Innovative and Cost-Effective Ways to Improve Water Quality Using Distribution System Models

Kelcia Mazana and Migdalia Hernandez

Water distribution systems throughout Florida are facing distribution water quality challenges caused by aging infrastructure, over-design of distribution piping, conversion from free chlorine to weaker distribution disinfectants, and changing source supplies. Water quality challenges, including loss of residual, bacterial growth, disinfectant byproduct formation, tuberculation, sediment buildup, and internal corrosion often result in discolored, turbid, and unpleasantly tasting and smelling water at the customer tap. Given the current economic atmosphere and more stringent distribution rules, such as the Stage 2 Disinfectant/Disinfection Byproducts Rule (D/DBPR), effective in 2012, utilities are using numerous techniques to minimize cost while maintaining water quality compliance. Several innovative ways to maintain water quality compliance using a water quality model are discussed.

Reiss Engineering Inc. worked with the City of Sanford (City) to utilize a water quality model for investigating a range of operation and maintenance (O&M) and treatment improvements that could be used in its potable water system. The O&M improvements considered included adjustments to system operations, targeted flushing programs, and selected areas for pipe rehabilitation. Water quality modeling results supported the City's foresight to actively obtain funding for both the O&M and treatment improvements simultaneously. The City has implemented several system operation improvements, including elevated tank design and operation modification, which has reduced the local water age by over 70 percent. In addition, a systematic flushing program was refined, which realized water and chemical savings of over $35,000 per year (19.2 mil gal per year).

To further improve distribution system water quality, strategic areas were selected, using a water quality model, for pipe rehabilitation projects that were initiated in 2010. With the success of the O&M efforts, the City is now evaluating treatment options for its auxiliary water treatment plant (WTP). Using field data incorporated into a water quality model, water quality improvements throughout the distribution system are predicted. Enhancing O&M and treatment throughout the potable water distribution system provides the City with improved water quality and financial benefits.

Distribution System Overview

The City currently has two water treatment plants that treat groundwater and serve over 60,000 customers. Figure 1 shows the general layout of the distribution systems and the location of the WTPs, booster station, and elevated tanks. The WTP #1 (Main WTP) operates 24 hours per day and supplies the majority of the water to the distribution system. The WTP #2 (Auxiliary WTP) operates four to 12 hours per day, depending on system demand. The French Avenue Booster Station provides distribution water storage (Tank #1) and pumping capacity to boost pressures within the area. The Mellonville and Silver Lake elevated storage tanks (Tank #2 and Tank #3, respectively) supply storage water to the distribution system based on system pressure (floats on the system). Figure 1 also shows the Stage 1 and Stage 2 sampling locations evaluated during the Initial Distribution System Evaluation (IDSE) of the D/DBPR.

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Distribution System Water Quality Improvement Planning

Utilities throughout the United States are currently preparing for the Stage 2 D/DBPR, which tightens distribution system disinfection byproduct (DBP) concentrations and emphasizes specific location compliance. Stage 2 compliance was effective in April 2012 for large utilities (>100,000 population). Historically, the City maintained running annual averages for trihalomethane (THM) below the limits for all quarters from 2005 to 2007, as shown in Table 1. Haloacetic acid (HAA) treatment was not evaluated in detail because

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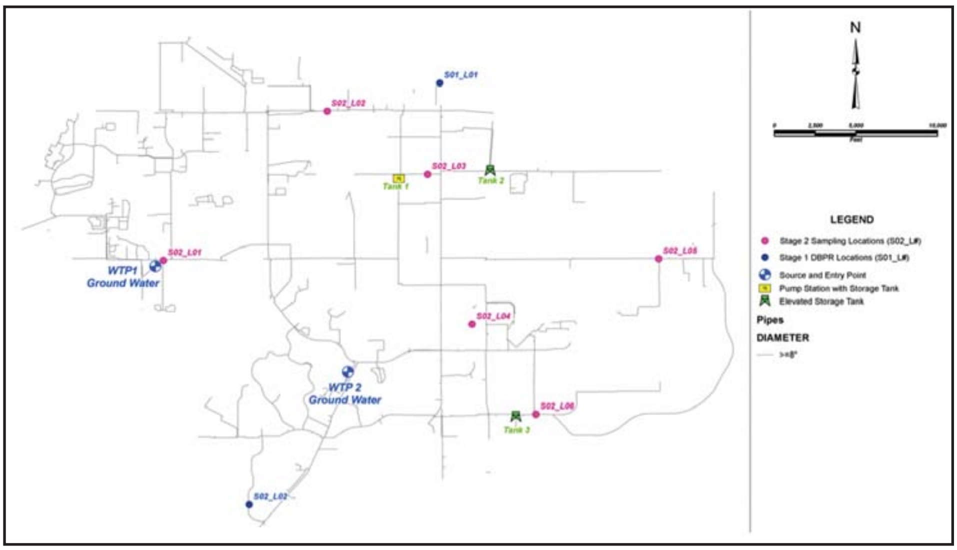

Figure 1. Distribution System Layout

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the City has found that controlling THM formation adequately controls HAA concentrations.

In preparation for Stage 2 compliance, the City performed THM sampling at the proposed Stage 2 sampling locations during the historical peak month (April). The THM sampling results revealed elevated THM concentrations in some areas of the distribution system (Figure 2). Based on this information, ways to reduce the THM formation throughout the distribution system using the City's distribution system water quality model were evaluated. As shown in Figure 2, THM concentrations increased significantly as water age exceeded three days. Therefore, to control DBP formation, the maximum water age goal was set at three days.

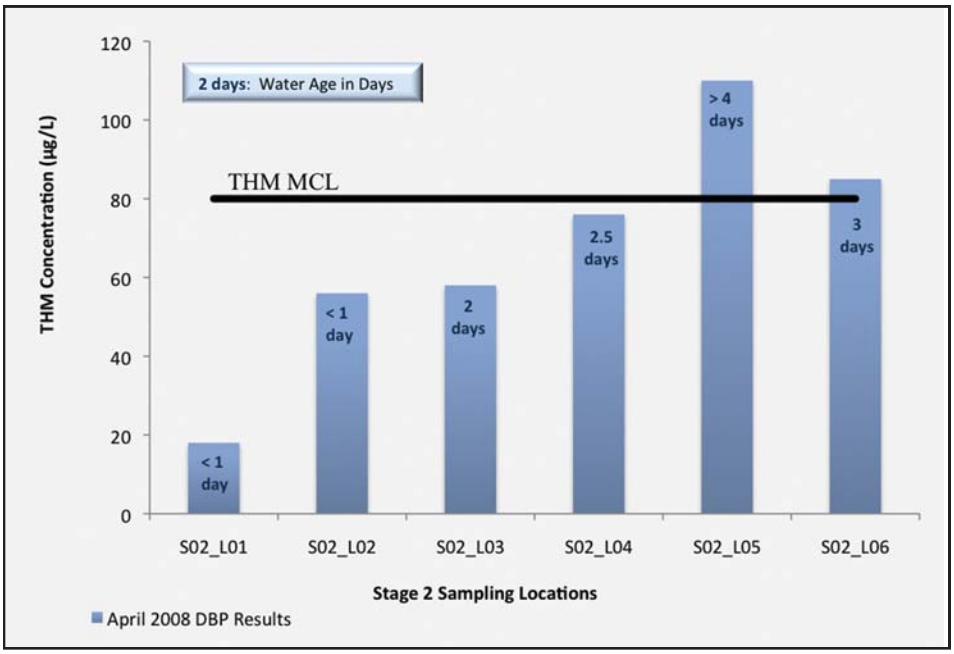
Table 1. THM Running Annual Average

Year	Quarter 1 (g/L)	Quarter 2 (g/L)	Quarter 3 (g/L)	Quarter 4 (g/L)
2005	40.8	41.4	42.9	39.2
2006	42.0	46.5	47.0	47.6
2007	48.1	49.4	53.1	58.8

Table 2. City of Sanford Water Service Criteria

Category	Criteria
Average Annual Daily Demand (AADD)	7.3 MGD
Maximum Daily Demand (MDD)	1.3 x AADD
Peak Hourly Demand (PHD)	2.5 x AADD
MDD plus Fire Flow Pressure*	> 20 psi
AADD, MDD and PHD Pressure	> 40 psi
Fire Flow*	600 gpm (residential) / 1250 gpm (commercial)
Maximum Water Age Goal	3 days
Maximum Pipe Velocity*	≤ 5 fps; ≤ 10 fps during fire events

*Based on city utility manual.



There are many ways to approach a reduction of DBP formation, including system water quality improvements through simple operational adjustments, infrastructure improvements, and physical and chemical treatment system improvements. Reiss worked with the City to utilize its model to determine the level and range of O&M and treatment improvements throughout the distribution system. To improve THM concentrations in the distribution system, several options were evaluated:

- Water age reduction
- Chlorination optimization
- Piping improvements
- Total Organic Carbon (TOC) removal from raw water

Water Age Reduction

As shown in Figure 2, water age has a direct correlation to the water quality in the distribution system. Water age reduction was evaluated in two components, including operations modifications (facility improvements and storage optimization) and flushing optimization, which are discussed in the subsections. Water age reduction was evaluated using the model, based on the criteria for the water system listed in Table 2.

Operations Modifications

The model was used to evaluate how various operation adjustments affect distribution system water age. The optimized operations provided improvement potential in the following areas:

- Stabilize point-of-entry (POE) pressures by installing variable speed pumps at the water treatment plants and the booster station. Installation of variable speed pumps ensures the management of POE pressures, reducing pressure spikes and the potential for main breaks in the system.
- Maximize tank turnover and provide a 75 percent decrease in the Mellonville elevated tank storage age by installing a variable speed pump on the bypass line (Figure 3). Bypass line use for the pump installation ensures that the elevated tank maintains the capability to float on the system when the pump is off.
- Improve water quality in the Silver Lake elevated storage tank area by increasing storage tank daily turnover.
- Optimize the pumping and filling times for each facility within the distribution system.

To ensure that the optimized operations

maintained fire flow storage, a typical 24-hour period simulation was evaluated. The simulation showed either improved or equivalent storage (Figure 4).

Automatic Flushing Optimization

The City's distribution system flushing plan consisted of two automated flushings at more than 20 manual locations, which are flushed in response to customer complaints. The automated flushing locations were operated weekly for approximately 15 minutes. Additional automated flushing locations were selected and strategically placed using the model. The maximum water age goal of three days was achieved with model-simulated flushing. However, the quantity of water needed to be flushed (>240 gpm) was too significant and impractical for water conservation. In addition, the significant water loss was not economically feasible for the City. As a compromise, the City elected to target a maximum water age goal of four days. With this adjustment, the quantity of flushing water was decreased and optimized to less than 60 gallons per minute (gpm) as predicted by the model.

The water age reduction realized by the implementation of the operations modification and the automatic flushing optimization provided a 7 percent reduction in THM formation at the longest detention time site (S02_L05).

Chlorination Optimization

The City uses sodium hypochlorite for disinfection of the finished water prior to distribution. The City is performing post-chlorination by dosing sodium hypochlorite to the water downstream of the ground storage tanks at the Main WTP and the Auxiliary WTP. The amount of sodium hypochlorite added to the finished water is based on flow. However, the dose is adjusted manually to reach a residual of 2.0 mg/L leaving the WTPs. Disinfection practices improvements are summarized.

- Install a chlorine residual analyzer with compound control loop to control the chlorine metering pumps and keep the chlorine residual at a specified residual set point, based on chlorine residual and the finished water flowrate. A controller (Plant PLC or independent chlorine pump controller) would receive the 4-20 mA signals from the flow meter and chlorine residual analyzer. The controller would first control the chlorine dose based on the flow rate (as currently practiced), then the controller would increase or decrease the dose based on the chlorine residual to reach the set point.
- Perform prechlorination by injecting sodium hypochlorite prior to aeration and the ground storage tank.

The City is not currently considering a switch to chloramines due to the age and condition of the piping in the distribution system.

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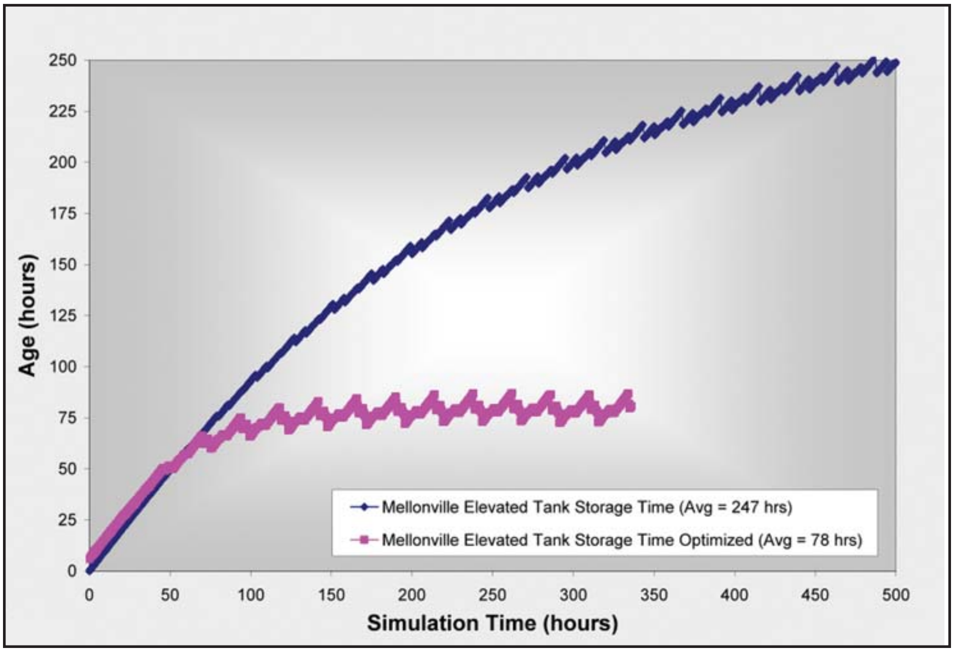

Figure 3. Mellonville Elevated Tank Storage Time Comparison

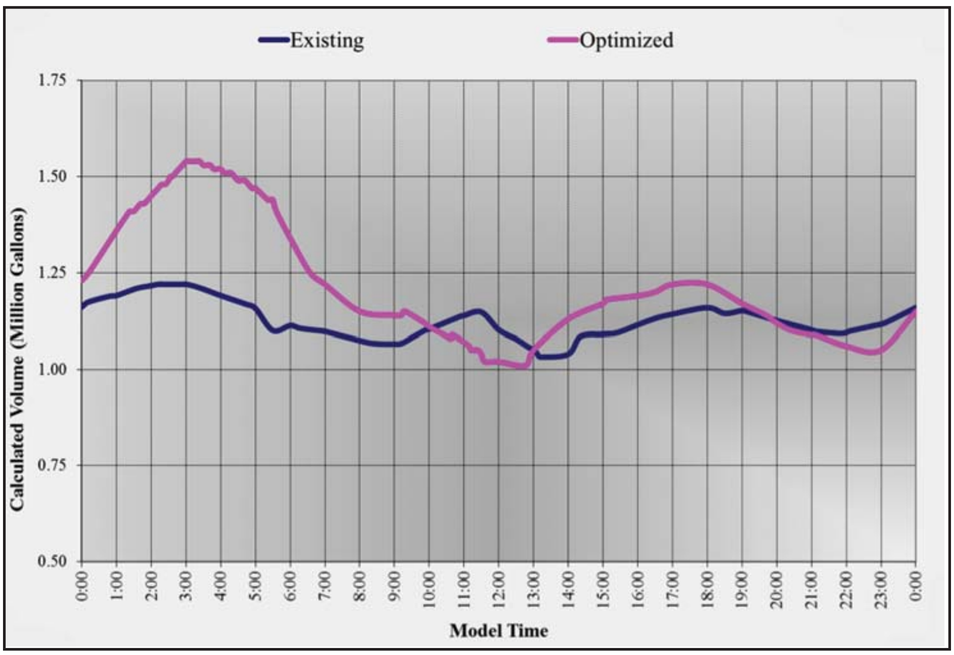

Figure 4. Optimized Operations Available Storage

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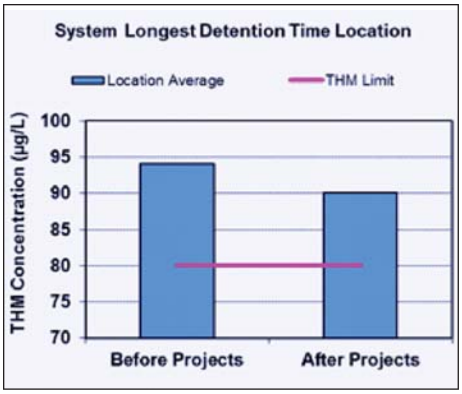
Piping Improvements

Using hydraulic modeling, the City identified several opportunities to improve water quality by replacing pipe. Modeling identified the following options:

- 38 pipe replacement projects
- Nine looping projects

Pipes were modeled to be replaced to match the existing sizes or have a maximum increase of two pipe diameters to avoid additional design cost.

In 2010, the City used American Recovery and Reinvestment Act (ARRA) grant funds to complete four pipe replacement projects and two looping projects (Figure 5), as well as make improvements to the Mellonville elevated tank variable speed pump. The model was used to evaluate the distribution system water quality improvements and conservation efforts based on the four completed pipe replacement projects. The piping improvements were evaluated based on water quality testing of chlorine residual and THM concentration, in addition to hydraulic modeling analysis. Though the local area of the piping improvement realized up to 80 percent improvement in water age, these improvements provided only a 5 percent decrease in DBP concentration at the location with the longest detention time site (S02_L05).



Although the four pipe replacement projects did not cause significant water quality changes in the distribution system, significant water loss savings resulted from the completed projects. Water savings also occurred in the City's flushing program since these completed projects were removed from the City's high-velocity, unidirectional flushing program, which is used to remove particulate buildup from piping throughout the distribution system.

Pipe Improvement Cost Savings

The annual water savings in gallons per year based on the four completed pipe replacement projects and improvements to the City's flushing program are summarized in Table 3. The water savings is approximately 19 mil gal per year, which is an annual monetary savings of about $35,000.

Though THM concentrations improved slightly, the operation modifications, flushing optimization, chlorination optimization, and piping improvements could not provide the reduction needed to comply with the pending Stage 2 regulations on a timely basis (before October 2013). Based on the improvements observed using the model and water quality testing, implementation of total organic carbon treatment is required to meet THM concentration at the longest detention time location.

Looping Project Location	Local Water Age Improvement
Project A – Loop 7	80 percent at the loop location
Project B – Loop 1	70 percent at the loop location

Figure 3. Mellonville Elevated Tank Storage Time Comparison

Table 3. Annual Cost Savings Summary

Item	Distribution System Water Saving	Annual Saving Estimates		Total
		Water	Chemical & Power	
	gallons/year	$/year	$/year	$/year
ARRA Pipe Replacement Project	15,550,000	$28,146	$531	$28,677
Flushing Program	3,630,000	$6,570	$124	$6,694
Total	19,180,000	$34,716	$655	**$35,371**

Note: Annual savings calculated using residential water rates of $1.81/Kgal and chemical and power rate of $0.0342/Kgal.

Total Organic Carbon Removal Evaluation

To effect improvements to meet Stage 2 requirements, the City moved forward with piloting granular activated carbon (GAC) for total organic carbon removal at the Auxiliary WTP. The GAC was evaluated to achieve the City's water quality goals through a pilot study conducted from January to March 2011. The GAC pilot data was used to (1) determine the feasibility of GAC for DBP reduction for the Auxiliary WTP source water supply, (2) establish preliminary design criteria, and (3) develop preliminary cost estimates. Model simulations were then used to evaluate the effectiveness of GAC treatment by predicting average THM concentrations after installation at the Auxiliary WTP.

The model calibration was verified to ensure that predictions were representative of the distribution system. The POE data, for the calibration verification, were obtained by collecting finished water chlorine residuals and THM concentrations at each water treatment plant. The data was used to determine decay and formation coefficients and were then input into the hydraulic model by means of a flow weighted average calculation. Initial THM concentrations were input into the hydraulic model to simulate concentrations throughout the distribution system. Chlorine residuals decay and THM bulk formation curves calculated for each of the City's water treatment plants are shown in Figure 6. Wall THM formation was assumed to be insignificant for this modeling effort. The simulated curves accurately represented field-collected THM concentrations.

Once these data were entered in the model, THMs were predicted at the future Stage 2 monitoring locations throughout the distribution system. Figure 7 shows the model-predicted THM concentration for the longest detention time site (S02_L05) after GAC treatment at the Auxiliary WTP. The model prediction was used to compare the effect of treating 2,000 bed volumes and 4,000 bed volumes prior to carbon replacement or reactivation. (The number of bed volumes is the amount of water that can be treated by the GAC unit before carbon replacement or reactivation is required.) A higher bed volume indicates lower carbon replacement or reactivation cost to the City.

The model scenarios were run for 600 hours to ensure that equilibrium was achieved. Based on the model output, equilibrium was achieved after approximately four days (100 hours). The model output data from hour 100 to hour 600 were interpreted as listed in Table 4. The model data indicates that GAC treatment at the Auxiliary WTP will reduce the THM formation throughout the distribution system. However, based on the existing operations, this 35 percent improve-

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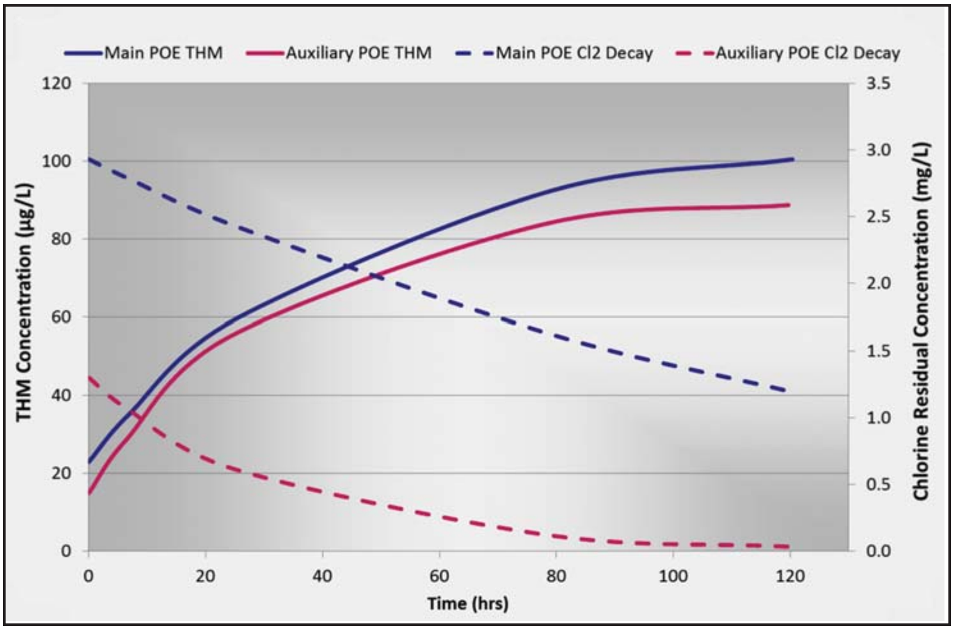

Figure 6. Average Main and Auxiliary Point-of-Entry THM

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ment in THM formation at the longest detention time site would be close to, or may exceed, the 80 µg/L THM regulated maximum limit.

Based on the model output, the City is considering additional means to reduce THM formation. Possible options include:

- Provide additional treatment via GAC by increasing the flow treated at the Auxiliary WTP.
- Provide GAC treatment at the Main WTP.
- Provide additional adjustment to the system operations at the Main WTP to minimize THM formation in the distribution system.

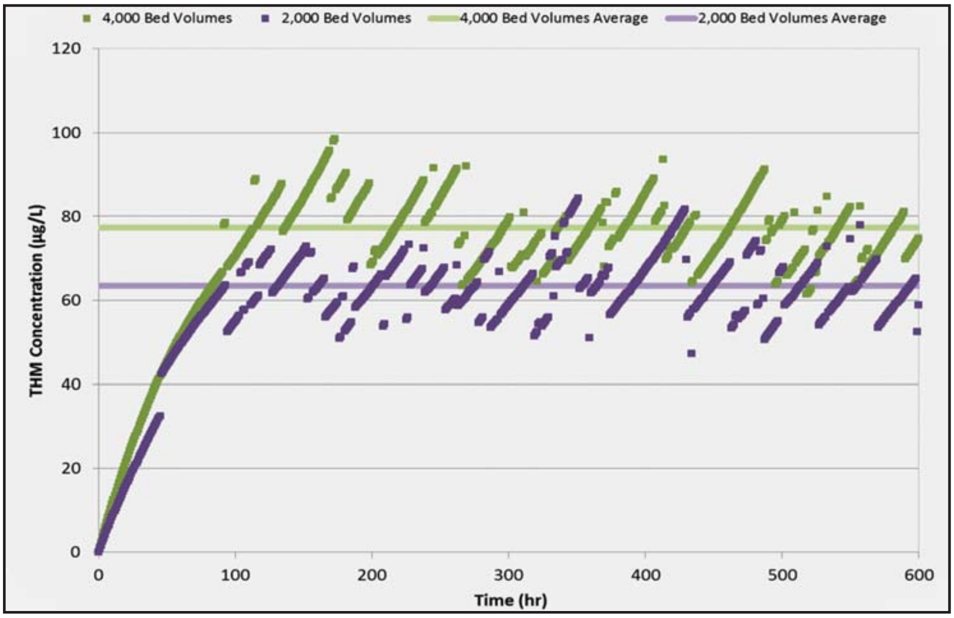

Figure 7. Longest Detention Time Site Summary

Table 4. Model Simulation Five-Day Water Age THM Formation Summary

Model THM Concentration	Unit	4,000 Bed Volumes	2,000 Bed Volumes
Average	µg/L	77	64
Minimum	µg/L	61	47
Maximum	µg/L	99	84

Future Work

The City is utilizing the model to evaluate operational and treatment alternatives for water quality improvement in the distribution system. Overall, the City has maximized the use of water quality modeling to achieve water age reduction, optimize chlorination practices, construct key piping improvements, and conduct TOC removal pilot testing. These efforts have realized a 35 percent reduction in THM formation at the longest detention time site. The City is currently evaluating additional treatment options to ensure that Stage 2 compliance is achieved. The additional evaluations include:

1. Pilot testing ozonation (Ozone) followed by GAC at the Auxiliary WTP to determine the feasibility of this treatment process to further control DBP formation and evaluate the cost-effectiveness. Ozone is being tested for both total sulfide removal and reduction in DBP formation. GAC is employed to reduce DBP formation potential below that which ozone alone can achieve.
2. Operating the GAC units in biological mode (BAC) after ozonation to reduce replacement and reactivation cost. Initial BAC pilot results are favorable and the ozonation-BAC treatment scheme is being piloted further.
3. Compare GAC, BAC, and nanofiltration treatment capital, operating, and life cycle cost on a conceptual basis to determine if nanofiltration treatment is more favorable for the City's needs.