CHLORAMINE REPLACEMENT ALTERNATIVE EVALUATION

Initial Findings Report

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PREPARED FOR

Hannibal Board of Public Works

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Abbreviations

ACT – accelerated column test

AMR – automated meter reading

ClO2 – chlorine dioxide

CT – contact time

DBP – disinfection byproduct

DNR – Department of Natural Resources

DOC – dissolved activated carbon

EPS – extended period simulation

GAC – granular activated carbon

GIS – geographic information system

gpm – gallons per minute

GWUDISW – groundwater under the direct influence of surface water

HAA5 - haloacetic acids

MCL – maximum containment levels

MDNR – Missouri Department of Natural Resources

MG – million gallon

mg/L – milligrams per liter

MGD – million gallons per day

nm – nanometers

PAC – powered activated carbon

PACI – polyaluminum chloride

RO – reverse osmosis

SCADA –Supervisory control and data acquisition

SDS – simulated distribution system

Stage 2 DBPR – Stage 2 Disinfection Byproduct Rule

TOC – total organic carbon

THM- trihalomethanes

TTHM – total trihalomethanes

ug/L – micrograms per liter

UV – ultraviolet

UVA – ultraviolet absorbance

UVDGM – UV Design Guidance Manual

WIMS – well information management system

WTP – water treatment plant

Executive Summary

The City of Hannibal, Missouri recently passed a referendum requiring that the application of chloramines at the City's surface water treatment plant (WTP) be discontinued within ninety days from the date of the referendum. The report summarizes findings from an initial screening of potential solutions to enable compliance with MCLs for TTHMs and HAA5s once the plant begins operating with free chlorine in place of chloramines. The initial screening consisted of a comprehensive review of the City's treatment alternatives, distribution system modifications, and potential source water alternatives.

The City may achieve their treatment objectives for TTHMs and HAA5s through alternative treatment solutions and modifications to the plant's current operations. In order to meet regulatory limits for DBPs, it is estimated than an additional 35 to 60 percent reduction of TOC (DBP precursor) would be required. Bench scale testing was conducted to evaluate treatment alternatives that can effectively reduce the amount of organic carbon and reduce the formation of TTHMs and HAA5s. Treatment alternatives considered under bench scale testing included enhanced coagulation, oxidation, adsorption and alternative treatment processes such as reverse osmosis, ion exchange resins and aeration. Treatment alternatives demonstrating high performance for either removal of DOC or reduction in DBP formation are being considered for further evaluation. The alternatives selected for further evaluation includes the use of alternative coagulant; ozone as either a pre-oxidant or intermediate oxidant; granular activated carbon (GAC) adsorption implemented as either a filter cap or post-filter GAC vessels; and stripping of TTHMs through aeration at strategic locations within the distribution system.

Analysis of the distribution system using a hydraulic model showed the average water age in the system is estimated to be less than 24 hours for a significant portion of the distribution system. However, within certain areas of the system, where several of the compliance points are located, the water age is greater than or equal to 5 days. An initial evaluation estimated the expected water age could be reduced by 1 to 2 days by removing the Clinic Road tank from service and by altering the operational controls between the high and low pressure zones. While reducing the water age in the distribution system will decrease overall DBP formation, treatment modifications would still be required at the water treatment plant for compliance with MCLs.

Because the option of alternative source water would require substantial capital investment, along with additional exploration to confirm acceptable water yields and water quality, it cannot be implemented in a timely or cost-effective manner. Therefore, alternative water supplies are not being considered at this time.

Additional bench scale and pilot testing will be conducted to identify and develop a long-term solution that meets regulatory requirements, while minimizing cost impacts to the consumers.

1.0 Introduction

The City of Hannibal, Missouri recently passed a referendum requiring the elimination of chloramine treatment at the City's surface water treatment plant (WTP). Chloramines have been in use since September 2015 based on the recommendation from a 2014 report (by Horner & Shifrin) titled Disinfection Byproducts Compliance Study. Chloramines were selected for controlling disinfection byproducts to meet regulatory compliance. The recently passed referendum however requires that the chloramine technology, specifically the addition of ammonia, be discontinued within ninety days from the date of the referendum.

Black & Veatch has been retained to identify a technical solution to eliminate chloramines while also maintaining compliance with the facility's regulatory requirements. Under the Environmental Protection Agency's Stage 2 Disinfection Byproduct Rule (Stage 2 DBPR), the City is required to maintain a local running annual average maximum containment level (MCL) below 80 µg/L for total trihalomethanes (TTHMs) and 60 µg/L for five regulated haloacetic acids (HAA5s) at each monitoring site. This Initial Findings Report evaluates solutions to comply with these regulations once the plant begins operating with free chlorine in place of chloramines.

1.1 OBJECTIVES

The objective of this report is to summarize findings from an initial screening of potential solutions that may enable compliance with MCLs for TTHMs and HAA5s once the plant has transitioned away from chloramines. To perform the initial screening, a comprehensive review of the City's potential source water alternatives, treatment alternatives, and distribution system modifications was conducted. The report includes the following evaluations:

- Evaluation of alternative coagulants, oxidants and treatment processes to reduce dissolved organic carbon (DOC) and disinfection byproduct (DBP) formation.
- Analysis of required free chlorine contact times to achieve disinfection compliance.
- Evaluation of alternative water supplies from nearby aquifers and surface waters.
- Analysis of distribution system modeling to reduce water age in the system.

The results of these evaluations will provide a basis for recommendations on viable alternatives to be investigated further. The ultimate goal is to identify and develop a long term solution that meets regulatory requirements, while minimizing cost impacts to the consumers.

1.2 TARGET TREATMENT OBJECTIVES

The treatment objective will be eighty percent of the maximum containment levels permitted for TTHMs and HAA5s, as indicated in Table 1-1.

Table 1-1. Hannibal WTP Treatment Objectives for Disinfection Byproducts

PARAMETER	TREATMENT OBJECTIVE (80 PERCENT OF MCL)	MAXIMUM CONTAMINANT LEVEL (MCL)
Total Trihalomethanes (TTHMs)	64 µg/L	80 µg/L
Five Regulated Haloacetic Acids (HAA5s)	48 µg/L	60 µg/L

2.0 Plant Site Assessment

Black & Veatch toured the Hannibal WTP on May 12, 2017 for the following purposes:

1) To verify current treatment strategy.
2) To obtain a better understanding of recent treatment optimization efforts.
3) To discuss treatment alternatives with plant staff and identify challenges associated with implementation.
4) To collect water samples for the purpose of bench-scale testing to screen various technologies that may reduce DBP levels.

2.1 EXISTING TREATMENT

Raw water is supplied to the treatment plant from the Mississippi River via an intake structure located north of downtown Hannibal. The raw water is treated with permanganate to address taste and odor causing compounds and periodically with an algaecide for algae control. Following chemical addition, the raw water enters a 3.5 million gallon (MG) pre-sedimentation basin. Powdered activated carbon (PAC) and polyaluminum chloride (PACl) coagulant are added in rapid mix chambers upstream of the primary flocculation and settling basin. Clarified water is then delivered to a secondary rapid mix, flocculation and sedimentation basin, where lime can be added for pH adjustment, if required. Additionally, operators have the ability to feed copper sulfate to the secondary basin as needed for algae control.

Sodium hypochlorite and fluoride are added in a splitter structure prior to the filter feed basins, which have a total volume of 0.7 MG. The City has the capability to feed filter-aid polymer at this location; however, filter-aid polymer is not being fed at this time. From the filter feed basins, pretreated water is conveyed through four multi-media filters consisting of anthracite and sand with a base gravel layer on top of clay tile underdrains. Under current operations, the target residual free chlorine across the filters is 0.5 mg/L. Filter effluent is pumped through ultraviolet (UV) disinfection reactors to an onsite 2.5 MG finished water reservoir. Prior to the reservoir chlorine is added to boost the chlorine residual and ammonia is added to form chloramines. Finished water from the reservoir is then conveyed either by gravity to the low pressure zone of the system, or through high service pumps to the high pressure zone of the distribution system.

The process flow diagram for the Hannibal WTP is presented in Figure 2-1.

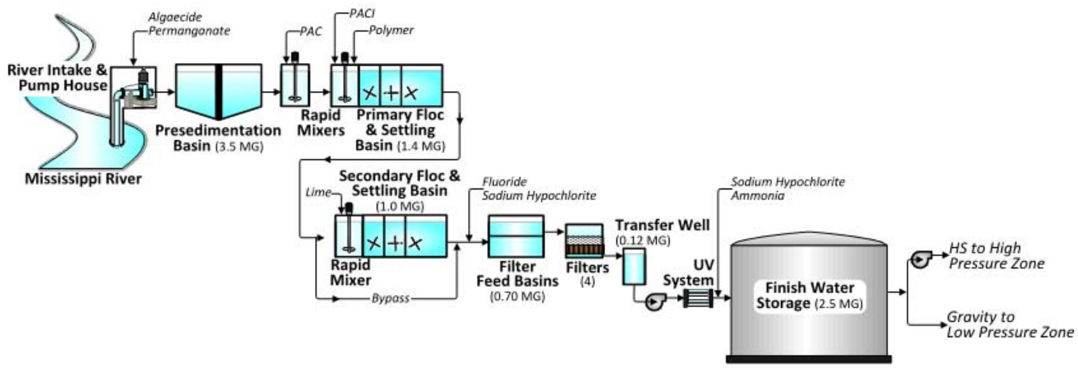


Figure 2-1. Hannibal WTP Process Flow Diagram

2.2 MAY 12, 2017 OPERATIONAL DATA

Plant operating data was recorded on the site visit date to be used as the basis of the current plant conditions for the site assessment. Table 2-1 summarizes the operation conditions for May 12, 2017. Table 2-2 summarizes the water quality parameters. The total treated water flow on that day was 3.17 MGD.

Table 2-1. Hannibal WTP Chemical Dosing on Day of Sample Collection (May 12, 2017)

CHEMICAL	DOSE	COMMENT
Algaecide	0 mg/L	Not applied during this period.
Sodium Permanganate	0.08 mg/L	
PAC (AquaNuChar)	22 mg/L	Typical dosages are 15-25 mg/L. This is considered a high dose being applied to enhance DOC removal.
Coagulant Dose (DFLOC 3610)	50 mg/L (9 mg/L as Al^{3+})	This dosage of coagulant is higher than typically applied to enhance DOC removal. The coagulant includes polymer.
Lime	0 mg/L	Raw water pH was high enough that didn't require pH increase.
Chlorine (Filter Feed Basin)	2.3 mg/L	Applied across the filter feed basins and filters to obtain disinfection credit.
Chlorine (Post-filter)	1.9 mg/L	Applied to boost residual and maintain a measurable residual throughout the distribution system.
Ammonia	0.7 mg/L as N	Applied to target a 4:1 chlorine to nitrogen ratio

Table 2-2. Hannibal WTP Water Quality (May 12, 2017)

WATER QUALITY PARAMETER	RAW WATER	SETTLED WATER	FILTER EFFLUENT	FINISHED WATER
Turbidity, NTU	10.9	1.0	0.06	0.05
pH, unitless	8.0	7.7		7.6
Hardness, mg/L as $CaCO_3$	254	-	247	-
Alkalinity, mg/L as $CaCO_3$	199	-	183	-
Total Dissolved Solid, mg/L	-	-	-	256
Free Chlorine, mg/L	-	-	0.6	-
Monochloramine, mg/L	-	-	-	2.7

2.3 OPTIMIZATION ACTIVITIES

The Hannibal WTP has implemented changes to several of the facility's treatment processes to improve overall plant performance over the last several years. These improvements include:

- Installation of ultraviolet (UV) disinfection system to meet new regulatory requirements for *Cryptosporidium* inactivation.
- Installation of new powdered activated carbon (PAC) feed system to optimize chemical usage and provide better control of chemical feed rates.
- Adjustments to chlorine application points and feed rates to minimize DBP production upstream of filtration. The modified chlorine application point is located upstream of the filter feed basins at a lower chlorine dose intended to maintain a residual of 0.5 mg/L across the filters. Chlorine is not added again until post UV to achieve the desired distribution system residual.
- Installation of a fabric cover over the filter feed basins to limit sunlight exposure to improve effectiveness of chlorine application.
- Removal of one of the two filter feed basins from service to reduce free chlorine contact time prior to filtration.
- Optimization of coagulation process through the use of a new coagulant and modified dose. Changes in coagulant type and dose have occurred over the last several years to enhance organics removal.
- Addition of copper sulfate dosing point at the Secondary Basin for algae control, used on an as-need basis.
- Relocation of sodium permanganate dosing from the secondary basin to the pump house, in lieu of the zebra mussel polymer.

In addition to the modifications made to the treatment facility, the plant staff has performed a number of bench-scale tests to evaluate the optimal coagulation conditions required to improve removal of total organic carbons (TOCs).

Based on the information collected during the site visit, the following treatment modifications were identified as potential solutions that could be implemented in the short term to minimize disinfection byproduct formation:

1) Maximize removal of organic carbon through increases in PAC and PACl doses.
2) Delay dosing of chlorine to as late in the process as possible.
3) Introduce pre-oxidants to enhance organics removal and reduce chlorine dose required.

2.3.1 Maximize Removal of Organic Carbon

Enhanced coagulation can be an effective way to maximize removal of organic carbon. Enhanced coagulation involves feeding excess coagulant to improve removal of total organic carbons (TOCs), a precursor to DBP formation. As indicated above, the plant staff has been actively evaluating various coagulants since 2012. Various PAC and coagulant products have been evaluated nearly annually as part of procurement with the primary evaluation criteria for selection of the chemical being TOC removal capabilities. The plant currently uses AquaNuChar PAC and DFLOC 3610 as a coagulant. AquaNuChar is a high-quality PAC commonly used in water treatment. The DFLOC 3610 is a high aluminum content polyaluminum chloride coagulant that includes polymer to enhance settling. The high aluminum content enhances removal of dissolved organic compounds (DOC) that can form DBPs. The product includes caustic to reduce the need for lime to raise the pH.

The bench scale testing performed by Black & Veatch as described in Section 4 included the evaluation of two alternative coagulants and compared those results to the existing coagulant. The bench scale testing also evaluated higher dosages of PAC and PACl to determine impact on the resultant DBP formation. Based on initial testing results no significant improvements in DBP reduction were identified by modifying the coagulant. Therefore, no immediate modifications to the current coagulation process are recommended as the plant staff have continuously evaluated various coagulants and appear to have selected an effective coagulant for TOC removal based on the chemicals tested and plant water characteristics. In addition, the Missouri Department of Natural Resources (MDNR) new policy is that any changes to chemical feed system (including changes in types of coagulants) must include the results of a detailed evaluation with bench scale test results. Approval from the department head is required prior to implementing any changes.

2.3.2 Delay Chlorine Application

The plant utilizes sodium hypochlorite (12% trade) to provide disinfection and chlorine residual. The first chlorine application point is upstream from filtration prior to the filter feed basins to provide disinfection credit for *Giardia* (>0.5 log) and virus (>2.0 log) inactivation. More chlorine and ammonia are added downstream from UV to form monochloramine. A monochloramine residual is maintained through the above grade reservoir. No disinfection credit is claimed across the reservoir.

Carrying a free chlorine residual across the reservoir provides an opportunity to achieve Giardia and virus inactivation at that location, thereby eliminating the need to maintain a free chlorine residual across the filter feed basins and filters. Relocating the pre-filter chlorine feed point to this post UV feed point would reduce the contact time with chlorine by approximately five hours on average. Although this reduction in chlorine exposure will reduce DBPs, the five hours is a relatively small incremental decrease in overall distribution contact time (which is on the order of

72 to 120 hours). However, delaying chlorine post filter could result in additional benefits, including allowing the multi-media filters to function as biological filters, potentially capable of removing an additional 10 to 15 percent of TOC during warm weather periods. Removal of additional TOC should result in reducing the formation of DPBs. However, operating biological filters can result in shorter filter run time and breakthrough of manganese can occur, which imparts color to the water.

In discussions with MDNR, biological filtration is currently not implemented in Missouri. However, it is a treatment technique that is growing in use and MDNR indicated this may be an acceptable approach. Additional analysis, including bench scale testing, and an engineering report submitted and approved by MDNR would be required to implement this approach.

Another potential option to further reduce chlorine contact time is to utilize the existing UV disinfection facility for *Giardia* disinfection credits. Currently, the existing UV system is sized to meet the *Cryptosporidium* removal requirements. The required UV dose for 0.5 log *Giardia* inactivation is less than the current design dose, so the existing UV system could be used with no modifications. After UV treatment, 2 log virus inactivation would be required with chlorine. A 2 log virus inactivation requires very little chlorine contact time, and it appears this could be achieved in the piping leaving the above grade reservoir. Therefore, the first chlorine application point could be delayed to the post reservoir piping. This would delay the chlorine in contact with the water an additional 16 hours on average, for a total of 21 total hours. For this alternative, there would be several challenges. First, MDNR currently does not grant *Giardia* inactivation credits for any UV facilities. Initial discussions with MDNR indicated they have concern with some of the regulatory framework associated with the UV Design Guidance Manual (UVDGM) in how it allows up to 5 percent of the water to flow through the reactor untreated. Significant discussions, validation testing, and regulatory review would be required if UV was used for *Giardia* inactivation. In addition, delaying chlorine addition completely until downstream of the reservoir may result in unforeseen issues associated with no chlorine residual in the reservoir. This would be an unconventional approach and would need further evaluation prior to implementation.

Therefore, based on our initial review, no immediate changes to the current chlorine feed points are recommended until further evaluation is conducted and approval is received from MDNR.

2.3.3 Pre-oxidants to Lower Chlorine Use

The only pre-oxidant available currently available at the plant is 40% sodium permanganate. The addition of permanganate may enhance TOC removal and satisfy some of the chlorine demand in the water. Therefore, an overall lower dose of chlorine can be applied at the pre-filter feed point. To determine the effectiveness of permanganate on reduction of DBP formation bench scale testing was performed and is summarized in Section 4. The initial results showed no significant reduction in DBP formation by utilizing permanganate.

2.4 ASSESSMENT SUMMARY

In 2012, the staff initiated the Disinfection Byproduct Evaluation. The decision from that study was to utilize chloramines to meet DPB limits. In addition to implementation of chloramines, the plant staff has continued to evaluate and modify the treatment process to improve performance and reduce disinfection byproduct formation. However, there is no data at this time to support those modifications to existing treatment processes (coagulation, PAC dose, chlorine dosing locations, and/or use of permanganate) will guarantee the WTP can meet DBP regulatory limits if chloramine use is discontinued. Therefore, a detailed evaluation and regulatory approval is required before implementation of any process improvements can be considered.

3.0 Historical System TOC Removal and Byproduct Formation

Historical plant data was evaluated to benchmark plant performance with respect to TOC removal and DBP formation. The data was used to establish trends and order of magnitude removal rates that would be required by additional treatment alternatives to comply with MCLs for disinfection byproducts. Further evaluation of this data will be conducted concurrently with bench scale testing and distribution system analysis to understand and define specific TOC and DBP reduction goals to ensure the system will be compliant with MCLs after transitioning from chloramines to free chlorine.

3.1 HISTORICAL TOC REMOVAL

Plant historical raw and finished water TOC data were evaluated to assess the overall TOC removal efficiency. Figure 3-1 summarizes the historical raw and finished water TOC concentrations from January 2005 to January 2017. The raw water TOC has typically ranged between 4.0 mg/L and 7.0 mg/L with an average concentration of 5.15 mg/L. The finished water TOC has ranged from 1.8 mg/L to 4.0 mg/L with an average concentration of 2.71 mg/L. The average TOC removal through the plant is 47.5 percent.

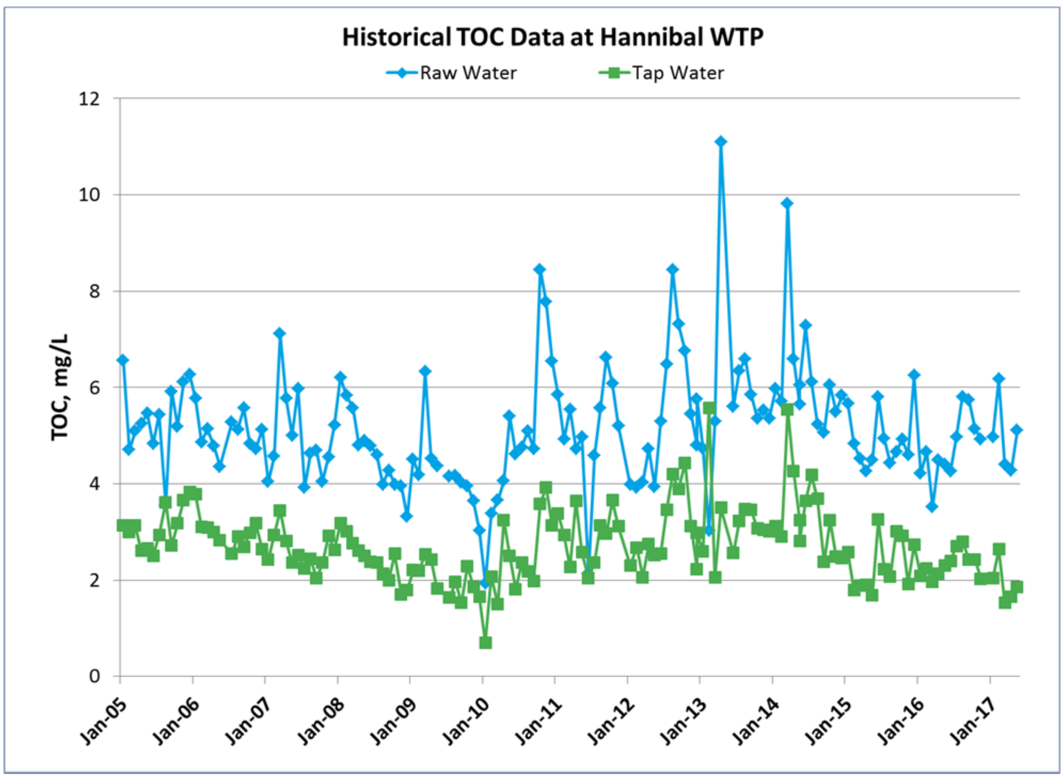


Figure 3-1. Raw and Tap Water TOC Data - Hannibal WTP

Further evaluation of recent TOC data was conducted to determine whether any trends could be observed as a result of process improvements made at the WTP since 2012. Figure 3.2 summarizes the finished water TOC concentrations and percent TOC removal from January 2012 to June 2017. The data points were normalized over a three month running average to better illustrate potential trends.

Initial observations from this analysis show increased removal efficiency of TOC and decreased finished water TOC concentrations from January 2015 to June 2017, relative to the 2012 to 2015 period. Since April 2015, the average finished water TOC concentration has been approximately 2.28 mg/L compared to the 2012 to 2015 average of 2.79 mg/L. TOC removal efficiency has also increased over this period, which demonstrates the effectiveness of the WTP's efforts to implement process optimizations focused on improving plant performance.

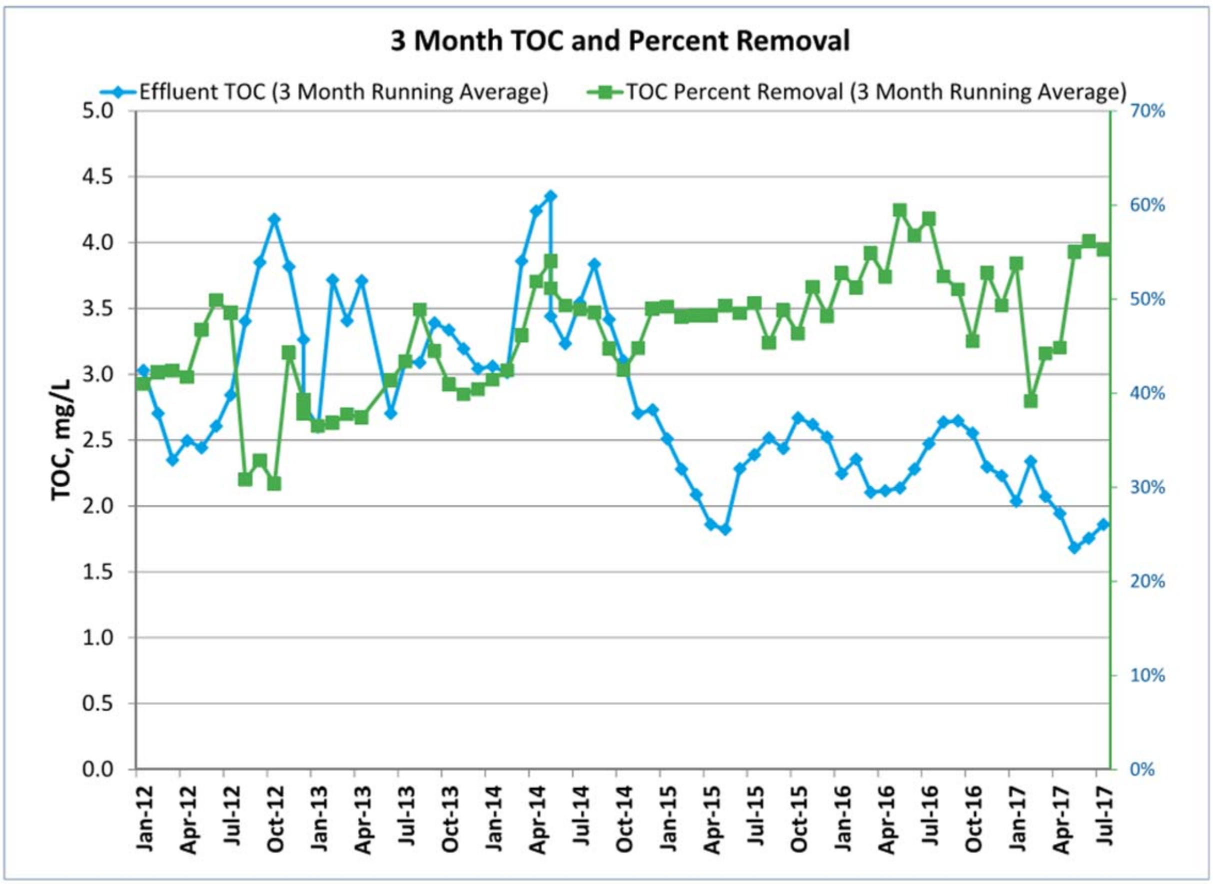


Figure 3-2. Recent Trends of Finished Water TOC and TOC Removal

3.2 HISTORICAL DISINFECTION BYPRODUCT FORMATION

Historical disinfection byproduct data for TTHMs and HAA5s at the City's compliance monitoring stations is provided in Figure 3-3 and Figure 3-4. The figures are representative of recorded TTHM and HAA5 concentrations at the monitoring site and do not represent locational running annual averages. Since new compliance monitoring stations were selected in 2014 for compliance with Stage II Disinfection Byproduct Rule, the data shown is limited to these locations from February 2014 through February 2017. The transition from free chlorine to a chloramine residual in September 2015 is depicted on the figures.

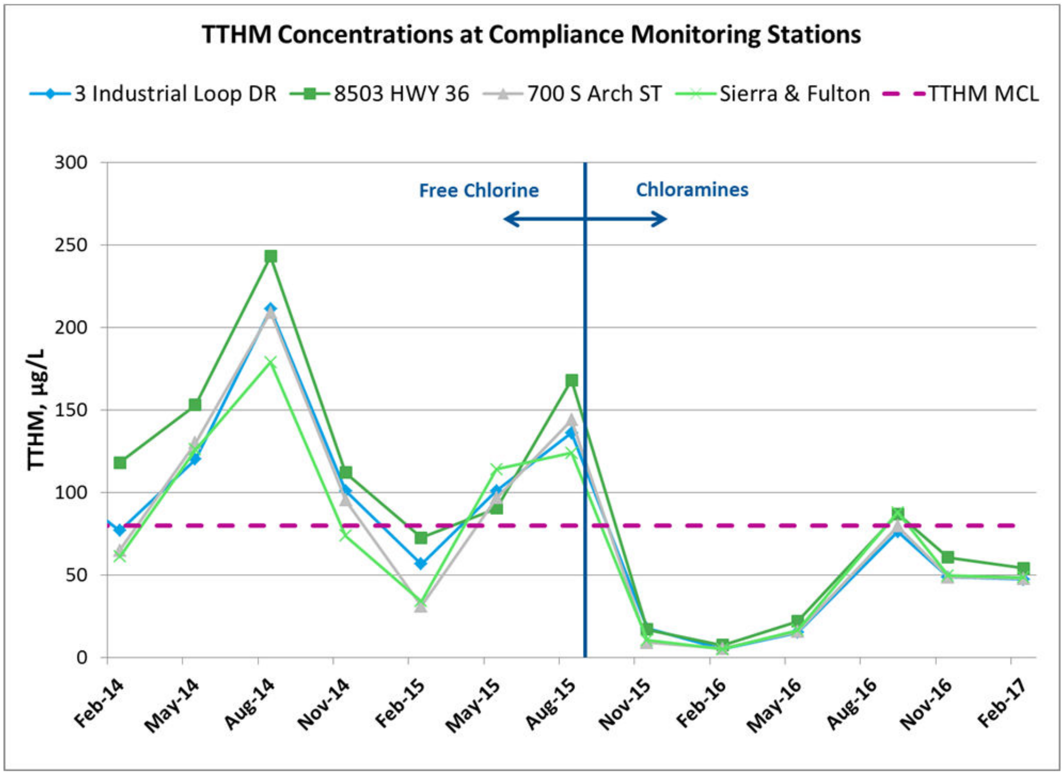
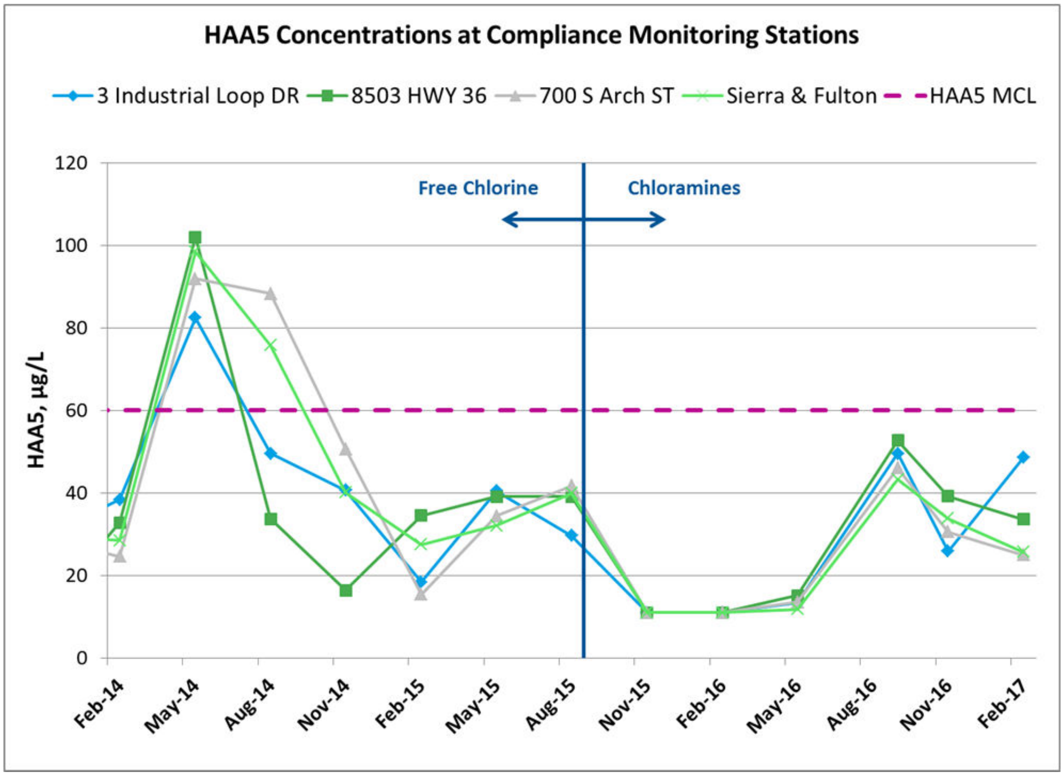


Figure 3-4. Concentration of TTHMs at Hannibal WTP Compliance Monitoring Stations



Note: Method reporting limit is less than 11 ug/L. Any values below this method reporting limit is conservatively shown as 11 ug/L.

Figure 3-5. Concentration of HAA5s at Hannibal WTP Compliance Monitoring Stations

Historical data for both TTHMs and HAA5s reveal the effectiveness of chloramines to meet the MCL requirements as both measured higher than the regulatory limit prior to chloramines, but within acceptable levels after conversion. There appears to be some correlation between the HAA5s and the lower finished water TOC concentrations depicted in Figure 3-2. The HAA5s appeared to stay below the 40 ug/L after the same January 2015 timeframe when lower finished water TOCs were observed, even prior to conversion to chloramines. However, within the same timeframe TTHMs were greater than 80 ug/L for all monitoring locations, spiking at 160 ug/L at the 8503 Highway 36 compliance location.

3.3 SUMMARY OF TOC REMOVAL AND BYPRODUCT FORMATION

Further evaluation of this data along with additional bench scale testing and distribution system analysis will be required to define specific design requirements for overall TOC removal at the plant and finished water TOC goals to assure the system can be compliant without the use of chloramines. However, based on this initial review, an additional reduction of TOC in the range of 35-60 percent from current levels may be required to meet regulatory limits. There are a number of variations and factors that will impact this overall removal goal, and the final solution may be a combination of process and distribution solutions evaluated. However, the need to achieve 35 to 60 percent reduction in TOC is a useful screening metric as a large improvement in TOC removal is required to meet DBP limits. Future testing will be performed to validate the percent removal and the target TOC level necessary to meet DBP limits.

4.0 Initial Screening of Treatment Alternatives

Bench-scale testing was conducted to perform an initial screening of potential solutions for compliance with maximum contaminant levels (MCLs) of disinfection byproducts. The solutions evaluated were selected based on the results of the plant assessment, review of historical data, industry standards, and recommendations from previous reports, including the Granular Activated Carbon System Preliminary Engineering Report dated February 22, 2017, prepared by Jacobs. This study outlined a number of potential alternatives for consideration. However, outside the scope of the study was bench scale and pilot testing, which was recommended to confirm the effectiveness and develop capital and operating costs for the alternatives. The objective of this initial screening is to identify viable treatment alternatives for further consideration and to eliminate alternatives that are considered ineffective. Future testing will then be conducted to optimize the remaining alternatives and ultimately select the best system solution for Hannibal to meet regulatory requirements and adhere to the referendum to eliminate ammonia from the drinking water supply.

4.1 BENCH-SCALE TESTING OVERVIEW

Plant water was collected on May 12, 2017 from the raw water, primary flocculation and settling basin effluent, filter influent, filter effluent, and plant finished water. The water samples were stored in coolers on ice and delivered to the Black & Veatch research facility in Kansas City, MO for analysis. Bench scale testing was conducted for the following treatment alternatives:

- **Enhanced coagulation** including testing of the existing coagulant (DFLOC 3610), ferric sulfate, and alternative coagulant (DFLOC 3606). Organic carbon testing was conducted at 40, 60, and 80 mg/L for each chemical with the most effective coagulants then being tested for DBP formation.
- **Oxidation** including testing of chlorine dioxide, permanganate, and ozone. Each process was tested at various dosages and feed locations with the best performing dosage selected for DBP formation.
- **Adsorption Technologies** including higher dosages of powdered activated carbon (PAC) and proof of concept for granular activated carbon (GAC)
- **Alternative Processes** included reverse osmosis (RO), ion-exchange resins, and proof of concept for tank aeration

In order to simulate DBP formation in the distribution system, simulated distribution system (SDS) testing was conducted over a 5-day hold period for each of the optimal conditions from the alternatives evaluation. Filtered samples were poured into amber glass bottles and dosed with free chlorine (sodium hypochlorite). The free chlorine dose was estimated to achieve a target chlorine residual of approximately 0.2 mg/L after five days. The five-day hold period was selected based on the estimated water age from the distribution system model.

The bench scale testing conducted in the initial screenings evaluation was primarily focused on the reduction of dissolved organic carbons (DOC), and reduction of TTHMs and HAA5s. Measurements of ultraviolet absorbance (UVA) at 254 nanometers (nm) was used as a surrogate measurement for DOC since DOC results were not immediately available.

DOC was selected as the primary source of evaluation instead of TOC as DOC is a better indicator of future DBP formation then the other component of TOC (particle organic carbon), which does not contribute to DBP formation.   Bromate and chlorite were monitored in cases where alternative oxidants, such as ozone and chlorine dioxide, were evaluated.

Initially, for the coagulation testing, measurements of ultraviolet absorbance (UVA) at 254 nanometers (nm) was used as a surrogate measurement for DOC.   The optimal conditions from this evaluation were repeated in subsequent testing involving a coagulation step of various dosages.

Additional testing and analysis is recommended prior to implementing any plant improvements.

4.2 COAGULATION RESULTS

One method for controlling the formation of TTHMs and HAA5s is by reducing the concentration of DOC prior to the addition of free chlorine. DOC is removed from the source water through coagulation and sedimentation. Since the degree of DOC removal varies by coagulant type and dosage, coagulation testing was conducted to determine whether alternative coagulants could improve the DOC removal efficiency.

An initial coagulant evaluation was performed to identify the optimal coagulant type and dosage to be used in subsequent testing. Assessment of optimal coagulant was based on settled water UV absorption as a surrogate measure for DOC. All coagulants were tested on an equivalent metal ion concentration with polymer, and each coagulant was tested with and without pH adjustment. Adjustments to pH were conducted for the various coagulants to quantify the reduction in DOC.

Coagulants evaluated under this test include the plant's current polyaluminum chloride (PACl – DFLOC 3610), ferric sulfate, and a high metal concentration PACl (DFLOC 3606). The plant's current coagulant DFLOC 3610 includes a filter-aid polymer. All coagulants were tested using the same filter-aid polymer at a ratio equivalent to the plant's current feed rate.

For reference, under current operations, the WTP applies a coagulant dose of 30-50 mg/L of PACl containing cationic polymer upstream from the primary flocculation & settling basin.

4.2.1 Comparison of Coagulation Conditions

Screening of the most viable coagulation alternatives was initially conducted based on available UVA measurements. As demonstrated in Table 4-1, the results of the UVA measurements showed the plant's current coagulant (DFLOC 3610) had consistently lower UVA values at each equivalent metal dose. Based on UVA, the current plant coagulant at 40 mg/L and 80 mg/L doses, and ferric sulfate at 40 mg/L dose, were determined to be the most viable coagulation conditions and were selected for subsequent SDS testing to evaluate effects on DBP formation. Since DFLOC 3610 only had 12 percent higher UVA removal (0.089 and 0.068 cm-1) at twice the current coagulant dose, it was determined that the 40 mg/L dose of DFLOC 3610 would be carried forward.

Table 4-1. UVA Results for Evaluation of Alternative Coagulants at Equivalent Metal Dosages

EQUIVALENT METAL DOSE	UVA (CM^{-1}) MEASUREMENT		
	DFLOC 3610	Ferric Sulfate	DFLOC 3606
40 mg/L Dose	0.089	0.090	0.102
60 mg/L Dose	0.076	0.077	0.096
80 mg/L Dose	0.068	0.084	0.079

Settled water DOC was measured for each coagulation condition. Figure 4-1 provides an illustration of the settled water DOC concentration for the three coagulants tested at metal concentrations equivalent to the current plant coagulant being dosed at 40, 60, and 80 mg/L.

The testing confirmed that by increasing the coagulant dose by 100 percent, very little additional removal of DOC was achieved and certainly not the 35 to 60 percent reduction needed to likely meet DBP limits. The testing also showed that adjusting pH was ineffective for enhancing DOC removal and therefore was not included in the summary of the results. The coagulant demonstrating optimal performance in terms of DOC removal was the DFLOC 3606 at 40 mg/L. Although DFLOC 3606 performed better in terms of DOC removal, the decision was made to proceed with subsequent testing of DFLOC 3610 based on available UVA results. Based on UVA data, the plant's current coagulant - DFLOC 3610 at 40 mg/L was selected to serve as the baseline to compare performance for DOC removal of alternative oxidants, adsorption technologies and alternative treatment technologies. However, DFLOC 3606 will be considered for further SDS testing since it provided more DOC removal than the product currently in use (DFLOC 3610).

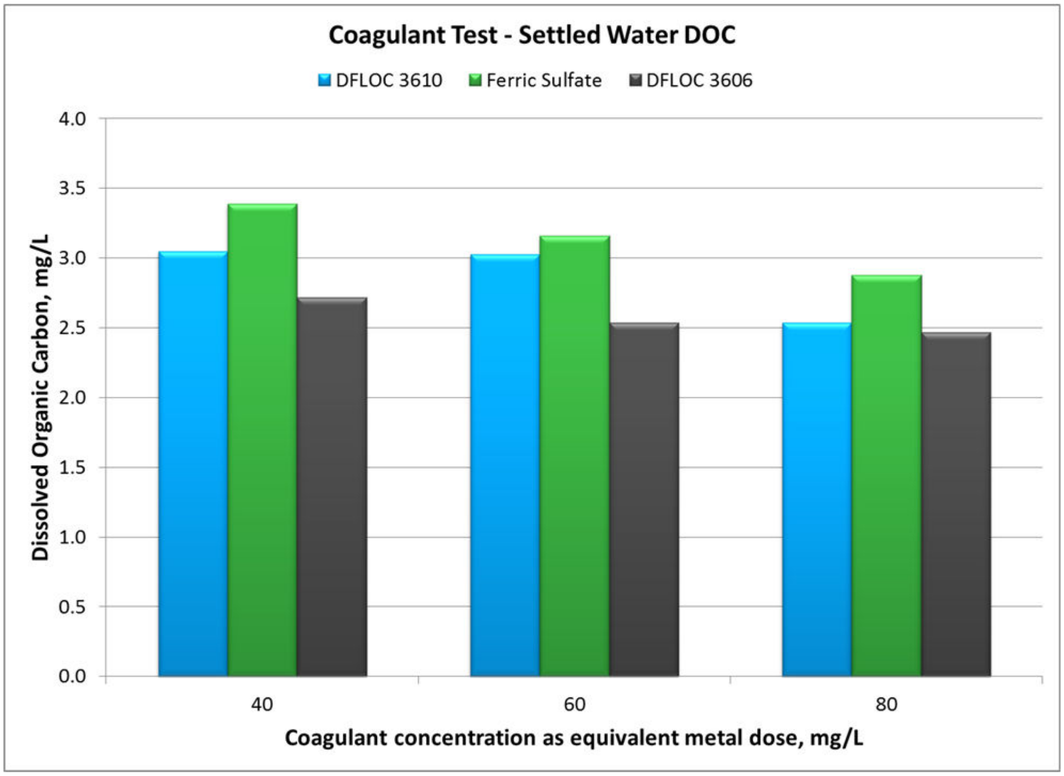


Figure 4-1. DOC Results - Coagulant Testing

Figure 4-2 provides a summary of the TTHM and HAA5 concentration after SDS testing for the three coagulants with lowest UVA. The concentration of TTHMs and HAA5s from SDS testing from the DFLOC 3610 at 40 mg/L will serve as the baseline to compare performance of alternative oxidants, adsorption technologies and alternative treatment technologies for reduction of DBP formation. Note that the test condition for the SDS resulted in zero residual and thus did not meet the target trace free chlorine residual, 0.2 mg/L, at the end of the 5-day hold period. Therefore, these results underestimate the true formation expected in the distribution system. However, the data is still valid for screening level comparison between treatment technologies. Subsequent testing will include higher chlorine dosages to confirm the treatment approach will meet DBP limits while maintaining representative levels of free chlorine.

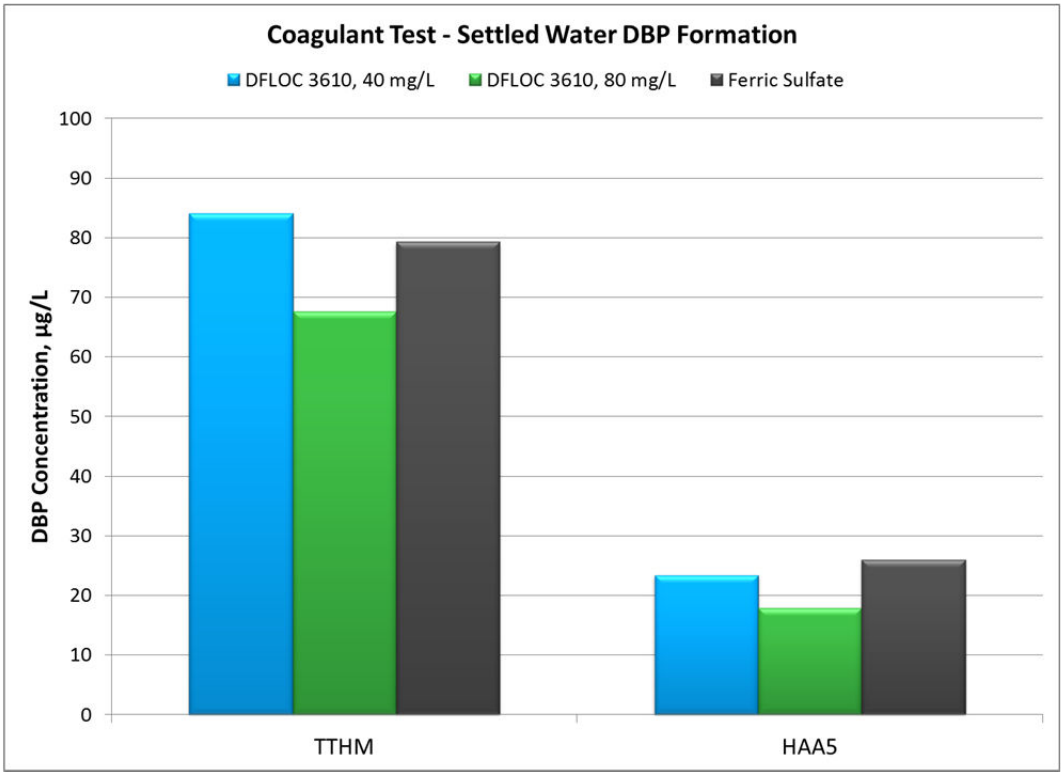


Figure 4-2. DBP Formation - Coagulant Test with 5-day SDS

4.3 OXIDATION RESULTS

Oxidation using chlorine dioxide, ozone, and permanganate was tested based on their abilities to achieve the following:

- Oxidize a wide variety of both organic and inorganic compounds.
- Control the formation of TTHMs, HAA5s, and other DBPs by oxidizing chlorination DBP precursors.
- Reduce the demand for chlorine.

Depending on the applied dose, the use of chlorine dioxide or ozone could earn the CT credit necessary to achieve the required log inactivation of *Giardia* and viruses to meet disinfection regulations. Any log inactivation achieved by these oxidants would reduce the free chlorine dose needed to achieve the remaining log inactivation, and as such would limit the formation of TTHMs and HAA5s. If all of the required CT credits could be earned from the alternative oxidants, then free chlorine would only be needed to supply a disinfectant residual in the distribution system.

Representative pre-oxidation tests were conducted with chlorine dioxide, ozone and permanganate to mimic oxidant dosing upstream of the pre-sedimentation basin. This pre-oxidation testing was achieved by dosing the oxidant into raw water followed by coagulation using the optimal coagulant condition described in Section 4.2. Additionally, chlorine dioxide was tested as a post-oxidant to represent the addition of chlorine dioxide upstream of the filter.

The optimal doses for each of the pre-oxidants and the post-oxidant underwent SDS testing, where the water samples were dosed with free chlorine and stored in the dark at room temperature for 5 days prior to measuring TTHMs and HAA5s.

4.3.1 Chlorine Dioxide (Pre-oxidant)

A major benefit of chlorine dioxide is (ClO2) its ability to oxidize a variety of constituents without forming TTHMs and HAA5s, but the production of other regulated byproducts (i.e., chlorite) can limit the applied chlorine dioxide dose.

An additional advantage to using chlorine dioxide is the opportunity to earn some or all of the disinfection credits necessary to achieve the log inactivation of Giardia and/or viruses.

Three chlorine dioxide doses were tested for the application of chlorine dioxide as a pre-oxidant, and the doses were selected to bracket a typical design dose of 1.5 mg/L chlorine dioxide. The initial dose of 1.5 mg/L was established through an evaluation of the source water demand. Chlorine dioxide residuals were measured over time to determine the decay rate for three doses when chlorine dioxide was applied as a pre-oxidant and for one dose when chlorine dioxide was applied as an oxidant upstream from filtration. The decay measurements also provide a means to determine the CT credits. Figure 4-3 summarizes the results of the demand decay testing.

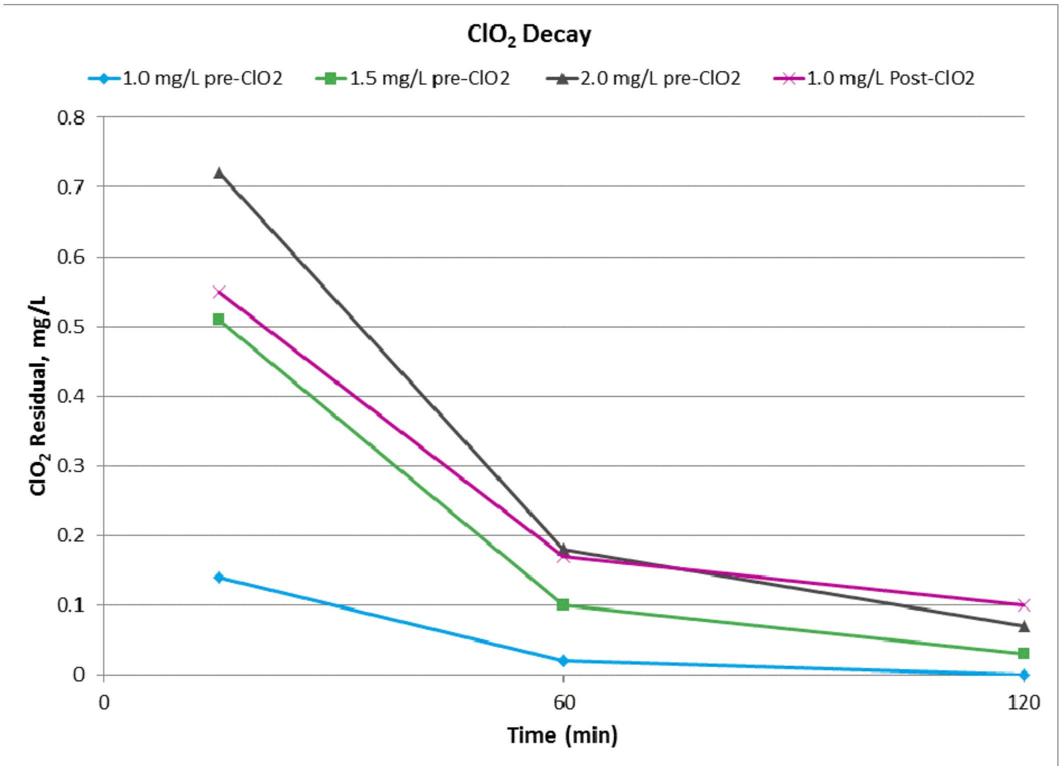


Figure 4-3. Chlorine Dioxide Decay using Raw Water and the Optimal Coagulant Dose for the Pre-Oxidant Tests and Primary Floc-Sed Water for the Post-Oxidant Test.

Based on this initial evaluation, CT credits were calculated for a chlorine dioxide dose of 1.5 mg/L, which represents the optimal ClO_2 dose for DOC reduction. At a water temperature of 20°C and CT credit of 6.07, 1-log inactivation of Giardia and 2-log inactivation of viruses can be achieved. Obtaining disinfection credits with chlorine dioxide would reduce the CT credits required from the addition of free chlorine, thus providing Hannibal with the option of delaying chlorination and reducing the total contact time with chlorine.

Chlorite was measured to determine if the residuals exceeded the MCL of 1 mg/L. Results from the testing had 0.93 mg/L of chlorite, which is near the MCL. Therefore, if chlorine dioxide is considered a viable alternative, additional testing will be completed that may result in the addition of a ferrous sulfate system to remove chlorite.

4.3.2 Permanganate (Pre-oxidant)

Permanganate is effective for the oxidation of iron and manganese, removal of some taste and odor compounds, reducing TTHMs precursors, and lowering the chlorine demand. The disadvantages of using permanganate as an oxidant include the possibility for pink-colored water if the dose is too high, and the inability to earn CT credits that would delay the use of chlorine. Permanganate is used to target specific constituents, thus the type of particulates in the water impact performance, and it cannot be used as a disinfectant.

The identification of the optimal permanganate dose was determined based on a test that incrementally increased the permanganate dose applied to the raw water until a pink color was visually detected. The threshold of the raw water prior to the visual detection of pink-colored water was a permanganate dose of 0.5 mg/L. The subsequent pre-oxidation tests with permanganate were conducted at dosages of 0.25, 0.5 and 1.0 mg/L of permanganate as a way to bracket the optimal dose. Results from the testing are shown in Figure 4-5 and Figure 4-6, which showed minimal effectiveness.

4.3.3 Ozone (Pre-oxidant)

Ozone is a powerful oxidant, second only to the hydroxyl radical among oxidants used for drinking water treatment. The benefits of ozone include the following: disinfection, oxidation of iron and manganese, oxidation of taste and odor compounds, oxidation of micro-pollutants, removal of color, oxidation of DBP precursors, no formation of TTHMs and HAA5s, and the reduction of chlorine demand. Detailed analysis of the ozone dose is required as it must be tailored to limit the formation of bromate, which is a regulated DBP from ozonation.

An initial ozone dose of 1.5 mg/L was selected as it was approximately 0.3 x the DOC concentration of the raw water, which is a common ratio used for ozone. However, the initial testing showed ozone demand of the raw water was greater than 1.5 mg/L, as depicted by a measured ozone residual of 0 mg/L at 30 sec in Figure 4-4. Two subsequent doses of 2.5 mg/L and 3.5 mg/L of ozone were tested to establish conditions that could provide primary disinfection of Giardia and viruses at 20°C.

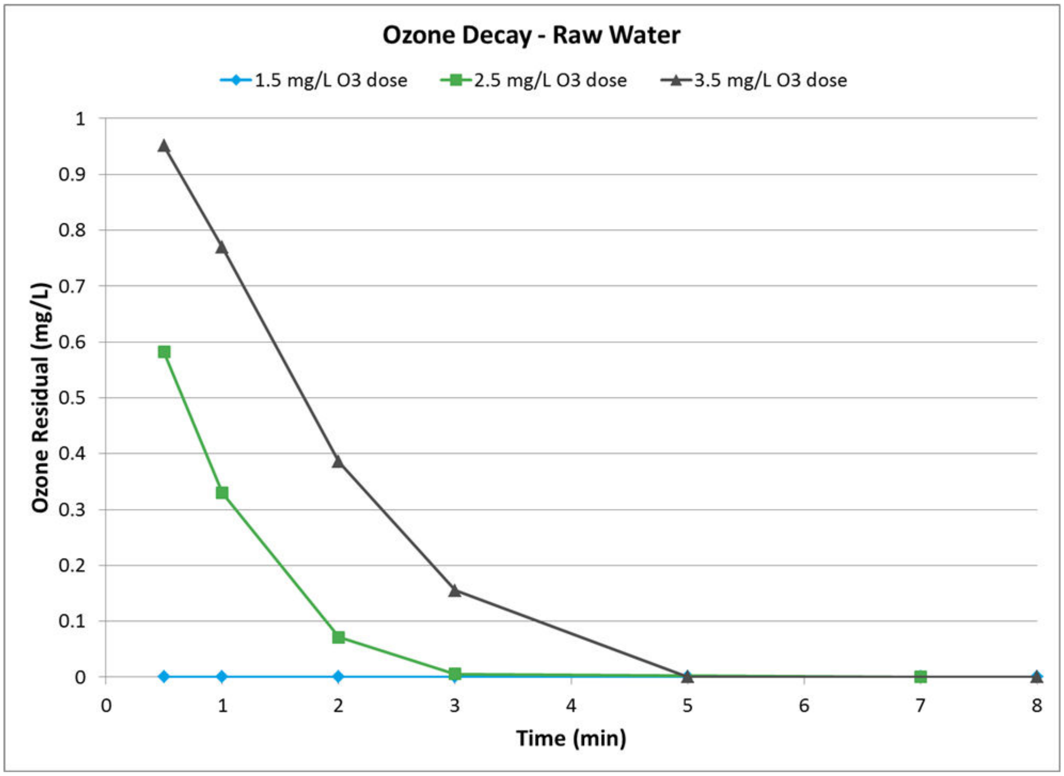


Figure 4-4. Ozone Decay for Raw Water at 20°C

Bromide in the raw water can be oxidized by ozone to form bromate, which is a regulated DBP (the MCL is 0.010 mg/L). The bromide concentration in the raw water was measured as 0.05 mg/L, and the measured bromate concentrations from the settled water after the pre-oxidation with ozone were < 0.001, 0.001, and 0.0025 µg/L bromate for the ozone doses of 1.5, 2.5, and 3.5 mg/L ozone, respectively. Therefore, bromate formation does not preclude the use of ozone and mitigation strategies are not required to limit bromate formation.

The optimal dose of ozone was identified as 2.5 mg/L ozone as it provided inactivation of Giardia and viruses, while producing the lowest UVA for all of the ozone tests. UVA was used as a surrogate for DOC as the measurements could be conducted on-site during bench testing. The DOC results are shown below in Figure 4-5, and they represent the optimal ozone dose of 2.5 mg/L.

4.3.4 Chlorine Dioxide (Post-oxidant)

In addition to the chlorine dioxide dosed in the raw water as a pre-oxidant, chlorine dioxide was applied as a post-oxidant to settled water from the primary flocculation and sedimentation basin to represent the addition of chlorine dioxide upstream of the filters. The chlorine dioxide dose chosen for this testing ranged from 1.0 mg/L to 2.5 mg/L. The optimal dose for pre-oxidant testing was 1.5 mg/L chlorine dioxide. The formation of chlorite and chlorate were measured to be 0.59 and 0.32 mg/L, respectively. Therefore, the use of chlorine dioxide as a post-oxidant under these testing conditions did not produce chlorite or chlorate at levels that exceeded regulations. The DOC results for this test condition are shown below in Figure 4-5.

4.3.5 Comparison of all Oxidants

The measured DOC values are important as they represent an opportunity to form DBPs, and lower DOC values represent the effectiveness of an oxidant's ability to oxidize organic compounds. The DOC values measured for all of the pre-oxidant tests and the one post-oxidant test are displayed below in Figure 4-5, so that all of the tests can be compared. Based on the measured DOC values, the optimal pre-oxidant doses for each oxidant were as follows:

- 1.5 mg/L of chlorine dioxide
- 2.5 mg/L of ozone
- 0.25 mg/L of permanganate.

The use of chlorine dioxide as pre-oxidant and the use of permanganate as a pre-oxidant showed no benefit in terms of decreasing DOC when compared to the baseline established using the existing coagulant. The use of chlorine dioxide as a post-oxidant only showed marginal benefits in terms of DOC reduction when compared to the baseline DOC. Overall the best oxidant was ozone, which displayed DOC values well below the baseline for the current operating conditions. The 2.5 mg/L ozone dose had the lowest DOC for all of the oxidants, which showed a 26 percent decrease in DOC when compared to the baseline DOC.

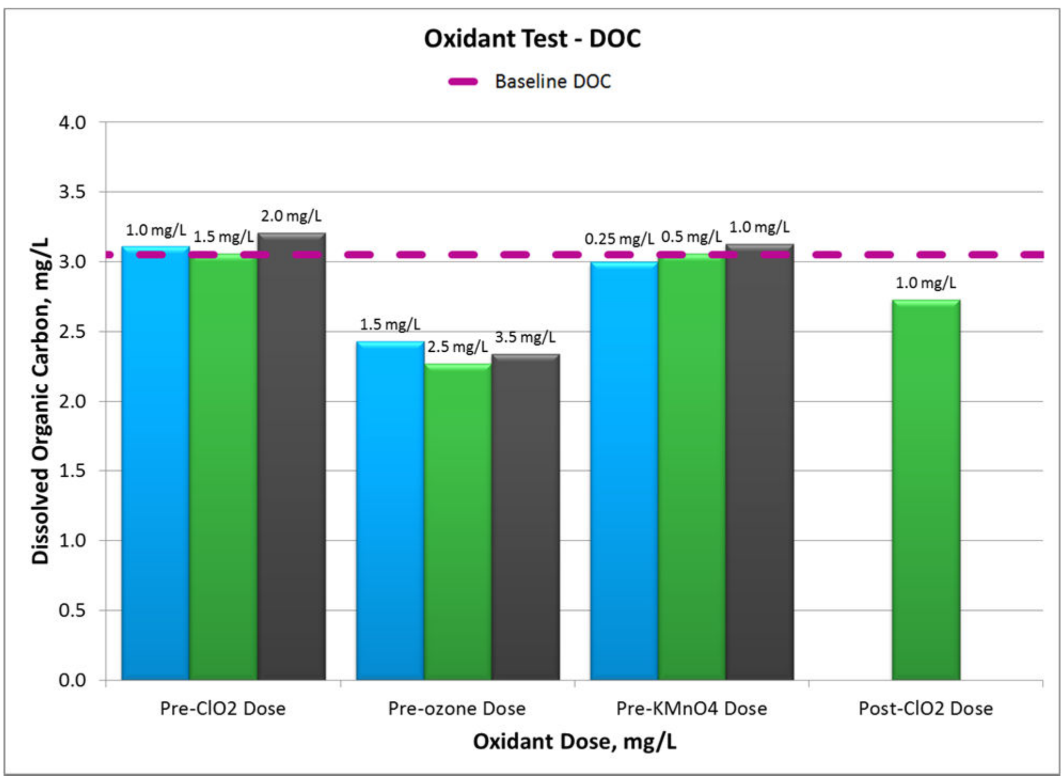


Figure 4-5. DOC Results from Pre- and Post-Oxidant Testing

Both TTHMs and HAA5s are regulated DBPs, and as such it was important to determine if any of the oxidants were able to lower these DBPs when compared with the current plant operations shown as the baseline. The permanganate dose of 0.5 mg/L was selected as the optimal dose based on the visual analysis of a pink color and the measured UVA, and that is why it was used in the SDS testing instead of the 0.25 mg/L permanganate dose.   Results from the testing are shown in Figure 4-6.

Similar to the DOC results, ozone was the best oxidant for reducing DBPs. The 2.5 mg/L ozone dose showed a 57 percent reduction in TTHMs and a 53 percent reduction in HAA5s when compared to the baseline. All of the other oxidants either showed minimal improvements in the reduction of DBPs or showed slightly higher DBP formation when compared to the baseline.

Ozonation was very impactful in regard to DOC and chlorination DBPs reduction. Ozone reacts with DOC to make it more amenable to removal during coagulation and modifies the organic compounds such that they no longer react with chlorine to form chlorination disinfection byproducts. That is the likely reason a larger improvement in DBPs was observed than removal of DOC alone.

However, as indicated before, it should be noted that chlorine residual after the 5-day hold period did not yield the expected 0.2 mg/L residual. Therefore TTHM and HAA5 values included in this report are underestimates of what would be observed in the distribution system, but can be used to compare alternatives.

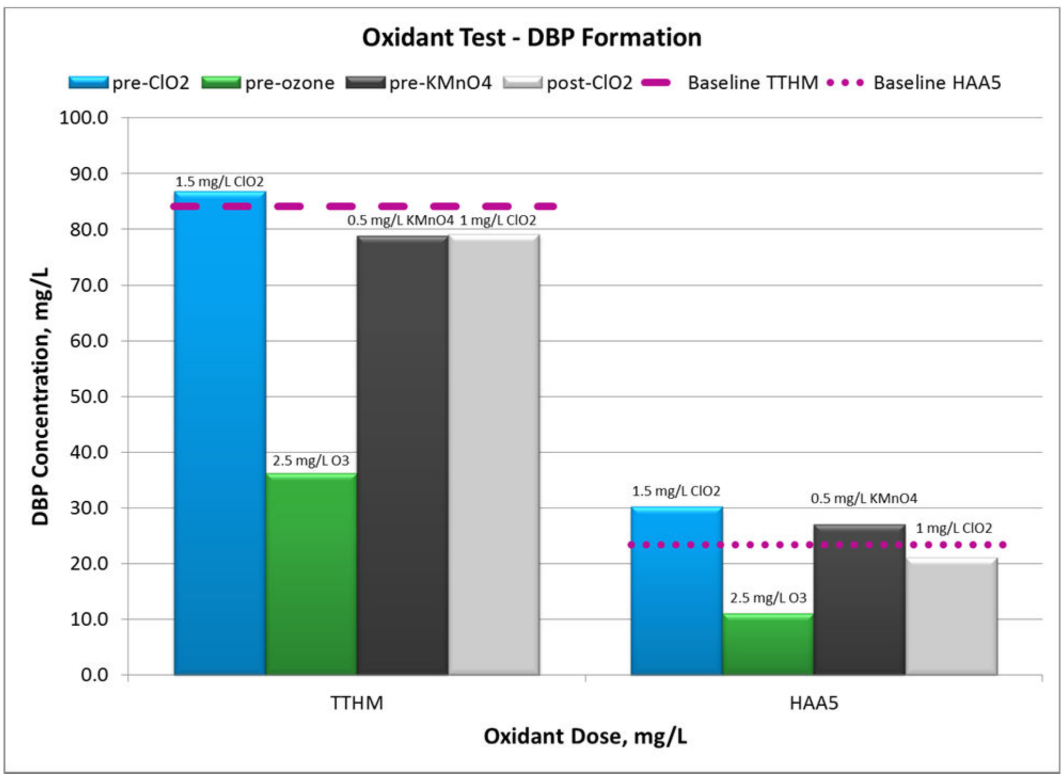


Figure 4-6. DBP Formation from Pre- and Post-Oxidant Testing with 5-day SDS.

4.4 ADSORPTION TECHNIQUES

Powdered activated carbon (PAC) has a small particle size and can be applied in a slurry form at various locations in the water treatment process to allow for adsorption to take place. The PAC is then removed through sedimentation and filtration. PAC is often applied to the coagulation process to adsorb organics and to aid in the control of taste and odor issues. The plant currently feeds PAC into the rapid mix chamber following the pre-sedimentation basin. The typical PAC feed dose is approximately 15-25 mg/L. In this testing, three doses of PAC was added to the raw water and subsequently coagulated with the optimal coagulant dose.

Granular Activated Carbon (GAC) is a media with larger particle size than PAC. GAC is used as a media bed through which water must pass through to allow for adsorption to occur. GAC contactors can be gravity feed, pressure contactors, or upflow and/or fluidized bed contactors. GAC is beneficial as both a treatment to remove DOC and thus limit the precursors for DBP formation, and also as a treatment to remove already formed DBPs.

Testing of GAC adsorption was conducted to compare the relative effectiveness of GAC adsorbing only DBP precursors verses the removal of pre-formed DBPs (post chlorination). Anticipated operational performance of GAC adsorption techniques considering the empty bed contact time, media bed life and other operational factors is being conducted separately through an accelerated column test (ACT) and pilot testing.

As part of the adsorption technologies evaluation, 55 gallons of filter effluent water was sent to Calgon Carbon to conduct an ACT. The ACT simulates flow through a GAC pressure vessel in one year in an accelerated test that lasts 27 days to evaluate the GAC life expectancy. Results of the ACT test will be summarized in the separate memorandum once the data has been received.

Actual removal efficiency in full scale operations may vary from that observed in bench scale testing. Therefore, this test was purely a proof of concept evaluation to determine if lower DBP levels would result by providing contact time with chlorine upstream from GAC.

4.4.1 Comparison of PAC/GAC Options

The three PAC doses and the two GAC scenarios were compared based on their ability to adsorb organics, and the DOC concentrations remaining in the test conditions are shown in Figure 4-7. The PAC testing showed that the current PAC dose of 15 mg/L is achieving reduction of DOC concentrations from the baseline measurement of 3.0 mg/L to 2.6 mg/L, a 14% reduction. Increasing the PAC dose from 15 mg/L to maximum dose of 45 mg/L resulted in another 13% reduction in DOC concentration.

The GAC testing demonstrated that pre-chlorination (GAC vessel) results in lower overall DBP formation since the pre-formed DBPs were removed during the treatment step. The non-chlorinated sample is labeled 'Filter Cap'. The overall percent reduction of DOC for GAC relative to the baseline was 34 percent. Again, GAC testing was performed to determine if pre-chlorinating and pre-forming DBPs would result in lower overall DPBs following use of GAC. The results cannot be used to develop design or operating information. That information will only be available from the ACT and/or pilot testing.

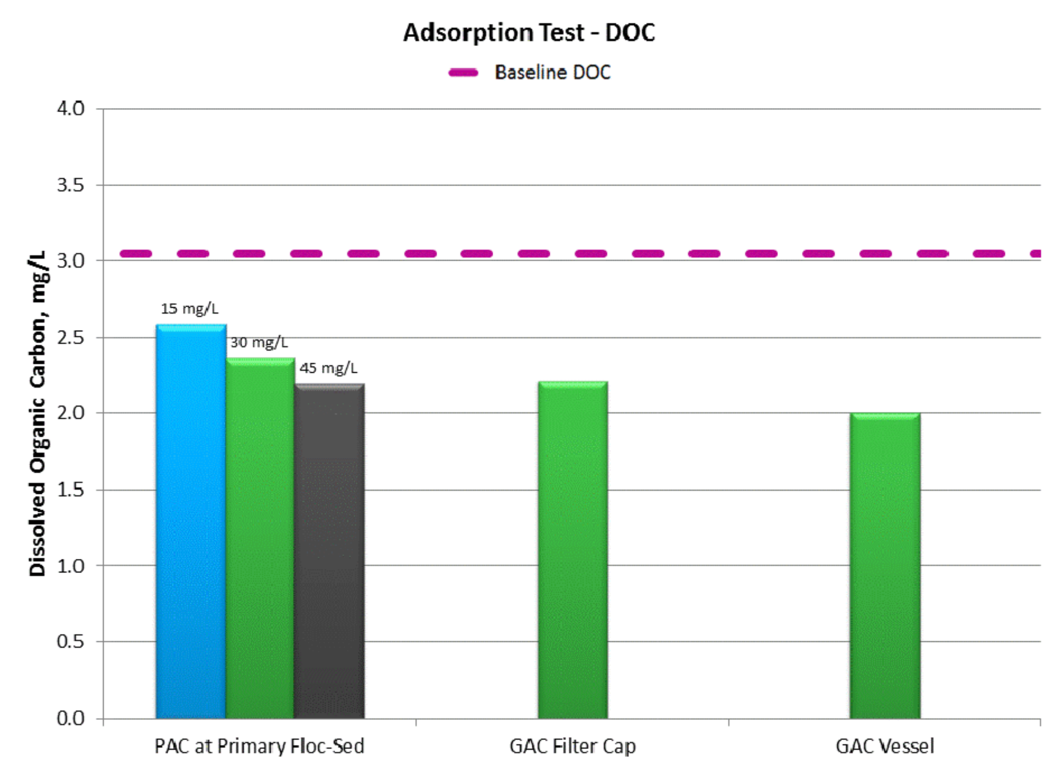
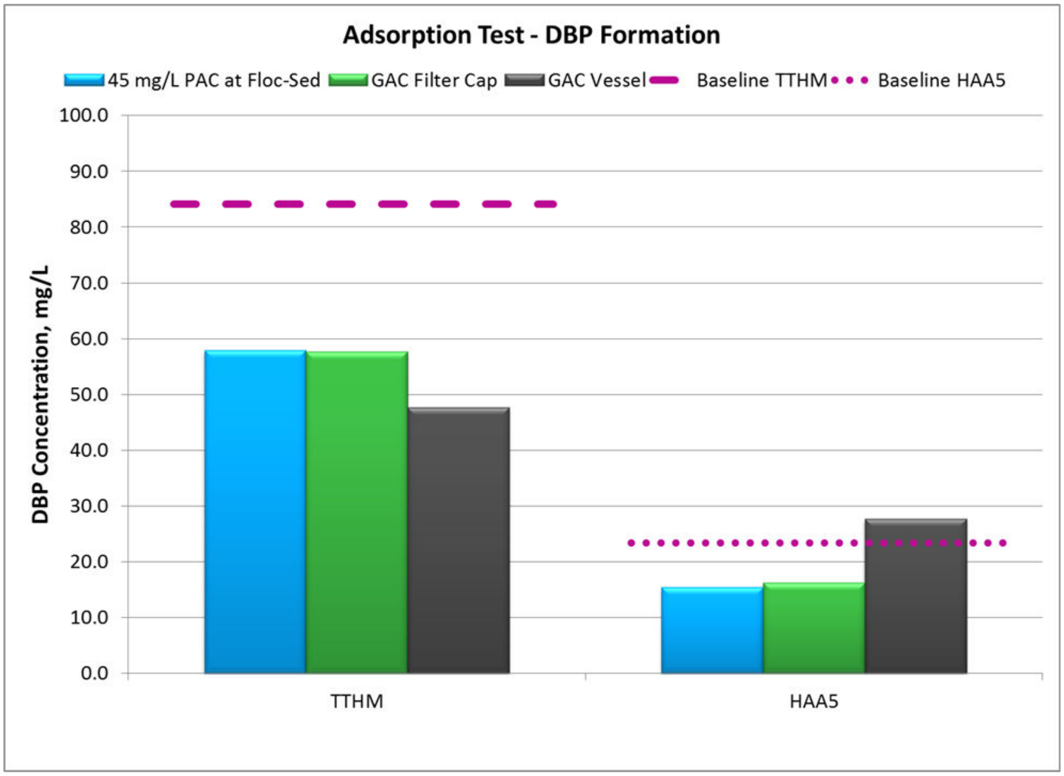


Figure 4-7. DOC Results for the Adsorption Tests with PAC and GAC

Disinfection byproduct testing was used to compare the 45 mg/L PAC dose and the two GAC scenarios for their abilities to reduce the formation of TTHMs and HAA5s, and in the case of the GAC vessel (pre-chlorinated) its ability to remove pre-formed DBPs. The PAC dose of 45 mg/L and the GAC filter cap (non-chlorinated) both demonstrated similar performance, with approximately 31 percent reduction in TTHMs and 30-35 percent reduction in HAA5 when compared to the baseline. The GAC vessel simulating removal of pre-formed DBPs showed a reduction of TTHMs by 43 percent, but an increase of HAA5s by 18 percent, when compared to the baseline. The increase in HAA5s relative to the baseline is likely attributed to the source water used to evaluate the GAC vessel. The GAC vessel simulation used filter effluent, which had been pre-chlorinated and subsequently quenched, whereas the baseline was conducted using raw water. Chlorine addition upstream of the filter effluent sampling location could have contributed to elevated DBP levels in the filter effluent source water, compared to the raw water samples used to establish the baseline. Therefore, the comparison for HAA5s relative to each other for GAC and PAC should not be used to determine any significant conclusions at this time. Further analysis of DBP formation from the GAC vessel simulation will be confirmed through additional GAC pilot testing.



**Note the GAC Vessel testing included pre-chlorinated water resulting in higher pre-formed DBPs. Therefore, the results should not be compared directly to PAC or GAC Filter Cap (non-chlorinated samples)*

Figure 4-8. DBP Formation for the Adsorption Tests with PAC and GAC with 5-day SDS.

4.5 ALTERNATIVE APPROACHES

Alternative treatment technologies known to remove dissolved organic compounds include reverse osmosis (RO) and ion exchange resins. Aeration of pre-formed DBPs was also evaluated as an alternative treatment technique as proof of concept.

4.5.1 Reverse Osmosis

In reverse osmosis, dissolved solids are removed by pressurizing water through a semi-permeable membrane. The portion of flow that passes through the membrane is known as permeate, and the flow rejected by the membranes is known as concentrate. RO membranes typically remove 95 percent to 99 percent of total dissolved solid and dissolved organics. In order to meet the treatment objectives for TTHMs and HAA5s, only a portion of the plant flow would need to be treated by reverse osmosis. Even with partial treatment, this process is highly energy-intensive due to the feed pressure required to force the water through the RO membranes. Additionally, the concentrated brine stream generated by the RO membranes may require special disposal considerations.

RO simulations evaluated under bench scale testing included operating scenarios where 25 percent and 50 percent of the total plant flow would be treated through reverse osmosis.

4.5.2 Ion Exchange Resin

Magnetic ion exchange resins are an emerging technology that have been designed specifically for removing negatively charged DOC in order to limit the formation of DBPs in downstream processes.

This process involves conveying source water through an ion exchange resin bed in a tank reactor configuration. One of the benefits of ion exchange resin is that it can potentially reduce coagulant usage by 50 percent or more. However, the process requires regeneration of ion exchange resin, which results in a brine waste stream.

Ion exchange resin was tested over two bed volume treatment rates and varying coagulant dosages. The optimal condition using ion exchange resins was found to be the 667 bed volume treatment rate with 20 mg/L coagulant.

4.5.3 Aeration

This alternative considers the volatilization of pre-formed DBPs by means of an air stripper or spray aerators located in the distribution system. Aeration techniques, however, are only effective for removing volatile THMs, primarily chloroform, and are ineffective for removal of HAA5s. In order to pre-form the DBPs for bench-scale testing, aeration was conducted at the end of the 5-day SDS testing. Lab testing of aeration showed the removal of a significant percentage of TTHMs in the sample, but was ineffective at removal of HAA5s. Lab evaluation of aeration provides a general basis for removal of pre-formed TTHMs. However, the agitation and air volume used in laboratory settings are difficult to simulate full scale installation. Therefore, additional testing utilizing equipment from an aeration supplier should be used to more accurately predict the results. Published data on tank aeration show the potential of 30-50% removal of TTHMs if a properly installed system is used. However, initial discussion with MDNR has indicated that aeration that results in suspended water particles in the air may eliminate the ability to achieve disinfection credits in the reservoir. If aeration appears viable further discussion with MDNR related to disinfection and aeration will be required.

4.5.4 Comparison of Alternative Approaches

Figure 4-9 summarizes the DOC results for the RO membrane and ion exchange resin technologies. Aeration is not shown in the table as the results from the lab evaluation were not applicable when comparing to the other alternatives. Based on the measured DOC values, all three alternatives showed significant reduction in DOC compared with the baseline of 3.05 mg/L from coagulant testing. When compared to the baseline, DOC was reduced by 28 percent and 50 percent when simulated for RO treatment of 25 percent flow and 50 percent flow, respectively. The use of ion exchange resin reduced DOC by 26 percent when compared to the baseline.

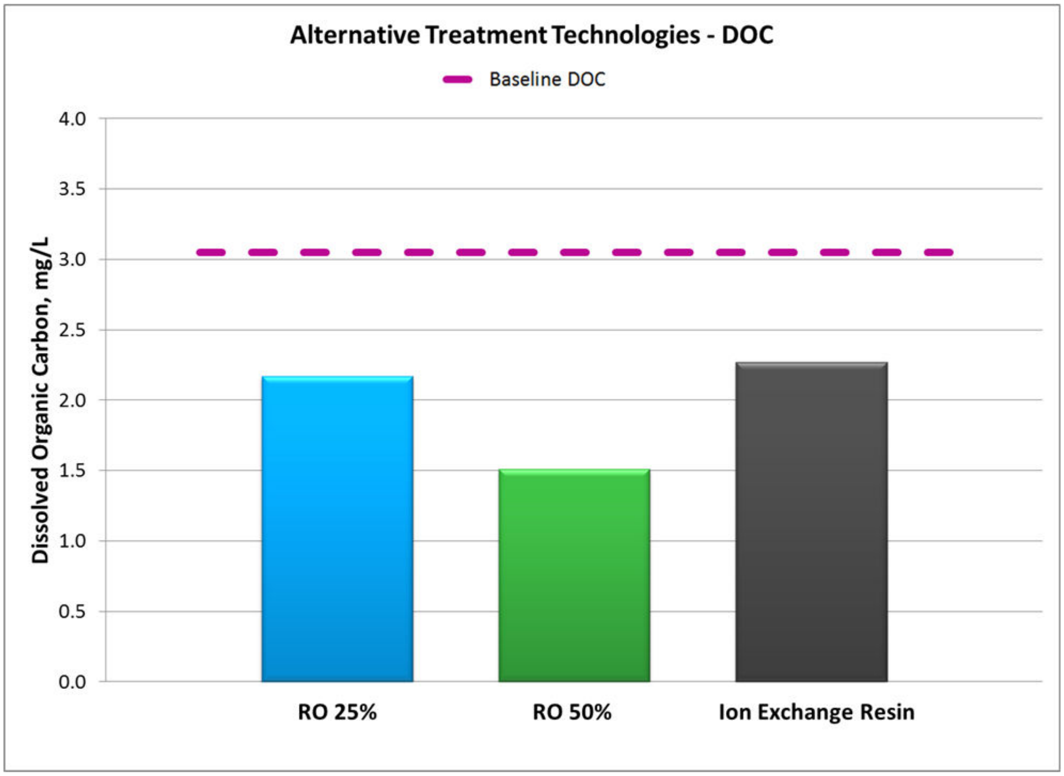


Figure 4-9. DOC Results - Alternative Treatment Technologies

All three conditions considerably reduced DBP formation as shown in Figure 4-10. RO treatment of 25 percent flow reduced TTHMs and HAA5s by 22 percent and 18 percent, respectively, when compared to the baseline. Of the alternative treatment technologies, treating 50 percent of the total plant flow through RO had lowest TTHMs and HAA5s after SDS testing. RO treatment of 50 percent flow reduced TTHMs and HAA5s by 44 percent and 40 percent, respectively, when compared to the baseline. The use of ion exchange resin reduced TTHMs and HAA5s by 25 percent and 31 percent, respectively, when compared to the baseline.

However, it should be noted that chlorine residual after 5-day hold period did not yield expected 0.2 mg/L residual. Therefore TTHM and HAA5 values included in this report are an underestimate of the levels that will form in the distribution system.

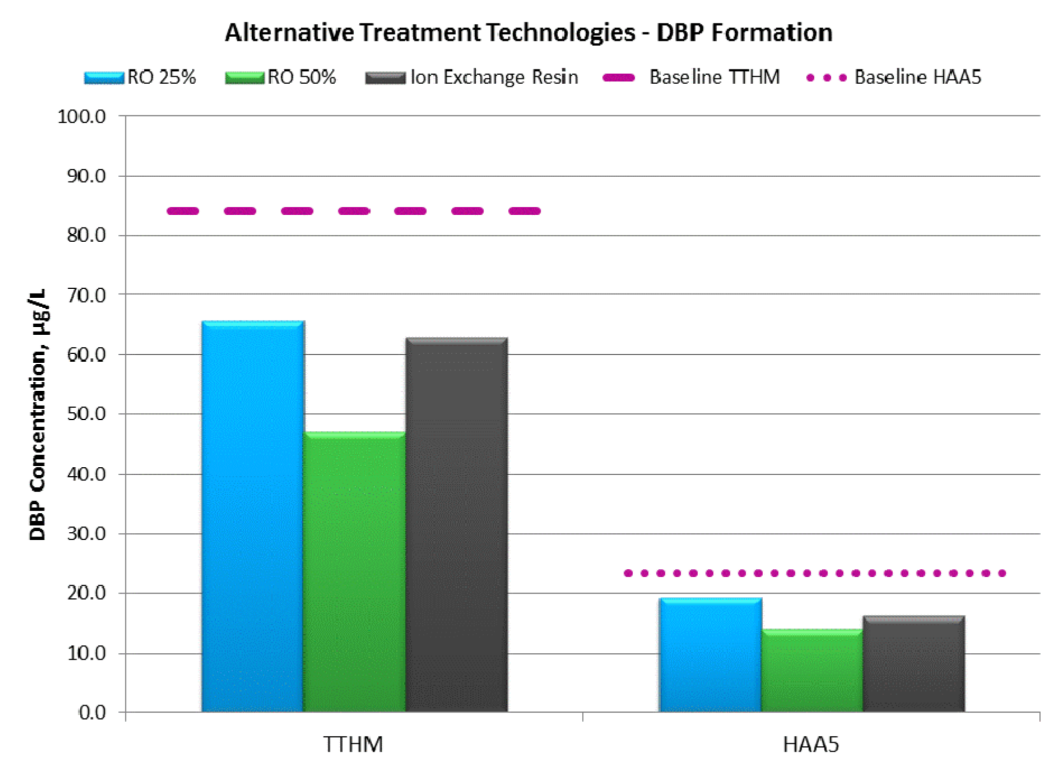


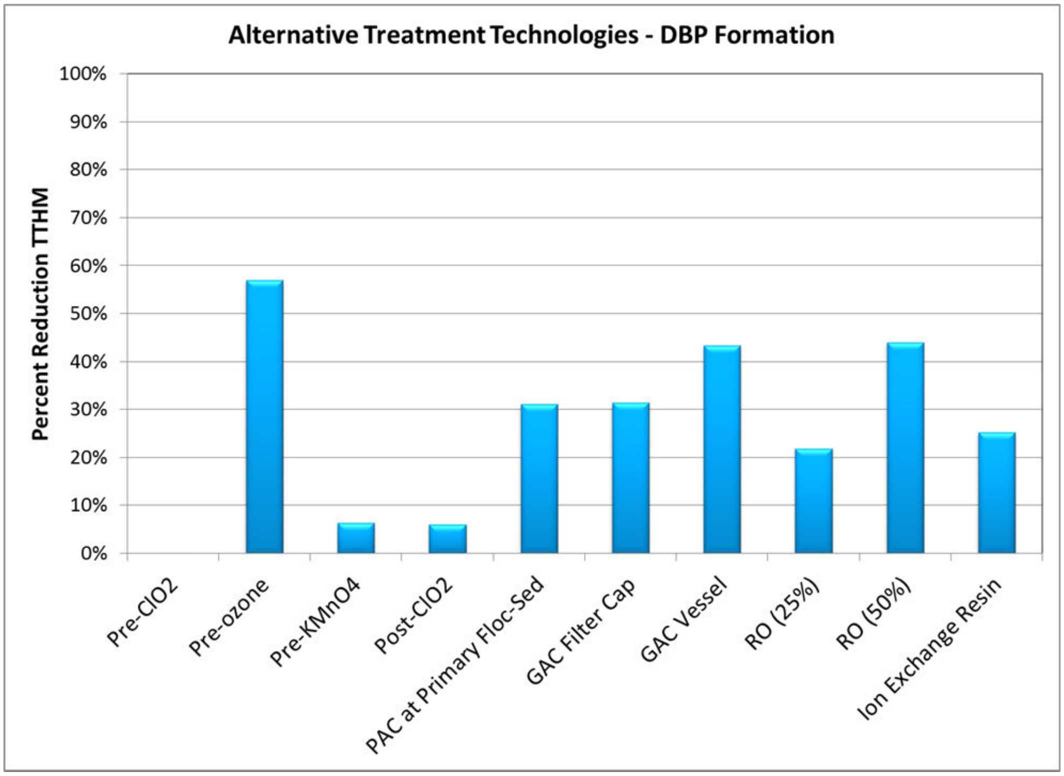
Figure 4-10. DBP Formation - Alternative Treatment Technologies with 5-day SDS

4.6 SUMMARY OF SCREENING ALTERNATIVES

4.6.1 Overall Performance of Potential Solutions

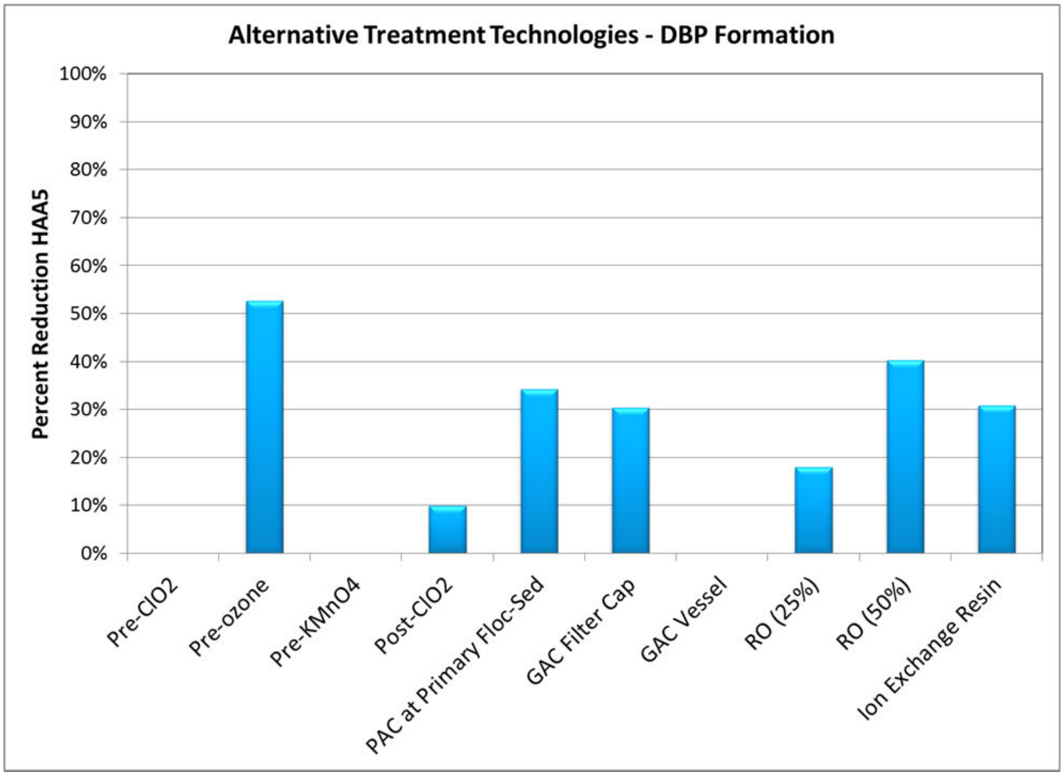
Figure 4-11 below shows the percent reductions of TTHMs when compared to the baseline for the optimized dose for the alternative treatments evaluated in this initial screening report. Similarly, Figure 4-12 below shows the percent reductions of HAA5s when compared to the baseline for the optimized dose for the alternative treatments.

The percent reductions of DBPs shown below in provide a basis for comparison between different treatment alternatives so as to determine which treatment alternatives should be further investigated. These results however are not meant to represent exact reductions that would be observed at the WTP. The bench scale testing attempts to simulate conditions at the WTP, but the resulting reductions in DBP precursors or DBPs are only useful for direct comparisons with other testing conditions at this time. Future testing will further define which alternatives are capable of meeting treatment objectives.



Note: Negative TTHM reductions are not displayed, as the y-axis begins at zero percent.

Figure 4-11. TTHM Reduction for All Alternatives Relative to Baseline Conditions



Note: HAA5 reductions are not displayed, as the y-axis begins at zero percent. No reduction shown for GAC Vessel but should be noted not comparable to other alternatives as source water had pre-formed DBPs

Figure 4-12. HAA5 Reduction for All Alternatives Relative to Baseline Conditions

4.6.2 Alternatives Eliminated from Further Evaluation

Treatment alternatives were eliminated from further evaluation if they either did not result in significant improvements for reduction of DBP precursors (DOC) or DBPs (TTHMs and HAA5s) compared to current operating conditions (i.e. baseline), or if the expected cost of implementation was high, relative to performance benefits. Based on these criteria, the following alternatives are not recommended for further evaluation at this time.

1) <u>Ferric sulfate:</u> Ferric sulfate is being eliminated as an alternative coagulant due to relatively low performance for reduction of DOC, TTHMs, and HAA5s, when compared to the plant's current coagulant.

2) <u>Increased PAC Dose:</u> Increasing the dose of powdered activated carbon applied upstream of the primary rapid mix basin provided marginal benefits for reduction of DOC, TTHMs and HAA5s. Current dosages will remain as it controls taste and odor causing compounds and does remove some DOC.

3) <u>Increased Coagulant Dose:</u> Increasing the dose of current coagulant (DFLOC 3606) was relatively ineffective at reducing DBP formation, relative to increased operational costs.

4) Permanganate: Permanganate as a pre-oxidant is being eliminated since it was ineffective at reducing DOC and is unable to earn CT credits to reduce required chlorine contact time. Intermittent permanganate use serves other process benefits such as oxidation or iron and manganese.

5) Chlorine dioxide: Chlorine dioxide is being eliminated as a pre-oxidant and as a post-oxidant, as it provided negligible improvement when compared with the baseline.

6) Reverse Osmosis & Ion Exchange Resins: RO and ion exchange resins are not being considered further due to the high cost of these solutions. While both technologies provided excellent removal of DOC, thus reducing the DBP formation in SDS testing, the overall percent reductions were comparable to other technologies that are considerably more cost efficient and operationally less complex. If, however, future testing of alternatives reveals the inability to meet treatment objectives and/or become more costly these alternatives may be reconsidered.

4.6.3 Approach for Further Evaluation of Treatment Alternatives

The following summarizes the recommended alternatives for further evaluation and proposed testing approach for each of the alternatives:

1) Alternative coagulant – DFLOC 3606: This coagulant slightly outperformed the plant's current coagulant, DFLOC 3610. Additional bench scale testing of the DFLOC 3606 at 40 mg/L will be conducted to evaluate DBP formation through SDS testing. To provide a baseline comparison, the same testing will be conducted using the plant's current coagulant at an equivalent dose.

2) Ozone: Ozone was selected for further evaluation as it substantially lowered the DOC and reduced the formation of both TTHMs and HAA5s. Ozone will be tested as both a pre-oxidant and intermediate oxidant at lower dosages to determine the optimal dose and application point in the water treatment process. Additional testing will evaluate whether the ozone system should be designed for the ozone demand caused by organics in the source water or for disinfection credits, as it would impact the size and cost of required equipment.

3) GAC: Bench scale testing conducted as part of this evaluation was used to only compare the relative impact of pre-chlorinated and non-chlorinated samples using GAC, as specific testing is required to determine effectiveness of a GAC system. The results from accelerated column testing from the May 12, 2017 sample period will provide the initial effectiveness of GAC for removal of DOC and estimate of bed life. It is anticipated pilot testing and one additional sample of accelerated column testing will be conducted to confirm effectiveness and costs of the GAC system. Samples will be collected to mimic both GAC filter caps and post-filter GAC vessels. The duration of the pilot will be confirmed with MDNR.

4) Aeration: The aeration testing proved effective at removal of TTHMs, with no removal of HAA5s. Reviewing the systems historical HAA5s there may be a possibility to meet compliance by reducing HAA5s by a smaller percentage if the TTHMS can be removed using aeration. A testing protocol will be developed with an aeration system manufacturer to conduct testing at the site to provide more accurate results from aeration. In addition,

further evaluation of previous reports and white papers will be conducted to define the expected reduction in TTHMs from tank aeration within the distribution system.

Subsequent testing will be conducted to further evaluate the selected treatment alternatives mentioned above. SDS testing will be repeated using multiple chlorine dosages to obtain measurable residuals at the end of the 5 day hold period. It is anticipated that the next round of sampling will occur towards the end of July.

5.0 Distribution System Modeling

Distribution system modeling was performed to evaluate the water age characteristics within the distribution system during a late summer/early fall condition. Distribution system water age modeling is useful as it can provide a surrogate parameter to estimate the potential for disinfection by-product formation. This modeling requires a predictive and up to date hydraulic model with accurate demands that simulate distribution system conditions. Although a hydraulic model had previously been developed, it was based on information for pipelines and demands that had subsequently been updated so it was necessary to reconstruct the model to more accurately represent current system behavior, inventory, and demands.

The purpose of the system modeling for this initial findings report is to update the existing model to the current conditions that accurately reflects the piping network and customer demands to establish a baseline water age to be used when conducting DBP testing. In addition, this analysis developed potential modifications to the operation of the existing system to reduce water age that do not require infrastructure improvements.

Based on the results of future testing at the treatment plant, if water age needs to be further reduced within the system to lower DBP formation additional analysis will occur that may result in infrastructure improvements such as modifying storage volumes, changes in pressure zone boundaries, water line interconnections, and flushing hydrants. The extent of these infrastructure improvements will be determined in future evaluations.

5.1 MODEL DEVELOPMENT

GIS files were provided for the current distribution system pipeline and valve inventory. Data on the booster pumping stations and tank characteristics were also provided. The model was constructed using this system inventory and facility data. The pipeline network was first constructed using GIS techniques and then facilities were added manually to the model using the characteristics provided. Background information and descriptions of pressure zones were also obtained from the report titled Hannibal Water Distribution System Extended Period Simulation Model Development and Calibration Report, prepared by Horner & Shifrin, April 2014.

Automated meter reading (AMR) data from September 2016 was used to allocate system demands. This AMR data provided a usage over approximately a week time period and a point location of where this usage occurred. In addition, usage data for several manually read meters was provided along with the customer address to allocate to the model. Demands were then allocated to their spatial locations within the distribution system.

The model was reviewed with City staff to identify all of the boundary conditions between the zones and to ensure that the flow of water from the model results would relate to how the system is truly operated. In a conference call workshop, City staff provided clarification to all boundary conditions and verified the model boundaries represented the system boundaries at all locations.

5.2 DIURNAL DEMAND DEVELOPMENT

Supervisory control and data acquisition (SCADA) data was provided for the week of September 16-25, 2016 that included hourly tank water levels and booster station runtimes. Additional data was provided in regards to the total flows at the New London Gravel, Head Lane, and Ely Street daily total consumption meters along with the Paris Gravel and Southside Booster Station daily totalized flows. Daily records of plant operations for the month of September, 2016 were also provided.

From the daily records it was noted that the overall demand during this time period was approximately 4.5 mgd with almost 60% of the demand being supplied to the Low Service.

The SCADA data was also used to determine hourly usage characteristics and patterns for the system. Because hourly flow data for the High Service WTP pumping and the gravity flow into the Low Pressure Zone were not available, staff provided SCADA screenshots of June, 2017 daily flows for four days. This data was used to identify a usage pattern that varied over the course of the day and was applied to the daily totalized flow into the High and Low Pressure Zones.

The final diurnal demand characteristics that were included in the model for the water age modeling are shown in Figure 5-1. As can be seen in this figure, there is an increased usage in the morning hours that dips slightly through the day and then another evening peak that is higher but experienced over a shorter duration. Southside and Paris Gravel Zones contain a minimal amount of demand relative to the High and Low Pressure Zones. This overall system usage pattern is similar to other cities with similar characteristics. It is important to note that during high irrigation times of the year, such as early to mid-summer, the morning peak may shift slightly to an earlier hour and could be higher or almost equivalent to the evening peak.

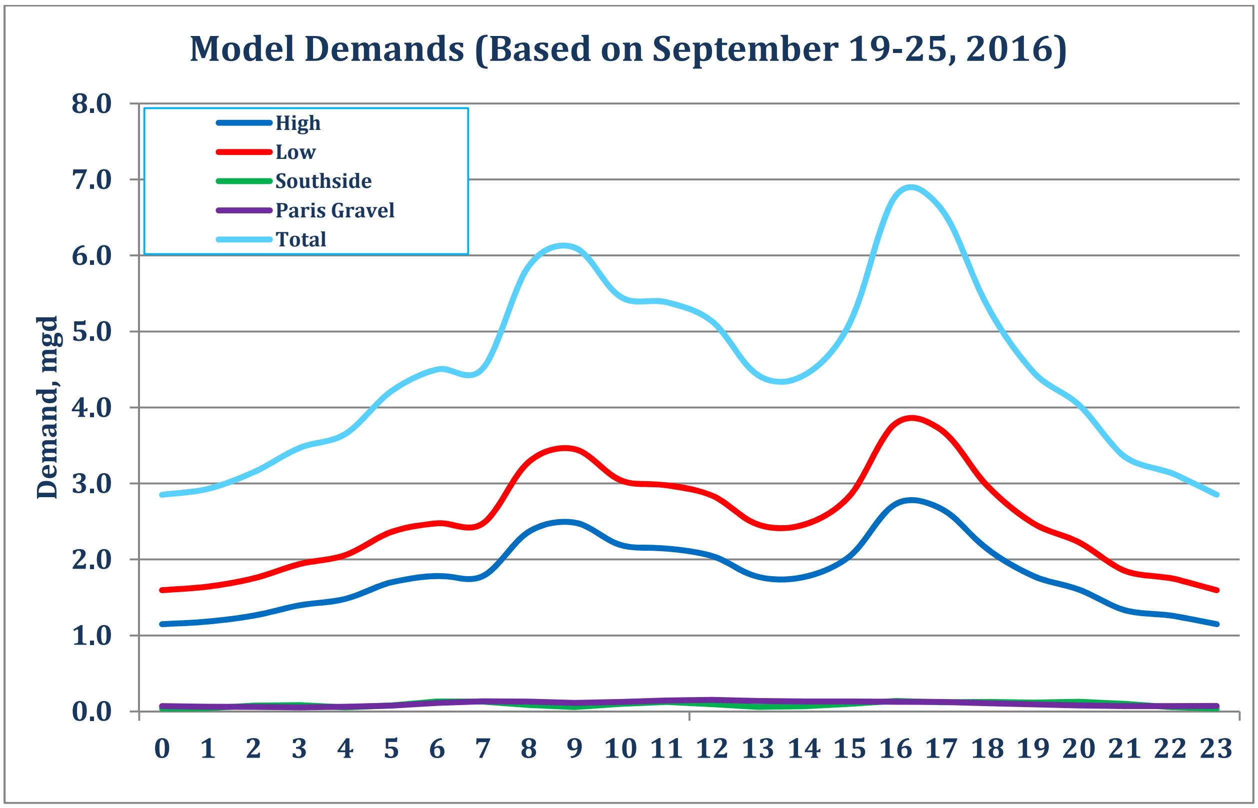


Figure 5-1. Hannibal Diurnal Model Demand Characteristics

5.3 MODEL CONTROL DEVELOPMENT

The SCADA data, and anecdotal information provided by City staff, was used to develop the model controls to be used in the water age evaluations. The most useful information was the tank water levels and this was used to iteratively develop controls for the base scenario that would mimic the system behavior as seen in September, 2016.

Figure 5-2 shows the tank water levels from September 19 through September 25 of 2016. Figure 5-3 shows the modeled tank water level results after iteratively modifying the model controls for a 24-hour period. Controls were simplified to repeat in order to provide the ability to simulate several days and weeks in a row which is necessary for water age model results to reach equilibrium.

As can be seen from these figures, the modeled tank water levels closely represent the observed tank water levels with slight deviations. The most notable deviation is that the Clinic Road Tank. Over the course of a weeklong extended period simulation (EPS) the tank cycled three times while the actual observed cycle was closer to 2 times. However, the same range of water level was achieved in the model as was observed in the system. Indian Mounds and Veterans Road tanks cycled at a slightly different range on day 3 of the observed behavior before again stabilizing at the same range as cycled in the model results. Warren Barrett tank model results range a bit more than the observed behavior as well. However, the differences were minor and overall the average cycle and ranges of the tanks were achieved in the model when compared to the observed results.

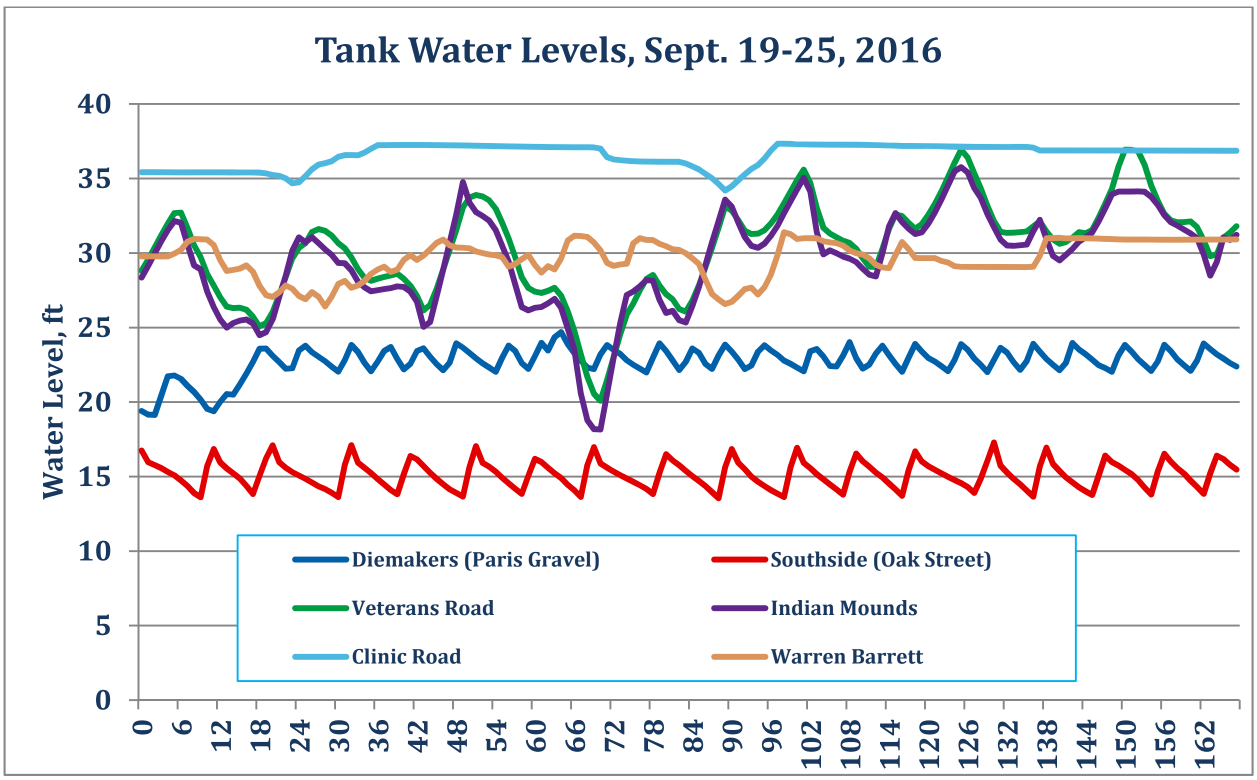


Figure 5-2. Observed Tank Water Levels

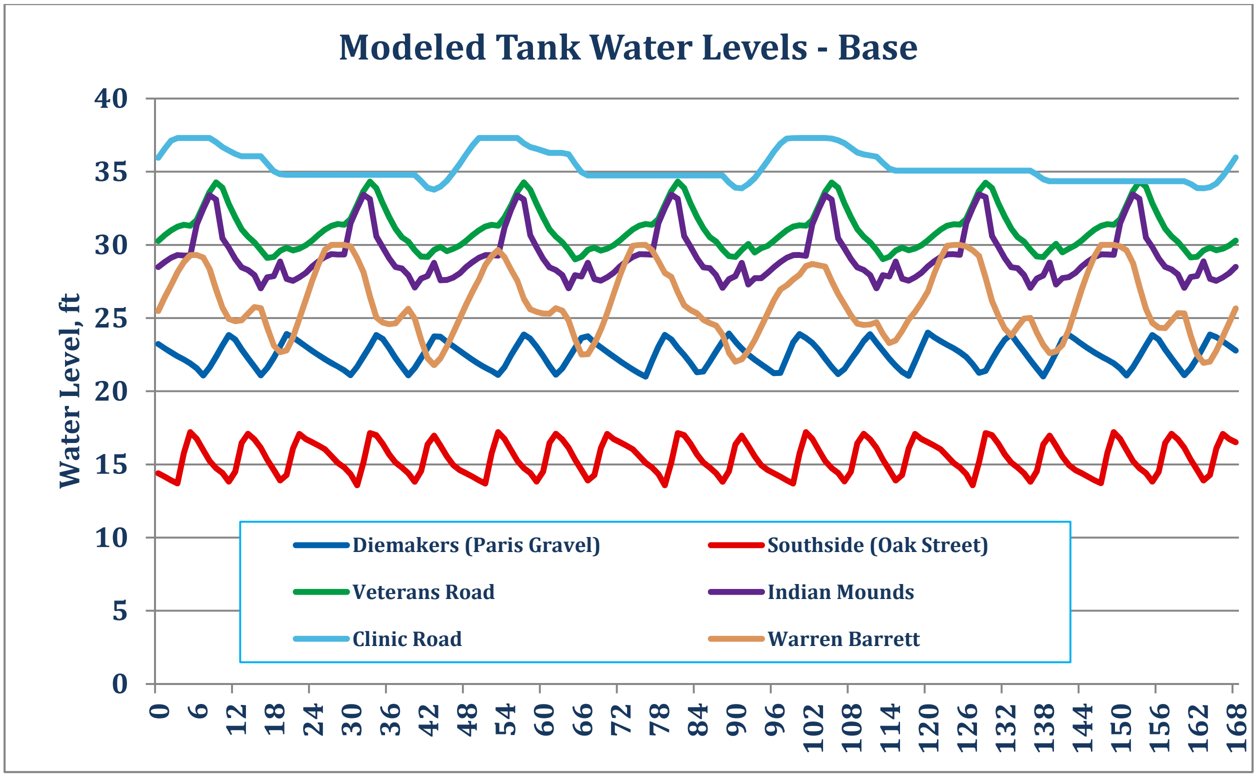


Figure 5-3. Modeled tank water levels – Base Conditions

5.4 WATER AGE RESULTS (BASE CONDITIONS)

The model EPS scenario of 24-hours was repeated for several weeks in order to achieve water age equilibrium in the model under current conditions. Figure 5.4 provides the water age results for tanks over the last week of the simulation. As can be seen from this figure, most of the storage residing in tank averages approximately 5 days of residence time with the exceptions of Veterans Road tank at the periphery of the High Pressure Zone and the Clinic Road tank because of the extremely low turnover these areas experience.

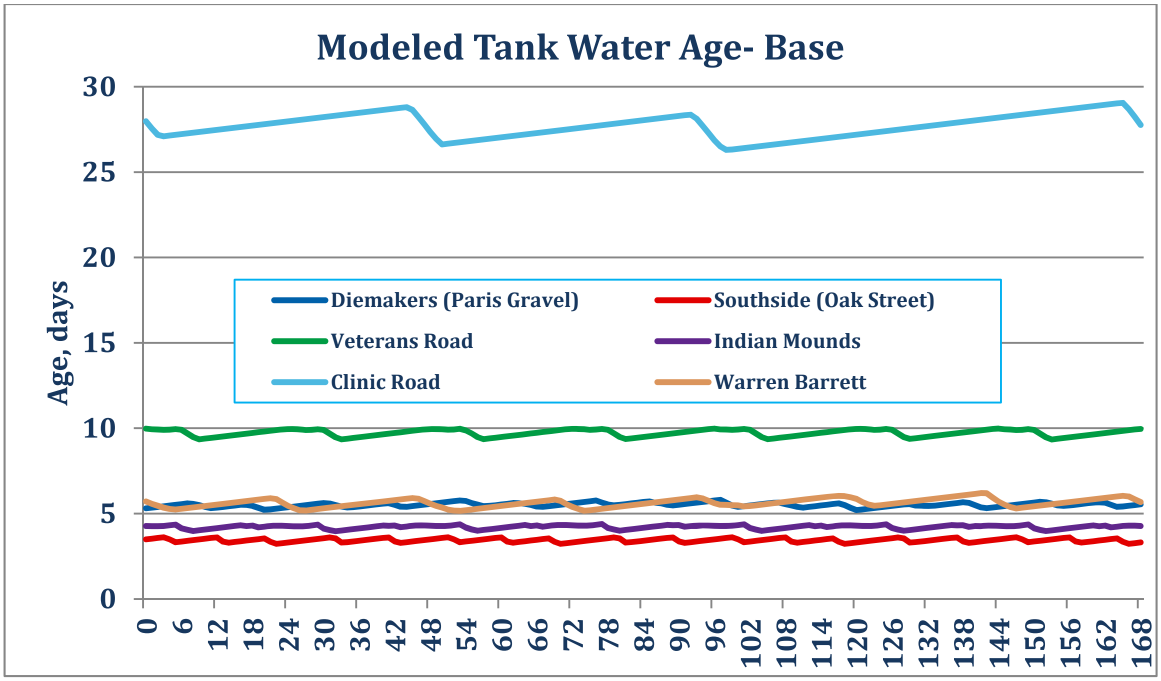


Figure 5-4. Modeled Tank Water Age

The water age experienced in the distribution system was developed into figures showing the average water age at any specific location experienced over the last week of the simulation (Figure 5.5) and the maximum instantaneous water age experienced at any location during the last week of the simulation (Figure 5.6). As expected from the results of Figure 5.4, the areas near Veterans Road tank and Clinic Road tank experience some of the highest instantaneous water age. Additionally the Southside and Paris Gravel Pressure Zones see the highest average water age. Many of the DBP compliance sample points, most notably the Hannibal Regional Hospital location, are in the highest water age areas.

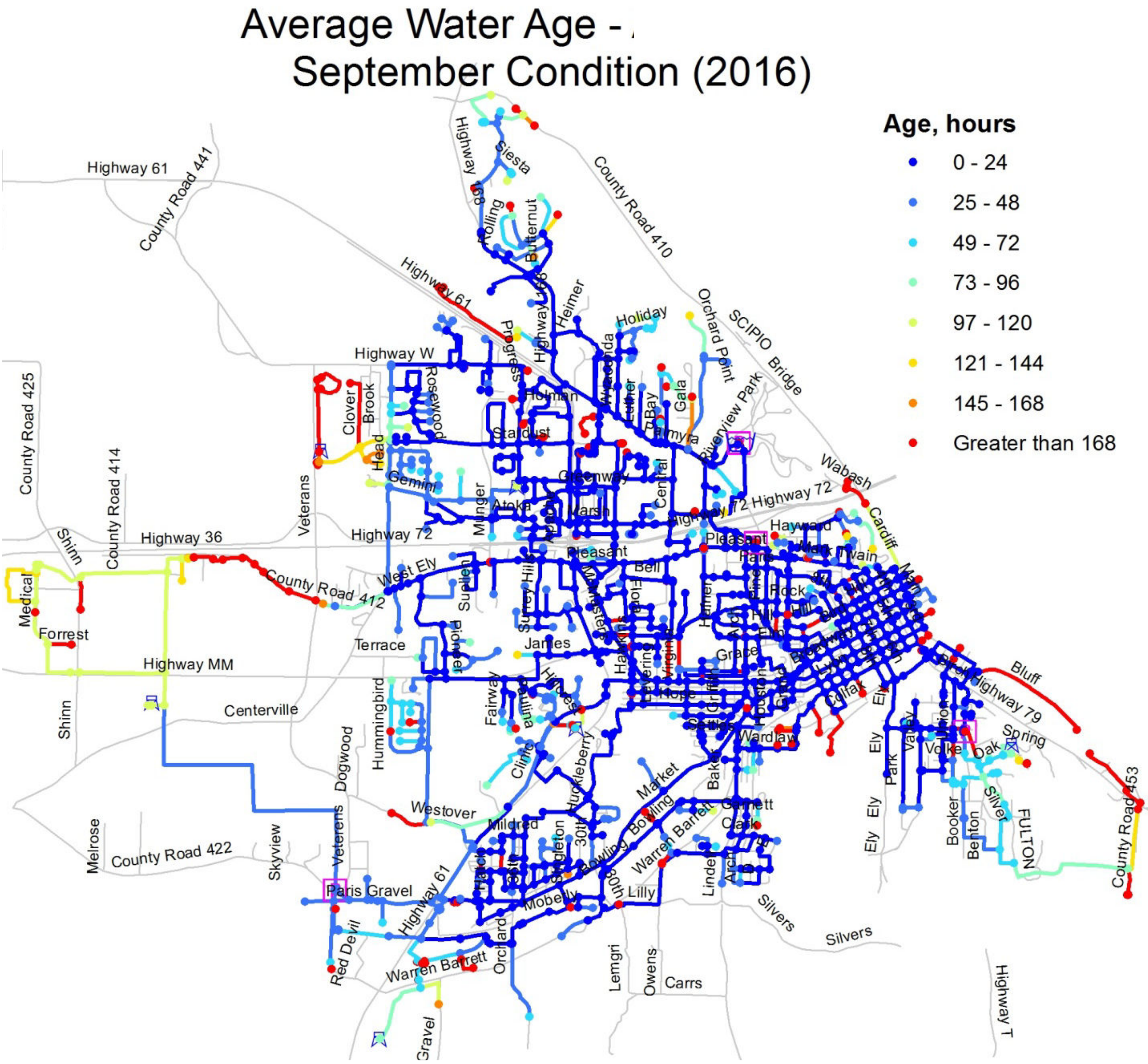


Figure 5-5. Average Distribution System Water Age (Base Concept)

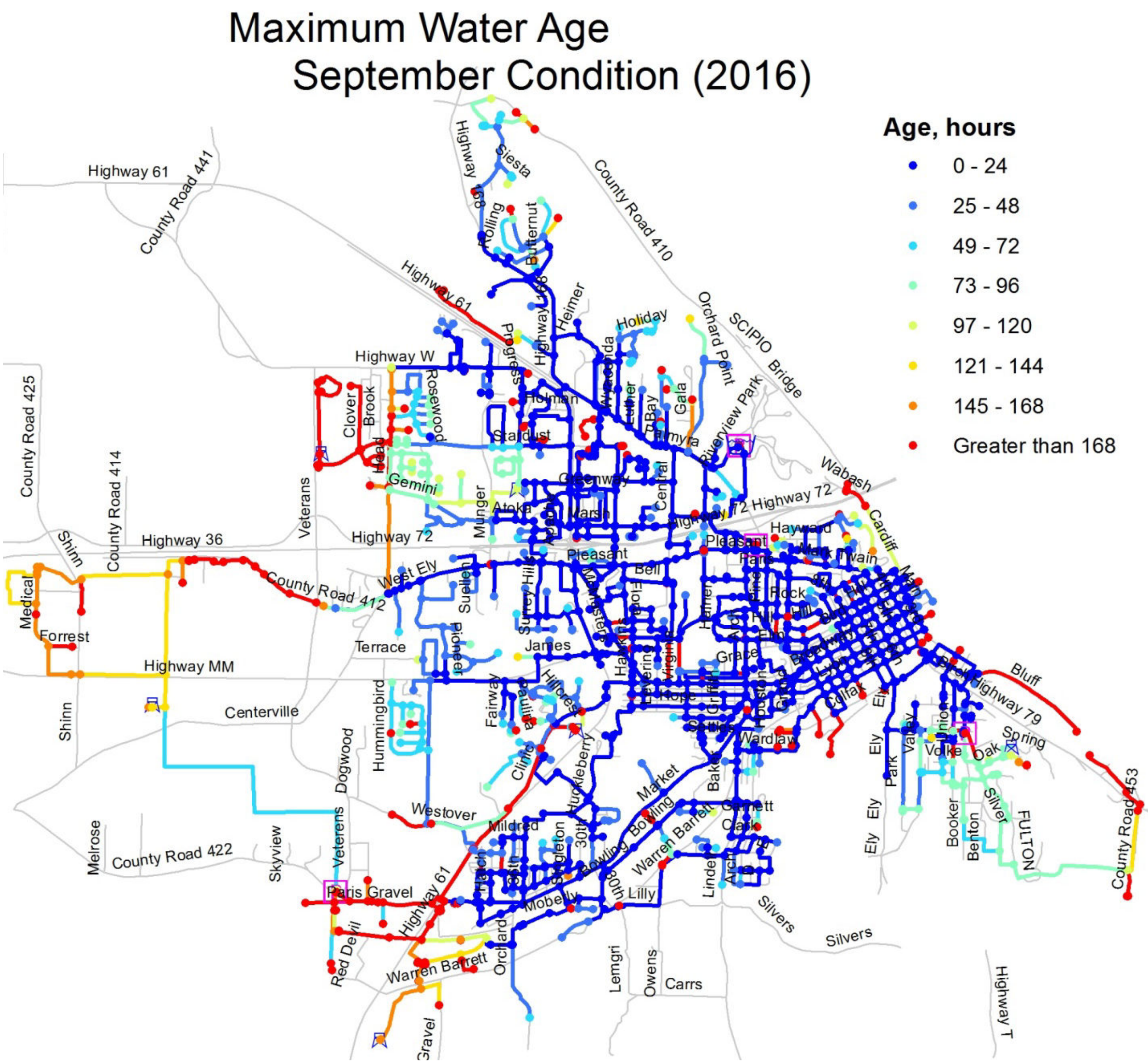


Figure 5-6. Maximum Distribution System Instantaneous Water Age (Base Concept)

5.5 WATER AGE RESULTS (ALTERNATIVE 1)

To evaluate the impact of changing operations without infrastructure improvements an operational alternative was evaluated. This scenario removed the Clinic Road tank from service but maintained the same controls as the base scenario. The removal of Clinic Road tank will identify how the decrease in system volume will impact the system water age. The hydraulic impact of the removal of the Clinic Road tank was illustrated by graphing the tank water levels, similar to Figure 5.2.

Figure 5.7 shows the tank water levels over the last week of the simulation. This scenario was almost identical to the hydraulic results of the base concept, except that the Warren Barrett tank cycles at a range of about 2 feet greater.

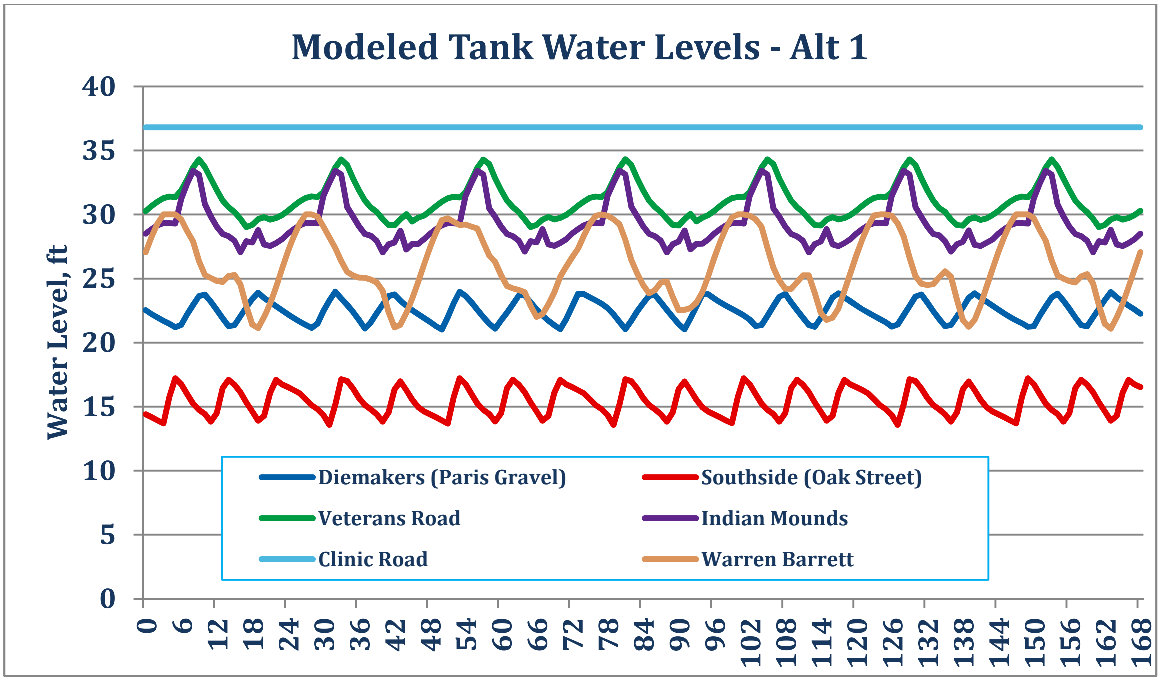


Figure 5-7. Modeled Tank Water Levels (Alternative 1)

The corresponding tank water age over the last week of the simulation and the distribution system water age (average and maximum instantaneous over the last week) for Alternative 1, without Clinic Road tank, are shown in Figure 5.8, Figure 5.9, and Figure 5.10.

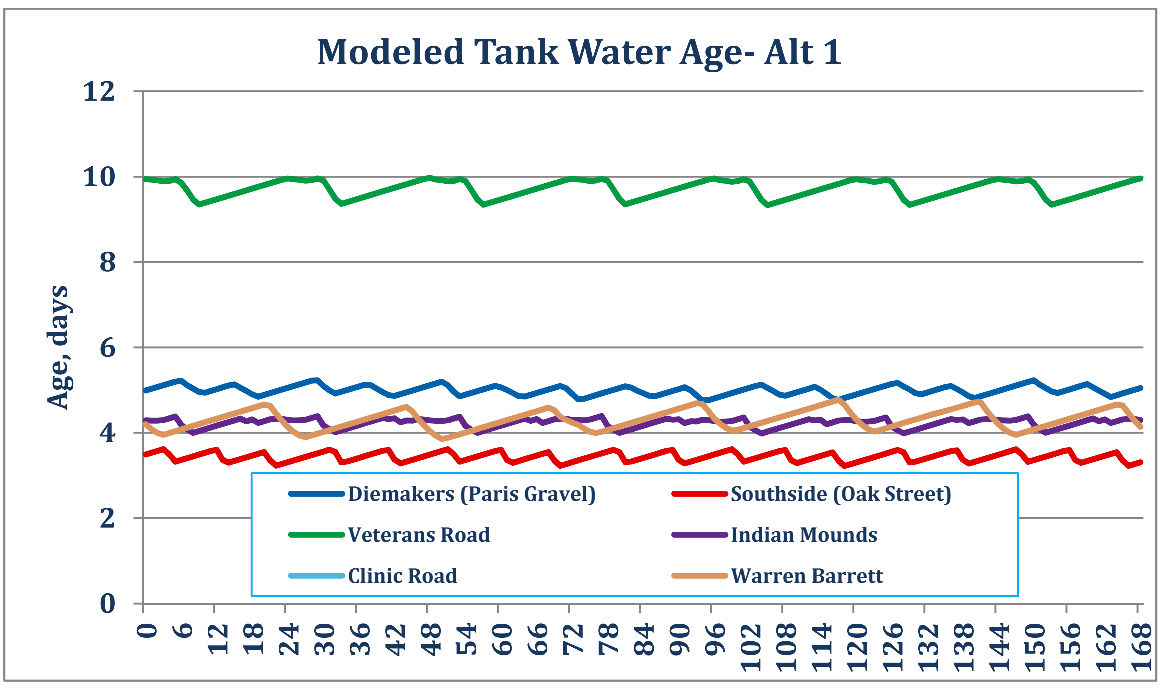


Figure 5-8. Model Tank Water Age (Alternative 1)

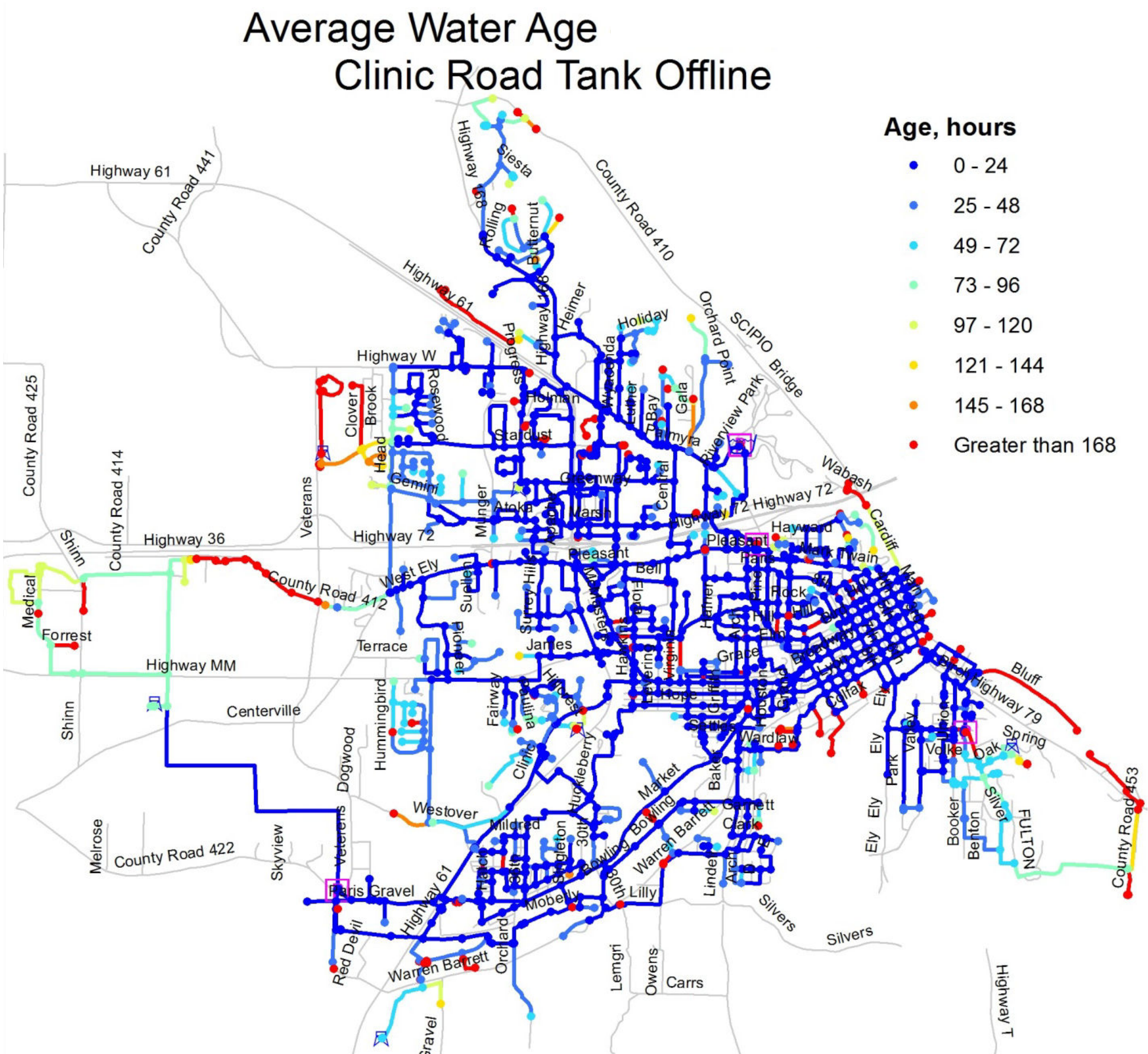


Figure 5-9. Average Distribution System Water Age (Alternative 2)

A comparison of the average water age for Alternative 1 to the base concept shows that the Paris Gravel Pressure Zone average age decreases by approximately 1 to 2 days. The average water age in the pipeline to the Warren Barrett tank and in the tank itself also decreases by about 1 to 2 days. This is important because two of the four THM sampling locations are in the areas that will see a reduction in water age, the Hospital on Highway 36, and at the Industrial Loop north of the Warren Barrett tank.

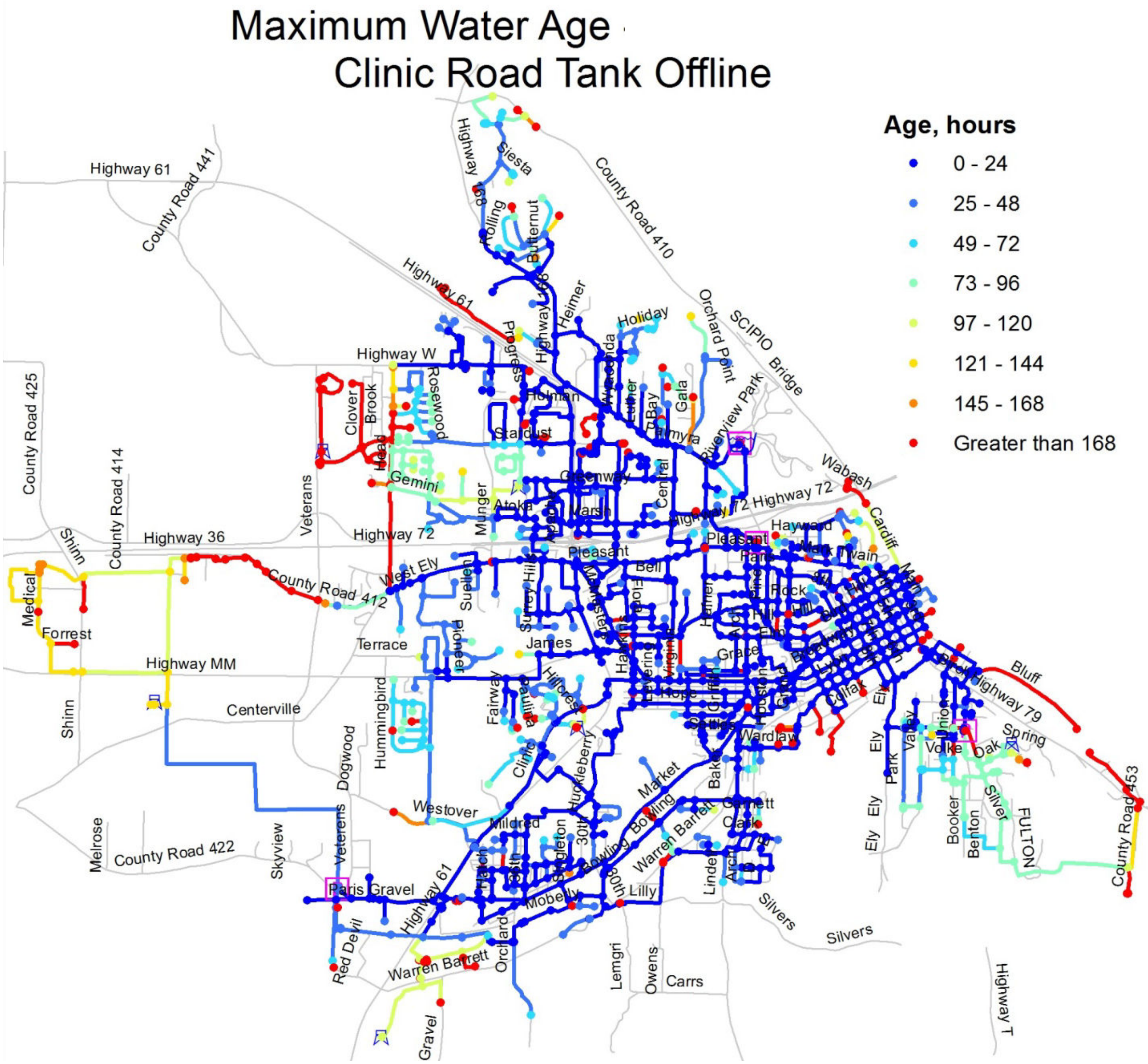


Figure 5-10. Maximum Distribution System Water Age (Alternative 1)

A comparison of the maximum instantaneous water age for Alternative 1 to the base concept shows that the Paris Gravel Pressure Zone maximum age also decreases by approximately 1 to 2 days. The maximum water age in the pipeline to the Warren Barrett tank and in the tank itself also decreases by about 1 to 2 days.

5.7 WATER AGE RESULTS (ALTERNATIVE 2)

This operational scenario was evaluated to determine how transferring water through the system differently might impact the water age. Because of the implications of removing the Clinic Road tank in terms of fire reserve capacity and emergency storage, as well as providing equalization storage, it was determined to leave the Clinic Road tank in the scenario but alter the operational controls. The valve that is open between the High and the Low Zones along St. Mary's south of Pleasant Street was closed. This will completely restrict the transfer of water between the High and Low Zones. In addition to this change, the water level ranges of the tanks in the High Zone were expanded a few feet. No changes were made to the controls for the Southside or Paris Gravel Zones. The resulting hydraulic behavior of the tanks in this alternative is shown in Figure 5.11.

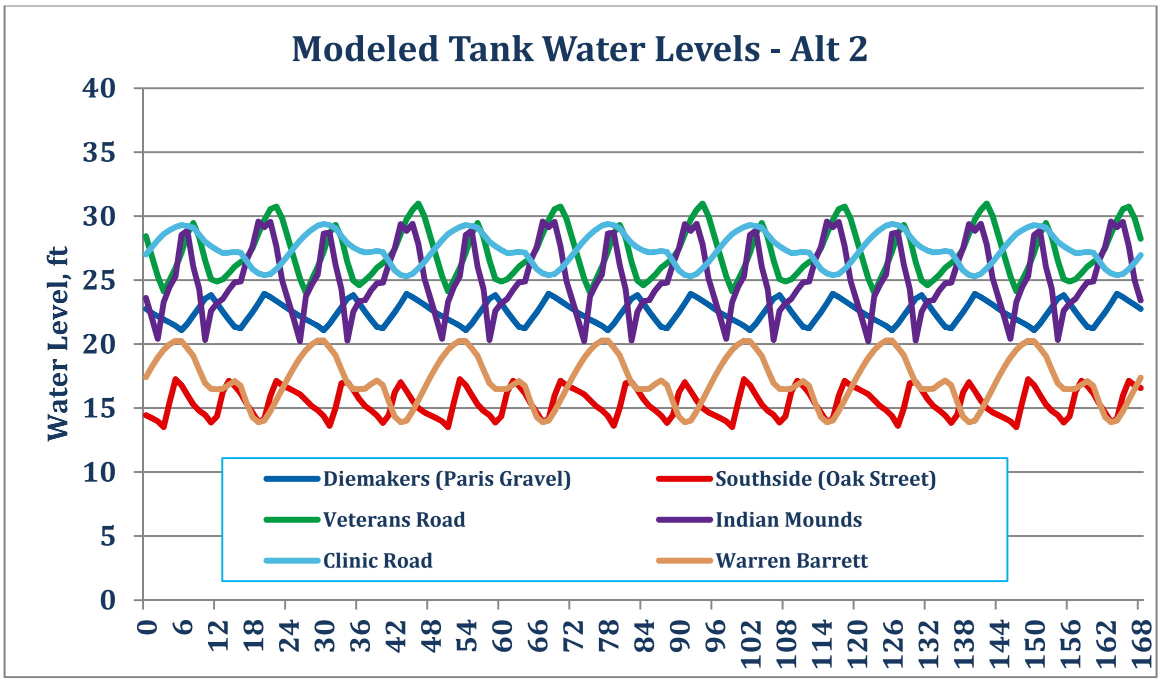


Figure 5-11. Modeled Tank Water Levels (Alternative 2)

The corresponding tank water age and distribution system water age for Alternative 2, with modified controls, are shown in Figure 5.12, Figure 5.13, and Figure 5.14.

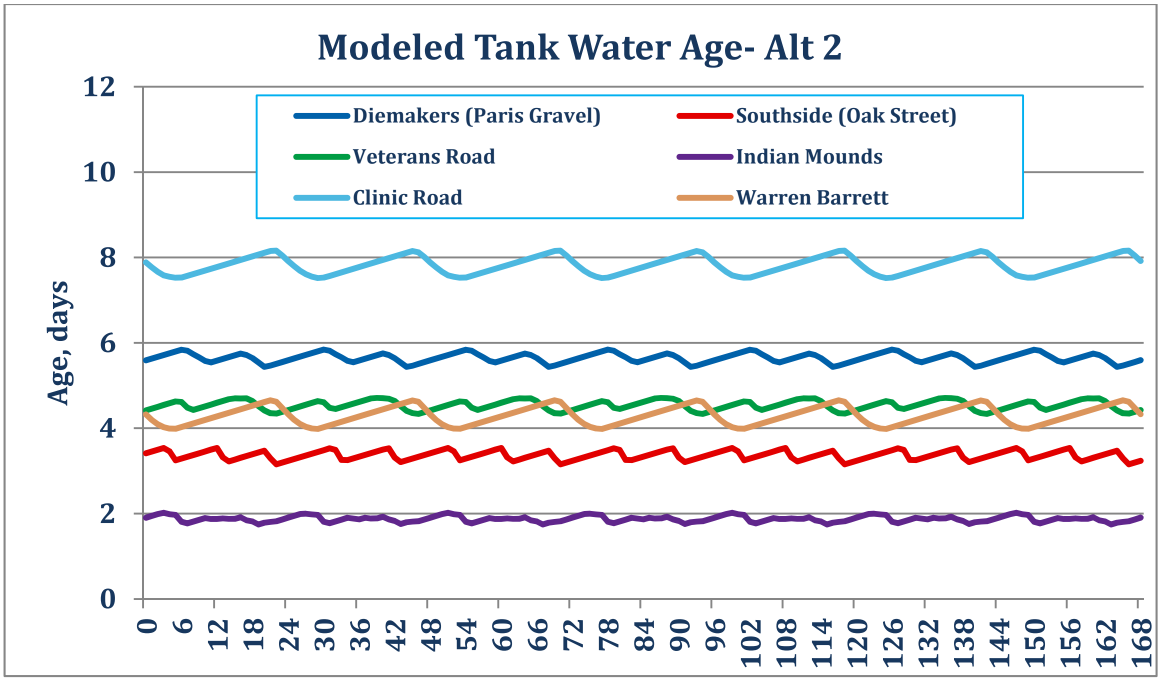


Figure 5-12. Model Tank Water Age (Alternative 2)

Review of Figure 5.12 shows that the greater cycling of Veterans Road and Indian Mounds, combined with the closing the High/Low valve leads to a great reduction of water age between all storage reservoirs in the High and Low zone when compared to base concept.

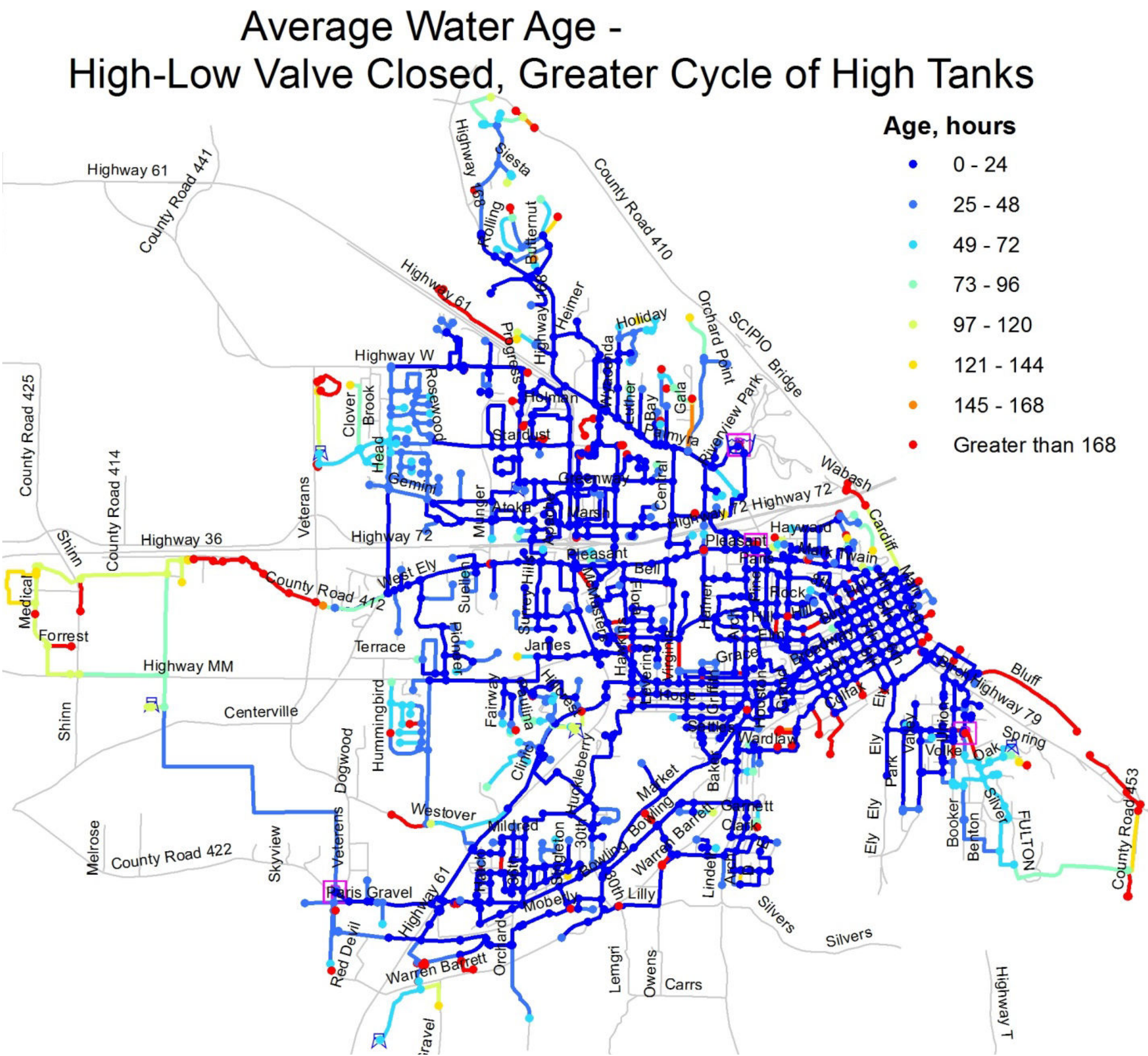


Figure 5-13. Average Distribution System Water Age (Alternative 2)

A comparison of the average water age for Alternative 2 to base concept shows that the Paris Gravel Pressure Zone average water age decreased almost a day. The area surrounding Veterans Road tank experiences a great reduction in water age. Areas near Clinic Road and Warren Barret tank also experience a reduction in average water age.

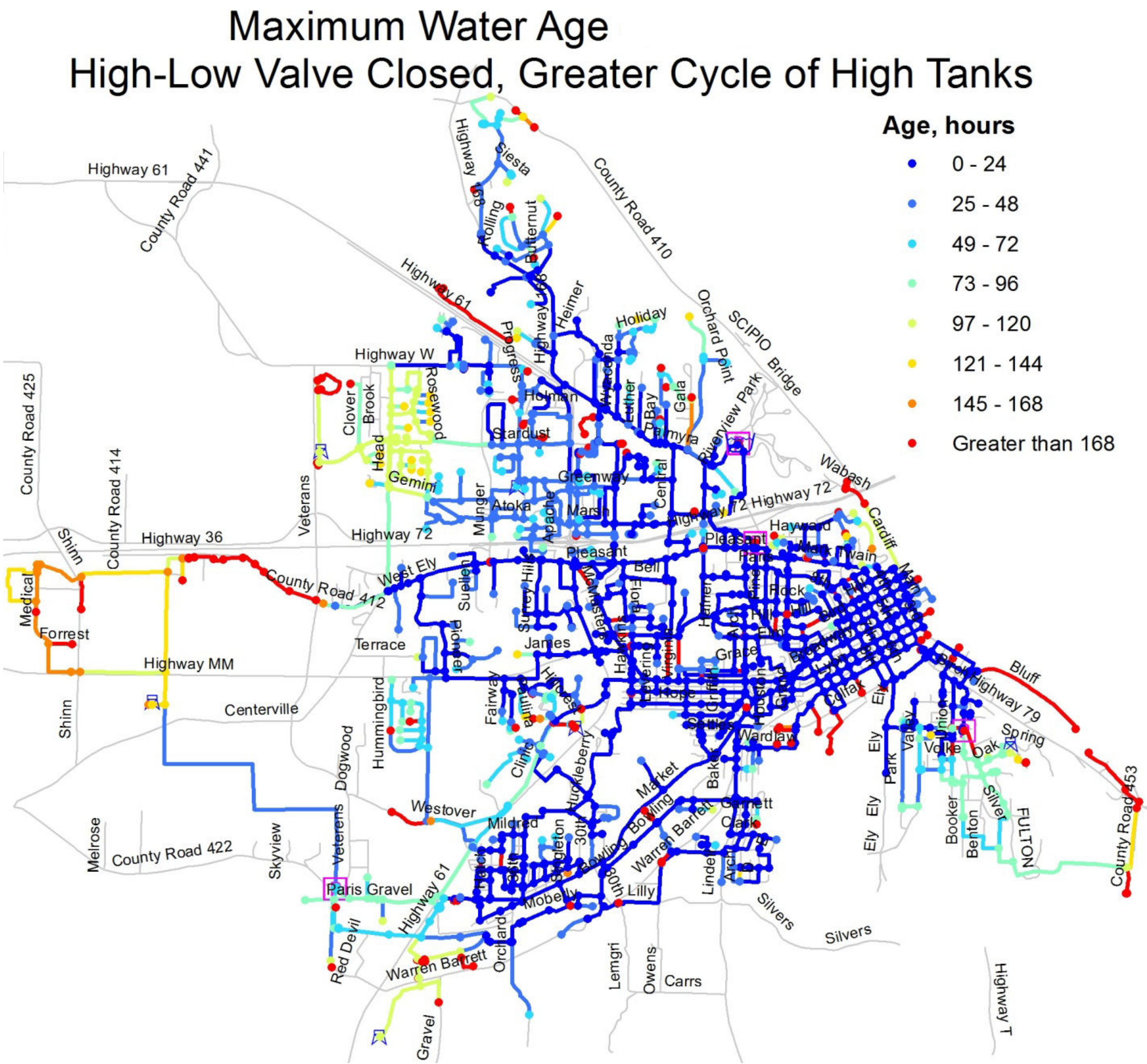


Figure 5-14. Maximum Distribution System Water Age (Alternative 2)

A comparison of the average water age for Alternative 2 to base concept shows that the Paris Gravel Pressure Zone maximum water age decreased almost a day. The area surrounding Veterans Road tank experiences a great reduction in maximum instantaneous water age as well. Areas near Clinic Road and Warren Barrett tank also experience a reduction in maximum water age.

5.8 DISTRIBUTION SYSTEM WATER AGE SUMMARY

The purpose of the distribution modeling completed as part of the initial findings report was to establish a baseline water age for future DBP testing, and to evaluate if operational measures could be easily implemented to greatly reduce overall water age. Based on these initial findings, the average water age in the system is less than 24 hours for a significant area of the distribution system. However, within certain areas of the system, where several of the compliance points are located, the water age is much higher, closer to 5 days and at some places even higher. Therefore, the previous SDS testing conditions that utilized 5 days of hold time to determine DBP formation was fairly representative of these areas. Based on operational procedures evaluated in Alternatives 1 and 2 the expected water age could be reduced by 1 to 2 days. Reducing the water age will have some impact on overall DBP formation. However, this limited reduction in water age would not result in sufficient reductions to meet DBP compliance without other treatment or system modifications. For future SDS testing the hold times for DBP testing will be varied to better evaluate the impacts of reducing water age. The benefits for reducing water age will be compared to the operational or infrastructure improvements required to determine the best overall solution to meet treatment objectives.

6.0 Alternative Water Sources

With the decision to eliminate the use of ammonia as part of the City of Hannibal's water disinfection process, the City will either need to modify the existing water treatment facilities for the Mississippi River supply or find and develop an alternative source of water supply and treatment. This section provides information from a brief desktop review of available published information to determine the potential for development of an alternative source of supply to yield a total of 3.5 million gallons per day (MGD) on an average day basis and up to 7.5 MGD on a maximum day basis to meet the City's water needs.

Sources of water evaluated included only groundwater supplies as any surface water supply would most likely require similar modifications to control DBPs using a free chlorine distribution system.

Figure 6.1 shows the location of the existing treatment plant in relation to the river and tributary streams surrounding Hannibal.

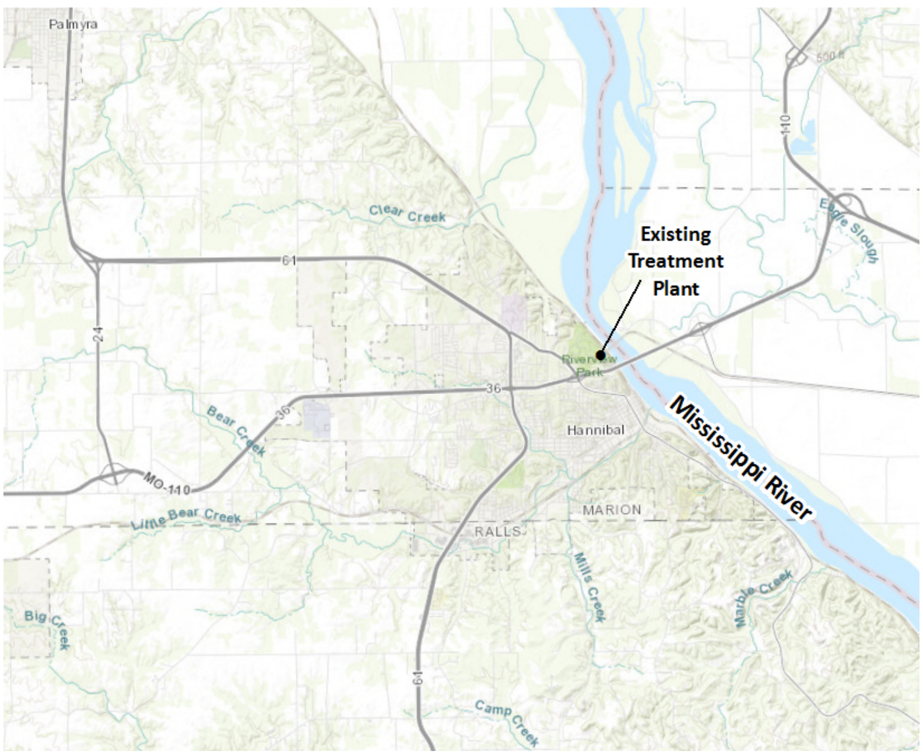


Figure 6-1. Study Area

6.1 GROUNDWATER RESOURCES

Groundwater typically has a lower concentration of organic matter and microorganisms than surface water since the aquifer acts as a natural filter, especially if a well is located some distance away from a source of recharge. If a high-capacity well is located in close proximity to a river, riverbank filtration occurs, although the water that is produced by the well is a mixture of groundwater that has been stored in the aquifer for some time and surface water that is induced into the aquifer. The resulting raw water quality is dependent upon a number of site-specific variables such as the hydraulic properties of the riverbed and aquifer and the raw water quality of the two sources, requiring more detailed field investigation (References 1, 2, 3). This desktop evaluation focuses on the potential yield of various sources of supply, with less focus on the quality of the water that will be produced.

The potential groundwater sources of supply for Hannibal include:

- Local shallow sand and gravel aquifers
- Stream-Valley Aquifers
- Mississippi River Alluvial Aquifers
- Local bedrock aquifers
- Mississippian Aquifers
- Cambrian-Ordovician Aquifer

Water supplies using Mark Twain Lake and aquifers located across the Mississippi River in Illinois weren't included in this initial evaluation as their supply costs would most likely be higher than the other alternatives evaluated. However, if an alternative water supply is further evaluated these sources of supply could be considered.

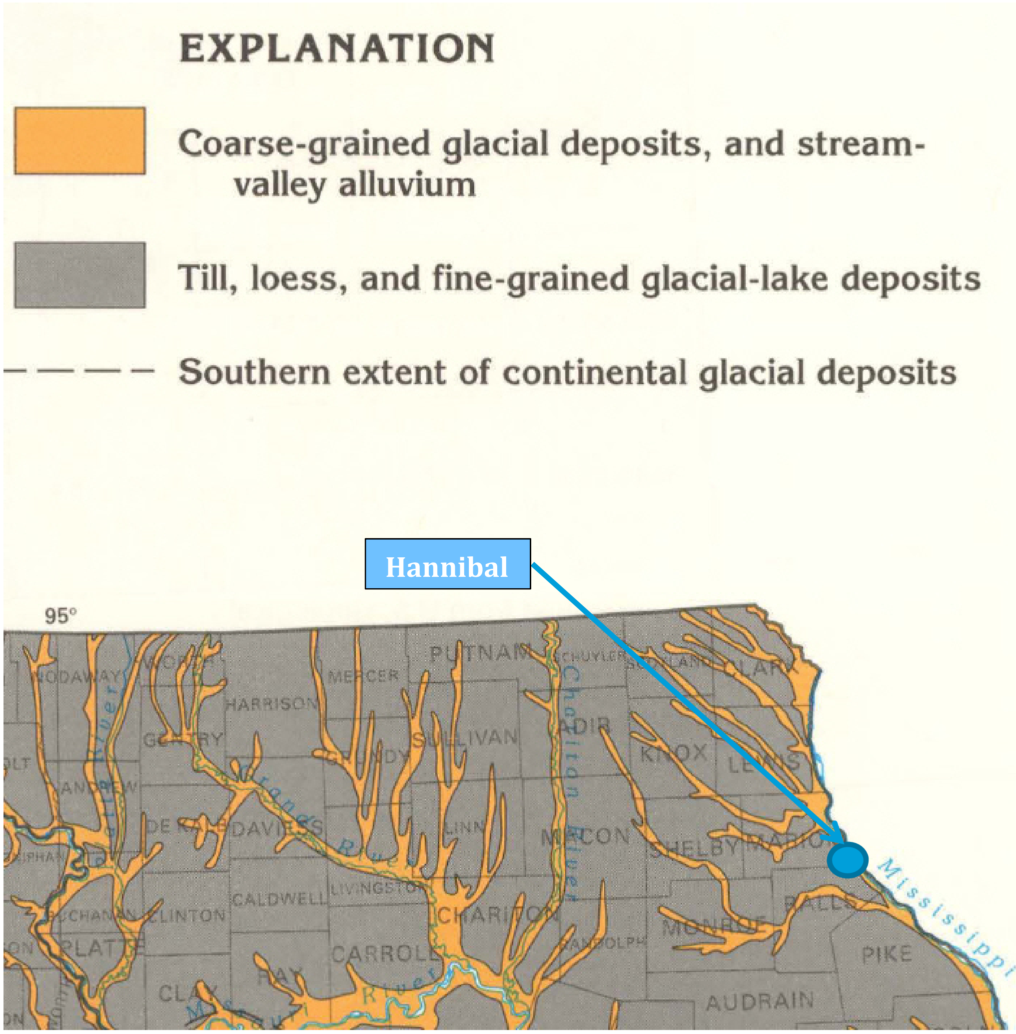
A description and potential viability of each of these aquifers are summarized below.

6.1.1 Local Shallow Sand and Gravel Aquifers

Hannibal is located within the Central Lowland Physiographic Province which extends across northern Missouri. Shallow sand and gravel aquifers (also referred to as water table aquifers or surficial aquifers) in Northern Missouri can be divided into alluvial aquifers and stream-valley aquifers. Alluvial aquifers are present along the large rivers including the Mississippi River and often consist of significant quantities of coarse-grained sand and gravel. The coarsest sand and gravel alluvial deposits with higher transmissivity are often buried beneath shallower, finer-grained deposits. Stream-valley aquifers are located along smaller tributary streams in the Hannibal area and also contain coarse-grained material, but the deposits are typically not as thick as alluvial aquifers and may contain higher percentages of fine-grained silt and clay than alluvial aquifers.

6.1.2 Stream-Valley Aquifers

The thickness and yield of a stream-valley aquifer may vary significantly across short distances depending on the manner in which the sediments were deposited, width of the permeable sediments contained within the valley, hydraulic and storage characteristics of the deposits, hydraulic connection with the stream, and streamflow. Figure 6-2 shows the shallow unconfined aquifer system in Northeastern Missouri (Reference 4).



(Orange areas indicate stream-valley alluvium containing sand and gravel and coarse-grained alluvial deposits beneath the Mississippi River valley; gray areas indicate finer-grained glacial deposits; Source: Figures 4 and 11 of Reference 4)

Figure 6-2. Surficial Aquifer System in Northeastern Missouri

Stream-valley alluvial aquifers are located about 10 miles or more to the north of Hannibal extending up the valleys of the North River, South Fabius River, Middle Fabius River, and North Fabius River (Reference 4). A 1954 well log was found along the North Fabius River near the junction of Highways 61 and 24; this log indicates "Warsaw" to a depth of about 45 feet, presumably referring to the Warsaw shale of Mississippian age, and does not indicate any unconsolidated soils or alluvium. The log indicates Burlington-Keokuk limestone is present below the Warsaw. It is possible that this log was not drilled immediately adjacent to the North Fabius River and may have missed any stream-valley deposits in this area. Another well log from 1938 was discovered along the South Fabius River; this log indicates the top of the Burlington-Keokuk limestone is encountered near ground surface. Again, it is possible that this test well missed any stream-valley deposits (Reference 6). Because of unknowns about the aquifer characteristics beneath the valleys of these smaller streams, along with the cost of extending a pipeline into these more distant areas, alternatives to develop these smaller stream-valley aquifers north of Hannibal were not considered further for purposes of this desktop analysis.

Approximately 6 to 7 miles to the south of Hannibal, regional mapping indicates a stream-valley aquifer beneath Salt River, downstream of Mark Twain Lake (Reference 4). The width of the valley is a little more than half a mile. DNR's WIMS database provides several logs that appear to be outside of the Salt River valley and show little to no unconsolidated stream-valley deposits; no well logs were discovered immediately adjacent to Salt River (Reference 6). In addition, Salt River streamflows in this area depend on upstream releases and could become quite low during dry weather (Reference 7). For these reasons, coupled with the distance from Hannibal to the Salt River valley, water supply alternatives in this area were not considered further for this desktop study.

6.1.3 Mississippi River Alluvial Aquifer

Closer to Hannibal, the Mississippi River alluvial aquifer is present beneath the river valley and is a significant source of water supply in localized areas (Reference 5). The width of the valley from bluff to bluff near the City is at least 5 miles. For more than 30 miles to the southeast of Hannibal, the Mississippi River follows the western bluff on the Missouri side, so most of the alluvium exists on the east side of the river. To the north of Hannibal, approximately 1.5 miles to 5.5 miles north of the existing treatment plant along Bay Island, the river meanders to the east, away from the western bluff along the valley, and reaches a maximum distance of about 3 miles from the bluff. The bluff is an indication of the underlying bedrock valley wall, forming the western edge of the alluvial deposits (as illustrated by Figure 9 of Reference 10). The farm land of Bay Island is protected by a flood levee and is designated as the South River Drainage District, named after the South River which drains from the southwest through the northern portion of Bay Island where it discharges to the Mississippi River.

In these areas located away from the western bedrock valley wall, there is potential for large-capacity wells where the alluvial deposits are coarse-grained and relatively thick. Ralls County PWSD No. 1 has installed a production well in the southwestern portion of Bay Island which has a reported yield of up to 1500 gpm (Reference 11).[1] The reported quality of the groundwater produced by this well is as follows:

- Elevated levels of iron and manganese which would need to be removed during the treatment process
- Low levels of organic matter, which would likely form lower concentration of DBPs
- Depending on the selected treatment process, the finished water is anticipated to have low levels of disinfection byproducts (Reference 11).[2]

Several additional well logs were discovered on the north end of Bay Island in the Missouri Department of Natural Resources' (DNR) Water Resource Center Well Information Management

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[1] The well was tested at a rate of 1507 gpm with a drawdown of 13.6 feet. The depth of casing is 55 feet, and the screen length is 30 feet, suggesting the base of the productive alluvium is approximately 85 feet below ground surface. The diameter of the casing and screen is 16 inches (Reference 11).
[2] Ralls County PWSD No. 1 is considering using this well as an alternative/redundant water source for the Hannibal area, depending on what is most cost effective for them in the future. In 2014, they purchased approximately 0.47 MGD of finished water on an average daily basis from Hannibal; in Year 2035, their projected average day and maximum day needs are estimated at approximately 0.52 MGD and 0.85 MGD, respectively.

System (WIMS) database.[3] A 1965 well log indicates about 100 feet of alluvial sand and gravel, documenting a pumping rate of 1400 gpm with 28.5 feet of drawdown. Another nearby 1957 well log on the north end of Bay Island indicates boulders and clay to a depth of 129 feet where bedrock is encountered; this log indicates a pumping rate of 215 gpm. These reported pumping rates indicate there are areas on the west side of the river to the north of Hannibal where the Mississippi River alluvial aquifer is thick and productive, although the alluvial aquifer properties can change significantly across short distances (Reference 6). On the south end of the island, no detailed boring logs were discovered in DNR's database that indicate the depth or composition of the alluvial deposits or reported pumping capacities.[4]

The potential to further develop the groundwater resources beneath Bay Island would need to consider the alluvial aquifer characteristics at selected locations, property ownership for viable well locations, farming practices, and any other existing irrigation wells in the area. A phased hydrogeological investigation would determine the site-specific groundwater quality and aquifer characteristics, along with the feasibility, number, type, and configuration of wells to obtain the desired quantity of water. Either traditional vertical wells or larger-capacity horizontal collector wells could be considered for the Mississippi River alluvial aquifer if favorable sites are discovered. Horizontal collector wells are often constructed immediately adjacent to large rivers to maximize yield; however, because of this, a collector well typically produces groundwater under the direct influence of surface water (GWUDISW) and would require similar treatment as surface water under the Surface Water Treatment Rule, although some credit may be given for in-situ riverbank filtration occurs before the water reaches the well. For this reason, the planning of a hydrogeological investigation should consider varying distances from the river to be able to evaluate the tradeoffs between yield, water quality, treatment requirements, and cost for vertical wells versus horizontal collector wells. This process would include close coordination with DNR to understand their interpretation of wells that would be considered GWUDISW, which would be factored into the selection of testing locations during a field investigation.

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[3] Any wells constructed in Missouri prior to 1987 were not required to be reported, so there is a possibility that there are older wells in the area that are not included in the well database.

[4] Correspondence with DNR did not reveal any other major water usage records along Bay Island. DNR mentioned several recent changes in sharing information for confidentiality reasons. A formal Open Records Request (or Sunshine Request) is required.

Figure 6-3. Location of Bay Island to the North of Hannibal (Source: Google Earth)

6.1.4 Local Bedrock Aquifers

Bedrock aquifers are present beneath the unconsolidated soil deposits in Missouri. The stratigraphy of the sedimentary bedrock (above the older Precambrian crystalline rock) is as follows (Reference 8):

- Mississippian
  - Meramec Group (lower portion)
    - Warsaw Shale (uppermost bedrock unit in the Hannibal area as indicated on well logs discovered for this desktop study)
  - Osage Group
    - Keokuk Limestone
    - Burlington Limestone
    - Fern Glen Limestone
  - Kinderhook Group
    - Sedalia Limestone
    - Chouteau Limestone
    - Hannibal Shale

- Devonian
    - Upper Formation
        - Louisiana Limestone
        - Saverton Shale
        - Grassy Creek Shale
        - Snyder Creek Formation
    - Middle and Lower Formations
        - Undifferentiated Limestone
- Silurian
    - Undifferentiated Limestone and Dolomite
- Ordovician
    - Upper Formation
        - Maquoketa Shale
    - Middle Formations
        - Kimmswick Limestone and Dolomite
        - Decorah Formation
        - Plattin Limestone
        - Joachim Dolomite
        - St. Peter Sandstone
        - Everton Formation
    - Lower Formations
        - Powell Dolomite
        - Cotter Dolomite
        - Jefferson City Dolomite
        - Roubidoux Sandstone and Dolomite
        - Gasconade Dolomite
        - Gunter Sandstone Member
- Cambrian
    - Upper Formations
        - Eminence Dolomite
        - Potosi Dolomite
        - Derby-Doe Run Dolomite
        - Davis Formation
        - Bonneterre Dolomite
        - Lamotte Sandstone
- Precambrian
    - Igneous Rock

If a productive bedrock aquifer is present immediately beneath Hannibal, and if the water quality is acceptable, the additional cost of local deep wells compared to shallow alluvial wells would be offset at least partially by a reduction in pipeline and pumping costs. Other potential advantages for drilling deeper production wells into bedrock could include less potential for contamination or less potential for well biofouling or mineralization over time. Potential disadvantages of deep bedrock wells may include slower recharge of the bedrock resulting in reduced yields or water quality issues such as elevated concentrations of dissolved solids, chlorides, or radionuclides.

6.1.5 Mississippian Aquifer

The uppermost bedrock in the area is of Mississippian age (roughly 325 to 350 million years ago) and is referred to in Missouri as the Mississipian Aquifer. Data suggests that the Mississippian bedrock was eroded away near Hannibal and toward the southeast along the Mississippi River. A 1934 test boring record was discovered for a pier of the old Hannibal Bridge, with the test boring drilled through the riverbed into the underlying formation. The river water surface elevation was apparently 452 feet at the time of logging the boring. The handwritten boring log appears to indicate only about 10 to 16 feet of alluvium which is underlain by what is indicated on the log as "Grassy Creek", in reference to the Grassy Creek shale formation, with the apparent top of shale at an elevation of about 436 feet (Reference 6), confirming that the Mississippian-age formations were eroded away beneath the Mississippi River at the bridge. However, a log from the 1943 report (Reference 9) on the bluff near Lover's Leap in southeast Hannibal indicates 111 feet of Burlington limestone, underlain by 70 feet of Hannibal shale and more than 30 feet of Louisiana limestone. Looking at the stratigraphy above from Reference 8, the 111 feet of upper limestone could be a combination of Burlington, Fern Glen, Sedalia, and Chouteau limestone formations; regardless, this would mean that the Mississippian aquifer was not eroded away along the bluff in the southeastern portion of Hannibal.

Where the Mississippian Aquifer is present, the most productive and accessible bedrock formations containing fresh water are likely the Keokuk and Burlington limestones. Records for bedrock wells drilled in the early 1900s in and around the west and northwest sides of Hannibal were obtained from DNR's WIMS database. The handwritten logs indicate the top of limestone is often encountered at shallow depths (References 6). The potentiometric elevation of groundwater within the Mississippian aquifer range is reportedly 600 feet just west of Hannibal, decreasing to about 500 feet in the Hannibal area, with the hydraulic gradient toward the Mississippi River to the east. The groundwater is reportedly fresh, with less than 1000 mg/l of dissolved solids in the area (References 4 & 8). The yield of a well will depend on the thickness of the bedrock aquifer and interconnectivity of solution features and other bedrock openings at the selected well location. Historically, relatively small wells were drilled into this aquifer for domestic and agricultural purposes with yields generally between 5 and 15 gallons per minute (gpm) (Reference 8). It is not clear if these yields are simply a reflection of the small amount of water desired or if these yields were limited by the water bearing capabilities of the bedrock aquifer. No information was discovered in DNR's WIMS database or through direct correspondence with DNR for actual production rates of existing wells tapping the Mississippian Aquifer.

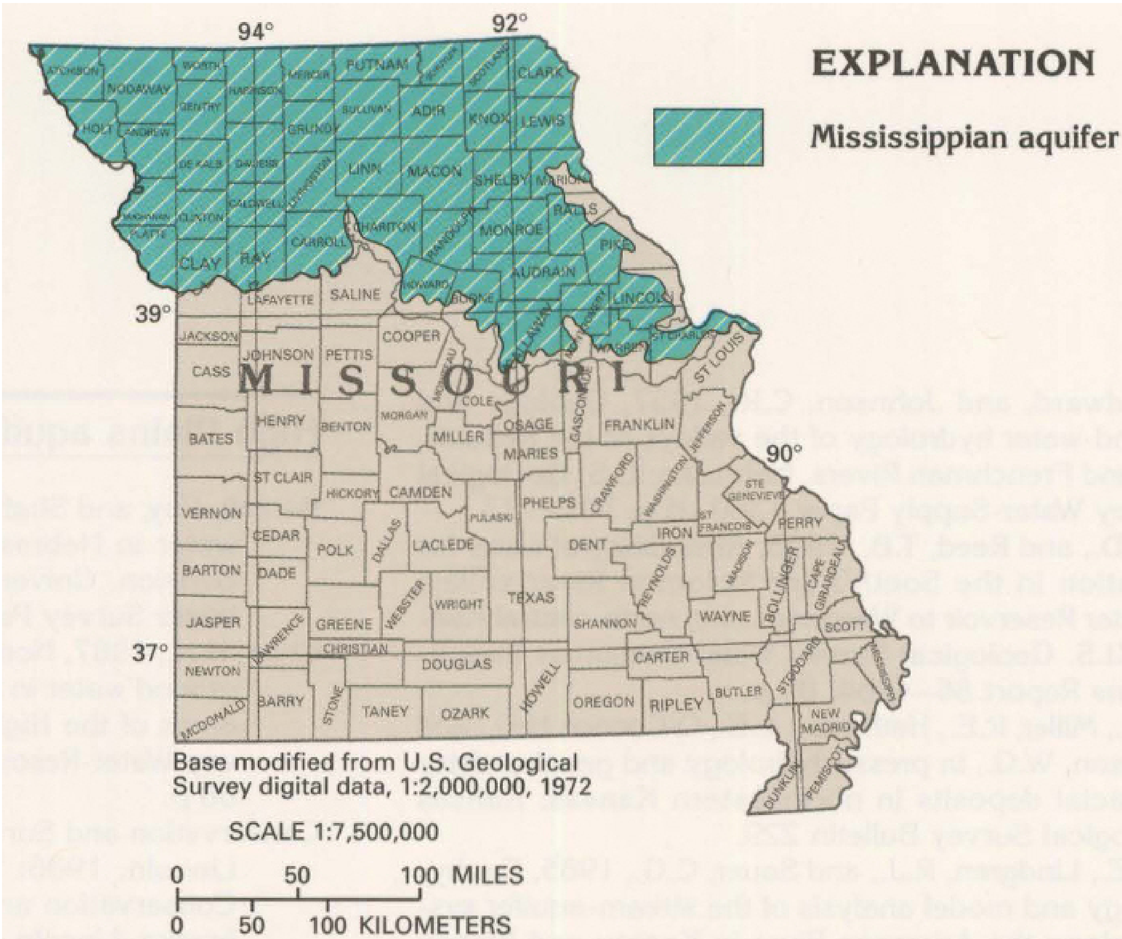

Figure 6-4. Mississippian Aquifer Coverage (Source: Reference 4, Figure 114)

6.1.6 Cambrian-Ordovician Aquifer

The Devonian, Silurian, Ordovician, and Cambrian sedimentary bedrock formations are present below these upper Mississippian-age bedrock formations. The Cambrian-Ordovician Aquifer consists of about 1000 feet to more than 1500 feet of sandstone and dolomite. In parts of Missouri, well capacities of between 400 to 1100 gpm can be produced from this aquifer (Reference 8). However, in the Hannibal area, the groundwater in the Cambrian-Ordovician Aquifer reported contains as much as 5000 milligrams per liter (mg/L) of dissolved solids (Reference 4). A 1938 well log along the South Fabius River to the north of Hannibal that was drilled 690 feet deep into the St. Peter sandstone aquifer was abandoned because of encountering salt water (Reference 6). Because of the reported salinity, these deeper formations were not considered further for this desktop study.

6.2 ALTERNATIVE WATER SUPPLY SUMMARY

Based on this brief desktop evaluation, it appears the best alternatives to surface water from the Mississippi River as a source of supply for Hannibal are the Mississippi River alluvial aquifer and the Burlington-Keokuk limestone aquifer. The Mississippi River alluvial most likely would have sufficient capacity, but preliminary water quality results from new wells drilled by Ralls County show high iron and manganese, requiring pre-oxidation upstream from filtration. In addition, land acquisition and raw water piping would be a substantial effort. The Burlington-Keokuk limestone likely has a slower recharge rate than the river alluvium and will likely yield less water, so bedrock wells would likely need to be spread out over a larger area than an alluvial wellfield to obtain the quantity of water needed by the City. A hydrogeological investigation at selected well sites is required to determine aquifer characteristics and groundwater quality, followed by numerical calculations to evaluate yield.

Based on this initial evaluation, any alternative water supply would require substantial capital investment, along with additional exploration to confirm acceptable water yields and water quality. Ultimately, the new water supply option would be compared to the capital and operating costs to implement the improvements at the existing water plant along with continued operation of the existing plant. Based on similar new facilities in the region it is estimated that a new water supply and treatment facility will cost in excess of $30 million dollars, and could potentially be higher. Therefore, unless the final recommended treatment and distribution system improvements, factoring in new operational costs, reach near this total, an alternative water supply should not be considered at this time.

References

Reference 1. Storck, Florian R., Carsten K. Schmidt, F.T. Lange, Jeff Henson, Kris Hahn, 2012, *Factors Controlling Micropollutant Removal During Riverbank Filtration*, Journal AWWA, December.

Reference 2. Kuehn, Wolfgang, and Uwe Mueller, 2000, *Riverbank Filtration: An Overview*, Journal AWWA, December.

Reference 3. Aiken, George R., and Eve L. Kuniansky, 2002, *Organic Matter in Ground Water*, US Geological Survey Open-File Report 02-89, Artificial Recharge Workshop Proceedings, Sacramento, California. https://water.usgs.gov/ogw/pubs/ofr0289/ga_organic.htm

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