: Hydraulic Model Piping Confirmation. (Jacobs, 2020)

Table 1. Finished Water Quality Goals for the Main Street Water Treatment Plant

Category	Parameter	Regulatory Standard	Water Quality Goal
DBP	Trihalomethanes (TTHMs)	< 80 µg/L	< 48 µg/L
	Haloacetic Acids (HAA5)	< 60 µg/L	< 48 µg/L
	Bromate	< 10 µg/L	< 8 µg/L
Biological Regrowth	Assimilable Organic Carbon (AOC)	N/A	Low enough to avoid adverse taste/odor events
	Cellular Adenosine triphosphate (cATP)	N/A	
	Dissolved Oxygen (DO)	N/A	High enough to avoid biologically generated odors in treated water within TWMP/SIPS pipelines
Aesthetics	Sulfide	< 0.3 mg/L	< 0.1 mg/L
	Sulfate	< 250 mg/L	< 150 mg/L
	Total Dissolved Solids (TDS)	< 500 mg/L	< 350 mg/L
	Turbidity	< 2 NTU increase above raw groundwater with chlorination of sulfide	
	Odor	< 3 TON	< 2 TON
	Alkalinity	-	100-200 mg/L as $CaCO_3$
	Calcium Hardness	-	Maintain calcium at a level, such that CCPP>0; prefer CCPP between 4 to 10 mg/L as $CaCO_3$

CCPP: calcium carbonate precipitation potential; $CaCO_3$: calcium carbonate; TON: threshold odor number

JEA contracted with CDM Smith to provide services for a water quality characterization and treatment alternatives study. The purpose of this effort was to evaluate available treatment alternatives (including those in the existing treatment train) while considering JEA's water quality goals, and to recommend a suitable treatment train for the upcoming Main Street WTP refurbishment and expansion project.

This article presents a water quality model that assisted JEA in predicting TTHM formation in the distribution system using collected water quality data and finished water quality goals.

Water Quality Goals

The Main Street WTP finished water quality goals developed for this project are presented in Table 1. Both CDM Smith and JEA discussed how the maximum contaminant level (MCL) for TTHMs may be reduced by future actions of the U.S. Environmental Protection Agency (EPA). Although the regulatory outlook is uncertain, the 48-µg/L TTHM goal is based on 80 percent of a potential future MCL of 60 µg/L.

Water Quality at the Main Street Water Treatment Plant

To establish existing water quality characteristics for the Main Street WTP, water quality data were collected for the 10 raw water wells serving the Main Street WTP in May and June 2021. The water quality data are summarized in Table 2.

A review of data in Table 2 indicates that the water supply wells feeding the Main Street WTP are slightly alkaline (i.e., pH>7), with moderate to high total dissolved solids (TDS), ranging from 244 to 411 mg/L. The raw water contains "significant" levels of hydrogen sulfide, as defined in the Florida Department of Environmental Protection (FDEP) Chapter 62-555.315, ranging from 1.25 to 2.10 mg/L, with an average concentration of 1.90 mg/L.

A hydrogen sulfide concentration of 2 mg/L was used as the design basis for this study. The water is characterized by low bromide concentrations when compared with other JEA water supplies in the South Grid and moderate levels of total organic carbon (TOC). The relatively consistent TOC and sulfide concentration in the Main Street WTP well field simplifies operations because the plant does not have to make major process adjustments to account for changing feed water quality.

Due to hydrogen sulfide levels in the Main Street WTP's raw water supply—and its location in the heart of downtown Jacksonville—the WTP uses ozone followed by cascade tray aeration to remove hydrogen sulfide. Before making additional investments in the existing treatment system, the process trains needed to be evaluated to meet treatment goals, including sulfide removal and distribution system water quality maintenance. Downstream, water quality drivers for this project included controlling

Continued on page 16

Table 2. Summary of Water Quality Results by Main Street Well (2021)

Parameter	Units	Well 1	Well 3	Well 4	Well 6A*	Well 7	Well 10	Well 12	Well 13*	Well 14*	Well 15*
Parameters Measured in Field											
Turbidity	NTU	0.55	0.21	0.15	0.19	1.18	---	0.53	0.66	0.45	0.64
pH	S.U.	7.60	7.65	7.76	7.75	8.01	7.62	7.67	7.79	7.75	7.88
Sulfide	mg/L	1.25	1.90	1.80	1.93	2.00	2.05	1.80	2.10	1.95	1.58
Parameters Measured by Laboratory											
Alkalinity	mg/L as $CaCO_3$	157	140	137	151	154	157	139	157	156	155
TDS	mg/L	296	384	411	261	306	283	297	249	270	244
Chloride	mg/L	16.2	14.6	13.9	28.8	17.9	16.8	16.0	20.2	25.4	38.8
Sulfate	mg/L	77.9	145.0	162.0	88.2	85.4	79.4	157.0	77.3	82.9	75.6
TDS	mg/L	296	384	411	261	306	283	297	249	270	244
Bromide	µg/L	64	59	60	66	74	65	61	82	100	71
TOC	mg/L	2.1	1.4	1.4	2.1	2.0	2.2	1.5	2.3	2.2	2.2

NTU: nephelometric turbidity unit; TDS: total dissolved solids; TOC: total organic carbon; $CaCo_3$: calcium carbonate; S.U.: standard units
*Value presented is an average value from two sampling events

Table 3. Blended Water Quality Design Basis and Flow by the Water Treatment Plant (2040)

WTP	Flow (mgd)[1]		Water Quality[3]		Water Quality - Blended		TWMP/SIPs Treated Water Age (hours)[4]
	Wellfield	Main Street	Br (µg/L)	TOC (mg/L)	Br (µg/L)	TOC (mg/L)	
Main Street	-	24.8[2]	75	0.54 (2.15[5])	-	-	-
Arlington	2.0	2.0	280	1.65	178	1.90	0.5
Oak Ridge	5.7	4.5	370	1.7	240	1.19	4.4
Deerwood	7.0	12.0	420	1.6	202	0.93	3
Greenland	4.5	6.7	120	1.3	93	0.84	14

[1] Projections from "Evaluation of Potential Impacts of Southside Integrated Piping System on South Grid Disinfection Byproduct Formation and Water Quality" (Jacobs 2020).
[2] Flow through East River Crossing. Main Street WTP may receive water from Fairfax WTP and McDuff WTP before crossing the river. Concentrations of TOC and bromide were higher at the Main Street WTP alone; therefore, data presented in the table, blending without Fairfax/McDuff, present a conservative approach.
[3] Based on data collected May and June 2021.
[4] Refers to the estimated time it takes for treated water to travel from the Main Street WTP high-service pump station to a specified WTP. This is different from the water age at DBP compliance sample points in the distribution system.
[5] Main Street WTP wellfield TOC is 2.15 mg/L and would be lowered to 0.54 mg/L after 75 percent TOC removal through treatment.

Table 4. General Finished Water Quality Results by Water Treatment Plant (May 2021 Sampling Event)1

Parameter	Units	Main Street	Oakridge	Deerwood III	Arlington[2]
Temperature	°C	27.3	22.0	23.3	25.5
Dissolved Oxygen (DO)	mg/L	7.45	6.88	7.30	7.06
pH	S.U.	7.94	9.42	8.28	8.72
Alkalinity	mg/L as $CaCO_3$	154	151	127	140
TDS	mg/L	311	537	657	460

[1] Samples were 100 percent local water supply and were collected downstream of aeration (to remove sulfide) and upstream of chlorination, unless otherwise noted.
[2] Represents a blend of TWMP and local wellfield supply (it's not possible to collect 100 percent local water supply downstream of sulfide removal).

Continued from page 15
corrosion, along with the main focus of this study, which is maintaining biostability and limiting TTHM formation.

Water Quality Changes With Southside Integrated Piping System

When the SIPS pipeline network is completed and more Main Street treated water is blended with groundwater from South Grid WTPs, finished water quality in the South Grid will change. The SIPS pipeline network is expected to be fully operational by 2040. Understanding the 2040 blended water quality will help JEA implement strategies to limit TTHM formation, improve biostability, and maintain the chlorine residual despite long finished water ages in parts of the South Grid.

Table 3 shows the anticipated blended water quality and water age at each WTP, using water quality data collected during 2021 sampling and modeling results provided in "Evaluation of Potential Impacts of Southside Integrated Piping System on South Grid Disinfection Byproduct Formation and Water Quality Memorandum" (Jacobs 2020). These blending ratios may change as JEA finalizes the SIPS plan.

Modeling results suggest that the longest water age is at the Greenland WTP; treated water age will be as high as 14 hours from the time water leaves the Main Street WTP to the Greenland WTP. Note that this is different from the compliance sampling point in the distribution system, where water age at Greenland WTP may reach 48 hours to the farthest customer in 2040. This long water age is a driver for focusing on treatment to limit TTHM formation.

Table 5. Main Street Water Quality Data Before and After Cascade Tray Aeration (May 2021)

Parameter	Units	Post-Ozone (before aeration)	GST Effluent (after aeration)
Hydrogen Sulfide	mg/L	0.57	< 0.05
cATP	pg/mL	19	80
ORP	mV	-79	-28
DO	mg/L	18.8	7.5

cATP: cellular adenosine triphosphate; ORP: oxidation-reduction potential

Table 6. cATP Concentrations (pg/mL) in the Total Water Management Plan Network

Sample Location	May 2021	July 2021
Main Street WTP[1]	80	19
Arlington WTP[2]	0.1	0.6
Arlington Booster Pump Station[3]	-	0.5

[1] Collected from Main Street GST.
[2] Represents blend of approximately 30 percent TWMP water and 70 percent local wellfield supply (both unchlorinated).
[3] TWMP water from Main Street WTP.

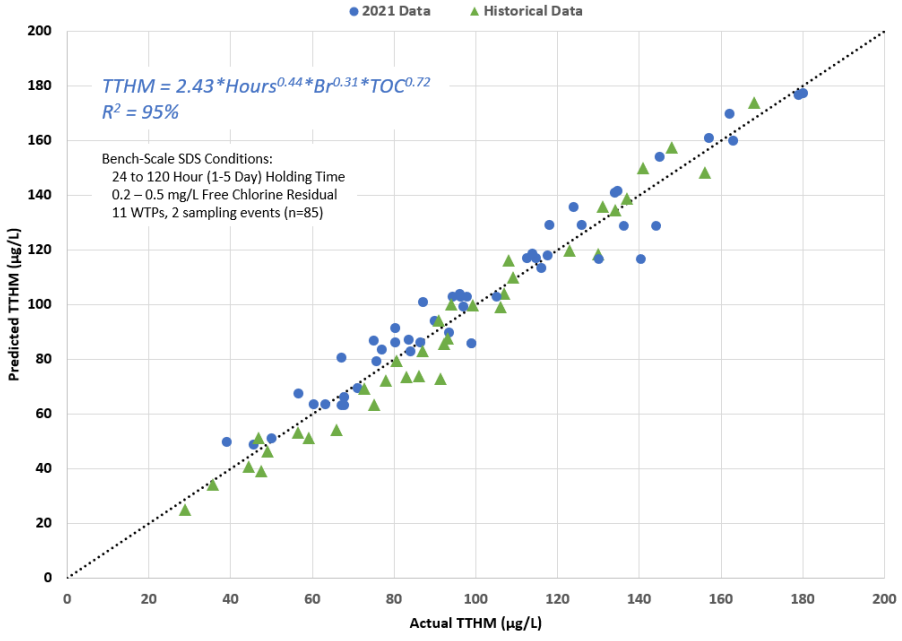

Figure 2. Bromide, total organic carbon, and water age model that predicts total trihalomethane formation.

Distribution System Water Quality

Additional sampling was performed in the South Grid to classify distribution system water quality. Table 4 summarizes general water quality parameters at each sampling location. Water samples from each WTP were also tested for TTHM formation potential through simulated distribution system (SDS) tests, per the American Water Works Association *Standard Methods for the Examination of Water and Wastewater*, 5710C.

Temperature, pH, and alkalinity were consistent across the sample locations, which is typical for water from the Lower Floridan aquifer. Water treatment plants in the South Grid have higher levels of TDS compared with the Main Street WTP.

Biological Stability

The first major downstream water quality driver evaluated was maintaining biostability in the system. Water quality data presented in Table 5 show the effect of cascade tray aeration on sulfide removal and biological activity. Water collected in May 2021 just downstream of the ozone system had detectable concentrations of sulfide and an observed odor, while still meeting the design concentration for sulfide at 0.6 mg/L. Sulfide was not detected in water from the Main Street GST, showing effective sulfide removal through the cascade tray aerator.

Adenosine triphosphate (ATP) monitoring provides a same-day indication of biological activity by detecting ambient adenosine triphosphate, which is a bioenergy molecule present in all living organisms. The term cellular adenosine triphosphate (cATP) refers to cell-bound ATP, calculated by a procedure subtracting free ATP from a

total ATP measurement. Data for cATP, also a bioenergy molecule present in all living organisms, suggested that biological activity increases through aeration in the presence of sulfur reducing bacteria.

After analyzing data from the first sampling event in May 2021, it was deduced that biological activity did not appear to increase through TWMP; however, during the May sampling event, it was not possible to collect 100 percent of the Main Street-treated water in the TWMP network. The project team worked with JEA to determine the proper sampling location to obtain unchlorinated TWMP samples, and sampled again in July. During the July sampling event, the buried chlorine injection vault at the Arlington Booster Pump Station became accessible, and 100 percent Main Street-treated water samples were collected prior to the chlorine injection vault, resulting in unchlorinated TWMP data.

The July 2021 sampling event indicated low biological activity (cATP) in the Main Street GST that did not increase through TWMP, as shown in Table 6. One notable difference for this event was the lack of a noticeable odor at the Main Street GST, suggesting complete oxidation of sulfide by ozone. Since the biological activity did not increase after the Main Street WTP in the TWMP water, continuous chlorination at the Main Street WTP does not appear necessary. Additionally, it was inferred that oxygen uptake in TWMP may be occurring at a high enough rate that, with the longer water age in SIPS, the addition of direct dissolved oxygen (DO) might be advisable to prevent anaerobic conditions that could lead to taste and odor issues.

The DO uptake from treated water in TWMP may be an indicator of respiration-associated biological activity. Also, DO could be consumed when unlined iron pipe corrodes in contact with water. In future phases of design, it will be important to review the pipe materials in TWMP to assess the condition of ductile iron pipe and determine if any unlined pipe is present that could be oxidized, thus consuming DO. Full oxidation and removal of sulfide were recommended at the Main Street WTP to eliminate sulfide and mitigate the potential for growth of sulfur oxidizing bacteria (*Thiothrix* and *Beggiotoa*) in TWMP.

Disinfection Byproducts

In addition to biological stability, DBPs are a concern in the distribution system where DBP precursors (i.e., TOC and bromide) and residual chlorine are present. When organic matter reacts with residual chlorine, DBPs can form. Based on initial sampling efforts, it was determined that there are low bromide concentrations and moderate TOC concentrations in the Main Street WTP well water that could contribute to DBP formation; therefore, it's important to remove TOC in order to meet water quality goals at the Main Street WTP and in the distribution system. The design team developed a predictive model to determine the TOC removal required to maintain DBPs less than 48 µ/L using fixed water age and bromide concentrations based on anticipated blending ratios.

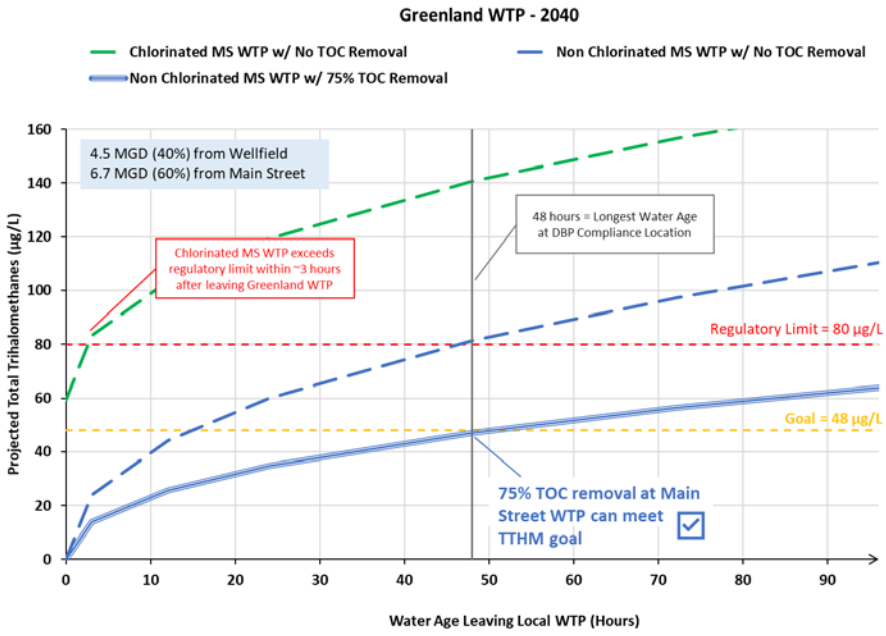

Figure 3. Total trihalomethane formation at Greenland WTP in 2040 with and without total organic carbon removal treatment at the Main Street Water Treatment Plant.

Developing a Disinfection Byproduct Model

Sampling and modeling efforts helped predict the formation of DBPs in the distribution system with and without chlorination and TOC removal at the Main Street WTP. Bromide, TOC, and SDS data from both this study and historical data were combined to develop an equation to predict TTHMs, as shown in Figure 2. With an R2 of 95 percent, the model appears useful for predicting TTHMs within 10 to 20 µg/L, based on TOC, bromide, and finished water age (after chlorination).

Using this model, TTHMs were predicted at different water ages, leaving South Grid WTPs for chlorinated and unchlorinated Main Street water with various levels of TOC removal in 2040. Water ages were based on DBP compliance sample points in JEA's distribution system, as documented in "Evaluation of Potential Impacts of Southside Integrated Piping System on South Grid Disinfection Byproduct Formation and Water Quality" (Jacobs 2020), and updated water age modeling data were provided via JEA.

Modeling results for the Greenland WTP are discussed because this WTP is the farthest away from the Main Street WTP (treated water age of approximately 14 hours) and is expected to receive 60 percent of its water, or 6.7 mgd, from the SIPS network in 2040. It represents the worst-case scenario compared to all the South Grid WTPs. If the goals can be achieved at the Greenland WTP, the other WTPs will be able to meet the water quality goals. Moreover, the DBP compliance location served by the Greenland WTP has the longest predicted finished water age of 48 hours in 2040.

At the Greenland WTP, chlorinated Main Street WTP water without TOC removal is projected to exceed the TTHM regulatory limit of 80 µg/L just three hours after leaving the WTP, as seen in Figure 3; however, provision of 75 percent TOC removal at Main Street, with blending and chlorination at Greenland WTP, is highly effective in mitigating TTHM formation, with TTHMs expected to remain below the goal until about 48 hours.

The TTHMs for Greenland WTP finished water for 2040 were also projected with different blending ratios of unchlorinated water from the Main Street WTP. The purpose

Continued on page 18

Continued from page 17

of this analysis was to assess if TTHMs could be effectively controlled without TOC removal, but rather by a simple adjustment in the blending ratio of Main Street water and groundwater at South Grid WTPs. Figures 4 and 5 show that a change in blending ratio is insufficient to bring TTHMs below the goal of a finished water age of 48 hours, and TOC removal is necessary. When 75 percent TOC removal is obtained through additional treatment at the Main Street WTP, projected TTHMs remain below the water quality goal of 48 µg/L at a finished water age for up to about 48 hours at the planned blend: 60 percent Main Street, and 40 percent Greenland.

Treatment Recommendation

After biological stability analysis and DBP modeling, it was concluded that continuous chlorination at the Main Street WTP is not recommended because it will increase TTHM formation, and sampling indicated biologically stable conditions within TWMP; however, a periodic chlorine maintenance dose may be needed to control treated water biogrowth in the pipeline. It was also concluded that finished water age is a critical factor in controlling TTHM formation. Changing the blend of South Grid and Main Street water appears insufficient to meet the TTHM goal; instead, it's recommended that supplemental treatment be implemented through TOC removal at the Main Street WTP. After evaluating costs and water quality performance, granular activated carbon (GAC) to remove TOC is recommended. The complete recommended treatment train at the Main Street WTP is ozone (for sulfide oxidation) and GAC followed by existing cascade tray aeration.

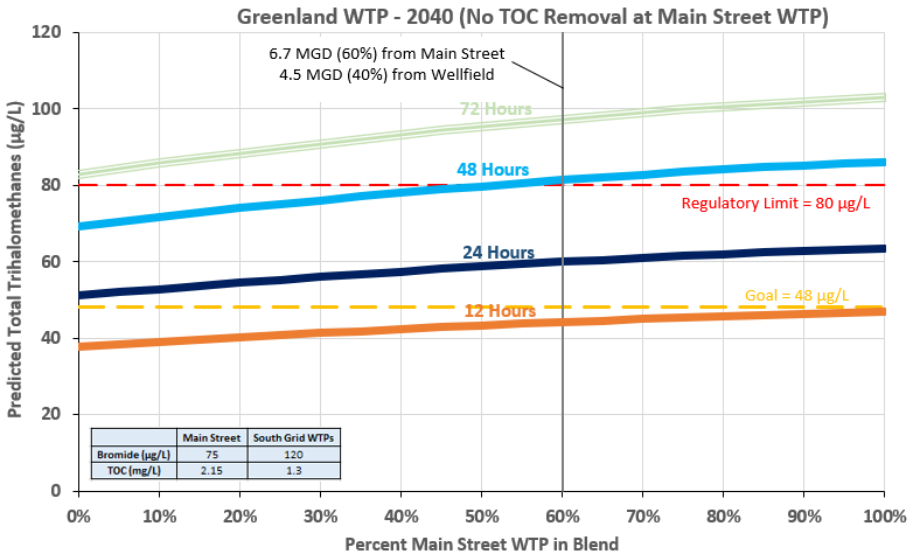

Figure 4. Total trihalomethane formation at the Greenland Water Treatment Plant in 2040 without total organic carbon removal at the Main Street Water Treatment Plant.

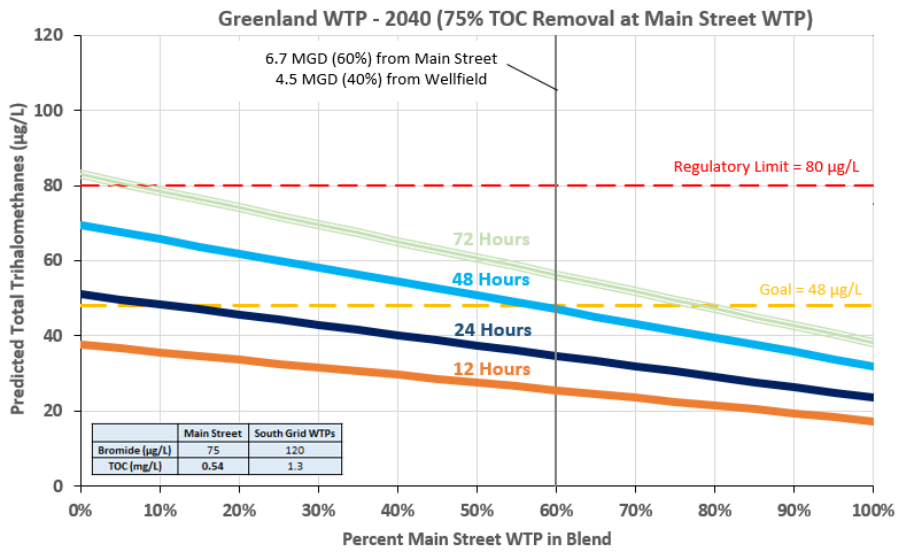

Figure 5. Total trihalomethane formation at the Greenland Water Treatment Plant in 2040 with total organic carbon removal at the Main Street Water Treatment Plant.

Conclusions and Recommendations

For this study, CDM Smith evaluated existing water quality at the Main Street WTP and the distribution system conditions. To recommend a treatment train that will meet future water quality goals, a TTHM formation model was developed, accounting for TOC, bromide, and water age, in JEA's water distribution system. Using the model, TTHM formation was assessed at the Main Street WTP and WTPs in the South Grid that receive (or will receive) water from TWMP and SIPS. Based on this model, it appears that 75 percent TOC removal at the Main Street WTP would be required to meet JEA's TTHM goal of 48 µg/L at the DBP compliance monitoring locations. To achieve this level of treatment, ozonation, followed by GAC and cascade tray aeration, are recommended at the Main Street WTP.

While this study is useful as a planning tool, additional bench- or pilot-scale testing is recommended during the design phase to verify the approach. The TTHM model could be validated in design through additional simulated distribution system testing with lower TOC water. Pilot testing of GAC is also recommended to determine TOC removal from biological activity, the optimal GAC media type, and how biostability changes after ozone and GAC treatment. Ozone pilot testing will be used to identify the optimum ozone dose and contact time to provide sulfide oxidation prior to GAC, without forming unacceptable levels of bromate, a regulated DBP.

This project demonstrates how municipalities can leverage water quality and SDS results to develop predictive models, which can then be used to determine treatment options to meet current and future DBP limits.