Georgia Ports Authority

City of Savannah Seawater Effects Study

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CDM

Savannah Seawater Effects Study
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Executive Summary

Background

This study evaluates the potential impacts of the Savannah Harbor Expansion Project (SHEP) on treated water quality at the City of Savannah Industrial & Domestic water treatment plant (I&D WTP). The I&D WTP provides drinking water to approximately 10,500 customers as well as a number of industries, and draws water from an intake on Abercorn Creek, which joins the Savannah River approximately 1 mile upstream of the I-95 bridge. Although the intake is well upstream of the proposed harbor deepening project, the deepening would increase the amount (percentage) of seawater that reaches the intake under conditions of high tide and low freshwater flow in the creek. Therefore, it is important to evaluate the potential impact of increased chloride levels on water quality.

This study supports the understanding of impacts of an increased percentage of seawater intrusion in the drinking water supply. Modeling provided under separate studies associated with SHEP estimated the increased chloride concentrations that may be seen at the intake. Harbor deepening is predicted to increase the average chloride concentration from 10.6 mg/L to 13.7 mg/L and the maximum concentration from 36 mg/L to 185 mg/L. **Figure ES-1** illustrates these changes with a histogram of model-predicted chloride concentration before and after harbor deepening.

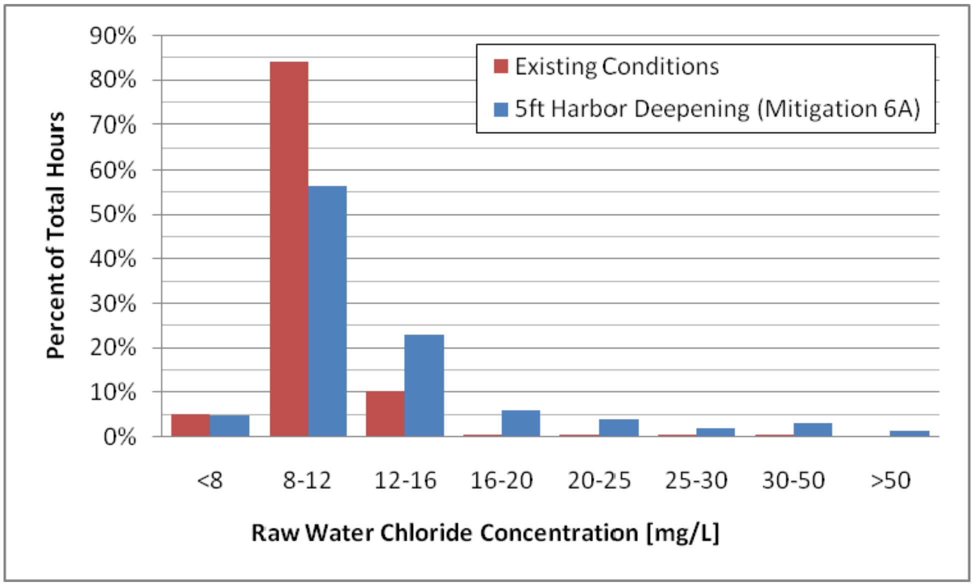

Figure ES-1: Histogram of model-predicted hourly chloride concentrations at Abercorn Creek intake.

Bench-scale testing was used to examine the impacts of elevated chloride concentration on treated water quality with respect to corrosion, formation of disinfection byproducts, and chemical treatability.

Bench-Scale Testing Methodology and Results

City of Savannah raw water was combined with seawater to simulate the range of expected chloride concentrations after harbor deepening. These seawater blends were treated with selected combinations of five pHs, two types of disinfectant, and two doses of corrosion inhibitor to evaluate the ability of chemical treatment changes to mitigate any impacts of the elevated chlorides. A total of 64 different test conditions were evaluated. Copper coupons galvanically connected to lead solder and mild steel coupons were exposed to each test water condition for six weeks. The water in contact with each coupon was changed twice per week, and water after exposure was analyzed for dissolved metals. **Table ES-1** summarizes the water quality conditions tested in this study.

Table ES-1: Summary of Water Quality Conditions

Chloride	pH	Disinfectant	Corrosion Inhibitor
Existing (10 mg/L)	Existing[1] (7.3 ± 0.15)	Free Chlorine (2.0 ± 0.2 mg/L)	Existing (0.75 mg/L as PO$_4$)
25 mg/L	7.5 ± 0.15[2]		
50 mg/L	7.8 ± 0.15	Chloramines (~1.2 mg/L)[4]	Existing + 0.75 mg/L as PO$_4$
75 mg/L	7.9 ± 0.15[3]		
150 mg/L (Sensitivity Test)	8.3 ± 0.15		

[1] Target finished water pH, according to plant staff.

[2] 25 mg/L and 50 mg/L with free chlorine and existing inhibitor only.

[3] 50 mg/L and 75 mg/L with free chlorine and existing inhibitor only.

[4] Chloramines were formed using procedures identical to full-scale treatment using a chlorine: ammonia ratio of 2.2:1. Exact residual was measured after formation but plant staff and data indicate that 1.2 mg/L is typical.

The results of the bench-scale study indicate that neither the existing corrosion inhibitor nor pH adjustment will consistently control lead and iron corrosion to the extent required to prevent a deterioration in drinking water quality. Higher chloride concentrations in the range expected to result from harbor deepening caused significant increases in trihalomethane (THM) formation, chlorine demand, and lead corrosion, and slight increases in total haloacetic acids (HAA9), iron corrosion and TOC. These impacts will likely make it difficult for the I&D WTP to continue complying with drinking water regulations. Increased chloride also appears to reduce the severity of copper corrosion and decrease the regulated HAA5 concentration. The decrease in HAA5 is expected, because this concentration excludes several bromine-containing HAAs that are favored when seawater is present. Coagulant demand was not appreciably affected by the percentage increases in seawater evaluated.

Figure ES-2 illustrates the impact of increased chlorides on treated water corrosivity for lead, copper, and iron. The concentration of each metal is normalized relative to the sample with the existing level of chloride. The dotted black line indicates the chloride to sulfate mass ratio (CSMR), which is an important indicator of the potential for lead corrosion. As shown, lead corrosion is significantly increased as chloride concentration increases, while copper is decreased and there is no meaningful effect on iron. Similar trends were observed at other pHs and at higher inhibitor doses. In water treated with chloramines, the increase in lead was even more significant.

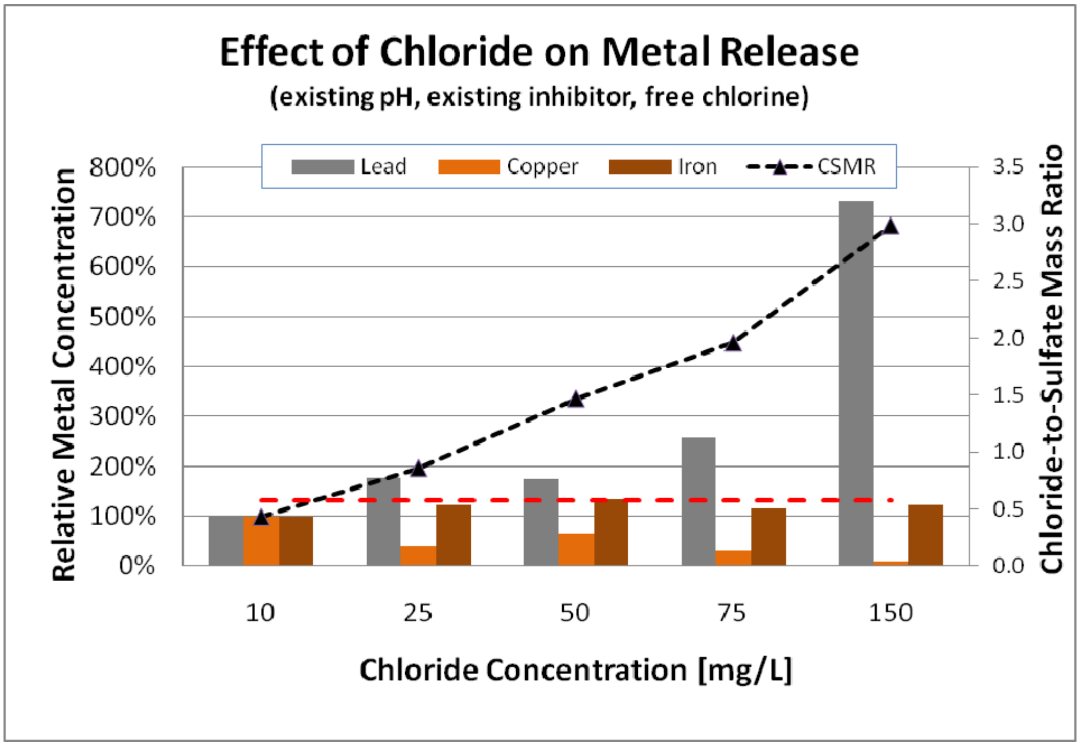

Figure ES-2: Effect of chloride concentration on metal corrosion in water treated with free chlorine. Concentrations are shown in relative units by comparing with the metals concentrations observed under existing water quality conditions. The dotted line indicates CSMR; the red dashed line indicates the CSMR threshold of 0.58, above which lead corrosion generally becomes a concern.

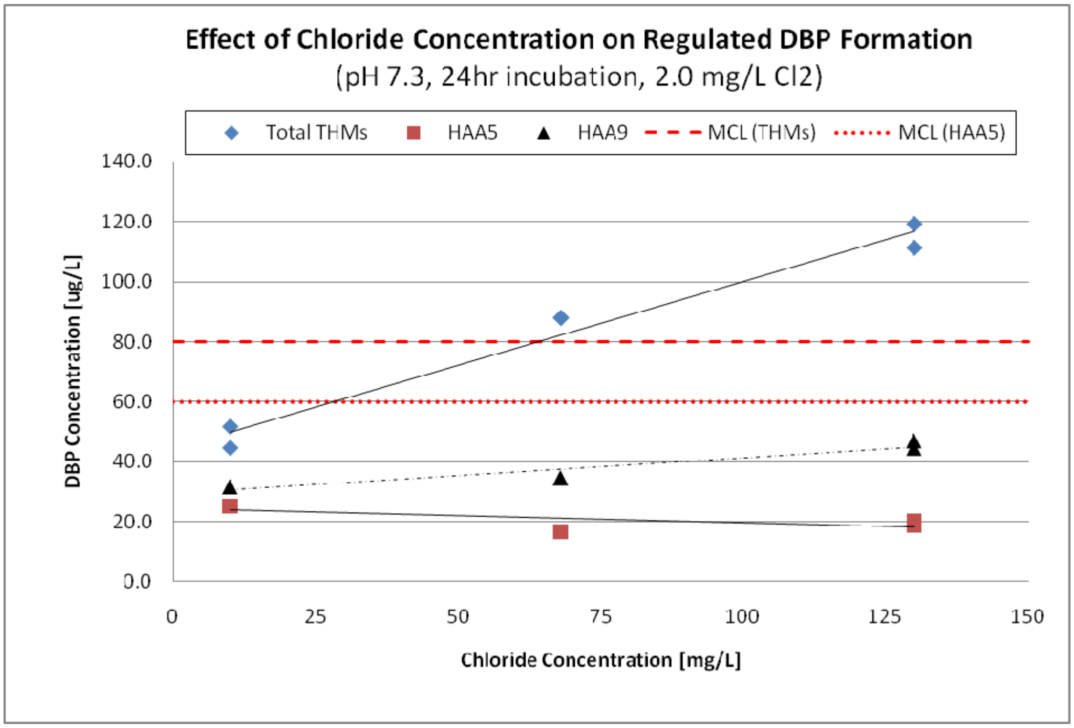

Figure ES-3: Effect of chloride concentration on regulated disinfection by-product formation. Red dashed lines show the respective MCLs for THMs and HAA5. HAA9 is shown in black for comparison to the regulated HAA5.

Figure ES-3 shows the effect of elevated chloride on regulated and unregulated disinfection byproduct (DBP) formation. As shown, trihalomethane (THM) levels increase by approximately 50% at a chloride concentration of 50 mg/L, and exceed the regulatory maximum contaminant level (MCL) at approximately 70 mg/L chloride. The five regulated haloacetic acids (HAAs) decrease with increased chloride because they do not account for all HAA species that may form. HAA9, which includes the missing species, increases with chloride, but at a slower rate than THMs.

Regulatory Implications

Lead and Copper Rule (LCR)

The 90th percentile lead and copper concentrations (which are the basis for regulation of lead and copper) in the City's distribution system were below the action levels of 15 μg/L and 1,300 μg/L, respectively, for all Lead and Copper Rule (LCR) sampling conducted between 2001 and 2008. However, over the same period 11 different sites exceeded the action level at some point, but only two exceeded it on more than one occasion. The results of bench-scale testing indicate that lead corrosion is likely to increase considerably as chloride concentration increases, while copper levels may stay similar or decrease slightly.

Based on the fact that some sites exceed the lead action level under existing conditions and that compliance with the LCR is based not on an average but a 90th percentile concentration, it is likely that increased chlorides will cause difficulties in complying with the LCR. Since the City is required to sample lead at 30 sites, a violation is triggered if more than 3 sites exceed the action level. Increased chlorides could easily raise the lead concentration at one or two sites enough to cause a violation. For example, in 2002, three sites exceeded the lead action level. The fourth highest concentration reported was 7.1 μg/L. If lead corrosivity had been increased by two- or three-fold due to high chlorides, which appears feasible based on bench-scale testing, the lead level at this single site may have exceeded 15 μg/L, raising the 90th percentile lead concentration above the action level and causing a violation of the LCR.

Two or three sites have exceeded the lead action level during three of the last five LCR sampling periods. As such, there is very little margin for lead levels to increase without risking violations of the LCR.

Disinfectants and Disinfection Byproducts Rule (D/DBPR)

The City will become subject to location-based monitoring for THMs and HAAs under the Stage 2 Disinfectants and Disinfection Byproducts Rule (D/DBPR) in 2014. The running annual average (RAA) for THMs at the current Stage 1 D/DBPR monitoring sites is 55 μg /L, and the maximum locational running average (LRAA) is 64 μg /L. Both values are below the MCL of 80 μg/L.

Increased seawater may create challenges for compliance with the Stage 1 and Stage 2 D/DBPR. Based on current THM levels, MCL violations would occur if the RAA increased by 45% or (after 2014) if the maximum LRAA increased by 25%. The testing results presented in Section 5 indicate that such increases would occur if the chloride concentration entering the plant reached 65 mg/L or 40 mg/L, respectively.

Alternatives to Mitigate Impacts of Elevated Chloride Concentration

Alternatives for mitigating these impacts and ensuring continued protection of public health can be broadly categorized as modifications to adapt the treatment process to increased seawater or measures that avoid increased seawater in the source water.

Adapting the treatment process to accommodate the high chlorides would require costly modification and multiple steps to address both corrosion and DBP impacts. The most suitable treatment alternative for removing seawater ions is membrane treatment, which was previously studied by others and estimated to cost in excess of $60 million, and would require further testing to confirm its impact on water quality. All parties at the July progress meeting agreed that there was no interest in pursuing membrane treatment further.

An alternate approach is to construct a new upstream supplemental intake to avoid the seawater spikes from the harbor deepening. The latest cost estimate for the upstream supplemental intake is $35.9 million.

A second means of avoiding increased seawater is to dampen the chloride concentrations to the plant through the construction of a raw water impoundment. An impoundment would smooth tidal fluctuations in chloride concentration and provide storage so that pumping during high tide could be avoided. Such a facility would stabilize source water quality and simplify plant operations while mitigating the impact of chlorides on both lead corrosion and DBPs. An impoundment with a usable volume of 77.5 million gallons would be required to mitigate the impact of the chlorides with a harbor deepening of 5 ft and mitigation strategy 6A, and has an estimated capital cost of $30.0 million, making this strategy the least-cost option for mitigating the impact of increased seawater percentage. Independent analysis by the City of Savannah using a different methodology suggested a nearly identical impoundment size.

The same approach was used to determine the recommended impoundment size and cost under other harbor deepening scenarios. These are presented below in **Table ES-2.** As shown, there are considerable economies of scale associated with the construction of the impoundment due to large fixed costs (such as the pump station) which are independent of volume.

Table ES-2: Recommended Impoundment Size and Estimated Cost for Alternate Harbor Deepening Scenarios

Harbor Deepening Scenario	2ft 6B	3ft 6A	4ft 6A	5ft 6A	6ft 6A
Recommended Usable Volume, MG	22.5	30	46.5	77.5	120
Total Volume, MG	28	38	58	97	150
Probable Construction Cost, $M	$24,333,000	$25,143,000	$26,883,000	$29,993,000	$34,073,000

Recommendations

CDM recommends that one raw water impoundment with a usable volume of 77.5 million gallons (MG) be constructed in order to stabilize and reduce the chloride concentration pumped to the plant, or that the supplemental intake further upstream be constructed. The total volume of the impoundment should be approximately 20% greater than the 77.5-MG usable volume to allow for sediment accumulation, for a total volume of approximately 97 MG. One reservoir is recommended (rather than two smaller reservoirs) since the City can treat river water during non-drought seasons to allow taking the reservoir out of service for maintenance.

Recommended Alternative

Raw Water Impoundment

- One pond
- 77.5 MG usable volume
- Stabilizes source water quality to plant
- Allows avoidance of pumping during high tide
- Simplifies plant operations

A 77.5-MG (usable volume) impoundment would be adequate to keep the chloride concentration entering the plant below 30 mg/L in 99% of cases, with a worst-case concentration of 40 mg/L based on the model predicted chloride concentrations under current conditions and after harbor deepening, which were provided by Tetratech. This impoundment volume was selected based on the existing firm raw water pumping capacity of 75 mgd and the maximum plant production of 62.5 mgd. Firm pumping capacity is the capacity with the facility's largest pump out of service. The use of firm capacity for design purposes is standard engineering practice, and is required by the Georgia Environmental Protection Division's *Minimum Standards for Public Water Systems,* Section 9.4.1 (2000). The use of plant design capacity for sizing this mitigation option is required by the Water Quality Certification letter for the SHEP project, issued to USACE by the State of Georgia, and is consistent with standard engineering practice.

The same effect could be achieved with a smaller impoundment if the raw water pumping capacity could be increased, but this option would require additional capital cost at the intake structure. The impoundment is preferred at this time based on discussion with City staff, because of space constraints in the existing intake structure, the need to save future pumping for future capacity, and most notably because the economy of scale found for the raw water impoundment with re-pump station suggested that further reduction in impoundment size would not offer savings large enough to justify the additional capital expense for raw water pumps.

The estimated capital cost of the recommended alternative is **$30.0 million** for a 77.5-MG usable volume impoundment, and is broken down in more detail in **Table ES-3**. If two impoundments are constructed instead of one, the estimated cost is increased by $3.1 million, hence the City agreed to the use of one impoundment in the interest of compromise and moving the project forward. The estimated 15-year present worth of operations and maintenance expenses is **$5.25 million**. A preliminary layout drawing showing the proposed facilities is presented in **Figure ES-4.**

Operational Guidance

In addition to the raw water impoundment, chemical treatment modifications, such as increased coagulant dose or the use of powdered activated carbon, may be needed to control DBPs during periods of high seawater percentage. Guidelines for these practices and for proper operation of the recommended raw water impoundment are provided at the end of this report.

Table ES-3: Estimated Capital Cost of one 77.5-MG (usable volume) Raw Water Impoundment

Item	Cost[a]	Contingency[b]	Total Cost
Land[c]	$1,930,000	n/a[b]	$1,930,000
LAND SUBTOTAL	**$1,930,000**	**n/a**	**$1,930,000**
Water Storage Ponds & Site Work	$12,380,000	$3,095,000	$15,475,000
Transfer Pump Station	$5,920,000	$1,355,000[b]	$7,275,000
Powdered Activated Carbon Silo	$1,070,000	$267,500	$1,337,500
Testing, Commissioning, Monitoring	$350,000	$87,500	$437,500
Mobilization / Demobilization	$60,000	$15,000	$75,000
FACILITIES SUBTOTAL	$19,780,000	$4,820,000	$24,600,000
Planning, Engineering & Design (7%)	$1,380,000	$345,000	$1,725,000
Supervision & Admin-Construction Management (6%)	$1,190,000	$298,000	$1,488,000
Geotechnical & Liner Testing Allowance	$200,000	$50,000	$250,000
CONSTRUCTION SUBTOTAL	**$22,550,000**	**$5,513,000**	**$28,063,000**
TOTAL COST (One 77.5-MG Impoundment)	**$24,480,000**	**$5,513,300**	**$29,993,000**
15-YEAR PRESENT WORTH OPERATIONS AND MAINTENANCE COST[d]			**$5,250,000**

[a] Item costs rounded up to the nearest $10,000 for planning purposes. All costs are given in 2011 dollars.

[b] Construction contingency is calculated as 25% of eligible item costs. Contingency was not added to the cost of providing electrical service to the site or to land, as these are direct costs to the City.

[c] Unit land cost is a placeholder until a specific site can be identified. Land costs do not include easements that may be required to connect the impoundment to existing raw water lines. Construction contingency was not added to land cost because this is a direct cost to the City.

[d] 5% discount rate

GENERAL NOTES:

1. **ALL INFLUENT, OUTLET, AND DRAIN PIPES UNDER RAW WATER IMPOUNDMENT SHALL BE ENCASED IN CONCRETE WITHIN IMPOUNDMENT AND BENEATH EMBANKMENT TO A POINT 20 FT. OUTSIDE TOE OF SLOPE.**
2. **THE LOCATION OF EXISITNG PROPERTY LINES, ROADS, PIPELINES, AND RAILROAD TRACKS IS APPROXIMATE AND FOR INFORMATION PURPOSE ONLY.**
3. **ELEVATIONS REFER TO THE NORTH AMERICAN VERTICAL DATUM OF 1988 (NAVD88).**

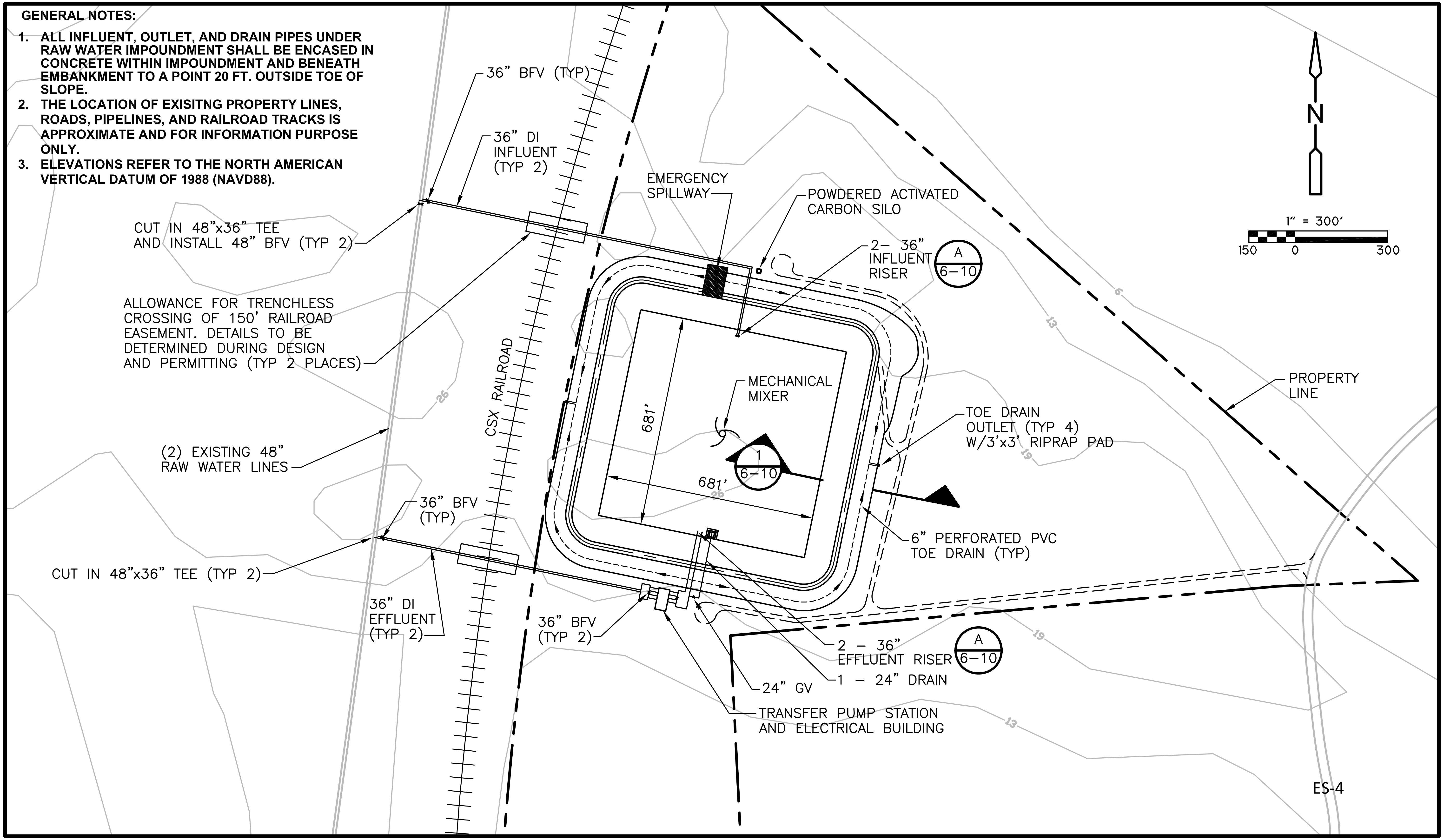

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Figure No. ES-4

Preliminary Raw Water Impoundment Site Layout

November 2011

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Section 1
Introduction

1.1 Background

The current Savannah Harbor Expansion Project (SHEP) authorization included in Section 101 of the Water Resources Development Act of 1999 authorized a deep draft navigation project up to a depth of 48 ft below Mean Lower Low Water (MLLW) level subject to further evaluation by the agencies and concurrence by the Secretaries of the Army, Commerce and Interior, and the Administrator of the Environmental Protection Agency (EPA; *Engineering Investigations* Draft Report, U.S. Army Corps of Engineers, 2010). Therefore, engineering evaluations were performed for project depth alternatives ranging from 44 to 48 ft below MLLW, a maximum of 6 ft below the currently authorized navigation channel at 42 ft below MLLW.

The City of Savannah Industrial & Domestic water treatment plant (I&D WTP) provides drinking water to approximately 10,500 domestic and industrial customers. This project supports the City of Savannah's mission to continue providing high quality drinking water by understanding and mitigating the impacts of increased percentage of seawater intrusion in the water supply.

In particular, this study evaluates the effects that the deeper harbor would have in terms of increasing the percentage of seawater that reaches the City of Savannah drinking water intake. The intake is located on Abercorn Creek, which joins the Savannah River approximately 1 mile upstream of the I-95 bridge. Although the intake is well upstream of the proposed deepening project, the harbor deepening would increase the amount (percentage) of seawater that reaches the intake under conditions of high tide and low freshwater flow in the creek. Modeling provided under separate studies associated with SHEP estimated the impact of deepening on the intake location in terms of increased chloride concentration. Therefore, it is important to evaluate the potential impact of increased chloride levels on water quality.

This project employs bench-scale testing to evaluate how the increased percentages of seawater could affect water treatment plant operations, regulatory compliance, and the quality of the drinking water delivered to City of Savannah customers. It is one of the many engineering studies, investigations and analyses that have been performed in developing the recommended project improvements for the Savannah Harbor Expansion Project (SHEP).

1.2 Project Objectives

The objective of this study is to quantify the relative impacts of increased seawater percentage in the source water for the City of Savannah's I&D Water Treatment Plant. The specific impacts that are studied include:

- Coagulant demand
- Variability in water quality
- Treated Water Corrosivity and potential impact on leaching of lead, copper, and iron
- Potential for formation of disinfection byproducts

Based on the findings, we recommend in Section 6 appropriate modifications to treatment process and other operational adjustments to assist the I&D WTP in adapting to increased percentage of seawater.

1.3 System Description

The I&D WTP employs a conventional flocculation-sedimentation-filtration process. Aluminum sulfate (alum) and coagulant aid polymer are added at the beginning of the treatment process. After flocculation and settling, lime is used to raise the pH of the settled water. A small amount of chlorine is applied prior to sand filtration. Filtered water is then split between the City of Savannah's two distribution systems.

The industrial system accounts for approximately 80-90% of the I&D WTP's flow and serves primarily large industrial customers. However, during the summer months this system is sometimes called upon to supplement groundwater supplies to the City, meaning that it also serves Savannah's 55,000 residents. This system uses free chlorine for both primary and secondary disinfection, contains predominantly ductile iron piping, and has a relatively short residence time (~12 hours). The free chlorine system does not contain a clearwell.

The residential system is much larger, although it only accounts for 10-20% of the I&D WTP's water production. As the name implies, it serves primarily residential customers. This system has residence times of 5 days or more and uses chloramines for secondary disinfection. It is preceded by a large clearwell, where water is treated with free chlorine for approximately 12 hours before entering the system. Lead and copper corrosion are a greater concern in this system due to the presence of a variety of plumbing materials and household plumbing fixtures. Because of the long free chlorine contact time in the clearwell, disinfection byproduct levels are generally highest in this system.

1.4 Organization of Report

This report is divided into eight sections, including this introduction. Sections 2 and 3 present a background and literature review on distribution system corrosion and disinfection byproducts, respectively. Section 4 presents an analysis of historical water quality data and a comparison of historical chloride levels with those predicted after harbor deepening. Section 5 describes the procedures and results of the bench-scale testing conducted at the I&D WTP in May – July 2011. Section 6 summarizes the impacts of increased seawater and presents alternatives for their mitigation. Section 7 provides a summary of the study and recommended next steps. Section 8 contains operational guidance to assist plant staff in adapting to the higher chloride levels using the recommended raw water impoundment. References are available in Appendix A. Subsequent appendices contain more detailed documentation of the bench-scale testing protocol development and procedures.

Section 2
Background on Corrosion

This section presents a review of literature specifically focused on current drinking water corrosion control treatment issues including role of pH, alkalinity, seawater (chloride), and corrosion inhibitors, industry research, and alternative management strategies to control lead, copper, and iron corrosion. References are attached in **Appendix A**.

2.1 Introduction

The use of lead pipes and lead-bearing plumbing materials in drinking water systems has been a common practice since Roman times (WaterRF, 1990). Lead is a soft and malleable material and is highly resistant to serious physical deterioration. However, due to its detrimental effects to human beings, control of lead from different sources including drinking water has been a high priority for the USEPA since the agency was formed in the early 1970s (WaterRF, 1990).

In May 1986, through the Safe Drinking Water Act (SDWA) Amendments, the U.S. Congress banned future use of materials containing lead in drinking water systems and limited the lead content in brass used for plumbing. The SDWA required that after June 19, 1986 only "lead free" pipe, solder or flux may be used in the installation or repair of Public Water Systems (PWS), or any plumbing in residential or non-residential facilities providing water for human consumption, which are connected to a PWS. "Lead free", as defined in the SDWA, means that solders and flux may not contain more than 0.2 percent lead, and pipes, pipe fittings, and well pumps may not contain more than 8.0 percent lead.

Copper has been used as a plumbing material since World War II and now accounts for approximately 80-percent of all tubing in distribution systems (Ferguson et al., 1996). Copper is an ideal material for water service due to its high corrosion resistance, ease of installation, and economic feasibility (Ferguson et al., 1996). However, excess soluble copper release is usually associated with pipe thinning, reduced service life, “green” or “blue” water complaints, stained plumbing fixtures, metallic taste, and can even cause nausea if enough copper is ingested (Ferguson et al., 1996).

Pitting corrosion of copper piping is also a concern because it can cause leakage and even failure of the piping (Edwards et al., 1994a). If the damage continues and public concern increases, it is possible that federal regulators will place restrictions on water qualities that cause pitting corrosion (Edwards et al., 1994a).

Unlined cast-iron mains have been in use for more than 300 years in Europe and over 200 years in the US (Benjamin et al., 1996). The most common problem encountered with iron piping is likely to be 'red' water at the consumer's tap (Benjamin et al., 1996). Almost all of the cast-iron pipes installed over the past few decades have been lined with bituminous or asphaltic material and/or with cement mortar, which are intended to prevent or at least minimize pipe corrosion by providing a coating of electrically inert material between pipe and water (Benjamin et al., 1996, WaterRF, 1991). These linings can be mechanically applied when the pipe is manufactured, in the field before it is installed, or even after the pipe is in service (Schock, 1999; WaterRF, 1991). The use of linings must be carefully monitored because they can be the source of several water quality problems, including support of bacterial re-growth, taste and odor, and leaching of highly soluble components, such as free lime, calcium carbonates, and a variety of silicates and aluminosilicates (WaterRF, 1991; Benjamin et al., 1996; Schock, 1999).

The Lead and Copper Rule (LCR), first published in 1991, recognizes that the corrosive action of different waters in distribution systems and household plumbing systems can result in elevated levels of lead and copper at the consumer's faucet. The LCR sets action levels at the tap for lead and copper at 0.015 mg/L and 1.3 mg/L, respectively. Treatment technique requirements are triggered when 10 percent of the lead or copper levels of first draw samples from high risk locations exceed the action level. Treatment techniques may include corrosion control treatment, source water monitoring/treatment, public education, and lead service line replacement.

In addition to routine sampling for lead and copper at customer's taps, the LCR also requires all large systems serving a population greater than 50,000 people to conduct water quality parameter (WQP) monitoring. Samples for WQP monitoring are to be collected from taps that are representative of water quality throughout the distribution system and should remain within the range of values specified by the State to reflect "optimal" corrosion control.

On October 10, 2007, the USEPA published the latest revisions to the LCR. Significant applicable changes made in this revision of the rule include the following items:

1. The requirements for providing public education if the lead or copper action levels are exceeded have been revised. The content of the message to be provided to consumers, the materials are delivered to consumers, and the timeframe in which materials must be delivered have been changed. Also, there are changes to the delivery requirements, which include additional organizations that systems must partner with to disseminate the message to at-risk populations. The rule revisions also require educational statements about lead in drinking water to be included in all Consumer Confidence Reports.

2. All water systems are now required to provide a notification of tap water monitoring results for lead to owners and/or occupants of homes and buildings who consume water from the taps that are part of the LCR sampling program. Notification must be provided no later than 30 days after the system learns of tap monitoring results.

3. All water systems must notify the State in writing prior to any upcoming long-term change in treatment (such as switching secondary disinfectants, switching coagulants, or switching corrosion inhibitor products) or addition of a new water source. The State must review and approve the addition of a new source or long-term change in water treatment before it is implemented.

In addition, the action levels for lead and copper, the EPA has established a secondary (non-binding) MCL for iron at 0.3 mg/L.

2.1.1 Potential Health Effects

The main corrosion contaminant of health concern is lead, which in even very small amounts can produce adverse effects in humans (USEPA, 2003). The U.S. Environmental Protection Agency (USEPA) has named lead as the most serious environmental health hazard to children because it can cause premature birth, reduced birth weight, anemia, colic, seizures, nervous disorders, behavioral problems, brain damage and lower IQ levels (Boffardi, 1990; USEPA, 1996a; USEPA, 2003). Some of the effects of lead poisoning on adults include: greater risk of cancer, damage to the brain, kidneys, liver, nervous, and hearing system, inhibited red blood cell formation, elevated blood pressure, and increased possibility of stroke (Boffardi, 1990; USEPA, 1996a).

Copper and iron are actually essential micronutrients that are necessary in small amounts for human health, but are in fact harmful over long-term exposure to elevated levels of copper and iron in drinking water (USEPA, 2007c). Research has shown that short term exposure to high copper levels can cause gastrointestinal disturbances, such as nausea and diarrhea, and long term exposure can lead to liver and kidney damage (USEPA, 2007c).

2.1.2 Sources of Lead

Exposure to lead is of particular concern due to its serious health effects at low doses. While the most common sources of lead poisoning are lead based paints, dust, or soils, lead may enter drinking water through source water, water treatment chemicals, corrosion from distribution system materials, lead service pipes or consumers' plumbing fixtures, piping, and appurtenances. Unlike other drinking water contaminants, the primary source of lead in drinking water is corrosion from the distribution system and premise plumbing.

2.1.2.1 Source Water

Lead can enter surface water through direct or indirect discharge from industrial or municipal wastewater treatment plants, or as lead particulates from the combustion of leaded gasoline or fossil fuels and from ore smelting (WaterRF, 1990). For this second transport mechanism, the particles settle into water or onto streets, and then enter surface waters through rainfall and runoff. The LCR requires source water monitoring and treatment once the action level is exceeded (USEPA, 1991). The USEPA recognizes several existing treatment technologies that can easily remove lead and copper in source waters including coagulation/filtration, ion exchange, lime softening and reverse osmosis (WaterRF, 1990).

2.1.2.2 Water Treatment Chemicals

Some treatment chemicals may potentially have lead impurities. These can include aluminum sulfate (alum), ammonium sulfate, calcium hydroxide (slaked lime), calcium oxide (quicklime), granular activated carbon (GAC), powered activated carbon (PAC), ferric chloride, ferric sulfate, ferrous sulfate, sodium aluminates and sodium carbonate (soda ash) (WaterRF, 1990). However, there is little evidence that the amounts of impurities in chemical additives are sufficient to contaminate water supplies (WaterRF, 1990).

2.1.2.3 Distribution System Materials

The low lead content in distribution system piping with a coating normally present, and the relatively high volume of water flowing in the pipes make distribution system piping an unlikely source of significant lead in drinking water (WaterRF, 1990). Some distribution system appurtenances such as large water meters, gaskets, and bell and spigot joints may contain small amounts of lead (WaterRF, 1990). However, the exposed lead surface areas in these appurtenances are relatively small and water contact times are short, minimizing the potential for lead release into the drinking water (WaterRF, 1990).

2.1.2.4 Lead Service Pipes and Premise Plumbing Fixtures

Numerous studies have indicated that the corrosion activities of the water on lead service piping, lead and copper plumbing, lead goosenecks, lead solders and brass or bronze faucets are the most likely contributors to high lead levels at consumer's tap (WaterRF, 1990; Schock et al., 1996). This study focuses on reviewing the relative impacts of increased seawater percentages (and hence increased chloride and bromide in the source water) on mechanisms for lead and copper release from these types of materials, and on related corrosion control strategies.

2.1.2.5 Other Sources of Lead

Besides drinking water, sources of lead for human exposure include air, food, dust, paint, gasoline and soil. Ingestion of paint chips containing lead and dust accounts for most of the reported cases of lead poisoning in children. Other important sources of lead are air deposition on food crops, leaching to food from lead-soldered cans, and lead in air arising from industrial emissions and past combustion of leaded gasoline in cars. Human populations located in areas near stationary lead sources, such as smelters and battery plants, are found to have higher blood lead levels.

2.2 Types of Corrosion

Corrosion is generally considered an electrochemical reaction between a metal and its environment, which results in property changes of the metal (Snoeyink and Wagner, 1996). Corrosion occurs when there is an electrochemical corrosion cell, consisting of an anode, a cathode, a connection between the anode and cathode for electron transport, and a conducting solution that transports ions between the anode and cathode (USEPA, 1993). The anode is where corrosion takes place and electrons are released. The actual mechanisms of corrosion in a water distribution system are usually a complex and interrelated combination of physical, chemical, and biological processes (Schock, 1999). The type of corrosion depends on the material to be corroded, construction of the distribution and plumbing systems, scale and oxide film formation and hydraulic conditions. The following sections provide a brief overview of the typical types of internal corrosion of drinking water systems.

2.2.1 Concentration Cell Corrosion

This type of corrosion occurs when two or more areas of a metal surface are in contact with different concentrations of the same solution (USEPA, 1993). Differences in pH, metal-ion concentration, anion concentration, oxidizing agents, or temperature can induce differences in the solution potential of the same metal (Snoeyink and Wagner, 1996). A common cause of corrosion is the presence of different concentrations of dissolved oxygen (DO) at different sites on a metal surface (Snoeyink and Wagner, 1996). Low DO concentration can prevail under sludge or a suspended solid that is attached to the pipe wall. Corrosion occurs at the site with lower oxygen (anode) since oxygen participates in the cathodic reaction (USEPA, 1993, Snoeyink and Wagner, 1996). An example of this type of corrosion in a water distribution system is metallic lead converting to lead ions (Pb(II)) due to the corrosion of lead service pipe.

2.2.2 Uniform Corrosion

Uniform corrosion occurs when the anode and cathode move rapidly across the surface of the pipe, which cause water to freely dissolve metals from the pipe surface (USEPA, 1993; Snoeyink and Wagner, 1996). The rate of metal loss is relatively uniform over the metal surface. An example of this type of corrosion in a water distribution system is the uniform corrosion of iron water mains.

2.2.3 Pitting Corrosion

When an anode is fixed for an extended period of time, the metal may deteriorate at one point, causing pitting corrosion (Edwards et al., 1994a; Snoeyink and Wagner, 1996). Pitting is a damaging, localized, non-uniform corrosion that forms pits or holes in the pipe surface (Edwards et al., 1994a). It actually takes little metal loss to cause accelerated pipe failure (Ferguson et al., 1996). Pitting corrosion is usually classified into three categories: type I (cold water), type II (hot water), and type III (soft water) (Edwards et al., 1994a). An example of this type of corrosion in a water distribution system is the pitting corrosion of copper tubing.

2.2.4 Galvanic Corrosion

Galvanic corrosion occurs when two different types of metals or alloys contact each other, and when all the elements of the corrosion cell are present (Snoeyink and Wagner, 1996). The metal that serves as the anode deteriorates resulting in metal species leaching into the solution, whereas the metal serves as the cathode is protected by receiving less dissolved metal compounds. An example of this type of corrosion in a water distribution system is the corrosion of lead-tin solder when it is galvanically connected to copper tubing.

2.2.5 Dealloying or Selective Leaching Corrosion

This type of corrosion is the preferential removal of one or more metals from an alloy in a corrosive medium (Schock, 1999). Dezinfication is a specific form of dealloying or selective leaching corrosion (USEPA, 1996a), caused by greater tendency for corrosion of zinc as compared with copper or lead within an alloy matrix (WaterRF and AWWA, 2000). Dezincification leaves the residual brass porous, spongy and mechanically weak (Reiber, 1993; Schock, 1990). It is the most common form of brass corrosion, which involves the leaching of zinc from the brass. Selective leaching also applies to the dissolution of asbestos-cement pipe, or the deterioration of cement mortar linings of iron water mains (Schock, 1999).

2.2.6 Erosion Corrosion

Corrosive waters with high velocities can lead to mechanical damage of the already thin corrosion protection layer, and expose the metal underneath (Snoeyink and Wagner, 1996). The bare metal corrodes at a higher rate than the protected pipe wall. Erosion corrosion is most prevalent in soft alloys (e.g. copper and lead alloys). Erosion corrosion is readily recognized by the characteristic roughening of the pipe interior (Ferguson et al., 1996). An example of this type of corrosion in a water distribution system is the erosion or wearing away of a pipe elbow from high flow velocity in the pipe (Schock, 1999).

2.2.7 Biological-Induced Corrosion

This type of corrosion results from interactions between the pipe material and microorganisms attached to the pipe wall (Snoeyink and Wagner, 1996). Bacterial re-growth can influence corrosion in drinking water systems in several ways. Bacterial re-growth in biofilms can create concentration cells that promote corrosion (Snoeyink and Wagner, 1996). Bacteria, such as sulfate reducing bacteria and iron oxidizing bacteria, may catalyze the reaction associated with the corrosion process (WaterRF and AWWA, 2000). Nitrification can also cause local changes in the vicinity of biofilm, which can enhance corrosive activity (USEPA, 2007a). An example of this type of corrosion in a water distribution system is observed when corrosion products interfere with the disinfection of coliform and heterotrophic bacteria, which leads to aggregated biological-induced corrosion (USEPA, 2007a).

2.3 Corrosion of Specific Materials

This section focuses on how different forms of lead and copper (e.g. soluble and particulate) enter the drinking water and influence lead and copper levels at the tap. In addition, the corrosion of iron is discussed in three parts: 1) the oxidation of metallic iron; 2) scale formation; and 3) iron release and occurrence of 'red' water.

2.3.1 Lead Corrosion

Lead can be present in a drinking water system in either a soluble, colloidal or particulate form (Schock, 1990; Schock, 1999; McNeill and Edwards, 2004).

2.3.1.1 Soluble Lead

Lead service pipes, lead-tin solder and plumbing fixtures made of lead-containing alloys (such as brass) are the principal sources of lead in drinking water. While the installation of materials containing high amounts of lead has been generally discontinued in the US as a result of the 1986 Lead Ban, lead-bearing materials, especially brass fixtures, within water service and premise plumbing systems are still widespread (WaterRF and AWWA, 2000). The corrosion process associated with each of these lead-containing materials is unique and is discussed in the following paragraphs. In addition to corrosion as a textbook-defined anodic reaction, dissolution and solubility reactions must be considered, particularly with respect to the performance of lead corrosion inhibitors.

1. Lead Pipe - In the case of lead pipe, the theoretical mechanism is the establishment of a corrosion concentration cell on the lead surface (Singley, 1994). Once lead is released into water, it can undergo secondary reactions with other ions, including hydroxide ions (OH-) and carbonate ions (CO32-), resulting in the formation of lead precipitates (Schock et al., 1996). The property of this precipitation, and whether it forms an adhered scale or becomes a particulate without forming an adhered layer, is important as it effects subsequent corrosion reactions (Schock et al., 1996). The presence of oxidants in water that accept electrons can drive these corrosion reactions.

2. Lead-Tin Solder - Galvanic corrosion is the dominant mechanism for lead release from lead-tin solder joining copper pipe (Singley, 1994). Both lead and tin have greater electrochemical tendency to corrode than copper, therefore when lead-tin solder is galvanically coupled with copper in corrosive water, lead and tin are mobilized (Schock, 1990; Oliphant and Schock, 1996). A large body of studies indicated that lead-tin solder in copper plumbing systems is a major source of lead in drinking water at the taps (Oliphant and Schock, 1996).

3. Lead-Containing Brass Fixtures - Brass is an alloy of copper (60 to 80%), zinc (4 to 32%), lead (2 to 8%), tin (6%) and trace amounts of other elements such as iron, aluminum, nickel, and silicon, depending on its application (USEPA, 1996a). Similar to lead solder, brass fixtures may be electrically coupled with copper that may cause galvanic corrosion (WaterRF, 1990; Oliphant and Schock, 1996). Numerous studies have shown that brass is a major source of lead at the tap (Lee et al., 1989; WaterRF, 1990; USEPA, 1996a). Even "lead free" brass fittings and plumbing fixtures, which can legally contain up to 8 percent lead, have been found to contribute high lead levels for a considerable period of time after initial installation. In a field study of tap water from 94 water companies and 1,405 houses, it has been revealed that in houses with lead-soldered copper pipes, brass fixtures contributed one third of the lead tested (Lee et al., 1989). In houses with plastic or galvanized pipes, brass contributed 100-percent of the lead (Lee et al., 1989). The same researchers also found that home plumbing containing brass or bronze fixtures leaches the highest levels of lead during the first five years after installation (Lee et al., 1989). The amount of lead that may leach into the water from a brass faucet or fixture is not solely related to the amount of lead contained in the product. The amount of lead leaching from a plumbing product is greatly, but not exclusively, influenced by the manufacturing process.

2.3.1.2 Particulate Lead

Particulate lead can be a significant fraction of total corrosion by-product released in distribution systems under certain conditions (WaterRF and AWWA, 2000; McNeill and Edwards, 2004). Lead particles in distribution systems may originate from the precipitation of lead solids, such as passivation films or corrosion products, or from removal of existing deposits by scouring or sloughing off during water flow. Relatively large pieces of solder on the interior of a pipe can be dislodged and travel down the pipe to a bend, elbow, restriction, or the screen in the faucet. It was noted that replacement of lead service lines and meters can contribute to increased levels of lead by introducing particulate lead, due to disruption of the existing pipe scales, deposition of lead filings, and galvanic-cell corrosion (AWWA, 2005). Because the uptake of particulate lead into the water is often caused by physical means, its impact is difficult to predict (Schock, 1990). A large amount of the variability in household lead levels can be attributed to this problem, along with the non-uniform corrosion in galvanic cell situations, which include solder, faucets and metal/metal connections (Lytle et al., 1993).

2.3.1.3 Colloidal Lead

Traditional lead corrosion studies have only focused on soluble and particulate lead corrosion. Some recent studies have shown that colloidal lead can also contribute to the total lead amount in soft water (Bisogni et al., 2000). De Mora et al. (1987) determined that colloidal lead was associated with iron oxides and humic acids, forming lead compounds derived from attrition of pipe-wall deposits. Kuennen et al. (1992) found that lead could exist in both soluble and particulate forms depending on the pH, alkalinity, and other chemical concentrations in the water. A follow-up study by Bisogni et al. (2000) supported Kuennen et al.'s finding and suggested that colloidal or particulate lead in water is due to exceedance of solubility. Further, the same study revealed that calcium may help remove colloidal or particulate lead by destabilizing the lead-bound colloids.

2.3.2 Copper Corrosion

Copper is used for tubing and copper alloys (e.g. brasses in fittings and gunmetals in valves) found in premise plumbing systems. Copper is more resistant to generalized corrosion as compared with other metals found in water distribution systems (Ferguson et al., 1996). Despite its corrosion resistance, copper corrosion does occur under the normal drinking water conditions with the presence of dissolved oxygen and residual chlorine (Reiber, 1989).

2.3.2.1 Soluble Copper

Utilities' experience in controlling the release of copper from copper tubing have generally been more reproducible than corrosion control efforts directed at lead release (Edwards and Reiber, 1997). The principle mechanism by which copper is released to water appears to be through dissolution of copper corrosion by-products (Edwards and Reiber, 1997). An important consideration with respect to copper levels at the tap is the control of copper solubility (Ferguson et al., 1996). The important factors affecting the solubility of copper include pH, dissolved inorganic carbon (DIC), sulfate, chloride, ammonia and orthophosphate (Ferguson et al., 1996).

Copper tubing corrosion is usually categorized as uniform corrosion, or localized or pitting corrosion. When uniform corrosion occurs, the entire copper surface corrodes evenly, contributing to the releasing of copper corrosion by–products to drinking water and the accumulation of copper-containing scales. Uniform corrosion is generally considered the major contribution of dissolved copper in drinking waters (Edwards et al., 1994a). Uniform copper corrosion is considered to be favored by low pH (<6) and low alkalinity, with or without inhibitors (Dodrill and Edwards, 1995). Uniform corrosion can lead to excess copper release and blue or green water complaints (Ferguson et al., 1996).

Copper pitting problems have been experienced in waters having high pH, low alkalinity, and significant levels of sulfate and chloride (Edwards et al., 1994a). Several studies (Edwards, et al., 1994b; Sosa et al., 1999) have found that elevated chloride concentrations may have a protective effect against pitting corrosion. Pitting corrosion is rarely associated with high copper level at the tap (Edwards et al., 1994a). Actual field or laboratory data indicating to what extent pitting corrosion may contribute to copper release at taps was not found under this literature review study. However, pitting corrosion can lead to pipe failure and significant damage to homes or structures (Ferguson et al., 1996).

2.3.2.2 Particulate Copper

Under certain circumstances, a large fraction of copper corrosion by-product can be attributed to particulate copper release (Ferguson et al., 1996). The use of orthophosphate was linked to reduced soluble copper levels but increased particulate copper levels from copper tubing (McNeil and Edwards, 2004). It was determined that orthophosphate inhibitors might have formed a less stable copper-phosphate solid, which led to higher levels of particulate copper release (McNeil and Edwards, 2004).

2.3.3 Iron Corrosion

2.3.3.1 Oxidation of Metallic Iron

When drinking water containing oxidizing agents is in contact with bare cast iron surface, the predominant anodic reaction on the surface is the oxidation of metallic iron and the predominant cathodic reaction on the same surface is the reduction of oxidants (Benjamin et al., 1996). The dominant oxidant in most drinking water systems is DO and the corrosion rate is limited by the rate at which oxygen diffuses to the surface and corrosion products diffuse from the surface (Benjamin et al., 1996). For a given temperature and water velocity, the rate of oxygen consumption is equivalent to the corrosion rate and is directly proportional to the oxygen concentration in the water, regardless of the concentrations of most other components dissolved in the water (Benjamin et al., 1996; Schock, 1999). In the absence of scale, an increase in either temperature or velocity increases the oxygen transport rate and corrosion rate. Scales that develop on the pipe walls decrease the corrosion rate by providing additional diffusion barriers to constituents approaching and leaving the surface (Schock, 1999). The effectiveness of these barriers is determined by the physical properties of the scale, such as porosity and thickness (Benjamin et al., 1996). Oxygen reduction might also take place in the scale layer as oxygen diffuses toward the pipe wall, further reducing the rate at which oxygen reaches the pipe surface (Benjamin et al., 1996).

2.3.3.2 Scale Formation

Scale formation is a complicated process that depends on a variety of physical and chemical conditions in each particular system (McNeill, 2000). There are mainly two well-known types of scales that are postulated to affect iron corrosion: calcium carbonate ($CaCO_3$) and siderite scales.

In the past, coating the interior of a pipe with $CaCO_3$ has been deemed the most common corrosion control approach. This is based on the theory that that $CaCO_3$ is a critical component of protective scales, which act as a barrier to the interaction of the corrosive water with pipe materials (Schock, 1989; USEPA, 1993; Benjamin et al., 1996). Langelier (1936) defined the calcium carbonate saturation index, also called the Langelier Index (LI), as the difference between the actual pH and the pH at which the solution would be in equilibrium with $CaCO_3$. LI has been widely used as an indicator of a water's corrosivity toward iron (USEPA, 1993; Benjamin et al., 1996). Despite of its popularity, however, studies have shown the failure of LI in predicting the corrosivity of water in contact with iron pipes (Larson and Skold, 1957; Stumm 1960). In reality, occurrence of $CaCO_3$ layers in piping system is very rare (USEPA, 1993). It was suggested that some cations, such as magnesium, copper, or zinc, and certain anions, such as ortho- or polyphosphates, might inhibit the formation of the $CaCO_3$ layer (USEPA, 1993). Neither LI nor other published indices, such as Saturation Index and Calcium Carbonate Precipitation Potential (CCPP), takes into account the inhibitory factors, especially phosphate-based inhibitors. Therefore, in systems employing phosphate-based inhibitors, calculations of any of these indices is not particularly useful (USEPA, 1993).

The siderite model postulates that the formation of reduced iron species, especially siderite ($FeCO_3$) or different types of green rust, provides a more protective scale than oxidized ferric scales such as goethite (FeOOH) (Benjamin et al., 1996). Green rust is a commonly observed iron corrosion by-product containing both ferrous and ferric iron, as well as other ions such as carbonate, chloride and sulfate (McGill et al., 1976). In most cases, direct and rapid oxidation leads to formation of a very porous Fe(III)-containing layer, whereas the formation of siderite or of certain other Fe(II)-containing solids leads to a much denser, relatively nonporous scale that strongly interferes with oxygen transport (Benjamin et al., 1996). The major water quality factors that determine whether siderite forms are the pH and buffer capacity, or equivalently, pH and DIC, of the water.

Benjamin et al. (1996) investigated the corrosion of iron and steel pipes and the formation of iron scales. Low alkalinity waters produced iron scales that were thick (~ 2-3 cm) and loose, with a dark orange-brown crust containing flecks of yellow-colored scale that could be easily cracked to expose a soft, porous, black or greenish-black interior. The scale formed tubercles that could be easily scraped off. In contrast, scales from high carbonate waters were thin, hard, and tightly bound to the metal surface. They appeared as dark brown patches of fairly uniform thickness (≤ 1 mm).

Iron corrosion can be either uniformed or localized (Benjamin et al., 1996). Localized corrosion of ferrous materials often leads to tuberculation, the development or formation of excessive corrosion products build-up on the inside of iron pipe (Benjamin et al., 1996). Tuberculation roughens the inside of the pipe, reduces the effective pipe size and may also provide potential sites for bacterial re-growth (Benjamin et al., 1996; McNeill, 2000).

2.3.3.3 Iron Release and Occurrence of 'Red' Water

Other than tuberculation, distribution systems with unlined iron pipes can also be subject to water quality problems related to corrosion referred to as 'red' water. Red water is treated water containing a colloidal suspension of very small oxidized iron particles due to corrosion by-product release (McNeill, 2000). Red water is often the most common water quality related customer complaint, as it leads to tap water with objectionable tastes, odors, and staining. In some cases, red water problems occur when sudden changes in flow velocity or water quality cause particles from existing scales to be released into the water. More often, red water problems arise through oxidation of ferrous irons in the bulk solution and the subsequent precipitation of ferric irons (Benjamin et al., 1996).

Iron corrosion can proceed even under conditions where there is negligible DO adjacent to the pipe wall (e.g. during periods of stagnation when the oxygen diffusion rate is low) (Kuch, 1988). Under such conditions, it was proposed that the previously deposited ferric scale could act as oxidant, producing ferrous iron at both the anode and cathode (Kuch, 1988; Benjamin et al., 1996):

$$Fe_{(metal)} + 2FeOOH_{(scale)} + 2H^{+} \leftrightarrow 3Fe^{+2} + 4OH^{-}$$

The ferrous ions may precipitate as green rust or siderite, or migrate toward the bulk water. The oxygen-rich water may permeate the scale layer again, oxidizing the ferrous products within the scale. The ferrous ions that are transported into the standing water are likely to be oxidized, leading to the formation of red water (Benjamin et al., 1996).

2.4 Factors Influencing Lead, Copper and Iron Corrosion

Many factors contribute to the corrosion and leaching of lead, copper and iron from drinking water distribution systems. However, the principal factors are type of materials used, age of the plumbing system, temperature, stagnation time of the water and corrosivity of the water in the system (Schock, 1999, Snoeyink and Wagner, 1996). Factors influencing the corrosion of lead, copper and iron, and the subsequent corrosion by-products release are discussed in this section.

2.4.1 Chemical Factors and Water Quality

Water quality characteristics play an important role in initiating or preventing lead, copper and iron corrosion (WaterRF, 1990). When selecting a control strategy, it is important to understand the chemistry of the finished water. This section examines the effects of the most significant water quality characteristics on lead, copper and iron corrosion.

2.4.1.1 pH

pH is generally considered an indicator of the corrosivity of water (Snoeyink and Wagner, 1996). Changes in pH are especially important to consider since they can impact so many other parameters and processes, including disinfection efficiency, coagulation, precipitation of iron and manganese, formation of disinfection by-products, and the formation and solubility of the protective scales for both metallic and cementitious materials (USEPA, 1993; Schock, 1999). The pH values for most drinking waters range from 6 to 10. In general, the dissolution of most materials used in water distribution systems (lead, copper, iron, zinc, and cement mortar) decreases as pH increases within the pH range of 5 to 10 in the absence of an inhibitor (Schock, 1999; USEPA, 2003).

Early studies on the solubility of the main lead corrosion by-products have focused on divalent lead solids (cerussite [$PbCO_3$], hydrocerussite [$Pb_3(CO_3)_2(OH)_2$] and lead hydroxide [$Pb(OH)_2$]), which were determined to decrease with increasing pH (Schock and Gardels, 1983; Schock, 1989; Singley, 1994; Schock et al., 1996). Solubility models show that the lowest lead levels occur when pH is around 9.8 (Schock and Gardels, 1983; Schock, 1989; Schock et al., 1996). However, these pH relationships may not be valid for insoluble tetravalent lead dioxide (PbO_2) solids, which have been discovered in lead pipe deposits from several different water systems (Schock et al., 1996). The pH relationship of PbO_2 may be opposite to that of divalent lead solids (Schock and Giani, 2004), and it was demonstrated that PbO_2 easily formed at pH 6–6.5 in water with persistent free chlorine residuals in weeks to months (Lytle and Schock, 2005). Utility experience has shown that the lowest levels of lead at the tap are associated with pH levels above 8 (Lee et al., 1989, Dodrill and Edwards, 1995). However, optimal pH levels will also depend on the inhibitor, if any, that is used.

Copper corrosion increases rapidly as the pH drops below 6; in addition, uniform corrosion rates can be high at low pH values (below about 7), causing metal thinning (Ferguson et al., 1996). At higher pH (above about 8), copper corrosion problems tend to be associated with pitting corrosion (Ferguson et al., 1996). High pH may also cause or enhance dezincification of brasses (Schock, 1999).

The effect of pH on iron corrosion is generally through its role in secondary reactions, such as the oxidation of ferrous iron, and on the formation of scales and corrosion by-products (Benjamin et al., 1996; Schock, 1999). Iron corrosion is found to increase with increasing pH in the range 7 to 9, as is the degree of tuberculation (Stumm, 1960). Iron solubility tends to increase at both high and low pH (Schock, 1999).

Although the pH measured at the pump station or treatment facility may appear to be stable, as it passes through the distribution system, it may increase or decrease significantly (AWWA 2005, WaterRF and AWWA, 2000). This depends on the size of the distribution system, flow rate, age and type of plumbing materials, and more importantly the buffering capacity of the water (Snoeyink and Wagner, 1996). pH fluctuations can cause solubilization and precipitation of scales (WaterRF and AWWA, 2000; AWWA, 2005). Significant pH fluctuations can also produce scales that are less adherent and that can contribute to water quality problems such as red water and turbidity (USEPA, 1993; AWWA, 2005). Therefore, maintaining a consistent target pH throughout the distribution system is always critical to minimize lead and copper levels at taps (AWWA 2005).

2.4.1.2 Buffering Capacity

The buffering capacity of water is defined as the ability of the water to resist a change in pH. Bicarbonate and carbonate irons are the most important buffering species in almost all drinking waters. At pH above 9, silicate ions also supply buffering. If water has low buffering capacity, the pH will fluctuate significantly. The fact that corrosion is highly sensitive to pH makes buffer capacity one of the most important factors for corrosion control (USEPA, 1993). Treated water in the pH range of 8.0 to 8.5 tends to have highly variable pH in the distribution system when the water has a very low amount of alkalinity (less than about 10 mg C/L as $CaCO_3$) (USEPA, 2003). Waters with low buffer capacity are prone to pH decreases from sources like uncovered storage, nitrification, corrosion of cast iron pipe, and pH increases from contact with cement pipe surfaces (USEPA, 2003).

2.4.1.3 Chloride and Sulfate

As indicators of corrosivity, chloride and sulfate have often been combined as a chloride to sulfate mass ratio (CSMR). The CSMR can be calculated as:

$$CSMR = \frac{[Cl^{-}]}{[SO_4^{2-}]}$$

Where $[Cl^{-}]$ and $[SO_4^{2-}]$ are the concentrations of chloride and sulfate in mg/L.

Numerous case studies have been documented in which higher CSMR has been linked to lead problems (Oliphant, 1983; Edwards, et al., 1999; Dodrill and Edwards, 1995; Dudi and Edwards, 2004, Triantafyllidou and Edwards, 2006, WaterRF, 2010, Nguyen, et al., 2011). Dudi and Edwards (2004) demonstrated that waters with high CSMR were aggressive to lead solder galvanically connected to copper and caused increased lead leaching from brass. A survey of 24 utilities (Dodrill and Edwards, 1995) in the U.S. revealed that utilities with CSMR lower than 0.58 had greater tendencies to meet the action level for lead. Edwards and Triantafyllidou (2007) concluded that a switch of sulfate containing coagulants to chloride based coagulants can increase the CSMR, which can lead to high lead levels in water.

The WaterRF study (2010) confirmed findings of Edwards and Triantafyllidou (2007) and demonstrated that CSMR increase could also be due to other treatment changes like (1) using anion exchange with the resin in the chloride form, (2) use of desalinated or membrane treated water, (3) road salt runoffs from roadways, and (4) chloride leak at utilities using brine for hypochlorite generation. Increase in CSMR's of the water generally led to increase in higher lead levels in water only when lead pipe or lead solder were galvanically connected to copper (WaterRF, 2010). The study evaluated a number of Utility case studies to examine the impacts of high CSMR on galvanic corrosion in a number of potable waters. A wide range of chloride-based, sulfate-based, and blended coagulants were also evaluated as part of the study. The differences between lead leaching results as a result of coagulant selection were most dramatic when the CSMRs of the treated waters were below 0.5 before the switch, and were raised to above 0.5 following the switch. Effect of high source water chloride concentrations on lead leaching was also evaluated by adding 20 mg/L chloride to polyaluminum chloride (PACl) treated water to simulate road salt runoffs in a case study (WaterRF, 2010). Lead leaching doubled compared to other conditions where no simulated road salt runoffs were evaluated. Localized pH drops (~3.0) at the surface of lead bearing pipe were observed with the bulk water pH of 8.0 and higher when galvanic connection to copper pipe was present (WaterRF, 2010). Effects of phosphate inhibitors and alkalinity produced mixed results, hence effect of these parameters need to be determined on a case-by-case basis (WaterRF, 2010).

Utilities with low alkalinity water, (< 50 mg/L as $CaCO_3$) with lead solder or partially replaced lead pipe and are considering a treatment change that results in final CSMR above 0.2 should examine potential impacts on lead release before implementation (Nguyen et al., 2011).

Iron corrosion and release have been determined to be increased dramatically with the increased concentration of sodium chloride or sodium sulfate (Benjamin et al., 1996). Based on the field studies of Larson with unlined iron pipe, the molar ratio of the sum of the chloride plus the sulfate to the bicarbonate concentration, sometimes called the Larson Ratio (LR) (Larson and Skold, 1957), should be less than about 0.2 to 0.3 to prevent enhanced corrosion of unlined iron (Schock, 1999).

$$LR = \frac{[Cl^-] + 2[SO_4^{2-}]}{[HCO_3^-]}$$

2.4.1.4 Dissolved Inorganic Carbonate (DIC)

DIC is the sum of total carbonates in the form of carbon dioxide gas (CO_2 or H_2CO_3), bicarbonate ion (HCO_3), and carbonate ion (CO_3^{2-}) in water. Its amount relates to the buffering capacity of the water. Sufficient DIC is necessary to provide enough buffering capacity in finished water for maintaining desired pH throughout the distribution system (Schock, 1999). DIC can also significantly affect lead, copper and iron solubility through the complexation effects of carbonate, bicarbonate, or both (Snoeyink and Wagner, 1996).

High levels of DIC in finished water need to be adjusted to prevent excessive amounts of CO_2 from entering distribution systems due to its corrosive effect on lead, copper and iron by forming more soluble complexes (Sander et al., 1996).

2.4.1.5 Oxidizing Agents

Oxidizing agents such as oxygen and chlorine species (such as HOCl, OCl^-, Cl_2, and chloramines) can transform the metallic lead, copper and iron to at least one of their oxidized forms. Oxidizing agents may also affect the nature of passivating films on a pipe by altering the crystalline characteristics and porosity of corrosion product films (Treweek et al., 1985; Lytle, et al., 1998). Lytle, et al. (1998) reported that high levels of oxidizing agents might accelerate the corrosion rate and the release of lead and copper into the water in a short stagnation period.

Dissolved oxygen (DO) is considered a key oxidizing agent in electrochemical corrosion reactions due to its strong tendency to accept electrons (USEPA, 1993). Oxygen may be depleted at a specific location due to corrosion reactions, corrosion by-production oxidization reactions, period of stagnation (e.g. dead end), or microbiological reactions (USEPA, 1993; Snoeyink and Wagner, 1996). Local differences in oxygen concentrations between one place on the pipe surface and another can produce concentration cells, which corrode the pipe at low-oxygen sites (USEPA, 1993; Snoeyink and Wagner, 1996; AWWA, 2005). Increases in oxygen can have an effect on the solubility of lead, copper, manganese, and iron (AWWA, 2005), and may encourage nitrification (AWWA, 1990). The corrosion rate of steel, cast iron, and ductile iron pipes increased directly with DO from 0.25 mg/L to saturation (WaterRF, 1990). By oxidizing Fe (II) to Fe (III), DO can potentially worsen red water problems (Schock, 1999). Continued attack at the low-oxygen site leads to iron and copper pitting corrosion (USEPA, 1993; Ferguson et al., 1996; AWWA, 2005). It was noted that ozone, another oxidant from an alternate disinfection processes, could also impact corrosion by causing high DO levels as a by-product of ozonation (Schock et al., 1996; USEPA, 1999c). The presence of oxygen may also fundamentally affect the speciation of microorganisms in the distribution system, which may affect the type and form of corrosion deposits (Schock, 1999).

The corrosion rate might be reduced by eliminating DO from water, but substantial DO concentration is also a component essential to scaling (lead, copper and iron oxides), which helps reduce the corrosion rate (AWWA, 2005). High DO also protects metal by functioning as the cathode (USEPA, 1993).

Chlorine is one of the most commonly used chemicals for water disinfection. Chlorine may be applied to a distribution system in either a gaseous form (Cl_2) or as an ionized solid [$Ca(OCl)_2$ or NaOCl)]. Each compound reacts in water to produce the disinfectants hypochlorous acid (HOCl) and hypochlorite ion (OCl^-), both of which contribute to what is known as the free chlorine residuals. Free chlorine residuals can impact the oxidation rates and the nature of scales that form on the interior wall of pipes, accelerating the conversion of metallic lead to Pb(II) or Pb(IV) (Lytle and Schock, 2005). Gaseous chlorine lowers the pH of the water which tends to make the water more corrosive by forming HOCl, hydrogen ion (H^+), and chloride ion (Cl^-) (Schock, 1999). Conversely, the addition of chlorine as $Ca(OCl)_2$ or NaOCl raises the pH (Schock, 1999).

Free chlorine residuals have been reported to increase copper corrosion at lower pH (Reiber, 1989), and decrease it at pH 9.3 (Edwards, et al., 1999). Excess free chlorine residual is considered detrimental to copper alloys in plumbing systems (Boffardi, 1990).

The presence of free chlorine residuals has been reported to increase iron corrosion (Schock, 1999; Cantor et al., 2003), either by directly increasing the oxidizing potential which favors the conversion of metallic iron to ferrous and then ferric iron, or through a sequence of chemical reactions that produce H^+, HOCl, OCl^-, and Cl^- (Schock, 1999). A serious health concern is the fact that iron corrosion by-products readily consume free chlorine residuals (Frateur et al., 1999). When iron corrosion is bacterially influenced, a higher level of free chlorine residual may actually decrease corrosion problems (LeChevallier et al., 1993).

Changing secondary disinfectant from free chlorine to chloramines (a weaker oxidizer) has been considered the most probable cause of the elevated lead concentrations at taps in Washington, D.C. drinking water system (Cohn, 2004; Renner, 2004, USEPA, 2005). It was determined that free chlorine leads to the insoluble lead dioxide deposits in lead pipes. By changing from free chlorine to chloramines the oxidizing potential of Washington, D.C. water was lowered, which caused accelerated dissolving of PbO_2 scales (Schock and Giani, 2004). Without an inhibitor, a significant amount of lead was leached into water (Schock and Giani, 2004; Renner, 2004; Lytle and Schock, 2005). They also observed that chloramines enhance galvanic corrosion. Edwards and Dudi (2004) performed laboratory experiments on chloramines and confirmed that chloramines tend to mobilize lead from brass. Chloramines were also found to react with certain types of rubber hoses and gaskets, such as those on washing machines and hot water heaters, forming black or greasy particles as these materials degrade (USEPA, 2007b).

2.4.1.6 Calcium

Theoretically, if water contains an appreciable amount of calcium hardness, it may act in conjunction with the pH and DIC to form a protective calcium carbonate layer (Schock, 1999). However, surveys of U.S. water companies and districts (most not using pH of saturation for corrosion control) revealed no relationship between lead or copper levels and calcium levels (Lee et al., 1989; Dodrill and Edwards, 1995). To be effective, this mechanism requires some calcium carbonate precipitation, which may make it difficult in some cases to avoid customer complaints and/or pipe clogging from the deposits.

2.4.1.7 Natural Organic Matter (NOM)

NOM can have both positive and negative effects on lead, copper and iron corrosion. NOM can increase the release of lead, copper, and iron by interfering with the formation of scales and forming soluble/colloidal complexes (Gregory et al., 1999). Conversely, NOM can also reduce corrosion by adsorbing lead, copper and iron, and forming protective coatings on pipe surfaces (Schock et al., 1996; Campbell and Turner, 1983). Although there is evidence that certain water treatments that alter or remove NOM, including coagulation, ozonation, activated carbon, and filtration impact lead and copper solubility (Edwards et al., 1994a), the ability of NOM in inhibiting corrosion is still not fully understood (Edwards et al., 1994a; Schock et al., 1996).

The effects of NOM are believed to depend upon the type of material. The corrosion of lead pipe and solder may be initially increased due to the scale formation with NOM, but once surface scales form a protective layer and NOM is reduced in water, the lead corrosion rate decreases and stabilizes (Korshin et al., 1998). A study by Korshin et al. (2005) demonstrated that the release of soluble lead and tin from corroding lead surfaces increased several fold in the presence of NOM, while large colloidal particles of lead and solder corrosion products tended to break down to form smaller fragments. Some NOM may react with lead corrosion by-products, increasing lead corrosion (Schock, 1999).

Research in copper plumbing pitting has indicated that NOM might alleviate pitting corrosion and possibly alter some scale formation characteristics of uniform copper corrosion (Campbell and Turner, 1983; Edwards et al., 1994a; Edwards and Sprague, 2001). However, some NOM can form a strong complex and thus increase the solubility of copper corrosion products (Korshin et al., 1998; Edwards, et al., 1999, Edwards and Sprague, 2001).

In some cases, NOM may become food for bacterial growth in the distribution system (Schock, 1999) and thus promote biological re-growth and cause bacterial-induced corrosion.

2.4.1.8 Total Dissolved Solids (TDS)

TDS refers to the total amount of all inorganic and organic substances (including minerals, salts, metals, cations or anions) that are dispersed in water. An elevated TDS concentration is generally related to high levels of ions (e.g. Na^+, Ca^+, Mg^{2+}, Cl^-, CO_3^{2-} and SO_4^{2-}) which can increase the conductivity of the water, leading to higher flow of electrons and thus helping promote electrochemical corrosion (Schock, 1999; AWWA, 2005). Low TDS water also has a strong tendency to corrode materials with which it is in contact in an attempt to reach equilibrium (AWWA, 2005).

TDS may also affect the formation of protective films, depending on their particular nature (Schock, 1999). If sulfate and chloride are major anionic contributors to high TDS, it is likely to show increased corrosivity toward iron-based materials. If the high TDS is mainly composed of bicarbonate and hardness ions, the water may tend to be noncorrosive toward iron and cementitious materials, but highly corrosive toward copper.

2.4.1.9 Nitrification and Ammonia

Chloramination treatment and decomposition often introduces ammonia into drinking water systems, which can potentially act as a food source for nitrifiers, causing nitrification occurrence in distribution systems. Nitrification is the microbially mediated two-step oxidation of ammonia to nitrite and then to nitrate. The two steps are performed by different groups of bacteria, the ammonia-oxidizing bacteria (AOB) and the nitrite-oxidizing bacteria (NOB). Nitrification is a common problem in drinking water distribution systems employing chloramines as secondary disinfectant (Wolfe et al., 1990). Once nitrification begins, it accelerates the loss of disinfectant residuals because the rate of chloramines decomposition increases as ammonia decreases (WaterRF and AWWA, 2004). Even though it has not been systematically studied, there is some evidence showing nitrification in chloraminated water may promote lead and copper corrosion (Murphy et al., 1997; WaterRF and AWWA, 2004). It is recognized that nitrification can lower the pH of the water in the distribution system and potentially promote lead and copper corrosion (Wilczak et al., 1996; Cates and Lavinder, 1999; USEPA, 1999).

Nitrification in drinking water systems is often incomplete, a condition in which not all ammonia is converted to nitrate (some of the ammonia remains as ammonia and some of the ammonia undergoes partial conversion yielding concentrations of nitrite). Typically, incomplete nitrification results in high levels of ammonia in the distribution system. Ammonia is highly corrosive towards copper and zinc-containing alloys (such as brass fittings) by forming strong copper complexes, which will interfere with the formation of the protective scale, but is less aggressive for lead and tin (Oliphant et al., 1996). High concentrations of ammonia and an absence of residual disinfectant also promote re-growth of bacteria, which exhibit slow growth and are often found in higher levels in the sediment and biofilm of distribution systems (Wolfe et al., 1990). Increased bacterial growth can lead to biological-induced corrosion (USEPA, 1999a; WaterRF and AWWA, 2004).

2.4.1.10 Oxidation-Reduction Potential (ORP)

ORP is the potential at which oxidation occurs at the anode and reduction occurs at the cathode of an electrochemical cell (Suslow, 2004). Disinfectant residual type and concentration, DO concentration, and pH can all impact ORP. ORP can be a potentially useful measurement in optimizing corrosion control (Lytle, 2006). It should be noted that a higher ORP may not mean greater corrosion problems (Lytle, 2006). For iron corrosion control, it is beneficial to maintain a high ORP, which will increase the formation of insoluble Fe (III). For copper corrosion control, however, a lower ORP is more desirable since it favors the formation of relatively insoluble Cu (I). As to lead corrosion control, studies have shown that, similar with iron, water with a high ORP produces Pb (IV), a more insoluble form of lead. At a lower ORP Pb(II), a more soluble form of lead, is formed in the absence of inhibitors (Schock and Giani, 2004).

Recent studies have highlighted the impact of ORP change on lead scales and lead release due to disinfectant change (Schock and Giani, 2004; Lytle and Schock, 2005, Vasquez et al., 2006). Disinfectant destroys the integrity of a cell membrane, which leads to the rapid death of the cell by pulling electrons away from the cell membrane, causing it to become destabilized and leaky (Suslow, 2004). In other words, ORP reflects the antimicrobial potential of the water (Suslow, 2004). If a water system switches from a strong oxidant (chlorine) to a weaker oxidant (chloramines), the ORP in the water may be reduced. As a result, more stable Pb (IV) compounds may be reduced to more soluble Pb (II) compounds.

2.4.1.11 Bacterial Activity

Coliform and heterotrophic bacteria are of particular concern to utilities from a regulatory and public health viewpoint. Other types of bacteria that may be present in distribution systems and can promote the internal corrosion of the piping systems include nitrifying bacteria and sulfate - and iron - oxidizing bacteria (WaterRF and AWWA, 2000). Iron corrosion products can provide habitats for microbial growth, and react with disinfectant residuals, preventing the disinfectant from penetrating the biofilm (LeChevallier et al., 1993).

2.4.2 Physical Factors

In addition to chemical factors, physical factors described in the following sections can affect corrosion of various materials.

2.4.2.1 Age of Materials

Lead concentrations at the tap originating from lead solders and brass fittings decline with age (Sharrett et al., 1982; Boffardi, 1990; USEPA, 1993). Studies have shown that the highest lead levels appear in the first year following installation of lead solders and brass fittings and level off after a number of years of service (Sharrett et al., 1982; Boffardi, 1988). Another study suggested that the corrosion rate of lead-tin solder can be reduced by 90 percent in a period of two weeks (USEPA, 1993). However, unlike lead-soldered joints and brass fittings, lead piping can continue to provide a consistently strong source of lead after many years of service (Schock et al., 1996).

Copper release into the drinking water largely depends on the type of scale formed within the plumbing system. At a given age, a corrosion by-product may govern the release of copper into the drinking water. Copper concentrations continue to decrease with the increasing age of plumbing materials, even after 10 or 20 years of service, when tenorite or malachite scales tend to predominate (Sharrett et al., 1982; Edwards and McNeill, 2002).

In general, iron corrosion rate and release can increase with time when a pipe is first exposed to water, but both are then gradually reduced as the scale builds up (McNeill, 2000). However, heavily corroded unlined cast iron pipes are easily subject to scouring and provide surface areas that favor iron release (Sarin et al., 2003).

2.4.2.2 Stagnation Time of the Water

Concentrations of lead, copper and iron in drinking water can increase significantly following a period of water stagnation time in the distribution and plumbing system (Kuch and Wagner, 1983; Ferguson et al., 1996; USEPA, 1996a; Lytle and Schock, 2000; Sarin et al., 2003). Due to the impact of stagnation time on corrosion, the LCR requires at least 6 hours standing time before sampling for lead and copper. Long sections of lead or copper pipe of small diameter produce the greatest concentrations of lead or copper, respectively, upon stagnation (Kuch and Wagner, 1983; Ferguson et al., 1996).

Lytle and Schock (2000) showed that lead levels increased rapidly with the stagnation time of the water, with the most critical period being during the first 20 to 24 hours. Lead levels increased most rapidly over the first 10 hours, reaching approximately 50 to 70 percent of the maximum observed value. In their experiment, lead levels continued to increase slightly even up to 90 hours of stagnation.

Copper behavior is more complex than lead behavior with regarding to the stagnation time of the water. Lytle and Schock (2000) showed that copper levels increased rapidly with the stagnation time of the water, but only until DO fell below 1 mg/L, after which they dropped significantly.

Stagnant conditions were found to help promote tuberculation and pitting in iron pipes (Benjamin et al., 1996). Most red water problems are caused by heavily tuberculated old unlined cast iron pipes that are subject to stagnant water conditions prevalent in dead ends (Sarin et al., 2003). In the absence of oxygen, a condition that is most likely to develop when the water is stagnant, it is possible for previously deposited ferric scale to act as alternative oxidant (Kuch, 1988; Benjamin et al., 1996). This reaction produces ferrous iron and allows the corrosion to continue even after DO is depleted.

Dead ends provide a stagnation period where the contact time between the water and the pipe is increased (USEPA, 1993). This longer contact time favors bacterial and chemical activity. Dead ends may be more susceptible to corrosion as a result of inadequate opportunity of inhibitor film formation and loss of disinfectant residuals (WaterRF, 1990).

2.4.2.3 Temperature

Temperature influences several water quality parameters, such as metals/chemical reaction rates, dissolution, dissolved oxygen solubility, solution property (such as viscosity and ion mobility), diffusion rates, activity coefficients, compound solubility, oxidation rates and biological activities (WaterRF, 1990). In general, as typical with chemical reactions, the rate of corrosion generally increases with increasing temperature (Schock, 1990). However, the effect of temperature on corrosion rate can be complicated by the fact that the solubility of many film-forming or scaling solids decreases as temperature increases (Schock, 1990).

2.4.2.4 Flow Velocity

Both excessively high and very low velocity can increase corrosion rates (WaterRF, 1990). High velocities can enhance corrosion by increasing the rate of dissolved oxygen transfer or inhibit corrosion by increasing the rate at which a protective scale can form (Schock, 1999). High flow velocity is also usually associated with erosion corrosion and can rapidly deteriorate pipe materials if combined with corrosive water (Schock, 1999). Low flow velocity in crevices and cracks results in loss of the passive film (WaterRF, 1990). Low flow velocity was found to have adverse impact on the effectiveness of phosphate and silicate inhibitors (McNeill and Edwards, 2004; Johnson, et al., 1993).

2.5 Corrosion Control Strategies

Corrosion control can be achieved by combinations of materials selection (e.g. limiting lead content in materials from distribution and plumbing systems), physical removal (e.g. removal of lead-containing materials from distribution and plumbing systems), point-of-use devices (e.g. use of devices attached to water taps or in lines near water outlets), protective barrier or lining between the water and the pipe (e.g. cement mortar lining for cast-iron piping), engineering considerations (e.g. avoiding dead ends, stagnant areas, sharp turns and elbows, and selecting appropriate flow velocity); and chemical treatment (e.g. pH/DIC adjustment or corrosion inhibitors addition) (USEPA, 1993; Schock, 1999).

This section focuses on chemical treatment control strategies and treatment criteria, which may influence what final treatment option, should be chosen for a specific water system. Typically, two modes of actions can be used to inhibit lead, copper and iron release:

Passivating Films. This mode relies on modifying pH and DIC concentrations and/or utilizing corrosion inhibitors (phosphate) to induce the formation of the relatively insoluble complexes on the pipe surface with targeted pipe materials (USEPA, 1993). It can be accomplished by two approaches: pH/DIC adjustment or phosphate-based inhibitor addition.

Precipitation Coatings. This mode involves altering water chemistry to form insoluble compounds in water and deposits onto the pipe interior surface to create a protective coating preventing contact between corrosive water and pipe materials (USEPA, 1993). Two available control approaches can be defined within this mode: calcium carbonate adjustment and silicate addition.

2.5.1 pH/DIC Adjustment

pH/DIC adjustment of the water offers “passive” protection from corrosion. For some water systems, merely adjusting the pH is adequate (WaterRF, 1990; USEPA, 1993). In this case, pH adjustment might be adequate to decrease equilibrium lead solubility, reduce the diffusion rate of lead into solution, and lower the lead leaching from lead solders or brass fixtures to acceptable levels (USEPA, 1993).

However, the adjustment of pH alone is often insufficient to control corrosion in waters with low carbonate or bicarbonate (Schock, 1999). The goals of adjusting DIC are to: 1) decrease lead, copper and iron solubility by limiting the formation of complexes; 2) form a protective deposit of $CaCO_3$ or mixed calcium/iron hydroxycarbonates, for instance, on ferrous materials or between the grains in cement based materials; and 3) provide the water a higher buffer capacity to maintain desirable pH within the distribution system (USEPA, 1993; Schock, 1999).

Caustic (NaOH, KOH), soda ash (Na_2CO_3), lime, hydrated lime, limestone contactors, sodium silicate and aeration (air stripping) are the principle methods to increase pH (USEPA, 2003). For DIC adjustment, the most common ways include: aeration, sodium bicarbonate ($NaHCO_3$), soda ash (Na_2CO_3), and CO_2 addition (USEPA, 2003). Aeration may decrease DIC while soda ash, CO_2, and sodium bicarbonate increase DIC. USEPA (2003) provided the following suggestions to assist utilities to choose appropriate treatment chemicals:

1. When using caustic (NaOH, KOH), a water system should have raw water DIC> 5 mg C/L. Systems with low DIC will have difficulty in maintaining a stable pH throughout the system by using caustic. This is due to the significant pH variations with caustic dosage.

2. When using soda ash, raw water DIC should be in the range of 2 ~ 25 mg C/L. Soda ash will increase both DIC and pH.

3. A limestone contactor is an enclosed filter containing crushed high purity limestone ($CaCO_3$). Like soda ash, this treatment can increase both pH and DIC. This treatment has to be used with caution as it may cause excess calcium carbonate precipitation.

4. Aeration is the only treatment that does not require chemical addition to the water and can reduce excess DIC while increasing pH in the water. This treatment is helpful for raw water with low pH and high DIC due to the presence of carbon dioxide at levels exceeding saturation values as with some groundwaters.

5. When considering sodium bicarbonate, a water system should have DIC $\leq$5 mg C/L before the bicarbonate addition. Sodium bicarbonate alone will not increase the pH above 8.3. When a significant increase in pH and DIC are needed, water systems can use soda ash or caustic and sodium bicarbonate to adjust the pH.

The solubility of Pb(II) can be greatly reduced by increasing the pH to the range of 9-10. Even in waters with low alkalinity, when the pH is raised to this range, there will frequently be enough DIC present to significantly aid in film formation, without additional carbonate or bicarbonate chemical additives (Schock et al., 1996). This treatment strategy has been used successfully in laboratory and field studies (Schock et al., 1996).

Any change in pH needs to be well-planned and tested before treatment starts. While elevating pH has the potential of decreasing lead, copper and iron solubility, this approach should be used with caution since it may: 1) lower disinfection efficiency and increase THM formation, thus potentially lowering utilities' abilities to comply with the Total Coliform Rule (TCR) and Disinfectants and Disinfection By-Products Rule (D/DBPR); and 2) cause excessive scale formation which can clog or reduce the flow in pipes, lead to buildups on hot water heaters, impart an alkali taste to the water, reduce the efficiency of the water heaters and other aesthetic problems.

2.5.2 Phosphate-Based Inhibitor Addition

Addition of a phosphate-based corrosion inhibitor induces the formation of the less soluble passivating film, decreasing the corrosion potential of the water. Phosphates can be added for corrosion control in the form of orthophosphates, zinc orthophosphates, polyphosphates or blends of orthophosphates and polyphosphates.

The use of orthophosphates has been a successful practice for minimizing corrosion of piping and lead-containing materials (USEPA, 1993). Orthophosphate usually forms an insoluble passivating films on the pipe, reacting with the metal of the pipe itself (particularly with lead, iron and galvanized steel) in restricted pH and dosage ranges (Schock, 1999). Zinc is often added to commercial orthophosphate treatment chemicals to deposit a protective zinc coating on the surface of asbestos cement pipe, mortar lined pipe, cast iron, and galvanized surfaces, given the proper chemical conditions (USEPA, 2003). Studies on brass or lead solder corrosion control suggested that zinc might be helpful by providing a counter to dezincification in brass and lead solder. It was also reported that the addition of zinc did not enhance the performance of orthophosphate, but tended to increase release of particulate lead or copper species (Edwards et al., 2001; and McNeill and Edwards, 2004). Some researchers believe that the formation of zinc orthophosphate can actually reduce the amount of orthophosphate available to react with the lead in the distribution system. Under certain pH and DIC conditions, zinc can precipitate either as zinc carbonate or as zinc orthophosphate, both causing turbid water. Due to zinc's toxicity on aquatic organisms in the downstream environment, water treatment plant discharges are often limited in order to lower zinc concentrations in wastewater treatment plant influent (AWWA, 2005).

For utilities with hard water and high levels of DIC, blended orthophosphates and polyphosphates have been used. Polyphosphates have long been used to prevent iron precipitation (resolving red water problem) and excessive buildup of calcium carbonate on pipe walls (Cantor et al., 2000). Polyphosphates' property of sequestering metals can make them unavailable for use in forming a protective film, and thus may actually increase the corrosion rate of lead and copper by stripping the protective film from the surface of the corroding metal. It was reported that the use of polyphosphate inhibitors above pH 7.0 with alkalinity between 30 to 74 mg/L as $CaCO_3$ seemed to have adverse effect on lead corrosion (Edwards and Reiber 1997). Studies have shown that polyphosphate could complex significant concentrations of lead under certain circumstances causing lead corrosion by-product release problems and thus should not be used for lead corrosion control (Holm and Schock, 1991; Dodrill and Edwards, 1995; and Cantor et al., 2000).

The addition of phosphorous may stimulate the potential for microbial re-growth in distribution system, especially where chloramines are used as secondary disinfectant, which may impact TCR and D/DBPR compliances. The re-growth may in turn cause bacteria-induced corrosion and lead and copper release in the distribution system. In addition, phosphate adds nutrients to wastewater facilities.

Solubility models for lead and copper indicate that the optimal pH for orthophosphate film formation is between 7 and 8 on lead surfaces (Schock, 1989) and between 6.5 and 7.5 on copper surfaces (Schock et al., 1995). At higher pH, orthophosphate has a significant impact on the corrosion protective film stability. A survey of 365 water utilities under the LCR also revealed that orthophosphate was effective at reducing lead levels when pH was below 7.4 and alkalinity was below 74 mg/L as $CaCO_3$ and was effective at reducing copper levels only when pH was below 7.8 (Dodrill and Edwards, 1995). Copper solubility is not significantly affected by phosphate inhibitors at reasonable dosages.

Maintaining stable pH throughout the distribution system is critical to the success of treatment using phosphate-based inhibitor. Since pH can drift in the distribution system, and pH leaving the plant fluctuates within a controlled range, some low alkalinity supplies using phosphates leave the water plant with a pH in the range of 7.5 to 8.5 (7.5 to 8.0 is more optimal for phosphates) to lessen the potential for some sites drifting below pH 7.0. When the pH is over 8.0, the high pH may be providing more lead corrosion protection than the phosphate.

Next to maintaining proper pH and background water quality consistency, the key to good corrosion inhibitor treatment is feed control. The inhibitors often must be fed continuously and at sufficient amount, as intermittent feeding may cause loss of protective films by dissolution and concentrations that are too low may prevent the formation of a protective film on all parts of the surface (Schock, 1999). For most water systems, when using orthophosphate for corrosion control, it is important to maintain adequate residuals (at least 0.5 mg/L as phosphate with 1 mg/L being more preferable) in the distribution system.

When adding phosphate blends that include polyphosphate, it is recommended that at least 0.5 mg/L (as phosphate) is orthophosphate (USEAP, 2003).

2.5.3 Calcium Hardness Adjustment

This treatment operates on the theory that a protective layer will precipitate on the pipe wall in the proper pH range. For corrosion protection, a water system having sufficient amount of calcium and carbonate can achieve the super-saturation and precipitation of calcium carbonate by slightly increasing the pH during treatment (USEPA, 1993). In other words, good coatings are likely to be found only in relatively hard waters, within appropriate DIC and pH ranges. For this reason, it may not be cost-effective to use a calcium carbonate saturation control approach when the source water has a very low hardness and pH.

Two chemicals are ordinarily used to provide hardness addition: lime (CaO) and slaked lime ($Ca(OH_2)$). Both also increase the pH. Quicklime (CaO) must be hydrated or slaked to $Ca(OH)_2$ before application. These chemicals, at proper dosages, can create conditions that provide super saturation of calcium carbonate in the bulk water or at the pipe surface.

DIC has a significant impact on calcium carbonate precipitation potential since it is directly related to the formation of the carbonate film on the pipe (WaterRF and AWWA, 2000). Insufficient amounts of calcium carbonate precipitate may cause spotty surface coatings and lead to localized corrosion (USEPA, 1999b). If the precipitation potential remains negative long enough, eventually the existing carbonate scale may begin to dissolve, effectively un-coating distribution system piping (AWWA, 2005). Before treatment, a critical question to be determined is whether the raw water has enough DIC to provide adequate buffer intensity at the targeted pH after adjustment (USEPA, 1993).

Care also needs to be taken to not over-dose calcium and/or carbonate as excess saturation can cause scale buildup and reduce hydraulic capacity of the pipe network. Any changes in pH in the distribution system can result in localized loss of the protective coating, or in excessive scale formation. Precipitation of $CaCO_3$ in the distribution system can also result in an increase in turbidity.

Despite common beliefs, significant calcium carbonate films do not usually form on lead galvanized, or copper cold-water pipes, so they are not primarily the causes of corrosion inhibition in these cases (Schock, 1999).

2.5.4 Silicate Inhibitor Addition

Silicate species, when present in sufficient concentration under certain water chemistry conditions, can absorb to pipe surfaces to create a protective film (USEPA, 1993). The films are self-limiting and do not build up in thick layers, but will gradually break down within a short period of time if the dosage is stopped (Vik et al., 1996). Sometimes, silicate can react with other metal or corrosion by-products to either form less soluble reaction products or to bind existing corrosion products into more uniform surface deposits (USEPA, 1993). In this case, silicate may act as a cementing agent over corrosion products, and thus become effective only over long-term exposure (USEPA, 1993). In some cases, the ability of silicate serving as corrosion inhibitor may be more a function of an increase in pH than the influence of silicate itself (Gregory, et al., 1999).

Sodium silicate is the most common form of silicate that is added to finished water as a corrosion inhibitor. The effectiveness of this approach depends on pH, silicate concentration, and hardness of the water (Schantz, 1994 and Kastanis, 1986). Dosages of sodium silicate for lead and copper control can be from 4 to 30 mg/L SiO_2 (USEPA, 1993).

The use of silicates is generally associated with the corrosion of iron as the primary metal of concern (Washington Aqueduct and CH2MHill, 2004). Silicates have been found effective for reducing ‘red’ and ‘black’ water complaints resulting from the oxidation of naturally occurring iron and manganese in waters (Robinson, et al., 1992). Polyphosphates that are commonly used to control ‘red’ and ‘black’ water problems are less effective at the higher pH range which assists lead and copper corrosion control. Silicate, however, can be used at higher pH and even increase the pH of the finished water, which is helpful for lead and copper corrosion control (Chiodini, 1998).

Similar to phosphate-based inhibitor treatment, feed control and higher-velocity flow conditions are very important factors for the success of silicate treatment (Schock, 1999). The continuous addition of sodium silicate (4 to 30 mg/L SiO_2) to water has been shown to be an effective way for controlling the corrosion of water piping (Lehrman and Shuldener, 1952; Schantz, 1994). A flow velocity of approximately 1 ft/second is required to form a protective coating (Johnson, et al., 1993). It was reported that under the predominantly static conditions in service piping and premise plumbing, where lead and copper corrosion typically occurs, silicate treatment has a greatly diminished benefit for corrosion control (Johnson, et al., 1993).

Section 3
Background on Disinfection Byproducts

This section presents an overview of regulated disinfection byproducts in drinking water, including current regulations, precursor substances, the impact of seawater, and control strategies. References are included in **Appendix A**.

3.1 Introduction

Free chlorine is the most widely used disinfectant in public drinking water supplies today, offering potent disinfection at a low cost. Free chlorine, however, can also produce undesirable byproducts such as trihalomethanes (THMs) and haloacetic acids (HAAs), which are regulated under the Disinfectants and Disinfection Byproducts Rule (D/DBPR). These halogenated substances are primarily the result of reactions with dissolved natural organic matter (NOM) that may be present in the water and the chlorine being added for disinfection. The presence of bromide, which occurs naturally in saline or brackish waters, can affect both the rate of formation of disinfection byproducts (DBPs) and the specific types that are formed.

3.1.1 DBP Regulations

Stage 1 D/DBPR MCLs for Disinfection By-Products

The Stage 1 D/DBPR, which intended to reduce the levels of disinfectants and disinfection by-products (DBPs) in drinking water supplies, became effective in February 1999 (U.S. EPA, 1998). Under the D/DBPR, two groups of chlorinated DBPs – total trihalomethanes (TTHMs) and five haloacetic acids (HAA5) - are regulated in two stages. In Stage 1, USEPA set MCLs of 80 μg/L and 60 μg/L, as annual averages, for TTHMs and HAA5, respectively. Compliance is defined on the basis of a running annual average (RAA) of quarterly averages of all samples. Monitoring requirements for systems serving 10,000 people or more include collection of four water samples from the distribution system per quarter per treatment plant. The sampling locations should be representative of the average residence time in the distribution system with at least 25 percent of the samples to be taken at locations that represent the maximum residence time of water. For systems monitoring quarterly, if the RAA of quarterly averages covering any consecutive four-quarter period exceeds the MCL, the system is in violation of the MCL and must notify the public, in addition to reporting to the State.

Total Organic Carbon (TOC) Removal

The Stage 1 D/DBPR also requires that utilities achieve specific TOC removals to control DBP precursors. The amount of TOC that must be removed is dependent upon the alkalinity and TOC concentration of the raw water. **Table 3-1** shows the percent removal of TOC that is required under this Rule. Based on source water characteristics, the Savannah I&D WTP generally falls into box 1 of the table, highlighted in light brown. Percent removal is measured upstream of the point of primary disinfection. Thus, if chlorine is not added until after the filters for chlorine contact time (CT), then the TOC of the filtered water may be compared to the TOC of the raw water to calculate TOC removal. In some cases the TOC removal requirements must be met with enhanced coagulation, which is the practice of using a coagulant dose in excess of what is normally required for turbidity removal to achieve a specific reduction in TOC concentration. Another approach is the use of ferric coagulant, which generally removes more TOC than alum.

Table 3-1: TOC Percent Removal for Enhanced Coagulation

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

The Stage 1 D/DBPR provides exemptions for meeting the TOC removal percentages in Table 3-1. The key exemptions are:

- Source or treated water TOC running average is below 2.0 mg/L
- TTHM < 40 ppb, HAAs < 30 ppb, and use only free chlorine
- Source water specific ultraviolet absorbance (SUVA) ≤ 2.0 L/mg•m running annual average
- Finished water SUVA ≤ 2.0 L/mg•m

Stage 2 D/DBPR MCLs and MCLGs for Disinfection Byproducts

The final Stage 2 D/DBPR, as promulgated in January 2006, is designed to reduce DBP occurrence peaks in the distribution system based on changes to compliance monitoring provisions. Compliance monitoring is preceded by an Initial Distribution System Evaluation (IDSE) to find the worst-case distribution system sample points. These locations will then be used by the systems as the sampling sites for Stage 2 DBP rule compliance monitoring. The number of compliance monitoring sites is determined by the population served and the source water type. Compliance is defined on the basis of a locational running annual average (LRAA) of TTHMs and HAA5. Compliance must be met at each monitoring location, instead of system-wide using the RAA under the Stage 1 D/DBPR. The Stage 2 D/DBPR will limit all sample points in the distribution system to RAA of 80 µg/L TTHMs and 60 µg/L of HAA5.

3.2 Factors Influencing the Formation of DBPs

3.2.1 Chemical Factors

3.2.1.1 Natural Organic Matter

Natural organic matter (NOM) is ubiquitous in natural waters. It refers to a complex mixture of dissolved, colloidal, and particulate substances arising from the photosynthetic activity of plants, decay of vegetative material, bacterial metabolism, and human activities such as agriculture or upstream wastewater discharge (Hudson, Baker, and Reynolds, 2007; Leenheer, 2009). Its exact composition in a given water varies widely, and is influenced by the source of carbon (plant material vs. bacterial activity), temperature, pH, and ionic composition of the water (Leenheer and Croué, 2003). Because most natural waters contain only trace levels of anthropogenic organic pollutants, total and dissolved organic carbon (TOC / DOC) are frequently accepted as surrogate measures for NOM (Leenheer and Croué, 2003).

NOM is widely known to act as a precursor material for the formation of a host of halogenated organic byproducts when exposed to chlorine (Rook et al., 1978; Krasner et al., 1989). Among these, chloroform, dichloro- and trichloroacetic acids are among the most abundant (Christman et al., 1983). The hydrophobic fraction of NOM, which is most easily removed by coagulation, has a higher potential for forming regulated DBPs with chlorine than the hydrophilic fraction (Liang and Singer, 2003).

3.2.1.2 pH

The pH of water treated with free chlorine has a significant impact on DBP formation. Higher pH has been shown to increase the formation of THMs (Amy, Chadik, and Chowdhury, 1987). The effect of pH on HAA formation follows the reverse trend. HAA formation is significantly greater at pH 7 than at pH10, but lowering the pH below neutral does not further increase HAA formation (Hua and Reckhow, 2008). In addition, low pH significantly increases the quantity of total organic halides (TOX, a surrogate measure of unregulated halogenated byproducts) that are formed (Johnson and Jensen, 1986; Hua and Reckhow, 2008). Therefore, the use of pH adjustment to control regulated DBP formation must be very carefully considered in terms of the potential overall impact on public health. High pH markedly reduces the quantity of unknown byproducts in waters treated with both free chlorine and chloramines. (Hua and Reckhow, 2008).

3.2.1.3 Disinfectant Dose

Both THM and HAA formation are increased with increasing free chlorine dose in a roughly linear fashion over the range of doses relevant to water treatment (Johnson and Jensen, 1986; Hua and Reckhow, 2008). The use of chloramines as a disinfectant greatly reduces the formation of THMs, but relatively small quantities of HAAs are formed. Considerably more TOX, or unregulated byproducts, are formed by chloramines than free chlorine, however. Increasing the chloramine dose has little to no effect on the quantity of HAAs formed, but does significantly decrease the proportion of unknown or unregulated byproducts (Hua and Reckhow, 2008).

3.2.1.4 Bromide

If bromide is present in water that is treated with free chlorine, as is frequently the case in coastal water supplies, both the rate and speciation of DBPs formed are affected. The presence of bromide both accelerates the formation of DBPs and increases the quantity of bromine-containing species that are formed (Symons et al., 1993). A more detailed discussion of the impacts of elevated bromide on DBP formation is given in the next section.

3.2.2 Physical Factors

3.2.1 Temperature

As with most chemical processes, increased temperature accelerates the rate of the reactions responsible for DBP formation. A common rule of thumb is that the rate of THM formation roughly doubles for every 10°C (18°F) rise in temperature (Hua and Reckhow, 2008). HAA concentrations also increase, but to a lesser extent. In individual distribution systems, elevated temperatures may also give rise to increased microbiological activity that can contribute to breaking down both HAAs and, to a lesser extent, THMs (Hua and Reckhow, 2008).

3.2.2 Disinfectant Contact Time

It is well-established that both THMs and HAAs form gradually and thus tend to increase with increasing water age. However, the rate of formation, particularly for THMs, is much greater during the first 12-24 hours of contact time. Conversion of free chlorine to monochloramine greatly slows the formation of THMs and HAAs. As such, for water systems that rely on free chlorine to meet disinfection "CT" requirements prior to adding ammonia, optimizing the free chlorine dose and contact time can reduce regulated byproduct formation.

3.3 Bromide as a DBP Precursor

Bromide occurs naturally in many surface drinking water supplies in coastal areas due to the intrusion of seawater. Groundwaters may also contain bromide for the same reason. A 1993 study of 11 utilities in the U.S. found bromide concentrations ranging from 10 µg/L to 800 µg/L in the source waters, with a median of 60 µg/L (Krasner et al., 1993). Thirty seven percent of U.S. water utilities surveyed as part of the Occurrence Assessment for the Stage 2 D/DBPR reported bromide concentrations between 30 µg/L and 100 µg/L, while 19% reported higher concentrations (U.S. EPA, 2005). The average bromide level in the I&D WTP source water is currently 50 µg/L. Based on measurements taken from the test waters in this study, that level could increase to 95, 180, or 250 µg/L if the chloride concentrations at the intake increase to 25, 50, or 75 mg/L chloride.

3.3.1 Impact on DBP Formation

When bromide-containing waters are disinfected with chlorine, bromide is oxidized to hypobromous acid, which subsequently reacts with NOM to form bromine-containing THMs, HAAs, and other by-products (Rook et al., 1978). Hypobromous acid reacts more quickly with NOM than hypochlorous acid (free chlorine), so the rate of DBP formation is increased in the presence of bromide (Symons et al., 1993).

As the ratio of bromide to TOC increases, the fraction of THMs and HAAs containing bromine increases (Krasner et al., 1989; Singer and Bilyk, 2002). This fact is significant because the bromine-containing halogenated by-products are thought to have a more detrimental public health impact than their chlorinated analogs (Richardson et al., 1999; Plewa et al., 2002; Singer and Bilyk, 2002).

One way to quantify the degree of bromine incorporation is the bromine incorporation fraction (BIF). The BIF is a value between 0 and 1 representing the bromine-weighted fraction of THM (or HAA) species relative to total THMs (or HAAs), and is defined as follows by summing over all the THM or HAA species of interest (Obolensky and Singer, 2005):

$$BIF = \sum \frac{(\# Br)(concentration)}{(\# Br + \# Cl)(concentration)}$$

Where *#Br* and *#Cl* are the number of bromine and chlorine atoms, respectively, and *concentration* is the mass concentration of each species.

3.3.2 Regulatory Implications

An increase in the level of bromide in the source water will most likely result in an overall increase in the concentrations of THMs and HAAs formed in the distribution system due to the faster rate of formation described above. Furthermore, bromine has a higher molecular weight than chlorine, meaning that the bromine-containing THM and HAA species are heavier than their chlorine-containing counterparts. Because bromide results in a greater fraction of these bromine-containing DBPs, concentrations (based on weight) will be higher even if the total number of DBP molecules is the same as in the water before the bromide was elevated. Thus, elevated bromide can create additional challenges for maintaining compliance with THM and HAA limits.

To fully understand the water quality implications of elevated bromide, it is important to consider the specific THM and HAA species that are regulated under the D/DBPR. There are 4 individual trihalomethane species that contain bromide or chloride, and all four are regulated. In contrast, there are 9 haloacetic acids containing bromide and chloride, but only 5 are regulated. The 4 unregulated species contain relatively more bromide than the regulated species. This fact is shown in **Table 3-2,** which shows the schematic structure of each of the bromine- or chlorine-containing THMs and HAAs. Chlorine and bromine atoms are highlighted in blue and red, respectively; species that are regulated are shaded in tan.

Table 3-2: Regulated and Unregulated THM and HAA Species

Haloacetic Acid Species			Trihalomethane Species	
H **Cl** C COOH H	H **Br** C COOH H	H **Br** C COOH **Cl**	**Cl** **Cl** C H **Cl**	**Br** **Cl** C H **Br**
H **Cl** C COOH **Cl**	H **Br** C COOH Br	**Cl** **Br** C COOH **Cl**	**Cl** **Br** C H **Cl**	**Br** **Br** C H **Br**
Cl **Cl** C COOH **Cl**	**Br** **Br** C COOH **Br**	**Cl** **Br** C COOH **Br**		

Because the regulations are based on only 5 HAA species, laboratory and compliance data can be misleading in waters with high bromide. After an increase in bromide concentration in the source water, the HAA5 concentration may decrease. However, it is likely that the *total* HAA concentration in the water has actually increased, but the increases are due to the 4 mostly bromine-containing species that are not accounted for in the HAA5 concentration. These unmeasured HAA species may account for a significant fraction of total HAAs present, even in waters with low to moderate bromide (Roberts, Singer, and Obolensky, 2002).

3.4 Strategies for Control of DBPs

Among the factors influencing DBP formation discussed in the preceding section, the two most easily controlled are the removal of NOM and the disinfection exposure (“CT”). Each of these strategies is discussed in more detail in this section.

3.4.1 NOM Removal

As noted above, the most significant factor influencing DBP formation is the presence of NOM. As such, the removal of NOM from water is a highly effective strategy for reducing DBP formation (White et al., 1997). In some cases conventional methods (i.e. coagulation) accomplish adequate NOM removal; if the source water contains NOM that is recalcitrant to coagulation then advanced treatment may be required.

Enhanced Coagulation

Enhanced coagulation, as described previously, refers to the practice of treating water to achieve a specific level of TOC removal, generally using a coagulant dose higher than what would be chosen for turbidity removal alone.

The specific ultraviolet absorbance (SUVA), defined as 100 times the UV absorbance at 254 nm divided by DOC concentration of a water, is an indicator of the hydrophobicity of the NOM. Waters with high SUVA are more suitable for treatment by coagulation than those with low SUVA, because alum coagulation preferentially removes the hydrophobic component of DOC (White et al., 1997; Liang and Singer, 2003). Coagulation for NOM removal is most effective in the pH range of 5-6, as the NOM molecules become more hydrophobic in this range (Krasner and Amy, 1995; White et al., 1997).

Many utilities in the region have found that the use of ferric coagulants in lieu of alum provides increased removal of natural organic matter and inorganics such as arsenic, iron, and manganese. Ferric coagulation allows better removal of iron and manganese when GAC filters are used because the optimum pH of ferric coagulation has a broad range, from 5 to 9. This allows the mixing/flocculation/sedimentation process to operate at a lower pH, about 5, for maximum organics removal, and then the water pH can be increased to 8 or higher for optimum removal of iron and manganese through the filters. Alum is a very effective coagulant with anthracite/sand filters, but it has a narrow optimum pH near 6.0, which must be maintained in both coagulation and filtration.

Because removal of flocculated NOM occurs through a physical separation process, coagulation does not remove bromide or most other dissolved ions. As a result, coagulation of bromide-containing waters increases the Br:DOC ratio.

Ion Exchange

In waters dominated by hydrophilic NOM (such as that often encountered in seawater), conventional coagulation may be inadequate for removing organic material and controlling the formation of DBPs. Anion exchange resins provide an alternative treatment option, and have been shown to be effective for removing NOM and reducing THM formation potential (Bolto et al., 2002; Singer and Bilyk, 2002; Humbert et al., 2005).

Ion exchange is a water treatment process in which a presaturant ion on the solid phase of a resin is exchanged for an unwanted ion in the water. In order to accomplish this reaction, a packed bed of ion-exchange resin beads or a continuous process that utilizes a mixed or fluidized bed reactor is typically used. The source water is continually passed through the bed until the absorbent is exhausted. In a packed bed application, the bed is taken offline and regenerated using an excess of the presaturant ion. In the mixed or fluidized bed reactor, a fraction of the absorbent is removed from the process and regenerated in a separate side process. Fresh or regenerated resin is added back into the fluidized bed to replace the resin removed. In a typical application, from 300 to 300,000 bed volumes of source water may be treated before exhaustion.

Magnetic Ion Exchange (MIEX) Resin

MIEX is a unique anion exchange resin developed by Orica Watercare specifically designed to remove DOC. The resin has unique features that allow it to be applied as a slurry in a completely mixed reactor rather than in a fixed bed (Boyer and Singer, 2005). It is generally installed at the head of the treatment train and can be used as a pre-treatment for conventional processes. This continuous-flow treatment scheme is preferable to fixed beds because it promotes turbulence and facilitates the exchange of NOM molecules onto the beads (Boyer and Singer, 2005). Several bench, pilot, and full-scale tests have documented substantial removal of DOC and UV-absorbing substances by MIEX resin (Fearing et al., 2004; Johnson and Singer, 2004; Humbert et al., 2005; Boyer and Singer, 2006), and it has been shown in some cases to be more effective than enhanced coagulation (Singer and Bilyk, 2002; Boyer and Singer, 2005; Humbert et al., 2005; Boyer and Singer, 2006).

In addition to removing DOC, MIEX resin treatment has been shown to remove bromide and other inorganic anions to a limited extent (Singer and Bilyk, 2002; Johnson and Singer, 2004; Humbert et al., 2005; Boyer and Singer, 2006; Hsu and Singer, 2009). Although polystyrene ion exchange resins are more selective for bromide than the MIEX resin (a polyacrylic type resin), polystyrene resins are not as effective for NOM removal (Hsu and Singer, 2009). Therefore, MIEX resin treatment is a viable choice where removal of both DOC and bromide is desired. The anon typically used to regenerate the resin is chloride, which cannot be used at the I&D WTP because it would further elevate the chloride concentration and related impacts. Instead, bicarbonate could be used to regenerate the resin, but this option costs appreciably more.

Activated Carbon

Granular Activated Carbon

Granular Activated Carbon (GAC) can be used as a substitute for granular filter media for the removal of organic materials that are precursors to DBP formation, taste and odor producing compounds, pesticides, and other synthetic compounds. Additionally, GAC has been cited by the United States Environmental Protection Agency as one of the best available treatment options for complying with the current and future regulations for THMs and HAAs.

In water treatment, physical adsorption is the typical mechanism responsible for the removal of organics that are precursors to DBP formation; however, biological activity on the GAC surface can also contribute to the removal of organic precursor materials. The GAC also has a finite capability to adsorb organics. Once the GAC adsorption capacity is exhausted, the GAC must be regenerated. On-site regeneration is usually not cost effective, unless a large amount of GAC is exhausted daily; therefore, the GAC would need to be removed and replaced after a certain amount of operating time.

There are three possible configurations for implementing GAC in a water treatment plant, which are:

- Pre-Filtration adsorption – Ahead of the conventional treatment process (Pre-Filter Adsorber)
- Post-Filtration adsorption – After the conventional treatment process (Post-Filter Adsorber)
- Filtration and adsorption – In lieu of traditional filtration after flocculation and sedimentation (Filter Adsorber)

The pre-filter adsorber has limited applications and benefits when treating surface water due to depletion of adsorption capacity and decreased efficiency caused by treating unfiltered water. The most conventional approach is to use a post-filter adsorber, because the influent is the highest quality water that can be applied to the GAC system. This approach generally maximizes the carbon usage and minimizes the required reactivation frequency.

Powdered Activated Carbon

A second configuration is powdered activated carbon (PAC). PAC can be added in slurry form to the raw water and is most suitable for dealing with transient water quality challenges, such as seasonal spikes in TOC or taste and odor compounds, and in this case, periodic increases in the seawater percentage.

Biofiltration

Biological filters, or biofilters, exploit the activity of microbial communities attached to granular filter media in order to remove biodegradable organic matter (BOM). In the U.S. most biofilters are retrofitted onto existing plant facilities, so that particle removal and BOM removal take place in a single treatment step (Smith and Emelko, 1998). Typically, a conventional filter will become biologically active if a disinfectant residual is not maintained in the influent (Crittenden et al., 2005).

Biofiltration offers several advantages compared to conventional rapid filtration. First and foremost, by removing BOM, biofilters increase the biological stability of the effluent, which helps control the growth of biofilms in distribution pipes (Urfer et al., 1997; Ahmad et al., 1998; Smith and Emelko, 1998; Amburgey et al., 2005). Biofiltration also removes precursor material for halogenated DBPs to a greater extent than conventional filters. Wang, Summers, and Miltner (1995) reported that biologically active anthracite-sand filters removed 13-37% of THM, TOX, and HAA6 formation potential, compared to 1-11% in a conventional pre-chlorinated filter of the same type. Similar findings were reported by Chaiket et al. (2002) and Amburgey et al. (2005).

Other benefits of biologically active filters include a reduction in the effluent chlorine demand and the dose required to maintain an adequate residual (Urfer et al., 1997, Ahmad et. al, 2001), control of taste and odor causing substances (Urfer et al, 1997; Amburgey et al., 2005), and removal of some micropollutants (Urfer et al., 1997).

Compared to conventional filters, however, biological filters tend to have shorter run times due to head loss accumulation. While biofilters can meet effluent turbidity requirements as well as conventional filters, bacterial counts and total particle counts in the effluent are generally higher than in effluent from filters in which particle removal is the only treatment objective (Amburgey et al., 2005). Finally, because biological filters must be operated without disinfectant in the influent, excessive biomass growth can occur, especially in warm waters (Smith and Emelko, 1998). However, steps can be taken to mitigate each of these operational difficulties.

3.4.2 Disinfection Optimization

Treatment plants can be optimized by minimizing the quantity and reactivity of DBP precursor materials at the point of disinfection. This can be accomplished by reducing the precursor content of the raw water, improving precursor removal through the plant, or by shifting the point of disinfection to a later stage of treatment, or some combination of the three. For a typical free chlorine disinfection system followed by chloramination, several options exist, including:

- Reduce pre-filter chlorine doses or refrain from adding chlorine prior to filtration in order to prevent contact between higher levels of NOM and chlorine. An alternative disinfectant (e.g. chlorine dioxide or ozone) might be used here instead.

- Reduce free chlorine contact time to the minimum required to achieve CT, then add ammonia to generate chloramines as soon as possible.
- Add or improve baffling in the clearwell to improve the effective detention time or"T10" used when calculating CT. This could allow for a lower chlorine dose.
- Use UV disinfection or ozone to achieve the required CT, then apply chloramines.

Section 4
Evaluation of Current and Historical Water Quality Data

This section presents a summary of the City of Savannah's available historical and current water treatment and water quality data for the I&D System.

4.1 Current Water Treatment

The City of Savannah's I&D WTP obtains raw water from Abercorn Creek, which is a tributary of the Savannah River. The source water can generally be characterized as having neutral to slightly acidic pH, low alkalinity, low to moderate turbidity, and low hardness. **Table 4-1** gives typical raw water characteristics based on historical raw water data from 2003 to 2010. Historical chloride concentrations in the raw water are further discussed in **Section 4-4**.

Table 4-1. Historical Raw Water Quality Characteristics

Parameter (Units)	Average Value	Range[1]
pH	6.5	6.0 - 6.9
Alkalinity (mg/L as CaCO3)	23.3	13.6 – 29.3
Turbidity (NTU)	18.4	10.0 – 39.2
Hardness (mg/L as CaCO3)	26.4	18.1 – 30.4
Chloride (mg/L)	10.6	5.5 – 14.2

[1] Range of monthly average values from 2003-2010

The surface water is treated through a conventional coagulation/ flocculation/ sedimentation/ filtration process using flocculation aid polymer and aluminum sulfate (alum) as the coagulant. The coagulant dosage typically ranges from 30 – 40 mg/L alum. After coagulation, lime is added for pH control. Free chlorine is used for primary disinfection, while free chlorine or chloramines provide a residual in the distribution system. The City uses Aquadene, a sodium hexametaphosphate inhibitor, at a dose of approximately 0.75 mg/L as PO_4 to inhibit corrosion. The target finished water pH is 7.3 and target disinfectant residual is 2.0 mg/L.

The WTP serves a population of approximately 10,500 persons as well as industrial customers. The distribution system is separated into two parts and fed separately from the WTP. A free chlorine residual is maintained in the industrial system and chloramines are used for disinfection in the domestic portion of the distribution system. Although the chloraminated domestic system covers a larger geographic area, only approximately 10 to 20 percent of the treated water goes to the chloraminated system. The WTP has a permitted treatment capacity of 62.5 million-gallons-per-day (mgd). Based on the 2003 to 2010 historical data, the WTP produces an average of 33 mgd and had a maximum day production of 46.5 mgd in August 2006.

4.2 Distribution System Water Quality Data

Historical data on pH, chlorine residual, and phosphate were available for 16 distribution system sites between 2006 and 2010. **Figures 4-1, 4-2, and 4-3** show monthly average pH, chlorine residual, and phosphate, respectively, at sites within the free chlorine (industrial) and chloraminated (domestic) portions of the distribution system. The pH at most distribution sites is between 7.0 and 8.5, however, a few sites in the industrial system have pH as low as 6.0 or as high as 9.5. In general the pH appears to be highly variable, particularly within the free chlorine (industrial) system. This may be related to tidal changes in water quality, the low alkalinity of the source water, or site-specific issues. Phosphate corrosion inhibitor levels in the distribution system are generally above 0.5 mg/L as PO_4. In the chloraminated (domestic) system, inhibitor levels before 2008 fluctuated considerably. Since the City has adopted its current corrosion inhibitor, however, phosphate levels have stabilized somewhat.

The sites closest to the WTP are the Herty site on the free chlorine system and Travis site on the chloraminated system (shown with orange lines on Figures 4-1 and 4-3). Since finished water quality data leaving the plant was not available for this analysis (except for finished water chlorine), these sites were considered representative of the finished water quality. **Table 4-2** summarizes the finished water quality data at these sites.

Table 4-2. Finished Water Quality Characteristics at Distribution Sites nearest the WTP

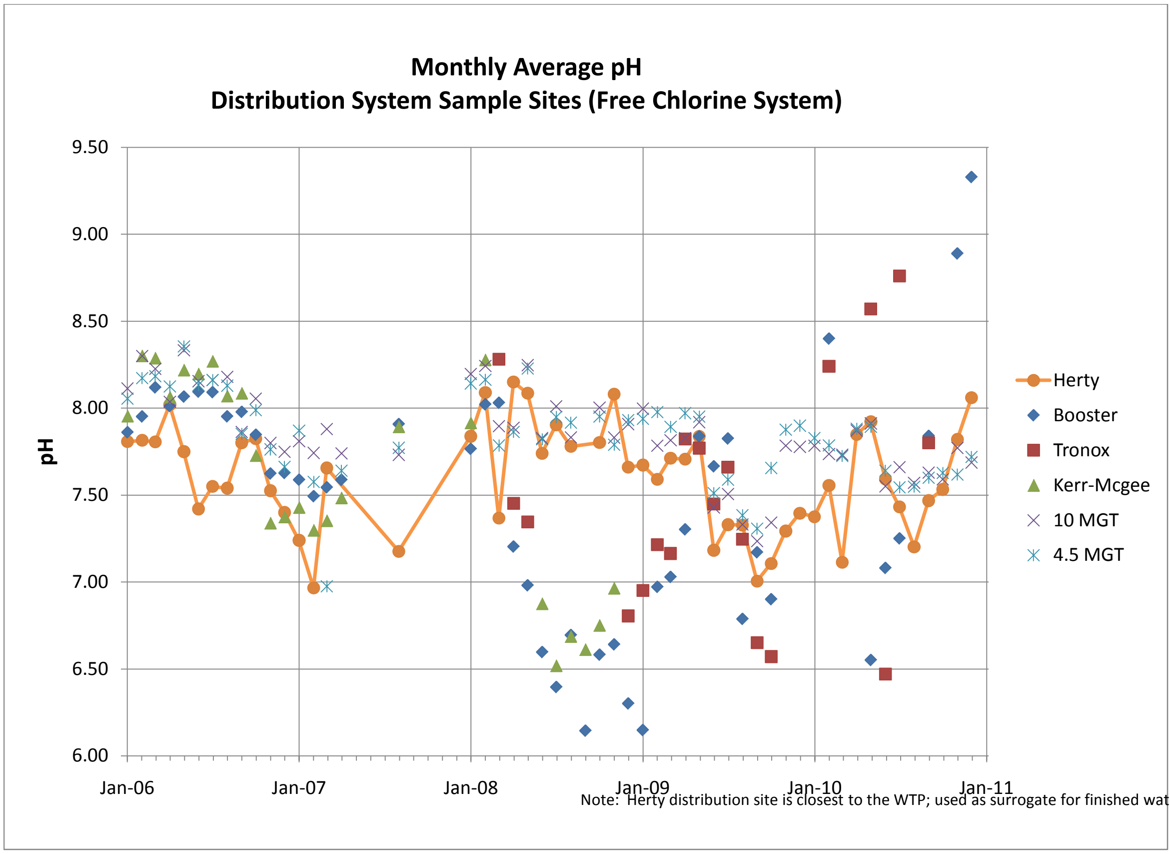
Parameter (Units)	System	Average Value	Range[1]
pH	Free chlorine	7.6	7.0 – 8.2
	Chloramines	7.8	7.0 – 8.3
Chlorine Residual (mg/L)[2]	Both	1.9	1.6 – 2.5
Phosphate (mg/L as PO_4)	Free chlorine	0.70	0.54 – 1.0
	Chloramines	0.79	0.50 – 1.1

[1] Range of monthly average values from 2006-2010
[2] Chlorine residual data is from finished water at the WTP

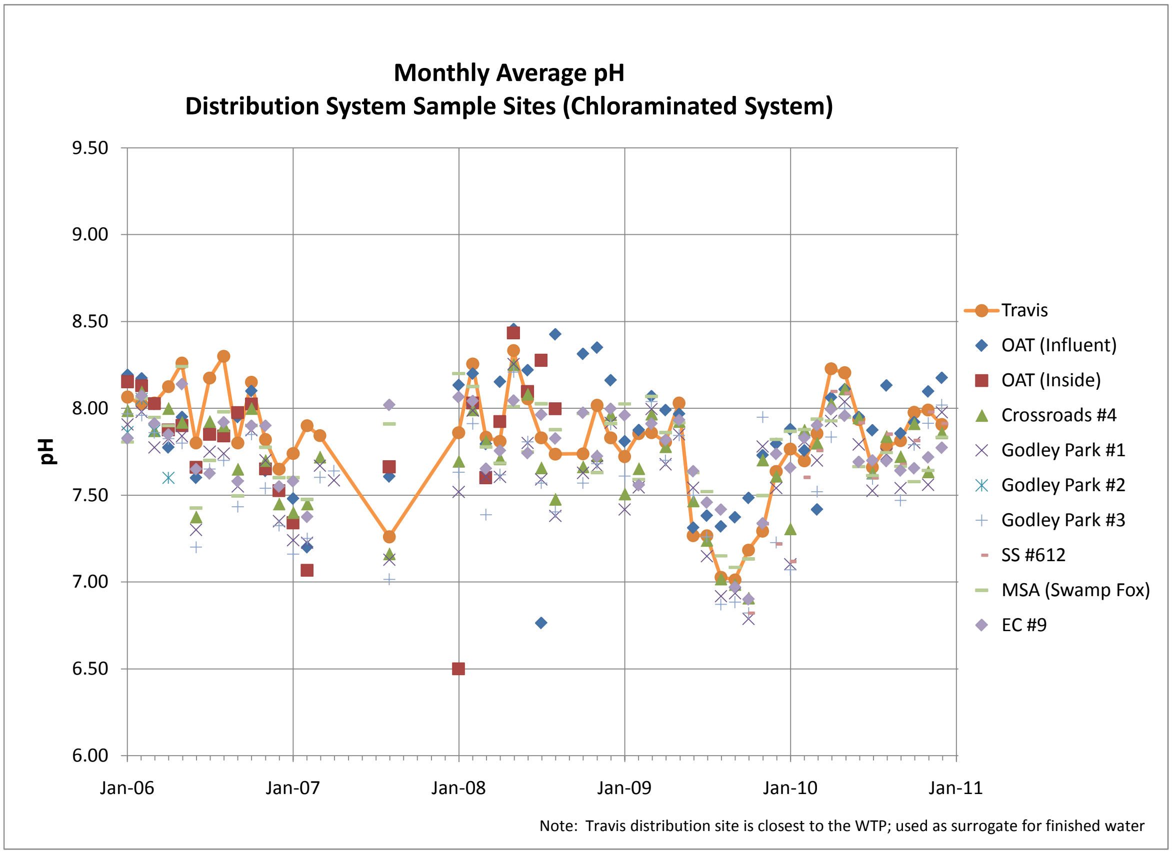
4.3 Drinking Water Compliance Data

4.3.1 Lead and Copper Rule (LCR)

Samples for the City's LCR monitoring program are collected at customer's taps. The Savannah I&D system monitored lead and copper annually until 2004, when it qualified for a reduced monitoring schedule, which requires that lead and copper samples are collected at 30 sites triennially. Sample sites are located primarily in free chlorine portion of the system (which receives the majority of the treated water), with five sites in the chloraminated portion of the system. The most recent 10 years of lead and copper data were analyzed (corresponding with the time period in which chloride data were modeled); the complete data for individual sites is available in Appendix H. The system has been in compliance with the LCR throughout this period. As shown in the summary in **Table 4-3**, the City's I&D System 90th percentile values for lead and copper were below the action level during all six samplings conducted between 2001 and 2008. However, lead levels are quite variable, as indicated by the differences in maximum concentration. All told, 11 individual sampling sites exceeded the action level for lead during this period, but only 2 sites have exceeded the action level more than once, demonstrating that lead corrosion problems can be transient in nature and not easily traced to a particular location.

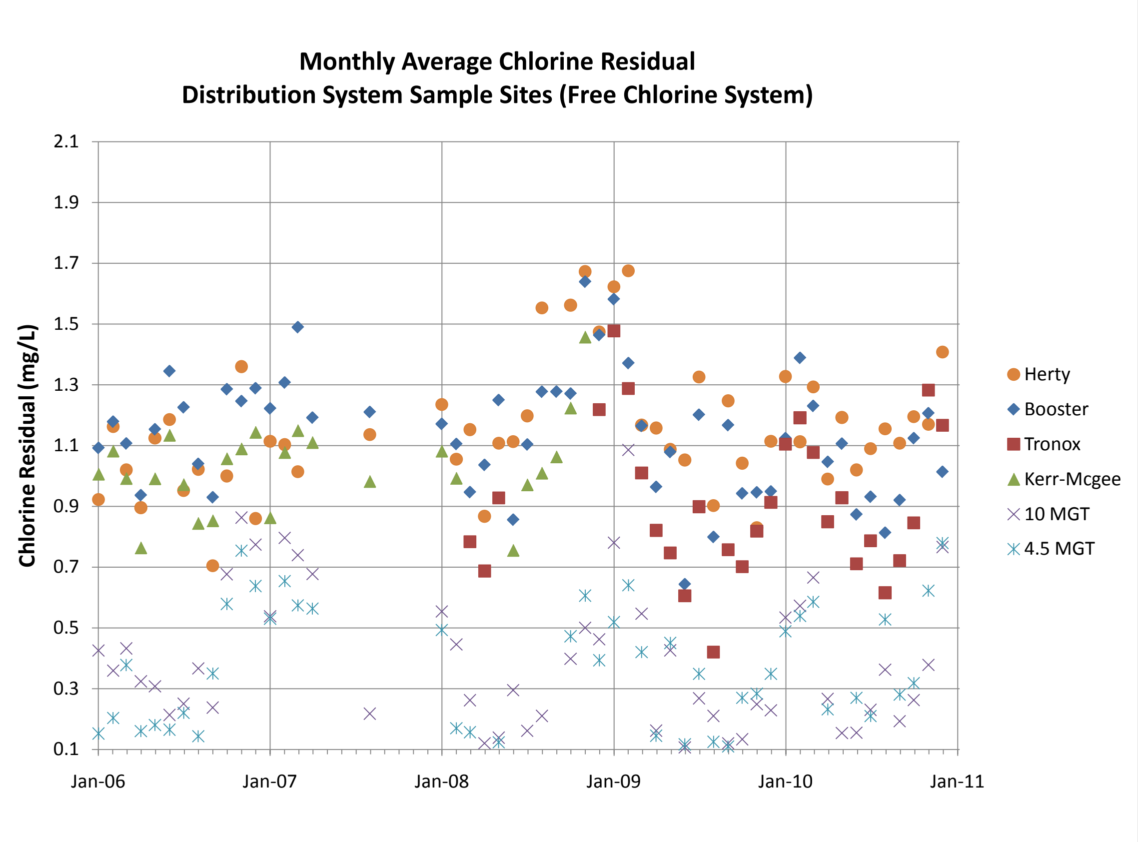


Note: Herty distribution site is closest to the WTP; used as surrogate for finished water



Note: Travis distribution site is closest to the WTP; used as surrogate for finished water

Figure 4-1
pH at Distribution System Sampling Sites



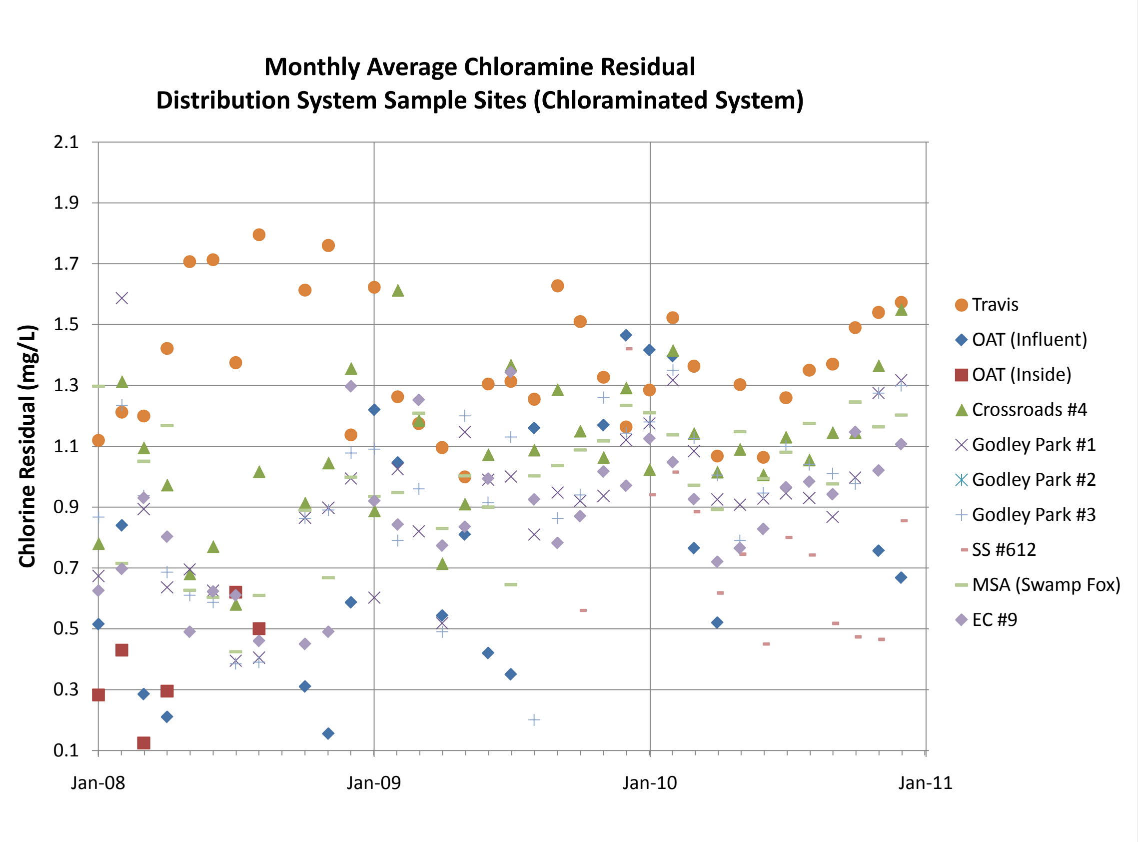
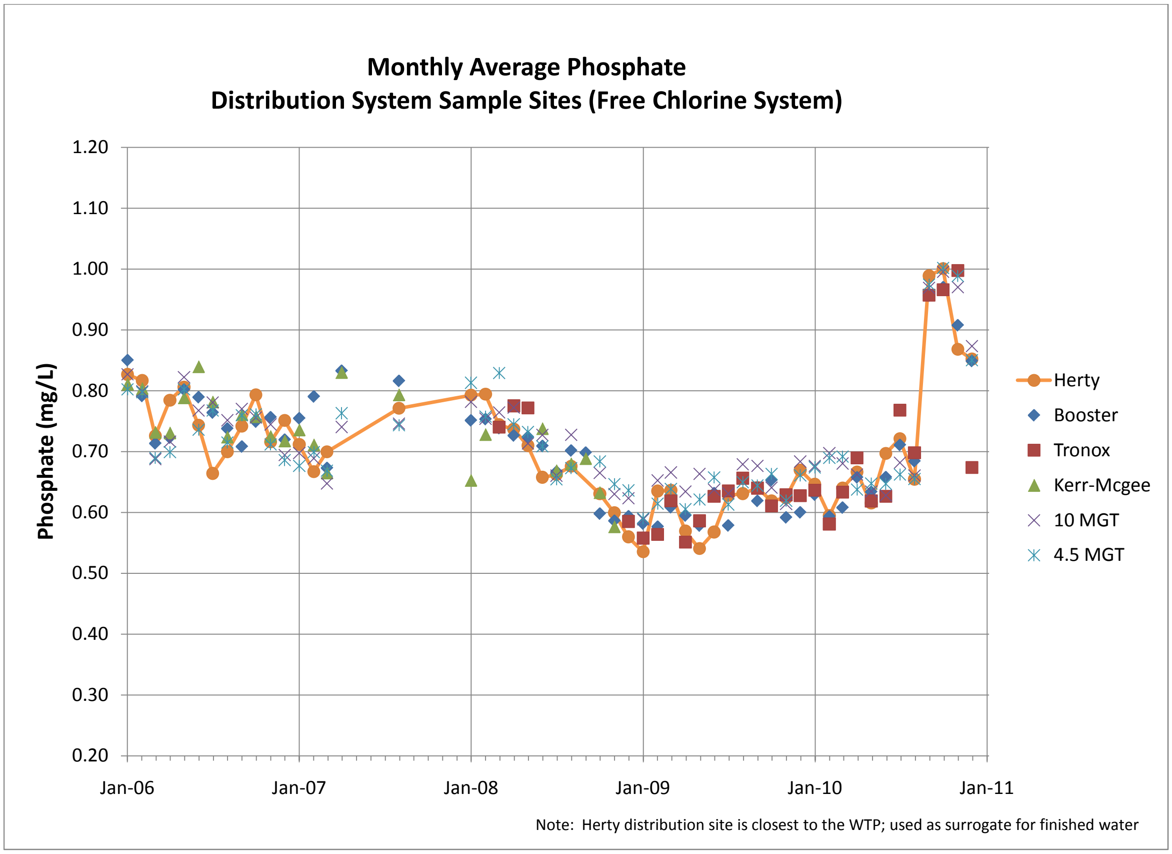


Figure 4-2
Chlorine Residual at Distribution System Sampling SItes



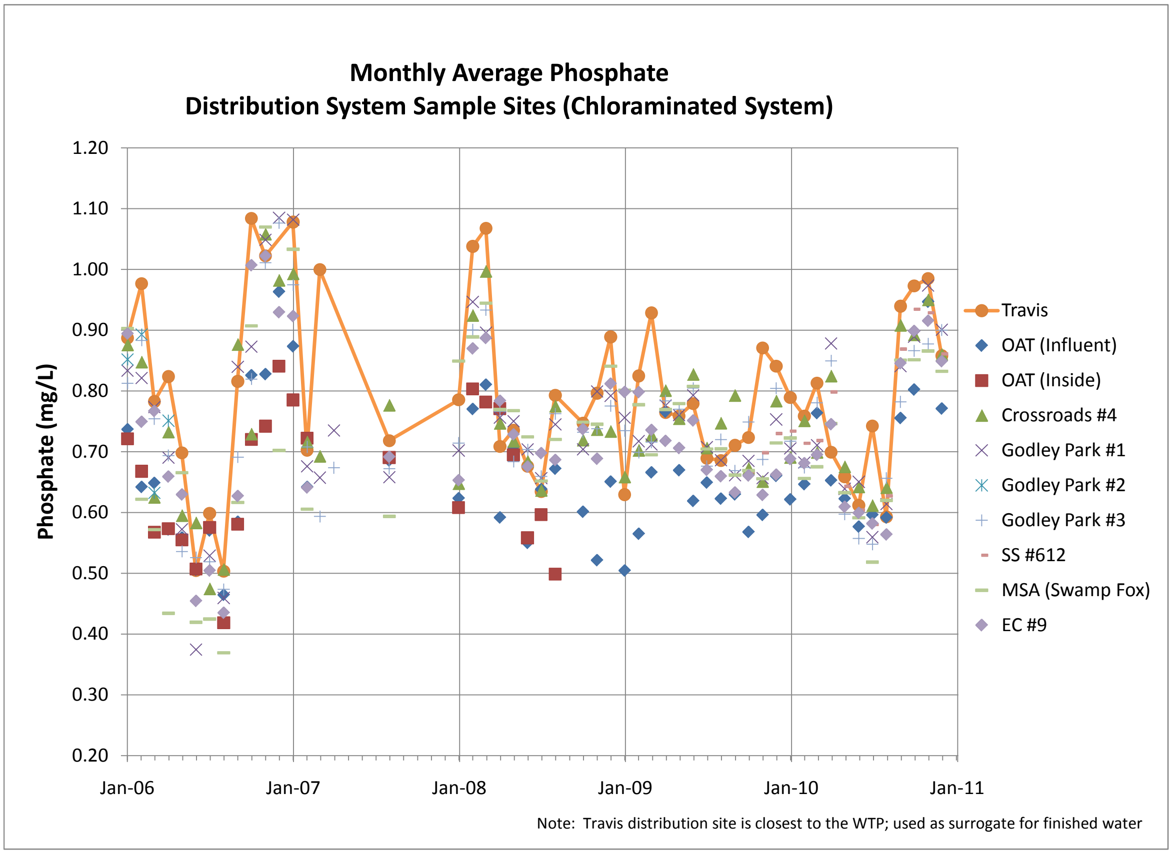


Figure 4-3
Phosphate at Distribution System Sampling Sites

Table 4-3: Summary of 2001 – 2008 Lead and Copper Rule Data

Parameter	**Lead** (µg/L)[a]			**Copper** (µg/L)[a]		
	Min	**Max**	**Avg**	**Min**	**Max**	**Avg**
90th Percentile Concentration	3.2	13	5.9	260	480	347
Maximum Concentration	5.4	260	100	330	910	612
# of Sites over Action Level	0	6[b]	2.2	0	0	0

[a] Minimum, maximum, and average concentrations from sampling conducted in 2001, 2002, 2003, 2004, 2006, and 2008.

[b] 61 sites were included in this round of sampling instead of the usual 30

4.3.2 Disinfectants and Disinfection Byproducts rule (D/DBPR)

Under the Stage 1 D/DBPR, the City collects TTHM and HAA5 samples at four locations within the I&D System quarterly. Stage 1 compliance is determined based on the running annual average (RAA) of quarterly samples at all sites. **Table 4-4** shows historical TTHMs from the 1st quarter of 2008 through the 2nd quarter of 2011 at the four sites on which the City's compliance is based. The Booster, Herty, and Kemira sites are located in the free chlorine system while the OAT site is in the chloraminated system.

The maximum RAA for TTHMs during this period was 55.0 µg/L, below the MCL of 80 µg/L. Individual HAA5 sampling data was not available for this analysis, however, the RAA for HAA5s during 2009 was 47.5 µg/L, below the MCL of 60 µg/L. Under the Stage 2 D/DBPR, compliance will be determined based on a locational running annual average (LRAA). Compliance must be met at each monitoring location, instead of system-wide using the RAA under the Stage 1 D/DBPR. The Savannah I&D system will begin compliance monitoring under the new Stage 2 rules in July 2014. Table 4-4 shows a calculation of LRAA for the current compliance data. The OAT sampling location on the chloraminated system generally has the highest LRAA of all the current sampling sites for TTHMs.

Table 4-4. Summary of Total Trihalomethanes[1] (TTHM) from 2008 through 2011

Date	**TTHMs (µg/L) by Location**									
	Booster		**Herty**		**Kemira**		**OAT**		**Average**	
	Quarterly Sample	**LRAA**	**Quarterly Sample**	**LRAA**	**Quarterly Sample**	**LRAA**	**Quarterly Sample**	**LRAA**	**Quarterly Average**	**RAA**
3/12/2008	33.6		36.3		34.7		44.8		37.4	**45.9**
5/28/2008	33.6		36.3		34.7		44.8		37.4	**38.1**
9/9/2008	39.5		51		63.3		51.2		51.3	**44.0**
11/24/2008	32.5	**34.8**	29.6	**38.3**	40.0	**43.2**	53.1	**48.5**	38.8	**41.2**
3/25/2009	40.9	**36.6**	40.6	**39.4**	44.8	**45.7**	53.8	**50.7**	45.0	**43.1**
6/3/2009	80.4	**48.3**	75.4	**49.2**	87.5	**58.9**	93.3	**62.9**	84.2	**54.8**
9/17/2009	48.7	**50.6**	44.3	**47.5**	53.6	**56.5**	56.3	**64.1**	50.7	**54.7**
12/16/2009	34	**51.0**	35.9	**49.1**	44.3	**57.6**	46.2	**62.4**	40.1	**55.0**
3/9/2010	23.7	**46.7**	22.6	**44.6**	28.5	**53.5**	27.9	**55.9**	25.7	**50.2**
5/26/2010	53.1	**39.9**	42.0	**36.2**	46.1	**43.1**	46.9	**44.3**	47.0	**40.9**
9/8/2010	42.4	**38.3**	34.4	**33.7**	51.6	**42.6**	49.5	**42.6**	44.5	**39.3**
12/8/2010	39.8	**39.8**	12.8	**28.0**	8.1	**33.6**	32.0	**39.1**	23.2	**35.1**
3/9/2011	36.7	**43.0**	36.2	**31.4**	40.8	**36.7**	42.2	**42.7**	39.0	**38.4**
5/18/2011	38.5	**39.4**	37.2	**30.2**	40.4	**35.2**	41.4	**41.3**	39.4	**36.5**
Maximum	*80.4*	***51.0***	*75.4*	***49.2***	*87.5*	***58.9***	*93.3*	***64.1***	*84.2*	***55.0***

[1] HAA5 data were not available for review but are expected to show similar trends

4.4 Chlorides Frequency Analysis

Deepening of the Savannah Harbor is expected to increase the percentage of seawater (and hence chloride) at the raw water intake for Savannah's I&D system. Currently, the average chloride concentration in the raw water is 10.6 mg/L. Maximum chlorides at the intake are well below the National Secondary Drinking Water Standard of 250 mg/L and are expected to remain below this level after dredging of the harbor. However, an increase in raw water chlorides to the WTP has the potential to impact compliance with the LCR and Stage 2 D/DBPR as well as impact maintenance requirements for the industrial users of the Savannah I&D system.

This section describes an analysis of historical and predicted future chloride concentrations at the Savannah I&D intake on Abercorn Creek.

4.4.1 Historical Chloride Concentration

Table 4-1 presents a summary of monthly average chloride in the raw water at the WTP. Daily chloride data measured at the raw water intake is also available from 1988 to 2009. During this period, the chloride ranged from 3.0 mg/L to 28.4 mg/L with an average of 10.6 mg/L. The 99th percentile chloride concentration is 15.3 mg/L, meaning that 99 percent of the daily chloride measurements are less than 15.3 mg/L.

4.4.2 Modeled and Projected Future Chloride Concentrations

Chloride concentrations at the I&D Plant intake before and after harbor deepening were calculated by Tetra Tech using output from the Environmental Fluid Dynamics Computer Code (EFDC) model. A description of the development, calibration, and application of this model to chlorides analysis can be found in the Engineering Investigations appendix of the General Reevaluation Report for the Savannah Harbor Expansion Project (SHEP; USACE, 2011).

Figure 4-4 shows a histogram of the hourly model-predicted chloride concentrations at the intake under historical river flows from 2001 to 2009 for the existing scenario as well as the harbor deepening scenario. The existing model-predicted hourly chloride concentration averaged 10.6 mg/L, with a 99th-percentile value of 14.8 mg/L and a maximum of 36 mg/L over this period; these values compare favorably with the measured data described above.

Output from the modeled scenario that includes harbor deepening (5 ft deepening with mitigation option 6A) indicates that the average hourly chloride concentration over the period 2001-2009 would have increased to 13.7 mg/L, with a 99th-percentile value of 53 mg/L and an hourly maximum of 185 mg/L.

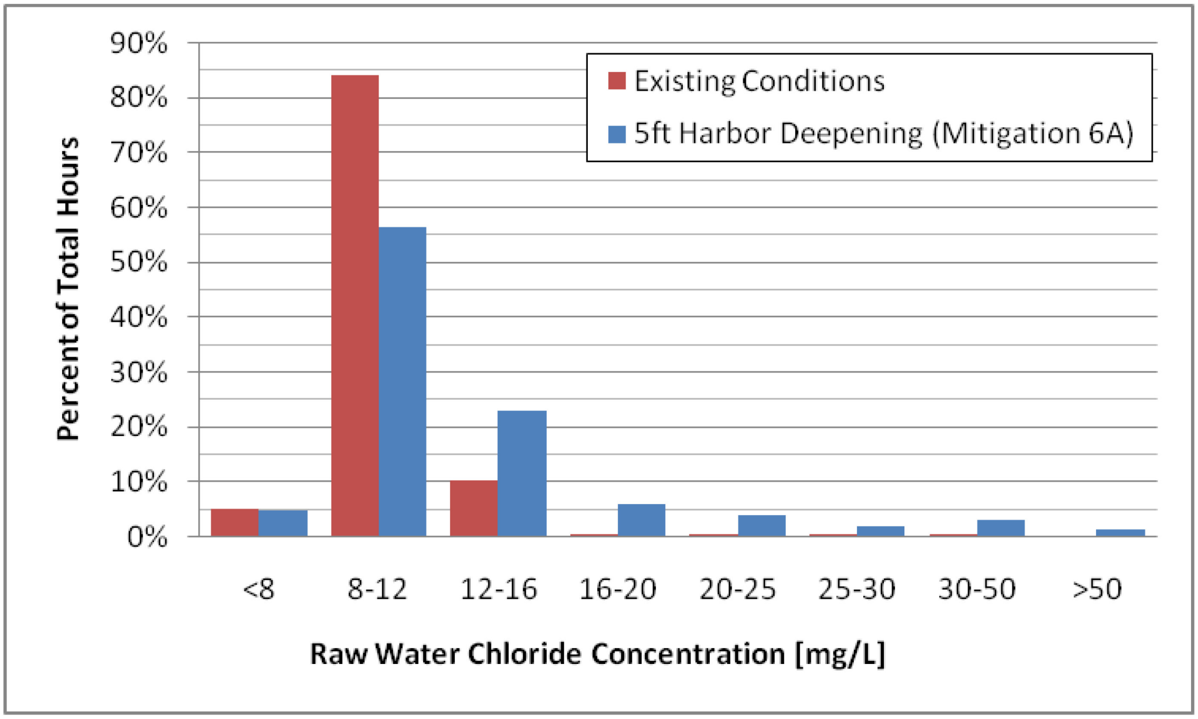


Figure 4-4: Histogram of model-predicted hourly chloride concentrations at Abercorn Creek intake.

4.4.3 Chloride Event Analysis

To gain further insight into the operational implications of elevated chlorides due to harbor deepening, the modeled chloride concentrations were analyzed with respect to various cutoff thresholds. The idea behind this analysis is that there may be threshold chloride concentrations above which treated water quality is significantly impaired, and so it may be desirable not to pump raw water when chlorides exceed the threshold.

A "high chloride event" is defined as a period of time during which the chloride concentration at the intake continuously exceeds the cutoff threshold. Both the frequency and duration of such events will have significant implications for future plant operations and for the design of any new infrastructure intended to cope with the elevated chloride levels.

Modeling data indicate that the median duration of high chloride events ranges from 3 to 6 hours, with worst-case durations as high as 12 hours, depending on the threshold. **Figure 4-5** shows the maximum, median, and 95th percentile event durations over the period analyzed for chloride cutoff concentrations ranging from 20 to 70 mg/L chloride.

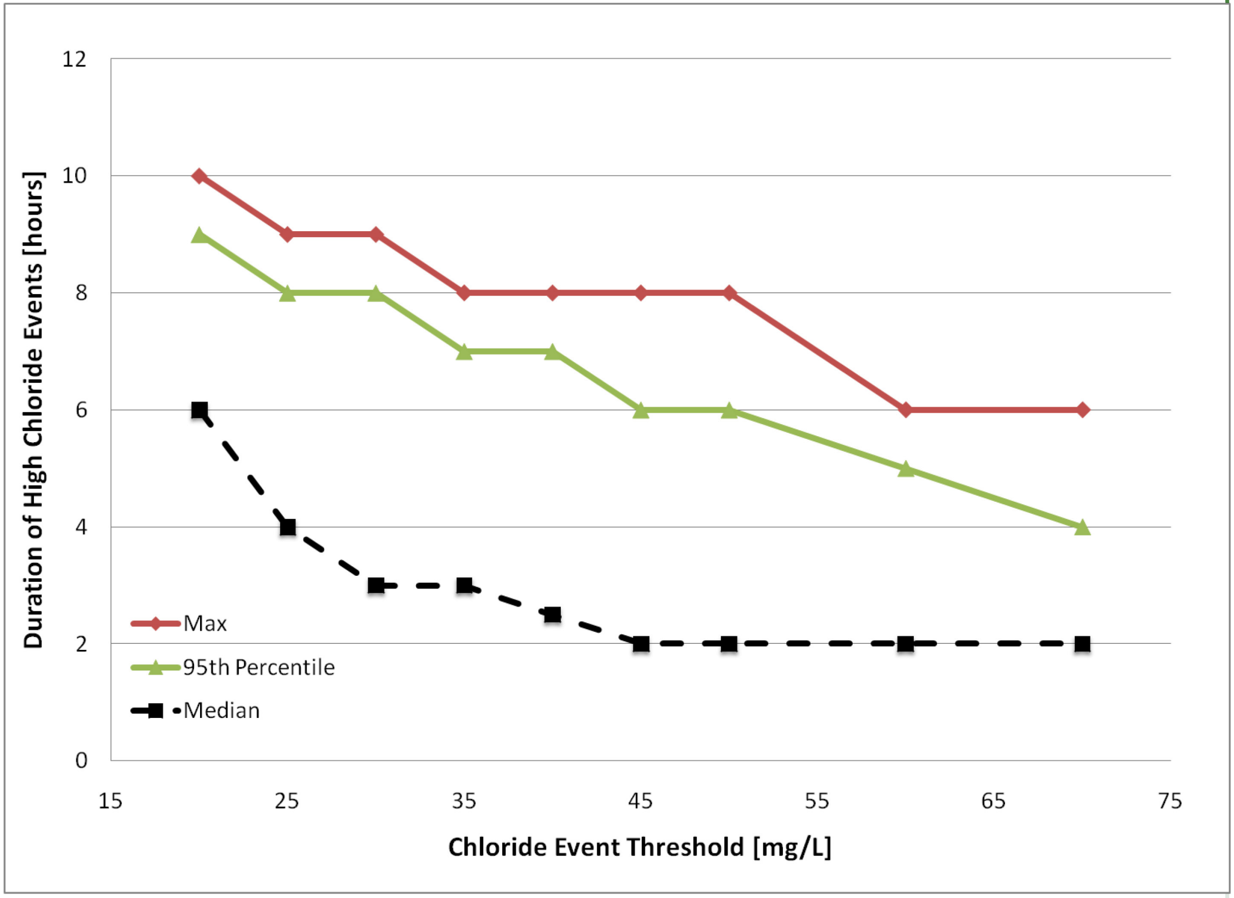


Figure 4-5: Duration of high-chloride events at various cutoff threshold concentrations.

Furthermore, simulations during the 2008 drought indicate that there were high chloride events greater than 2 hours long for as many as 39 consecutive days, depending on the threshold. **Table 4-5** shows the consecutive days of high chloride events at various cutoff concentrations.

Table 4-5: Consecutive days with high-chloride events exceeding the threshold concentration for more than 2 hours

Cutoff Concentration	25 mg/L	30 mg/L	35 mg/L	40 mg/L	50 mg/L	75 mg/L
Days	39	37	24	12	10	4

As shown, this analysis indicates that the I&D WTP will likely have to pump water containing as much as 50 mg/L chloride for one or several hours in a row during an extreme drought event, as it is impractical to construct storage facilities to meet water demand for more than a few days.

Section 5
Bench Scale Testing Procedures and Results

A bench-scale testing protocol was developed in order to evaluate the potential impacts of increased seawater percentage of treated drinking water from the I&D WTP. This protocol was designed to mimic full-scale treatment of raw water containing a range of chloride concentrations spanning the range expected to result from harbor deepening. Test conditions were chosen to assess the extent to which changes in disinfectant, pH, or the level of corrosion inhibitor could mitigate any adverse water quality impacts caused by the elevated chlorides.

5.1 Test Conditions

A total of 64 distinct water quality conditions were evaluated in this study. These conditions comprised combinations of 5 chloride concentrations, 3 pH levels, 2 types of disinfectant, and 2 corrosion inhibitor doses. Two additional pH levels were tested on two selected water matrices, bringing the total to 64 conditions. Existing treatment conditions were used as a base case for each parameter, which were then varied based on anticipated treatment changes resulting from increased seawater intrusion. **Table 5-1** summarizes the conditions tested.

Table 5-1: Summary of Water Quality Conditions

Chloride	pH	Disinfectant	Corrosion Inhibitor
Existing (10 mg/L)	Existing[1] (7.3 ± 0.15)	Free Chlorine (2.0 ± 0.2 mg/L)	Existing (0.75 mg/L as PO_4)
25 mg/L	7.5 ± 0.15[2]		
50 mg/L	7.8 ± 0.15	Chloramines (~1.2 mg/L)[4]	Existing + 0.75 mg/L as PO_4
75 mg/L	7.9 ± 0.15[3]		
150 mg/L (Sensitivity Test)	8.3 ± 0.15		

[1] Target finished water pH, according to plant staff.
[2] 25 mg/L and 50 mg/L with free chlorine and existing inhibitor only.
[3] 50 mg/L and 75 mg/L with free chlorine and existing inhibitor only.
[4] Chloramines were formed using procedures identical to full-scale treatment using a chlorine: ammonia ratio of 2.2:1. Exact residual was measured after formation but plant staff and data indicate that 1.2 mg/L is typical.

Each of the 64 water matrices described above was exposed to two different plumbing materials, mild steel and copper galvanically connected to lead solder. Water was exposed to the plumbing materials in batch using a “fill and dump” procedure two times per week. The frequency of the fill and dump was intended to simulate the worst-case time of exposure to these plumbing materials in a typical residence or commercial building. Samples were collected for laboratory analysis during one of these cycles each week. The study continued for 6 weeks.

5.2 Water Treatment Procedures

Enough water for two fill-and-dump cycles was prepared each week of the study. This required collecting approximately five gallons of estuarine water from the Savannah River at the beginning of the study. The estuarine water was collected by City of Savannah staff just upstream of the river's confluence with the Atlantic Ocean. The sample was collected using a boat which was positioned in the main flow of the river to avoid near-shore effects. This aliquot of estuarine water was analyzed for chloride, conductivity, and total organic carbon (TOC). The estuarine water was determined to contain approximately 4,700 mg/L chloride. Based on these results, samples of raw water from the plant intake were spiked with appropriate quantities of estuarine water to achieve 25, 50, 75, and 150 mg/L chloride. The 150 mg/L chloride concentration is twice the maximum predicted daily average value, but was included as a sensitivity test in consideration of the potential for hourly spikes. In addition to the estuarine water, approximately 50 gallons of plant raw water was collected each week for use in preparing the seawater blends and subsequent matrix waters. The plant raw water was collected in a 60 gallon polypropylene drum between high and low tide each day that seawater blends were prepared. Unused plant raw water was discarded following production each week.

Seawater blends were prepared in 20 liter carboys by first adding a specified amount of estuarine water and then filling to volume with plant raw water. The estuarine water was stored in a refrigerator but warmed to room temperature each week prior to the preparation of the seawater blends. The estuarine water was measured and transferred to the carboys using graduated cylinders. The carboys were vigorously shaken to ensure complete mixing.

Prior to the beginning of the corrosion study, jar testing with alum was performed on each of the four blends and on unblended raw water to determine treatability and the optimum coagulant dose. The details of the jar testing procedure, which are included in Appendix D (Testing Plan for Seawater Effects Study), were intended to simulate full-scale treatment as closely as possible. A standard Phipps and Bird six station jar tester (see **Figure 5-1**) with 2-liter square beakers was used to simulate the settling process.

Figure 5-1 Jar Testing Apparatus

Each of the seawater blends and the plant raw water were coagulated using the coagulant dose determined for the plant's full scale operation at the time the raw water was drawn from the plant's raw water tap. The same procedures as used for jar testing were employed except that the water was allowed to settle until the turbidity of the supernatant was approximately equal to the full-scale settled water turbidity (about 90 minutes). The supernatant was then filtered once through glass microfiber filters and again through 0.45 micron membrane filters. All filters were pre-rinsed with 500-mL of deionized (DI) water prior to use.

Every week, each filtered water blend was sampled and analyzed for chloride, bromide, sulfate, TOC, UV absorbance at 254nm, alkalinity, total phosphorous, orthophosphate, lead, copper, and iron. The remaining volume of each of the treated blends including the unaltered plant raw water was further adjusted to match the conditions described in Table 5-1. To do so, each treated blend was divided into two portions, one to simulated water treated with free chlorine and the other to simulated water treated with chloramines. As necessary, the pH of both portions was adjusted to match that of the full-scale filtered water (pH ~6.5) by bubbling gaseous CO_2 or adding hydrated lime solution prepared by plant staff. Chlorinated water was drawn from the plant's chemical feed system at the settled water feed point. Using this stock solution of chlorinated water, chlorine was added to one portion of each of the treated blends to achieve the desired dose of 2.0 mg/L. Both portions of each blend were then allowed to incubate at room temperature for 12 hours to simulate the contact time in the clearwell on the chloraminated portion of the treatment system. After 12 hours, the chlorine residual was checked and boosted to 1.0 mg/L if lower. Ammonium hydroxide was added at a Cl_2:NH_3 weight ratio of 2.2:1, per standard plant operations. At this time, chlorine was added to the remaining portions of each blend to achieve a 2.0 mg/L residual to simulated waters treated with free chlorine. Each portion (both chloramines and free chlorine) of each blend was then further divided into three aliquots which were adjusted to the three target pHs using lime and gaseous CO_2 as necessary. As noted earlier, additional portions of the 25, 50 and 75 mg/L blends treated with free chlorine were adjusted to achieve the additional pH levels indicated in Table 5-1.

Finally, portions of each pH adjusted, chlorinated (free-chlorine or chloraminated), treated seawater blend were transferred to bottles labeled to match the coding scheme illustrated in Figure 1 of Appendix D. The color-coded scheme was utilized to minimize human error. Corrosion inhibitor was added as indicated in Table 5-1.

During week two, additional water was prepared for use in simulated distribution system (SDS) testing. Five test conditions were prepared for SDS testing: treated raw water at pH 7.3, 7.8, and 8.2 plus 75 mg/L and 150 mg/L chloride blends at pH 7.3.

5.3 Plumbing Materials

Each of the 64 water matrices described above was exposed to two different plumbing materials using specially-made exposure containers. The containers were:

- 60-mL glass jars containing a copper coupon galvanically connected to lead solder
- 35-mL sections of PVC pipe with mild steel coupons affixed to one end

The two plumbing materials are illustrated in **Figure 5-2**.

Testing on lead/copper solder unions was conducted in triplicate, while testing on the mild steel coupons was conducted in duplicate, for a total of 192 jars and 128 pipe segments, respectively. Samples were collected from each material on a weekly basis, as described below.

Figure 5-2: Exposure containers with Copper/Lead coupons (left) and Mild Steel coupons (right).

5.4 Sample Collection and Analysis

5.4.1 Exposure Testing and Sample Collection

Each water matrix was continuously exposed to the plumbing materials using the purpose-built exposure containers. Water in each container was changed twice per week, Monday and Friday (Thursday in one instance). Samples from each container at the time of the change were composited and sent for laboratory analysis every week. All exposed water was collected and analyzed so that mass balance calculations could be performed at the conclusion of the study. Sampling procedures are diagrammed in **Figure 5-3** and described in detail in Appendix D. Exposure jars and sampling containers were labeled according to the coding scheme illustrated in Figure 2 of Appendix D.

During the first week, each exposure container was filled with the matching matrix water from the appropriate bottle. Following the initial fill operation, the exposure containers were manually dumped and refilled twice each week. During the first and last week, the water in each replicate exposure jar was dumped into a separate container. During the intervening weeks, the water from each of the three lead/copper triplicates was composited into one container, and from each of the two steel duplicates into another. In all cases, the water dumped Monday and Friday was combined into the same container.

5.4.2 Simulated Distribution System (SDS) Testing

As noted above, extra water was prepared during week two for conducting simulated distribution system testing. These waters were sent to a laboratory, where chlorine demand testing was performed to determine the free chlorine dose that would produce a residual of 2.0 mg/L at the end of the incubation period. Then, each water was treated with that chlorine dose and allowed to incubate in a headspace-free container for 24 hours. At the end of the incubation period, the waters were analyzed for total THMs and nine HAAs.

Note that SDS testing was conducted only on waters treated with free chlorine, since chloramines form negligible quantities of regulated DBPs. In the I&D chloramine system, the vast majority of DBPs are formed in the plant clearwell, which is treated with free chlorine prior to ammonia addition. Therefore, the results of the SDS testing are applicable to both the industrial (free chlorine) and residential (chloramine) distribution systems.

City of Savannah Seawater Effects Study
Figure 3: Sampling Plan

Combine Estuary Water[1]
with Plant Raw Water[2]
To Achieve Varying Chloride Levels:
0 – no added chloride
1 – 25 mg/L chloride
2 – 50 mg/L chloride
3 – 75 mg/L chloride
4 – 150 mg/L chloride

[1] Note 1: measured at 4,700 mg/L chloride
[2] Note 2: assume 10 mg/L chloride from plant data

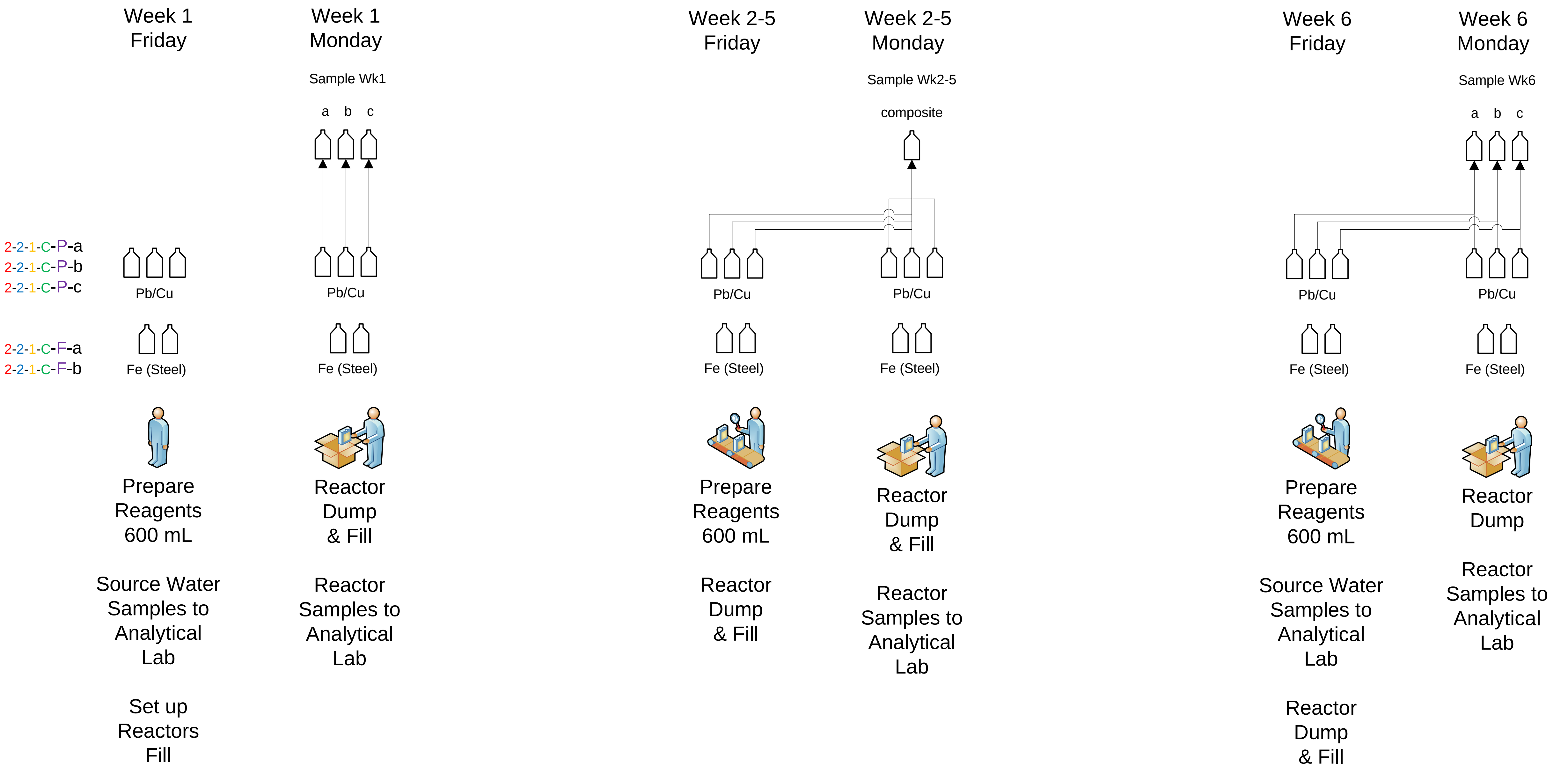
pH adjust with
NaOH or H_2SO_4
0 – existing pH
1 – plus 0.5 units
2 – plus 1.0 units
3 – plus 0.2 units
4 – plus 0.6 units

Add:
Corrosion Inhibitor
0 – Existing or
1 – Higher Conc.

Add:
Disinfectant
C – Free Cl2 or
A – Chloramines

1 L bottles
60 Matrices
Prepared Weekly

Distribute to Reactors
P – Pb/Cu triplicates
F – Fe duplicates



First Week
Friday – Fill
Monday – Sample & Dump & Fill

Middle Weeks
Friday – Dump & Fill
Monday – Sample & Dump & Fill

Sixth Week
Friday – Dump & Fill
Monday – Sample & Dump

5.4.3 Laboratory Analysis

Table 5-2 presents a listing of the samples analyzed at the laboratory throughout the study. Testing for corrosion products (metals) was performed every week. Note that samples for the replicate exposure jars were analyzed separately during the first and last round of sampling, but were composited during the other rounds of sampling. Water quality testing of the treated seawater blends (prior to pH adjustment or chemical addition) was performed each week to provide confirmation that source water quality remained relatively consistent. SDS testing was performed during week two of the study.

Table 5-2: Laboratory Samples

Analyte	No. of Waters	No. of Samples per Week per water	Duration (weeks)	Waters to be Analyzed
Lead and Copper	64	1	4**	All treated, exposed waters
Lead and Copper (triplicate)	64	3	2*	All treated, exposed waters (+ all triplicates)
Iron	64	1	4**	All treated, exposed waters
Iron (duplicate)	64	2	2*	All treated, exposed waters (+ all duplicates)
Lead and Copper	5	1	6	Filtered seawater blends only
Iron	5	1	6	Filtered seawater blends only
Chloride	5	1	6	Filtered seawater blends only
Bromide	5	1	6	Filtered seawater blends only
Sulfate	5	1	6	Filtered seawater blends only
Total Organic Carbon	5	1	6	Filtered seawater blends only
UV Absorbance at 254nm	5	1	6	Filtered seawater blends only
Orthophosphate	5	1	6	Filtered seawater blends only
Total Phosphate	5	1	6	Filtered seawater blends only
THM4	5	2	1	Treated waters: ambient, 75 mg/L, and 150 mg/L chloride at existing pH, ambient chloride at existing pH, +0.5, +1.0 only, duplicate for three of the five
HAA9	5	2	1	Treated waters: ambient, 75 mg/L, and 150 mg/L chloride at existing pH, ambient chloride at existing pH, +0.5, +1.0 only, duplicate for three of the five

*Triplicate / duplicate analysis was performed only during the first and last round of sampling. Triplicates/duplicates were composited during the other rounds.

5.5 Results and Discussion

5.5.1 Test Matrix Water Quality

Fresh batches of each test water (raw water and four different seawater blends) were prepared each week of the study using the procedures outlined above and in Appendix D. Basic water quality measurements were made every week to confirm that the composition of the test waters remained relatively consistent throughout the study. **Table 5-3** provides a summary of the water quality characteristics measured.

As shown in the table, the chloride concentration in each test water was close to the target value throughout the duration of the study. Furthermore, there was no contamination of either metals or phosphate in the source waters, with the exception of week 1. During week 1, all blends had an uncharacteristically high UV absorbance, low sulfate, and trace levels of copper and iron. The reason for the inconsistency is not clear, but is most likely related to a transient change in raw water quality. The metals concentrations were several orders of magnitude lower than those measured during the study and therefore have no impact on the results, but the UV absorbance and sulfate readings for week 1 skew the average values for both parameters as well as for the chloride-to-sulfate mass ratio (CSMR) and specific UV absorbance (SUVA).

Increases in seawater percentage (chloride concentration) are accompanied by increases in bromide and sulfate concentrations and a slight lowering of the UV absorbance and SUVA. Bromide increases in nearly direct proportion with chloride, which is consistent with expectations, while the sulfate concentration increases more slowly. The increase in sulfate is not directly related to chloride because of additional sulfate added to the water during coagulation. Reductions in SUVA, which is an indicator of the hydrophobicity of the organic carbon in the water, are also consistent with expectations because the TOC found in seawater tends to be more hydrophilic than that found in freshwater.

As noted in Section 2.4.1.3, the chloride to sulfate mass ratio (CSMR) is a key parameter in determining what chemical species control the solubility of lead, and therefore is a measure of the susceptibility of water to lead corrosion. In general, if the CSMR is greater than 0.58, there is cause for concern. As the table shows, even under existing conditions, the I&D Plant raw water has a CSMR of nearly 0.5, which increases in near direct proportion with the chloride concentration. As such, virtually any increase in the chloride concentration above the existing level raises concerns about lead corrosion.

Table 5-3: Summary of Treated Test Water Quality Measurements (weeks 1 – 6)

Parameter	Unit	Blend 0 (Treated Raw Water)[a]		Blend 1 (25 mg/L Chloride)		Blend 2 (50 mg/L Chloride)		Blend 3 (75 mg/L Chloride)		Blend 4 (150 mg/L Chloride)	
		Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
Chloride	mg/L	12	10-16	25	23-29	48	46-54	71	68-75	138	130-140
Sulfate	mg/L	25	13-31	27	14-32	30	17-36	34	21-40	44	30-50
Bromide	µg/L	50	38-63	95	85-100	177	160-190	252	230-280	475	460-490
CSMR	-	0.49	0.37-0.77	0.99	0.78-1.64	1.69	1.36-2.76	2.18	1.85-3.29	3.27	2.80-4.67
TOC	mg/L	2.1	1.8-2.8	2.2	1.8-3.0	2.1	1.8-2.9	2.3	1.9-3.3	2.5	2.2-3.2
UV254	1/cm	0.054	0.025-0.140	0.048	0.018-0.150	0.056	0.015-0.140	0.048	0.021-0.140	0.045	0.019-0.130
SUVA	L/mg-m	2.38	1.35-5.00	1.98	0.95-5.00	2.46	0.75-4.83	1.87	1.00-4.24	1.69	0.86-4.06
Lead	µg/L	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]	0	ND[b] - 1.6
Copper	µg/L	2.0	ND[b] – 7.1	1.0	ND – 6.0	1.2	ND[b] - 71	1.4	ND[b] – 8.5	1.7	ND[b] – 10.0
Iron	µg/L	460	0-1400	183	ND - 1100	183	ND[b] - 1100	183	ND[b] - 1100	160	ND[b] - 960
Orthophosphate	mg/L	0.015	ND - 0.087	0.014	ND – 0.086	0.014	ND[b] – 0.085	0.013	ND[b] – 0.078	0.011	ND[b] – 0.065
Total Phosphorous	mg/L	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]

[a] Baseline condition, representing existing water quality and treatment.

[b] ND or "not detected" denotes a value below the detection limit. These measurements were treated as 0 for averaging purposes.

5.5.2 Coagulant Demand / Treatability

Preliminary jar testing was conducted on four different chloride blends bracketing the range of expected concentrations resulting from harbor deepening. This testing indicated that seawater percentage did not have a significant impact on the optimal coagulant dose for turbidity removal. **Figure 5-4** shows that the optimal dose for raw water blends with chloride ranging from 11 to 200 mg/L was approximately the same.

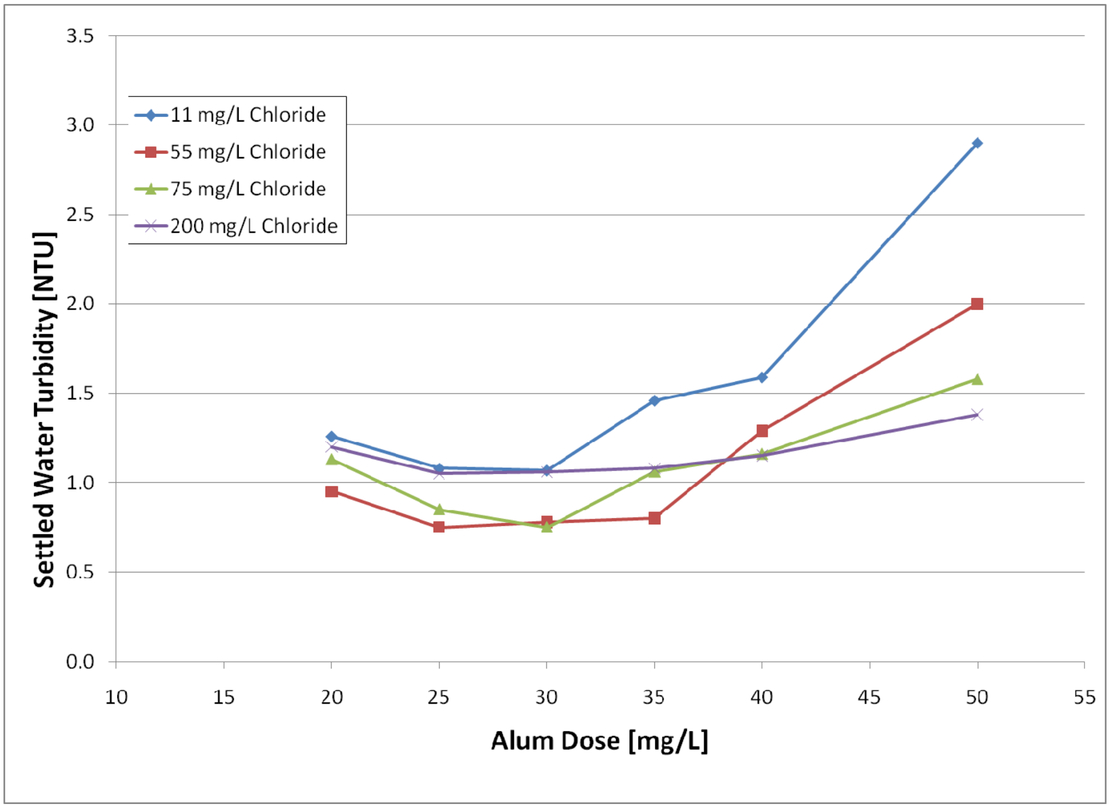


Figure 5-4: Effect of chloride concentration on coagulant demand.

With regard to TOC removal, measurements indicate that increased seawater percentage interferes slightly with TOC removal. **Figure 5-5** shows the relationship between chloride concentration, filtered water TOC, and filtered water UV absorbance. The 11 mg/L chloride blend corresponds to existing raw water. The reduction in TOC removal is consistent with expectations, because the TOC found in seawater is often hydrophilic in nature and therefore difficult to remove by coagulation. Similarly, the slight decrease in UV absorbance indicates that the TOC is less aromatic, and therefore more hydrophilic in nature.

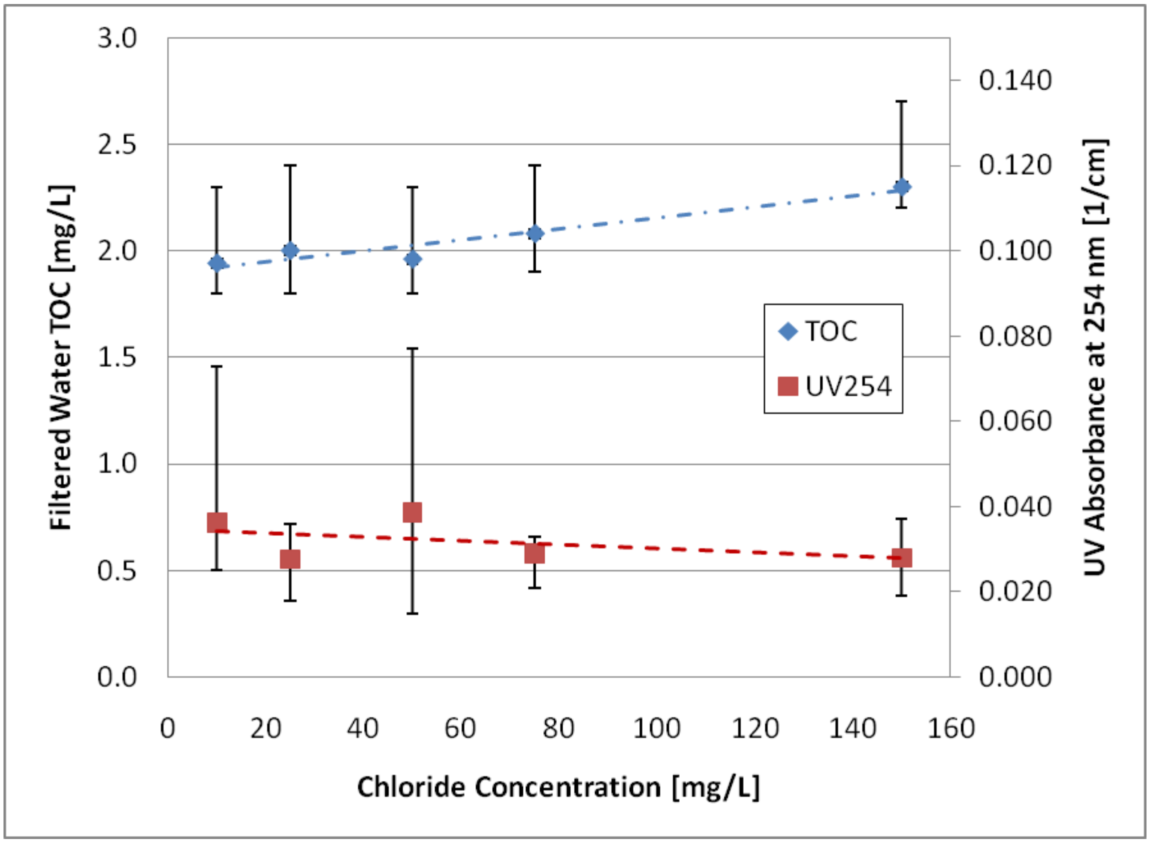


Figure 5-5: Effect of chloride concentration on filtered water TOC and UV absorbance. Values shown are averages of the raw/blended water quality for weeks 2-6 of the corrosion study. The leftmost data point (10 mg/L chloride) corresponds to existing conditions. Week 1 is excluded because its data were inconsistent with measurements taken during all subsequent weeks. Error bars represent the minimum and maximum weekly filtered water TOC for each blend.

5.5.3 Corrosion

Effect of Time

Laboratory studies of corrosion must be conducted over extended periods of time because it takes new plumbing materials (such as the coupons used in this study) a period of weeks to come to equilibrium with the surrounding water and establish a relatively steady-state dissolved metal concentration. **Figure 5-6** illustrates this process for one test condition, corresponding to existing chloride, pH, and inhibitor doses and free chlorine disinfection. As shown, lead concentrations during the first 2 weeks were very high but decreased sharply and eventually stabilized. Copper concentrations show an opposite behavior, beginning very low and climbing as the lead concentrations decreased. This behavior was typical of the other conditions tested as well. Because the initial concentrations were so much higher (or lower) than the approximately steady-state values reached near the end of the study, the summary results in this section include averages of only weeks 3 through 6 of the data. Full results are provided Appendix F.

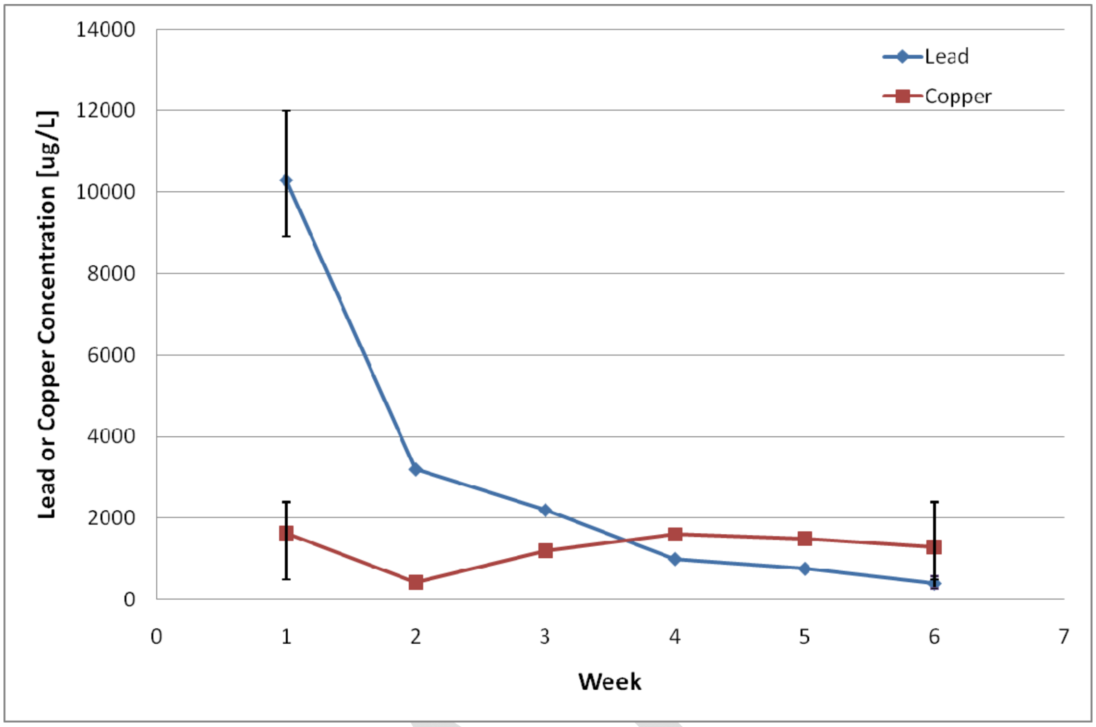


Figure 5-6: Time-dependency of lead and copper concentrations for the existing chloride, existing pH, existing inhibitor, free chlorine test condition. Error bars represent the range of values measured in triplicate during week 1 and 6.

Effect of Chloride

The effect of increased chloride concentration on lead, copper, and iron corrosion is shown in **Figure 5-7** and **Figure 5-8** for water treated with free chlorine and chloramines, respectively. This plot compares metals concentrations in reactors under existing conditions (chloride, pH, inhibitor dose) with those in the reactors with elevated chlorides. The CSMR (introduced in Section 2.4.1.3) is shown as dotted line in both plots. This parameter plays a key role in controlling lead solubility. The threshold value of 0.58, above which there is cause for concern about lead corrosion, is shown as a dashed red line.

As the figures show, increased chloride concentration has a clear detrimental effect on corrosion of lead. The effect is more pronounced with free chlorine than chloramines at the highest chloride tested, but at lower chloride concentrations lead release was increased more when using chloramines. In both cases the lead concentrations with 50 mg/L chloride were 2-4 times the concentration under existing conditions. It is unclear why the highest chloride concentration resulted in lower lead release for chloramines. It is possible that the elevated chloride interacted with the inhibitor so as to make it more effective under those particular conditions. Finally, all elevated chloride concentrations tested increased the CSMR above the recommended maximum of 0.58. Moreover, the CSMR appears to be a useful indicator of the severity of lead corrosion in Savannah water as it increases in similar fashion with dissolved lead.

In contrast, increased chloride in the finished water appears to have a beneficial effect on copper corrosion. This trend holds for both disinfectants. Finally, chloride in the finished water did not have a significant impact on iron corrosion, regardless of disinfectant.

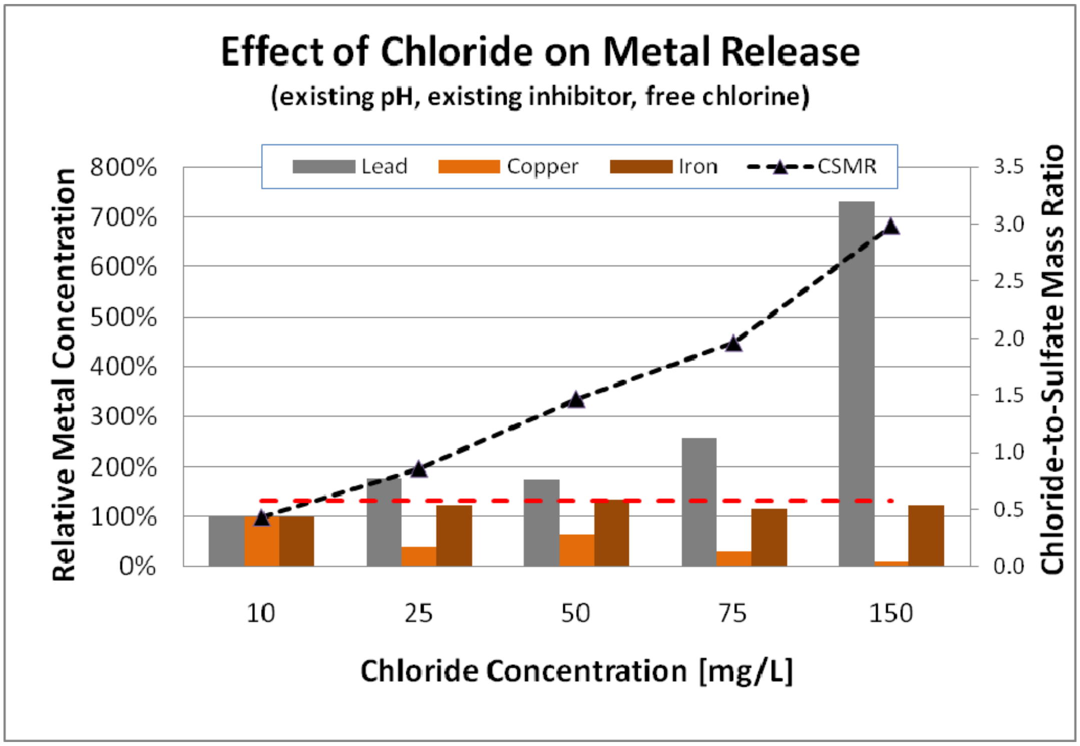


Figure 5-7: Effect of chloride concentration on metal corrosion in water treated with free chlorine. Concentrations are shown in relative units by comparing with the metals concentrations observed under existing water quality conditions. The dotted line indicates CSMR; the red dashed line indicates the CSMR threshold of 0.58, above which lead corrosion generally becomes a concern.

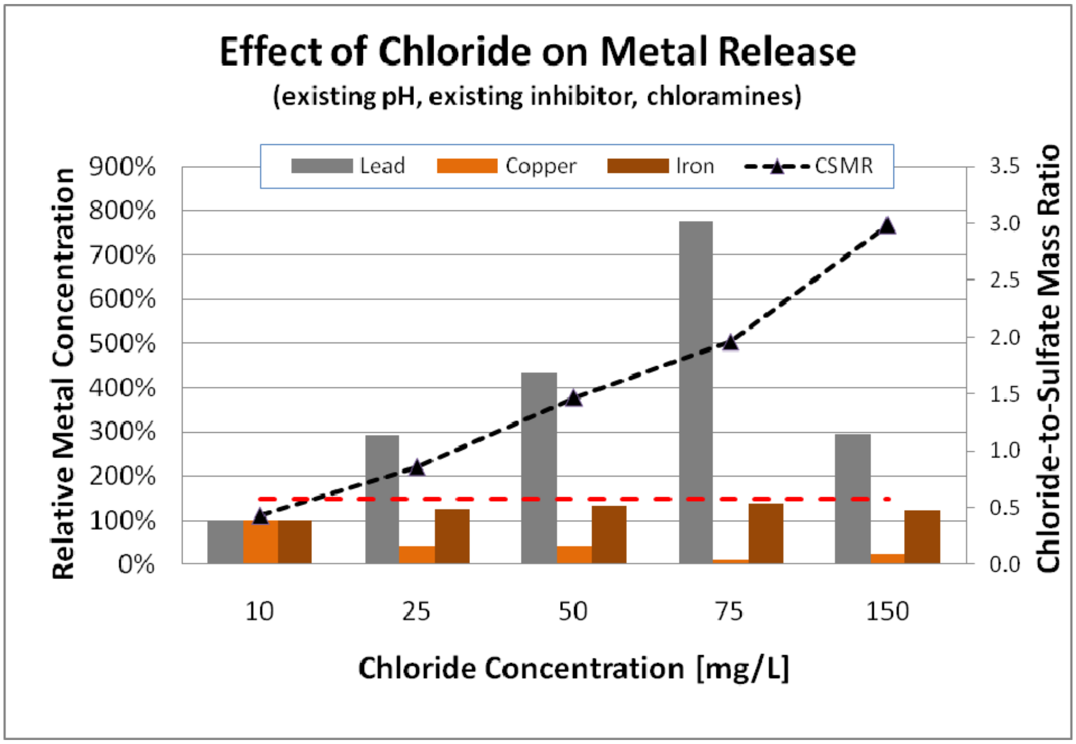


Figure 5-8: Effect of chloride concentration on metal corrosion in water treated with chloramines. Concentrations are shown in relative units by comparing with the metals concentrations observed under existing water quality conditions. The dotted line indicates CSMR; the red dashed line indicates the CSMR threshold of 0.58, above which lead corrosion generally becomes a concern.

Effect of pH

Previous work by Freedman Associates had suggested that increased pH may have a beneficial effect on lead corrosion. The results of this study do not support that conclusion. **Figure 5-9** illustrates the relationship between lead release and pH for each chloride concentration tested with free chlorine. As shown, there is not a clear, consistent trend in lead concentration with respect to pH. At higher chloride concentrations, increasing pH appears to increase lead corrosion, while at existing or low chloride levels changing the pH has essentially no effect. For chloramines, as shown in **Figure 5-10**, increasing pH generally increased lead release, with the effect most pronounced at low chlorides.

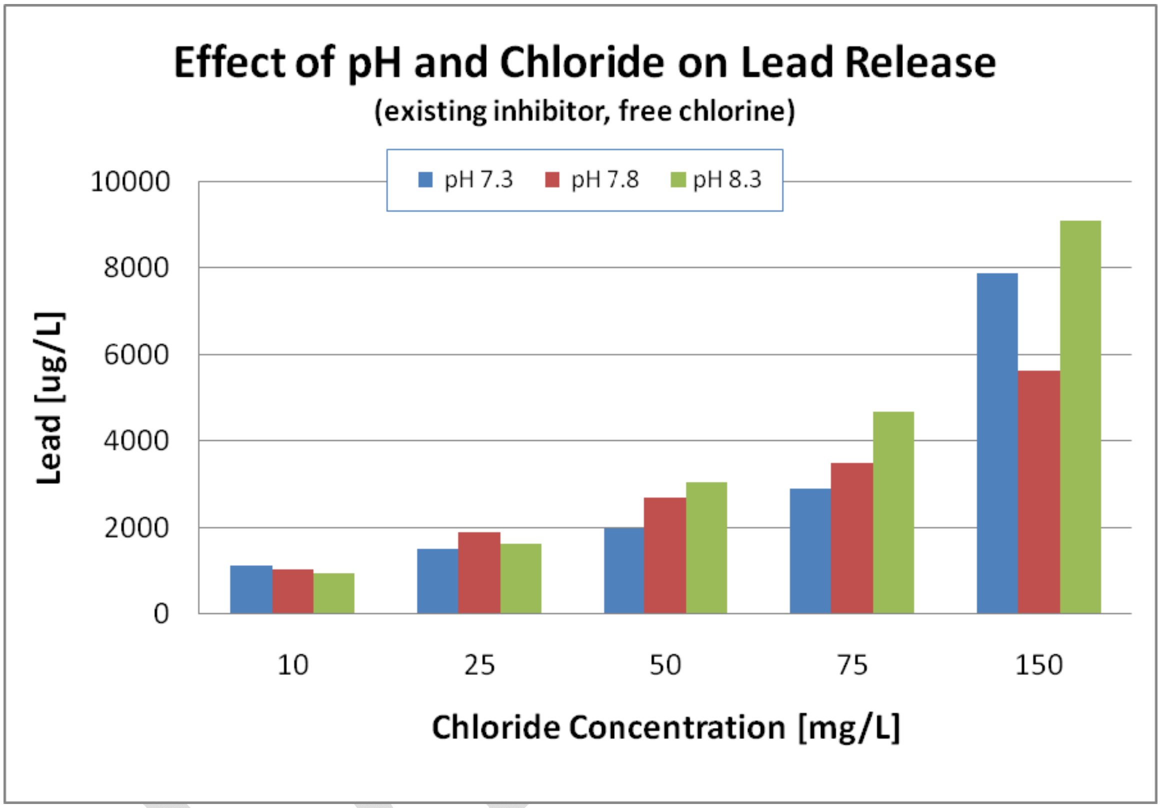


Figure 5-9: Relationship between pH, chloride concentration, and lead corrosion. Data shown represent the average lead concentration for weeks 3 through 6 of the study in the existing inhibitor, free chlorine test condition. Concentrations are normalized to the baseline scenario (existing chloride, pH, and inhibitor).

For both free chlorine and chloramines, increased pH was associated with slight increases in iron concentration, shown in **Figure 5-11** for free chlorine. Complete data are available in Appendix F**.**

The increase in lead and iron concentration at high pH could have been a result of poor buffering capacity near pH 8.3, which is a consequence of the carbonic acid naturally dissolved in all surface waters. A second explanation is pH-inhibitor interactions. Edwards and Reiber (1997) reported that the use of polyphosphate corrosion inhibitor (similar to that used by the City) above pH 7.0 with alkalinity between 30 and 74 mg/L as $CaCO_3$ had an adverse effect on lead corrosion. Although the City's water has a lower alkalinity than the range cited, a similar effect may be responsible for the increased lead at high pH.

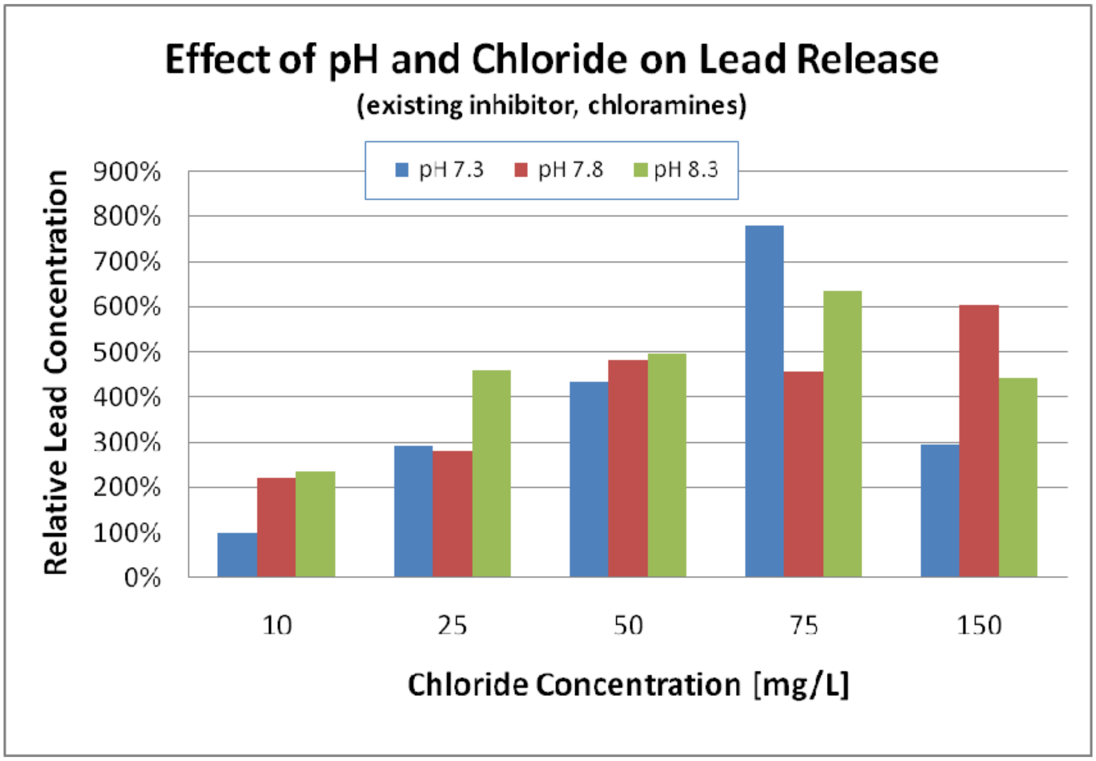


Figure 5-10: Relationship between pH, chloride concentration, and lead corrosion. Data shown represent the average lead concentration for weeks 3 through 6 of the study in the existing inhibitor, chloramines test condition. Concentrations are normalized to the baseline scenario (existing chloride, pH, and inhibitor).

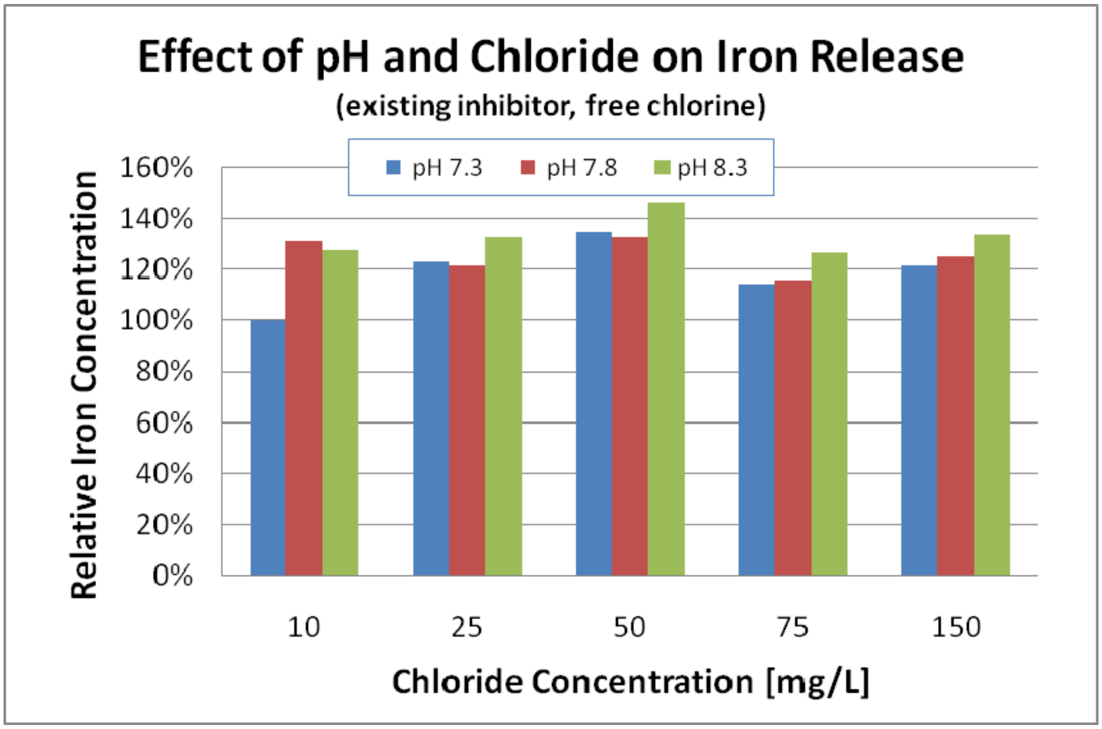


Figure 5-:11: Relationship between pH, chloride concentration, and iron corrosion. Data shown represent the average iron concentration for weeks 3 through 6 of the study in the existing inhibitor, free chlorine test condition. Concentrations are normalized to the baseline scenario (existing chloride, pH, and inhibitor).

Copper corrosion was affected by increased pH. As shown in **Figure 5-12**, raising the pH from 7.3 to 8.3 reduced the copper concentration significantly at low chloride concentrations, and to a lesser extent at higher chlorides. A similar trend was observed in water treated with chloramines (not shown; refer to Appendix F for complete data).

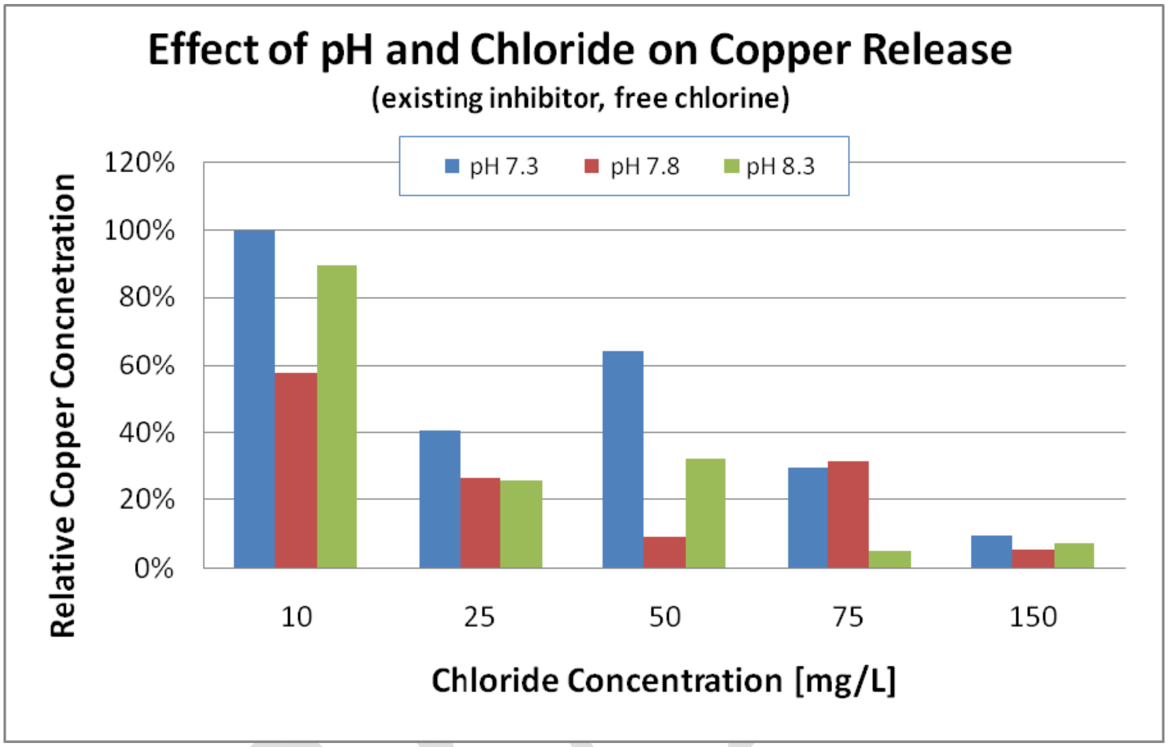


Figure 5-12: Relationship between pH, chloride concentration, and copper corrosion. Data shown represent the average copper concentration for weeks 3 through 6 of the study in the existing inhibitor, free chlorine test condition. Concentrations are normalized to the baseline scenario (existing chloride, pH, and inhibitor).

Effect of Inhibitor

In general, increasing the dose of the current polyphosphate corrosion inhibitor (Aquadene) from 0.75 mg/L to 1.5 mg/l as PO4 was not found to mitigate the impacts of increased chloride on metals corrosion. **Figure 5-13** and **Figure 5-14** illustrate the effect of increased inhibitor on lead concentration in water treated with free chlorine at pH 7.3 and pH 8.3, respectively. As shown, increasing the inhibitor dose appears to increase the amount of lead corrosion at existing pH and lower chlorides. At higher pH or higher chloride, an increased inhibitor dose helps lead corrosion somewhat, but the effect is overwhelmed by the impact of the elevated chlorides. Similar, but less consistent results were observed for chloramines (not shown; refer to Appendix F for complete data).

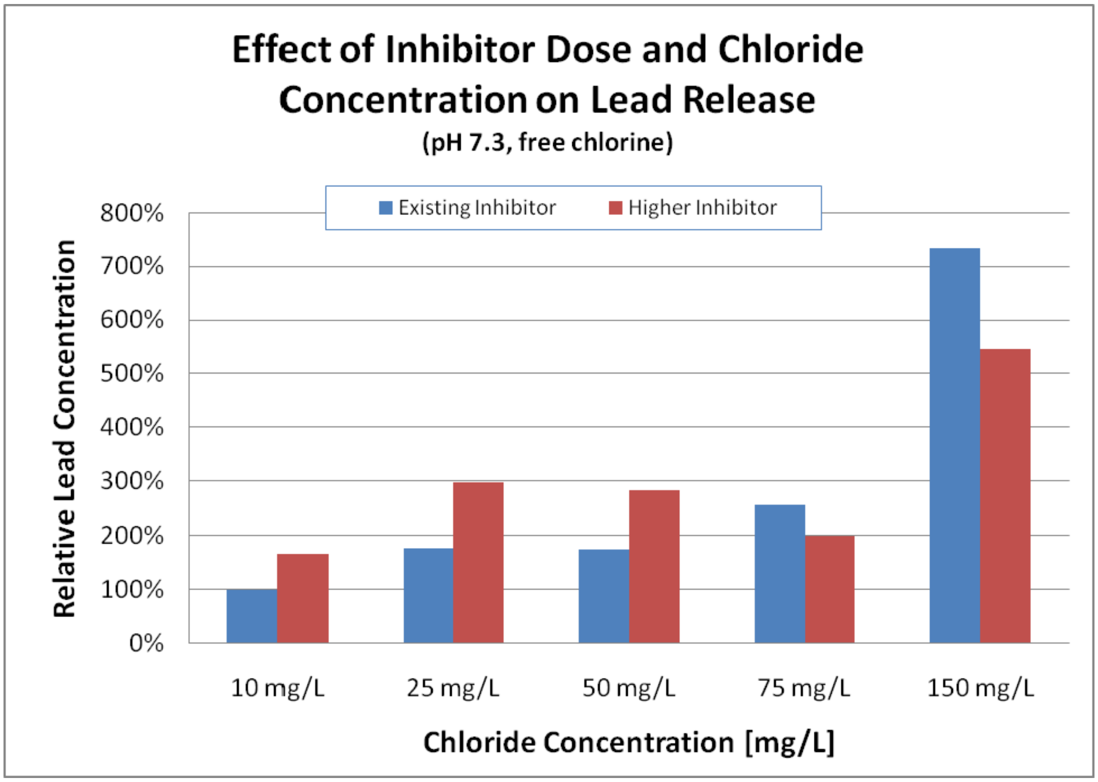


Figure 5- 13: Effect of inhibitor dose and chloride concentration on lead corrosion. Data shown represent the average lead concentration for weeks 3 through 6 of the study in the existing pH, free chlorine test condition. Concentrations are normalized to the baseline scenario (existing chloride, pH, and inhibitor).

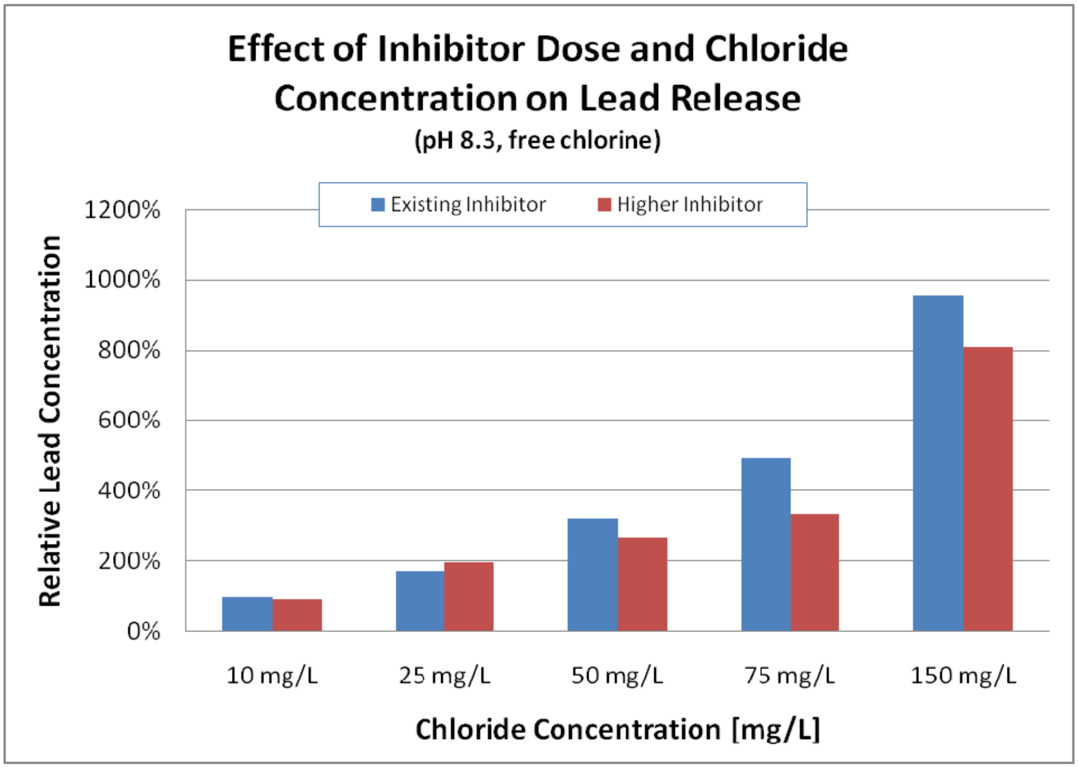


Figure 5-14: Effect of inhibitor dose and chloride concentration on lead corrosion. Data shown represent the average lead concentration for weeks 3 through 6 of the study in the high pH, free chlorine test condition. Concentrations are normalized to the baseline scenario (existing chloride, pH, and inhibitor).

Increasing the inhibitor dosage appeared to show some benefit in controlling copper corrosion at existing pH, for both chloramines, shown in **Figure 5-15,** and free chlorine. This effect did not hold for higher pH, however. Iron corrosion was not significantly impacted by the corrosion inhibitor dosage for any of the test conditions.

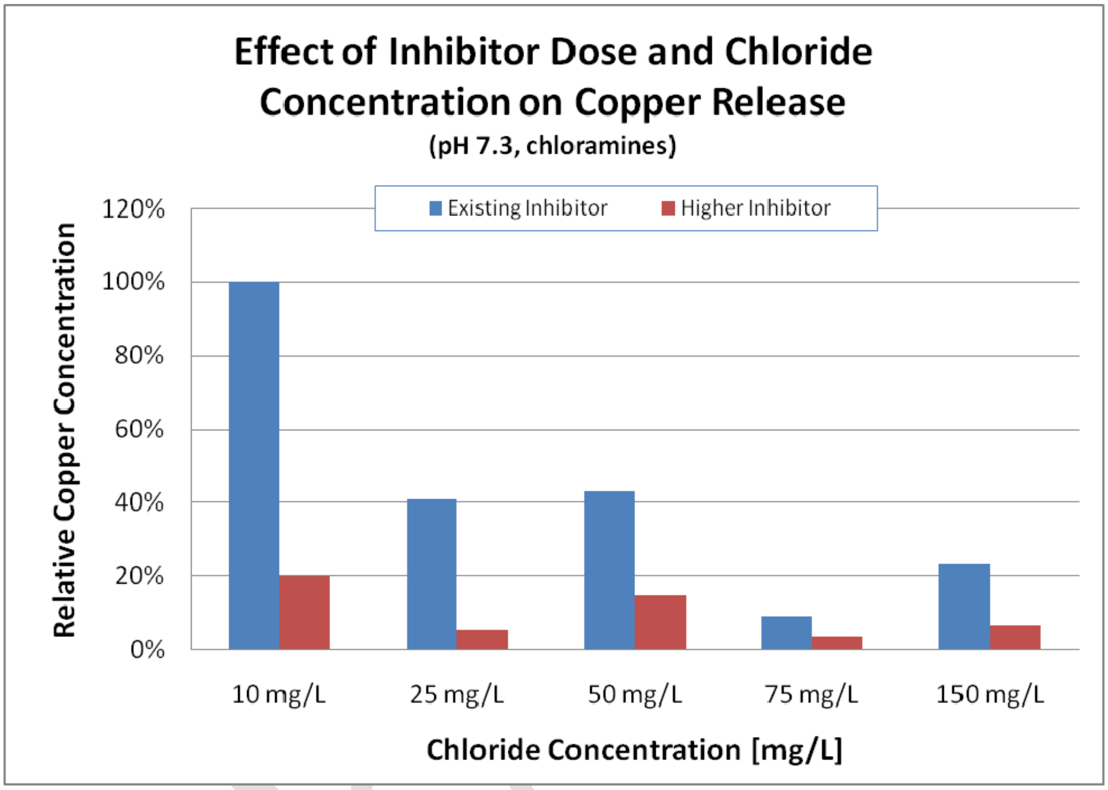


Figure 5-15: Effect of inhibitor dose and chloride concentration on copper corrosion. Data shown represent the average copper concentration for weeks 3 through 6 of the study in the existing pH, chloramines test condition. Concentrations are normalized to the baseline scenario (existing chloride, pH, and inhibitor).

Taken together, data from the various test conditions suggest that there are complex relationships between inhibitor dose, pH, chloride concentrations, and potentially other uncontrolled factors such as alkalinity. While it is possible that inhibitor may effectively control corrosion under certain circumstances, it seems unlikely that this would provide a robust solution in the face of fluctuating source water quality.

5.5.4 Disinfection Byproducts

The results of simulated distribution system testing are summarized in **Table 5-4.** A total of five water matrices were evaluated: existing chloride at pH 7.3, 7.8, and 8.3, and 75 mg/L and 150 mg/l chloride at existing pH. All waters tested were treated with free chlorine. Inhibitor was not added to these waters as it is not relevant to DBP formation.

Table 5-4: Summary of Simulated Distribution System Testing Results[c]

Chloride Concentration (mg/L)	pH	Chlorine Demand (mg/L)	SUVA (L/mg-m)	Total THM (µg/L)	Bromine Incorporation Factor for THMs[b]	HAA5 (µg/L)	HAA9 (µg/L)	Bromine Incorporation Factor for HAA9[b]
10[a]	7.3	0.3	1.39	48	0.12	25	32	0.09
10	7.8	0.6	1.39	55	0.12	26	32	0.09
10[a]	8.3	1.3	1.39	57	0.11	27	33	0.08
68	7.3	1.0	1.63	88	0.50	17	35	0.47
130[a]	7.3	0.9	1.32	115	0.64	19	46	0.64

[a] Values reported are the average of duplicate samples.

[b] The bromine incorporation factor is a value between 0 and 1 representing the fraction of DBP species that contain bromine. It is explained further in Section 3.

[c] Water for simulated distribution system testing was collected during week 2 of the study. As such, the parameters reported here differ slightly from the values shown in Table 5-3, which average all weeks of study.

Several trends are apparent from the table. First, at ambient chloride, increasing the pH caused a slight increase in both THMs and HAAs formed, but no appreciable change in the degree of bromine incorporation as indicated by the bromine incorporation factor (BIF; defined in Section 3). Second, increasing the chloride concentration caused a significant increase in both THM formation and the BIF, accompanied by a slight increase in HAA9 formation. As noted above, the bromide concentration in each seawater blend increased in a nearly direct proportion with the chloride concentration. Higher levels of bromide are expected to increase the rate of DBP formation and also lead to a greater proportion of bromine-containing species. The regulated HAA5 concentration decreased somewhat due to the higher bromine incorporation: four of the most highly brominated HAA species are not currently regulated.

Although the SUVA of the middle (68 mg/L) chloride blend is higher than the existing source water, the SUVA of the high chloride blend is slightly lower. A slight decrease in SUVA with increasing chloride is consistent with observations over all weeks of study, as discussed in Section 5.5.1. SUVA is frequently used as an indicator for DBP formation potential. The fact that DBP concentrations in the high chloride blend more than double relative to the 10 mg/L blend despite its lower SUVA underscores the importance of bromide in promoting DBP formation.

Finally, the data indicate that increased seawater percentage is associated with increased chlorine demand. Again, the middle blend is a bit of an anomaly, with a chlorine demand higher than that of the high chloride blend, but when duplicate values are considered the trend seems clear. This is illustrated in **Figure 5-16.** The average chlorine demand roughly triples between the existing source water and the high chloride blend. This finding is consistent with the fact that increased seawater reduced the removal of TOC (see Section 5.5.2).

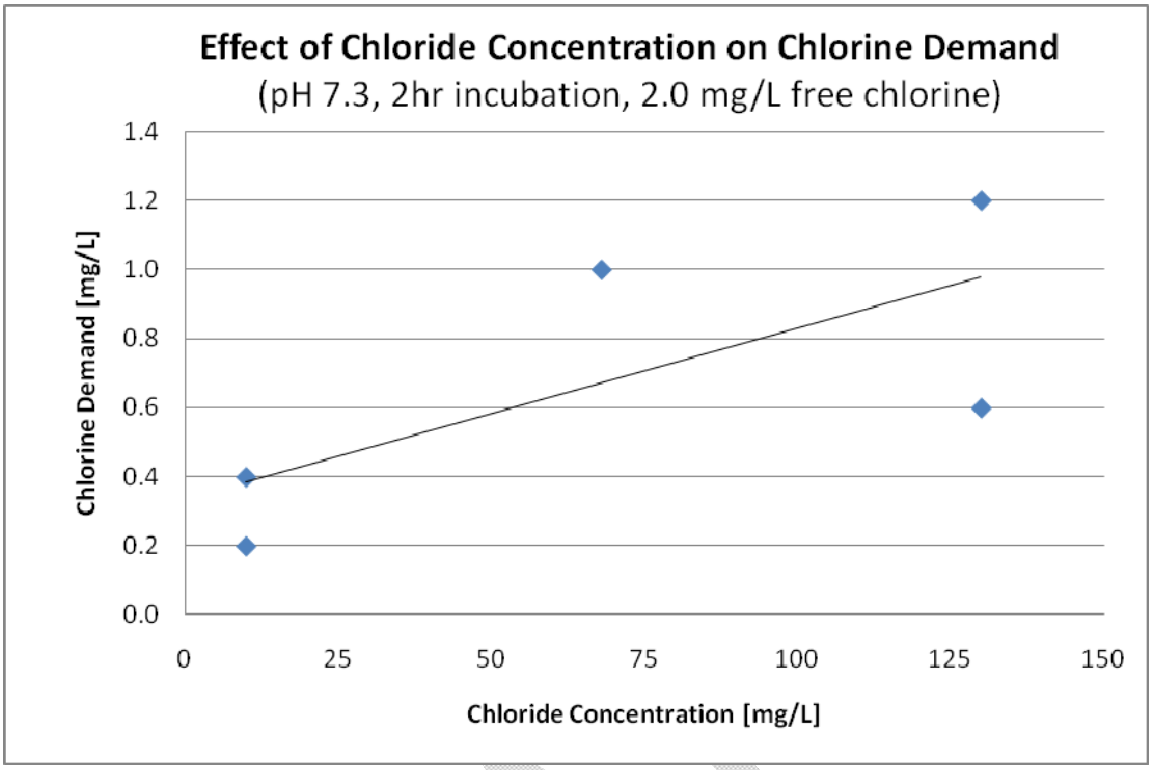


Figure 5-16: Effect of chloride concentration on chlorine demand. Data are shown for all samples (including duplicates) at pH 7.3. Chlorine demand data were collected in the course of determining appropriate doses for use in simulated distribution system testing.

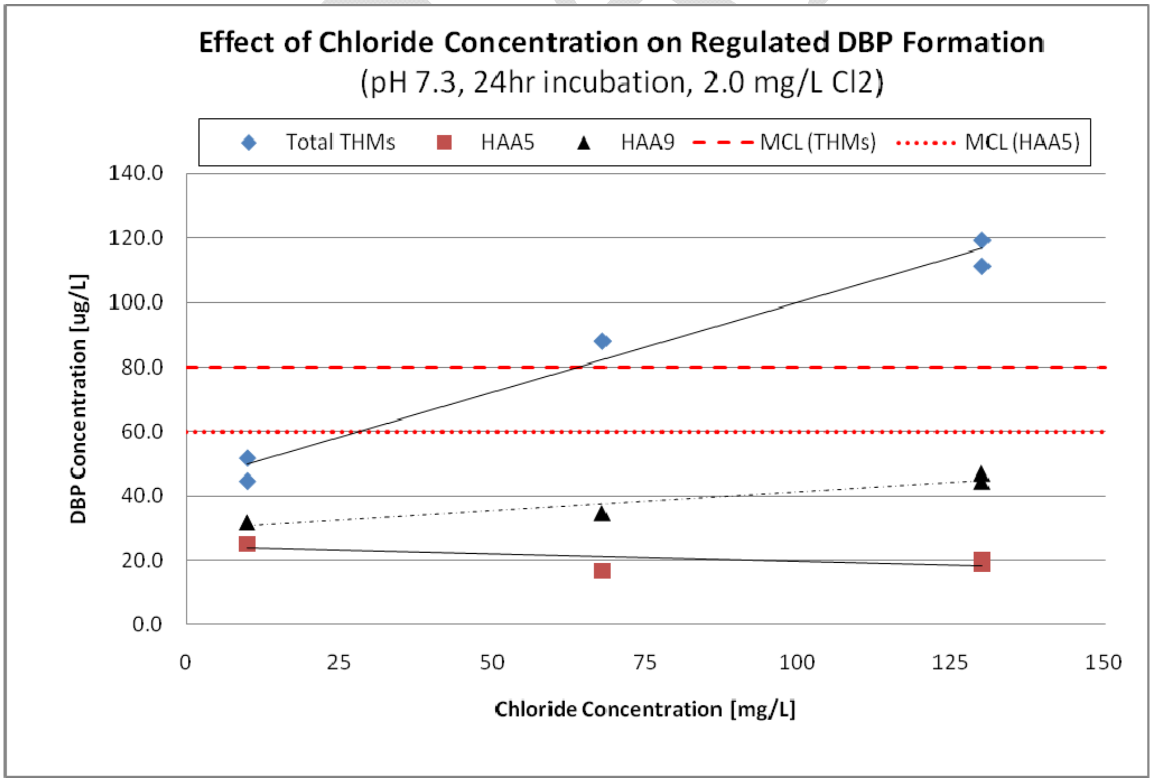


Figure 5-17: Effect of chloride concentration on regulated disinfection by-product formation. Red dashed lines show the respective MCLs for THMs and HAA5. HAA9 is shown in black for comparison to the regulated HAA5.

The impact of increased chloride concentration on regulated DBP formation is illustrated in **Figure 5-17.** As discussed above, increases in THMs were significant, and levels in these experiments exceeded the MCL at a chloride concentration of approximately 65 mg/L. This corresponded to an increase of 45% over the THM levels with existing chloride. The HAA5 concentration decreased as chloride increased, but HAA9 increased somewhat. This difference is consistent with expectations and is discussed further below.

Figure 5-18 and **Figure 5-19** illustrate the individual THM and HAA species concentrations, respectively, that resulted from this experiment. The colored sections of each bar represent individual THM or HAA species. The four THMs are chloroform (CHCl3), bromodichloromethane (CHBrCL2), dibromochloromethane (CHBr2Cl), and bromoform (CHBr3). The five regulated HAAs are chloroacetic acid (CAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), bromoacetic acid (BAA), and dibromoacetic acid (DBAA), and are indicated by colored sections in the figure. The remaining four unregulated HAAs comprising HAA9 are tribromoacetic acid (TBAA), bromodichloroacetic acid (BDCAA), chlorodibromoacetic acid (CDBAA), and bromochloroacetic acid (BCAA); these are represented by the black-and-white sections in the figure. In both figures the individual species are stacked roughly in order of increasing bromine content, with the most bromine-containing species at the top of each bar. The EPA maximum contaminant level (MCL) for total THMs and HAA5 are shown as dashed lines on the respective plots.

The figures illustrate both the increase in overall DBP concentrations and the increase in bromine-containing DBP species described above. Both results are consistent with expectations and can be attributed to the elevated bromide concentration in the seawater blend. Note that another part of the reason for the increases is that the brominated THMs and HAAs have higher molecular weights than their chlorine-containing counterparts.

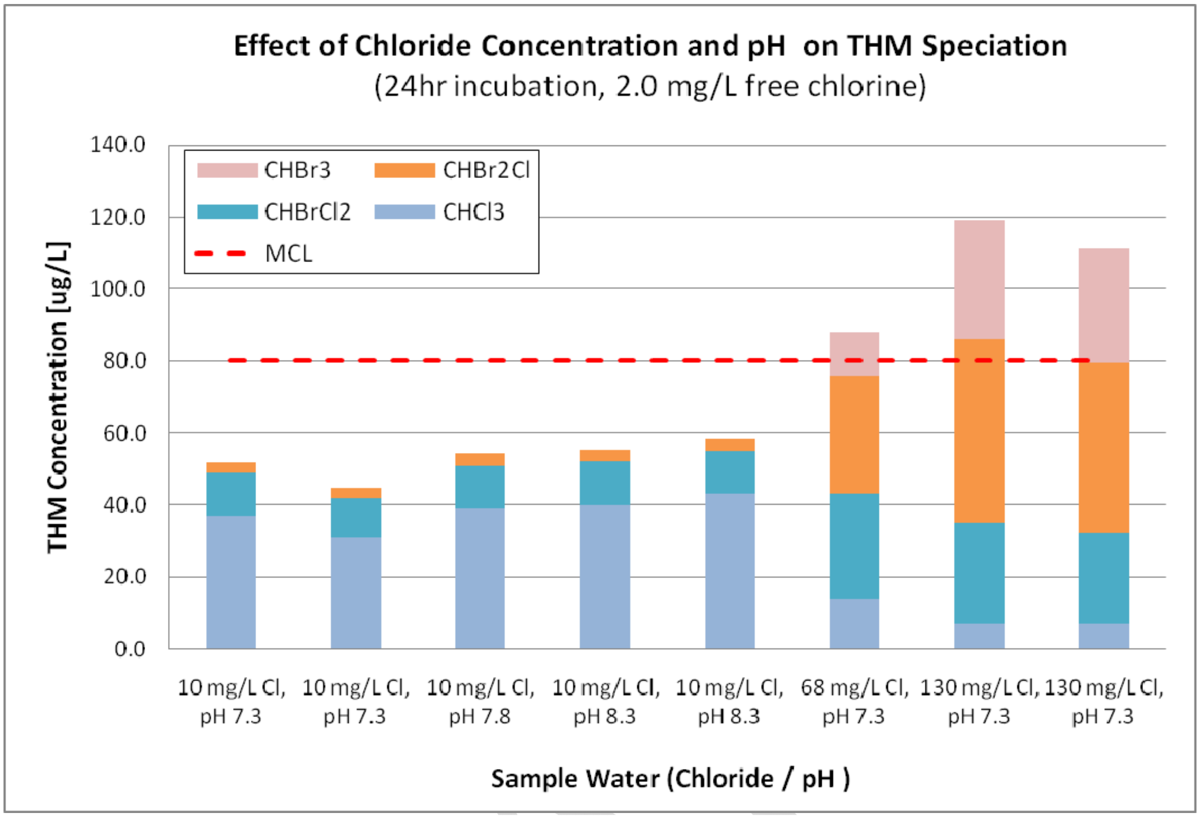


Figure 5-18: Quantity and speciation of THMs formed during simulated distribution system testing. The colored sections of each bar represent individual THM species while the overall height represents the total quantity formed. Duplicate samples are shown individually to illustrate the reproducibility of the results. The MCL for total THMs is shown as a dashed line.

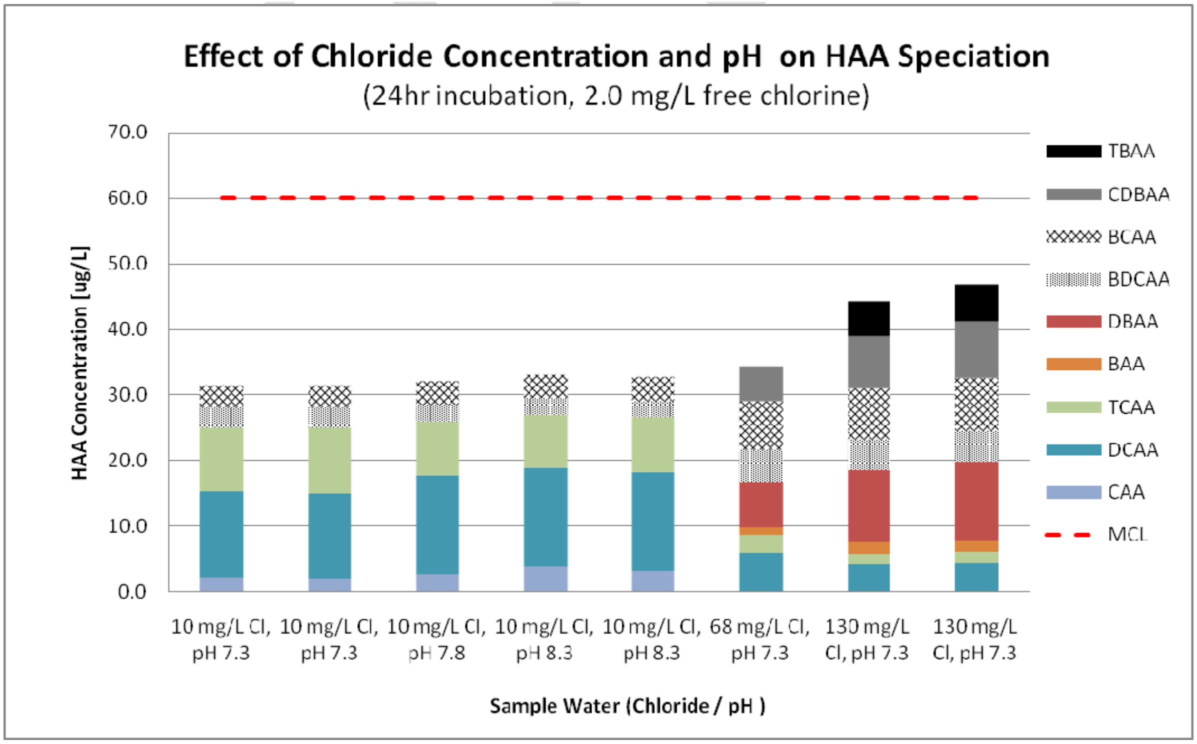


Figure 5-19: Quantity and speciation of HAAs formed during simulated distribution system testing. The colored sections of each bar represent individual HAA species while the overall height represents the total quantity formed. Colored sections represent regulated HAA5 species while black-and-white filled sections are unregulated HAAs. Duplicate samples are shown individually to illustrate the reproducibility of the results. The MCL for HAA5 is shown as a dashed line.

5.5.5 Summary

The results of bench-scale testing of numerous combinations of pH, chloride concentration, inhibitor dose, and disinfectant support the following conclusions:

- Increased seawater percentage is associated with increases in source water bromide, chloride, and sulfate, a significant increase in CSMR, and a slight decrease in SUVA. Any increase in chloride concentration raised the CSMR above the recommended maximum level.
- Increased bromide associated with seawater leads to significant increase in the formation of THMs and slight increases in the formation of HAAs, as well as a shift to more bromine-containing DBP species.
- Higher chloride concentrations have a detrimental effect on the corrosion of lead and a positive effect on the corrosion of copper, and an insignificant effect on iron corrosion. The effect on lead is more pronounced with chloramines except at the highest level of chloride tested.
- Elevated pH (from 7.3 to 7.8 or 8.3) did not reduce lead and iron corrosion relative to existing pH for either disinfectant, but appeared to increase the effectiveness of the corrosion inhibitor somewhat. Elevated pH appears to decrease the corrosion of copper.
- Increasing the dosage of the current inhibitor from 0.75 mg/L to 1.5 mg/L did not adequately mitigate the impact of increased chlorides on lead corrosion. Increasing the inhibitor dose does appear to have benefits under certain very specific water quality conditions, suggesting complex interactions between pH, chloride, inhibitor dose, and other water quality parameters.

Key study results are summarized in **Table 5-5**. The table lists the lead, copper, and iron concentrations for each disinfectant/chloride combination at both the existing (7.3) and highest (8.3) pH. Red shading indicates a negative impact relative to existing conditions while green shading indicates a positive impact. Where available, THM and HAA results are also listed.

As shown, virtually every test condition involving elevated chlorides resulted in higher lead and iron concentrations, but lower copper concentrations. THM concentrations violate the federal standard at a chloride concentration of 71 mg/L

Table 5-5: Summary of Seawater Impact on Corrosion and DBPs

Disinfectant	Chloride (mg/L)[a]	pH	Lead[b] (µg/L)	Copper[b] (µg/L)	Iron[b] (µg/L)	Total THM[c] (µg/L)	HAA9[c] (µg/L)
Free Chlorine	12	7.3	1133	1198	20750	48	32
		8.3	950	1073	26500	57	33
	25	7.3	2000	487	25500	n/a	n/a
		8.3	1623	312	27500	n/a	n/a
	48	7.3	1970	770	28000	n/a	n/a
		8.3	3050	388	30250	n/a	n/a
	71	7.3	2900	356	23750	88	35
		8.3	4675	61	26250	n/a	n/a
	138	7.3	8300	115	25250	115	46
		8.3	9075	85	27750	n/a	n/a
Chloramines	12	7.3	628	1900	18250	n/a	n/a
		7.3	1475	540	20750	n/a	n/a
	25	8.3	1833	777	22750	n/a	n/a
		7.3	2875	140	24000	n/a	n/a
	48	8.3	2723	821	24250	n/a	n/a
		7.3	3100	139	27000	n/a	n/a
	71	8.3	4875	175	25000	n/a	n/a
		7.3	3975	60	26250	n/a	n/a
	138	8.3	1850	446	22250	n/a	n/a
		7.3	2770	44	26500	n/a	n/a

[a] Values listed are the average measured chloride in the test waters over the duration of the study and equate to nominal chloride concentrations of 12, 25, 50, 75, and 150 mg/L, respectively.

[b] Concentrations shown represent the average values from weeks 3 through 6 of the study.

[c] All DBP testing employed free chlorine. The results are equally applicable to both the industrial and residential systems because the residential (chloramine) system is preceded by a clearwell with a long free-chlorine contact time.

Section 6
Evaluation of Alternatives

6.1 Water Quality Impacts of Increased Seawater Percentage

The potential increase in chloride concentrations resulting from harbor deepening is likely to have numerous impacts on treated drinking water quality based on the bench-scale testing conducted for this project. As discussed in the previous section, higher percentages of seawater are associated with:

- Increased TOC
- Increased DBP formation
- A greater fraction of bromine-containing DBP species
- Increased chlorine demand
- Acceleration of lead corrosion

These impacts demonstrate that elevated chloride levels will have a detrimental effect on drinking water quality from a human health standpoint. The increase in lead concentration is of particular concern because it was found to be greater in water treated with chloramines than with free chlorine. Water in the chloramine distribution system serves primarily residential customers, so will be directly consumed year-round. Water from the free chlorine system is also consumed by Savannah's 55,000 residents during the summer months, when it is used to supplement groundwater supplies.

Due to complexities such as premise plumbing issues, age and condition of distribution pipelines, and the schedule for sampling, it is not feasible to calculate a probability of noncompliance with any specific regulation due to elevated chlorides. Nevertheless, it is clear that increased seawater percentage will affect the operation of the I&D WTP, the quality of the finished water, and the City's ability to comply with drinking water regulations. Furthermore, International Paper and Weyerhaeuser, two of the City's largest industrial exporters, have expressed concern that treated water chloride concentrations in the range of 25-50 mg/L may cause problems with their processes.

This section presents alternative strategies for coping with the increased seawater percentage while protecting public health.

6.1.1 Impacts on Regulatory Compliance

Lead and Copper Rule

As presented in Section 4.3.1, the 90th percentile lead and copper concentrations were below the action levels of 15 µg/L and 1,300 µg/L, respectively, for all Lead and Copper Rule sampling conducted between 2001 and 2008. However, over the same period 11 different sites exceeded the action level at some point, but only two exceeded it on more than one occasion. The results presented in the previous section indicate that lead corrosion is likely to increase considerably as chloride concentration increases, while copper levels may stay similar or decrease slightly.

Based on the fact that some sites exceed the lead action level under existing conditions and that compliance with the LCR is based not on an average but a 90th percentile concentration, it is likely that increased chlorides will cause difficulties in complying with the LCR. The City is required to sample lead at 30 sites, so a violation is triggered if more than 3 sites exceed the action level. Increased chlorides could easily raise the lead concentration at one or two sites enough to cause a violation. For example, in 2002, three sites exceeded the lead action level. The fourth highest concentration reported was 7.1 µg/L. If lead corrosivity had been increased by two- or three-fold due to high chlorides, which appears feasible based on bench-scale testing, the lead level at this single site may have exceeded 15 µg/L, raising the 90th percentile lead concentration above the action level and causing a violation of the LCR.

Two or three sites have exceeded the lead action level during three of the last five LCR sampling periods. As such, there is very little margin for lead levels to increase without risking violations of the LCR.

Disinfection Byproducts Rule

As discussed in Section 4, the City will become subject to location-based monitoring for THMs and HAAs under the Stage 2 D/DBPR in 2014. The running annual average (RAA) for THMs at the current Stage 1 D/DBPR monitoring sites is 55 µg /L, and maximum locational running average (LRAA) is 64 µg /L. Both values are below the MCL of 80 µg/L.

Increased seawater may create challenges for compliance with the Stage 1 and Stage 2 D/DBPR. Based on current THM levels, MCL violations would occur if the RAA increased by 45% or (after 2014) if the maximum LRAA increased by 25%. The testing results presented in Section 5 indicate that such increases would occur if the chloride concentration entering the plant reached 65 mg/L or 40 mg/L, respectively.

6.1.2 Impacts on Operations

Coagulant Demand

The jar testing conducted at the beginning of this study indicates that increased chloride concentration will have minimal impact on the coagulant dose required for turbidity removal.

Chlorine Demand

As noted in Section 5, increased seawater appears to increase the chlorine demand. If chlorides entering the plant reach the 50-75 mg/L range, the chlorine demand may be expected to increase by 50-75%.

Pipeline Maintenance

Although increased chlorides did not appear to have a significant impact on iron corrosion in this study, it is possible that over longer periods of time corrosion may be accelerated somewhat. Extra attention should be paid to monitoring steel or ductile iron distribution pipes for leaks. Increased chloride levels are known to increase concrete or cement lined piped corrosion. In addition, as noted in Section 2, increased sulfate coupled with low alkalinity can promote pitting corrosion of copper pipes without causing significant levels of dissolved copper. Thus, although the results of bench-scale testing do not suggest that dissolved copper will be a problem, customers may experience an increased incidence of pinhole leaks.

6.2 Alternatives for Mitigating Impacts

The sections that follow present a variety of options for mitigating the impacts of increased chloride (seawater) concentration. These options can be classified into two major approaches: 1) adapting water treatment practices to increased seawater and 2) avoiding the increased seawater altogether. Within the first approach, involving changes to the treatment process, some options are best suited to controlling corrosion while other options are appropriate for reducing the formation of DBPs. Thus a combination of options will likely be necessary if the treatment process is to be adapted to the higher salinity source.

6.2.1 Alternatives to Control Corrosion Only

Several chemical treatment strategies are available to control the amount of metals corrosion in the distribution system. These are summarized in **Table 6-1** and discussed below. It should be noted that none of the combinations of disinfectant, inhibitor, and pH adjustment that were evaluated during the bench scale testing achieved a consistently comparable level of lead corrosion to the base case (existing inhibitor and pH) in the face of elevated chloride concentrations. The data indicate that the relationships between chloride, inhibitor dose, pH, and disinfectant are complex, and therefore that corrosion levels will be sensitive to changes in any of these aspects of water chemistry.

Table 6-1: Possible alternatives to control corrosion only

Alternative	Description
Increase pH	Increase the finished water pH to make the water less aggressive to metallic fixtures. This option is not likely to be adequate by itself.
Increase dose of corrosion inhibitor	Increase the dose of the existing corrosion inhibitor. This option would not likely be adequate by itself.
Optimize use of corrosion inhibitor	Change type and/or modify corrosion inhibitor dose. This option would involve further study with multiple types of inhibitor at a range of doses.
Advanced Treatment to reduce chloride levels	Investigate advanced treatment processes to remove seawater ions, such as reverse osmosis

pH Adjustment

Early studies by others indicated that pH adjustment may provide a means to reduce lead or iron corrosion. However, as discussed in Section 5, the results of this study do not indicate that pH adjustment is a viable strategy for controlling metals leaching at the current inhibitor type and dose. Increasing pH is also undesirable because it can be expected to increase the formation of DBPs slightly.

Increase dose of Existing Corrosion Inhibitor

Results of this study suggest that increasing the dose of the existing corrosion inhibitor is unlikely to be effective in controlling lead or copper corrosion in the face of increased chloride concentration.

Optimize Corrosion Inhibitor

As discussed in Section 2, studies have shown orthophosophate to be effective for controlling lead and copper corrosion. The current inhibitor, Aquadene, contains some orthophosphate but mostly polyphosphate, which is generally better suited to controlling iron. Experimentation with different ortho:polyphosphate ratios and different inhibitor doses may identify a combination that is more effective at combating the effect of increased seawater. However, the seawater effect on lead corrosion was dramatic. Moreover, the City previously had a negative experience when trying to change corrosion inhibitors. As such, all parties agreed that further optimization of the corrosion inhibitor is highly unlikely to offset the effects of seawater on lead corrosion.

Advanced Treatment

Advanced treatment encompasses a range of technologies that enhance the conventional treatment process. Those most appropriate for controlling the effects corrosion in this case is membrane treatment.

Nanofiltration or reverse osmosis membranes could be used in place of or in addition to the existing conventional filters. These membranes achieve very high removal of NOM, other DBP precursors, and many dissolved ions such as bromide and chloride. However, the addition of membranes to the I&D WTP treatment process would be capital- and energy-intensive. Membrane treatment was previously estimated by others to cost in excess of $60 million.

6.2.2 Alternatives to Control Disinfection Byproducts Only

Numerous options exist for reducing the occurrence of disinfection byproducts, as discussed in Section 3. These range from optimization of existing chemical treatment to major modifications of the treatment process train. Some of the most common alternatives are listed in **Table 6-2.** Many utilities employ a combination of these measures to ensure that DBPs can be effectively controlled through seasonal and sudden changes in water quality. Note that the alternatives below are unlikely to have a significant impact on corrosion relative to the effect of seawater, but their corrosion impacts can be tested to be more certain.

Table 6-2: Possible alternatives to mitigate increased disinfection byproduct formation only

Alternative	Description
Enhanced Coagulation	Practice enhanced coagulation, including possibly changing coagulant to ferric sulfate, to improve natural organic matter (NOM) removal. This option is not likely to be adequate by itself.
Optimize Chemical Treatment	Investigate modifications to coagulant dose, chlorine dose, contact time, and pH that may achieve superior NOM removal and reduced DBP formation while still meeting disinfection goals. This option is not likely to be adequate by itself.
Powdered Activated Carbon (PAC)	Apply PAC during periods of high seawater percentage to improve the removal of NOM and other precursors. This option is not likely to be adequate by itself.
Advanced Treatment	Investigate advanced treatment processes to improve NOM removal or remove seawater ions, such as magnetic ion exchange, granular activated carbon adsorption, or biofiltration.

Enhanced Coagulation

As noted in Section 3, the removal of precursor material, especially NOM, is of utmost importance in controlling the formation of DBPs. As such, optimizing the coagulation process to maximize TOC removal can be very effective. For the I&D WTP, this may mean using a somewhat higher alum dose or switching to ferric sulfate, since the plant already practices enhanced coagulation.

Optimization of the coagulant dose and pH would simply require additional jar testing to document TOC removal. A switch to ferric may require minor modifications to the existing chemical feed equipment. Note that, as discussed in Section 5, increased seawater percentage appears to slightly decrease TOC removal. Although the effect is small, additional jar testing may be warranted to ensure good removal whether or not enhanced coagulation is pursued in earnest.

Optimize Disinfection

The I&D WTP employs a combination of free chlorine and chloramines for disinfection purposes. In the system that receives chloramines, the free chlorine is the primary disinfectant, providing the majority of the exposure, or "CT" (concentration x time) that is required to inactivate harmful pathogens. The chloramines, added downstream of the clearwell, stabilize the disinfectant residual for distribution and slow the formation of DBPs once finished water leaves the plant.

As plant operations staff have noted, the majority of DBPs are formed inside the plant clearwell before ammonia is added. Optimization of the disinfection regime at the I&D WTP would involve a study of the CT exposure achieved at the plant to see whether the free chlorine contact time could be minimized by relocating the feed point, adding additional baffling to the clearwell, or other means. It is also possible that an alternative disinfectant, such as ozone or chlorine dioxide, could be used in place of free chlorine to provide the majority of the CT exposure. A second step warranting consideration is the use of an alternative disinfectant prior to the filters. This practice would avoid exposing the unfiltered water containing higher levels of NOM to free chlorine.

Optimization of the disinfection scheme can be effective in reducing DBP concentrations if the free chlorine contact time can be significantly reduced without compromising CT. Some utilities alter their chlorine and ammonia feed locations seasonally to account for warm weather, since elevated temperatures cause both disinfection and DBP formation to take place more quickly. Further study would be required to determine the extent to which the contact time could be reduced. However, it is unlikely that this option would reduce DBP formation to the degree needed to ensure compliance with regulations in the face of higher seawater percentage, given the acceleration of DBP formation caused by bromide.

Powdered Activated Carbon

A powdered activated carbon (PAC) system would provide a means to enhance NOM removal as-needed during periods of poor water quality. The PAC is generally applied to the raw water as a slurry and removed via the conventional treatment process. PAC also has the benefit of limiting algae formation when fed prior to a raw water impoundment.

Adding a PAC system to the I&D WTP would involve construction of one or more storage silos for the carbon in addition to feed equipment.

Advanced Treatment

As noted in the previous section, advanced treatment technologies provide enhanced removal of NOM and other DBP precursors. Membranes offer a viable alternative for reducing the formation of DBPs in addition to mitigating the impacts of increased seawater. Magnetic Ion Exchange (MIEX), granular activated carbon (GAC) and biofiltration are three additional technologies that can reduce the formation of DBPs, but are not likely to impact the chloride concentration.

Magnetic Ion Exchange

Magnetic Ion Exchange (MIEX) resin is applied to the raw water as a slurry in a package plant located near the rapid mix area. After mixing, the resin enters a dedicated high-rate settling tank, where it is removed quickly from the process stream and regenerated on-site. The MIEX process has a relatively small footprint and would involve minimal modification to the remainder of the existing treatment process.

The use of MIEX in this way would likely reduce the required coagulant dosage, as the resin achieves substantial removal of NOM, and thus reduces a major source of DBP precursors. An added benefit of ion exchange for the I&D WTP is that the resin removes bromide and other anions to some extent. MIEX is available in a form that uses bicarbonate as the exchangeable ion, which would increase alkalinity and potentially stabilize the pH of the raw water during coagulation. The use of the bicarbonate form of the resin may allow removal of limited amounts of chloride from the water. Use of the more traditional chloride form of the resin, however, would further elevate chloride concentrations and potentially exacerbate related corrosion impacts.

Granular Activated Carbon

Granular activated carbon offers benefits similar to PAC, but provides superior removal of NOM and other DBP precursors and is better suited for continuous (as opposed to as-needed) treatment. GAC could be added to the existing treatment process either by replacing the media in one or more of the filters with GAC, or by adding dedicated GAC contactors after the filters. In either case, the GAC would have to be replaced after its adsorption capacity were exhausted.

Biofiltration

Biologically active filtration exploits the activity of microbial organisms that are allowed to grow in conventional filter media to achieve enhanced removal of NOM and other DBP precursors. No new infrastructure is required to implement biofiltration; generally a conventional filter will become biologically active on its own as long as no disinfectant is added upstream.

Effective implementation of biofiltration involves adjustments on the part of operations staff, as procedures for backwashing, cleaning, filter run times, and effluent turbidity may all be affected.

6.2.3 Alternatives to Avoid Increased Seawater

The most straightforward way to mitigate the impacts of increased seawater percentage is to avoid it altogether. These solutions require physical changes to the raw water infrastructure to allow water of similar quality to continue to be withdrawn for treatment after the dredging of the harbor is complete.

This can be accomplished either by pumping water from a location further upstream where tidal influence is minimized, by diluting brackish water at high tide with fresher water before sending to the plant, or by preventing the mixing of fresh river water and seawater near the intake. Options for achieving each approach are listed in **Table 6-3.**

Table 6-3: Possible alternatives to avoid increased seawater percentage

Alternative	Description
Supplement raw water intake	Construct a supplemental raw water intake further upstream in order to reduce the percentage of seawater at the plant.
Add raw water storage for extreme events	Construct an impoundment or storage tank to hold a 1-week supply of raw water to be used during extreme high-chloride conditions. This alternative would allow I&D to avoid pumping raw water from the river during periods of low river flow, when chlorides may be highest.
Add raw water storage to avoid high tide	Construct an impoundment or storage tanks to store a 1 to 2-day supply of raw water to be treated during high tide. This alternative would minimize pumping of raw water from the river during high-chloride periods.
Low-head dam or sill	Construct a low-head dam or sill downstream of the raw water intake to prevent the mixing of river water with seawater

Supplemental Raw Water Intake

Construction of a raw water intake location further upstream would reduce the degree of tidal mixing between Savannah River water and seawater, leading to fresher overall water quality. This option has already been studied by the U.S. Army Corps of Engineers. Previous investigations proposed a supplemental intake structure approximately 10 miles upstream of the existing intake at Abercorn Creek. This plan would require approximately 8.7 miles of pipeline through Chatham and Effingham counties. A conceptual map of the proposed pipeline route is shown in **Figure 6-1.** **Figure 6-2** shows a conceptual schematic of the new intake.

Operationally speaking, the new intake could either be used as a complete replacement for the existing intake, or as a supplemental source to be used only during periods of very high chloride concentration. The cost of this option was estimated by others to be $35.9 million.

Figure 6-1: Proposed route of pipeline to supplemental water intake. Reproduced from "Engineering Investigations: Savannah Harbor Expansion Project" USACE, November 2010.

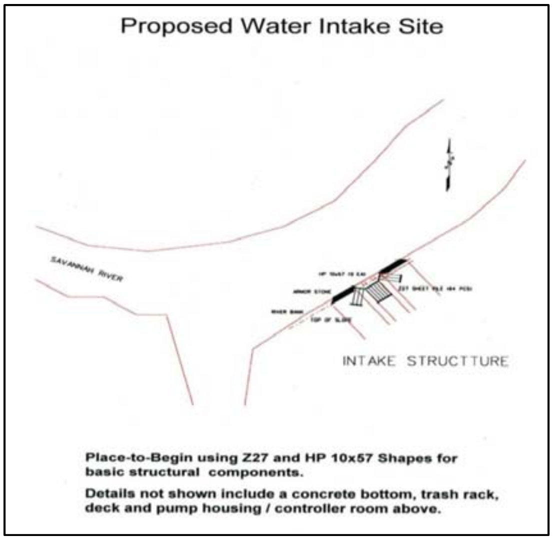


Figure 6-2: Conceptual schematic of supplemental water intake. Reproduced from "Cost Estimate for Supplemental Water Supply to City of Savannah Intake at Abercorn Creek" USACE, April 2011

Raw Water Storage

A raw water impoundment provides a means of storing source water in a protected area for later treatment. For a tidally-influenced source such as the Savannah River, an impoundment could serve two functions. The first would be to average out tidal variations in water quality. The second would be to provide storage so that raw water pumping could be avoided altogether during periods of extremely high salinity. An example of a raw water impoundment is shown in **Figure 6-3.**

Location

In discussions with the City, it has been determined that the most appropriate location for raw water storage would be a tract of land that is as close as possible to the I&D WTP and the existing raw water pipelines.

Figure 6-3. Example raw water impoundment.

Process Configuration

The proposed impoundment would operate in series with the raw water pumps. In other words, all flow going to the I&D WTP would pass through the impoundment, as shown in **Figure 6-4**, though it would have a valved bypass ability.

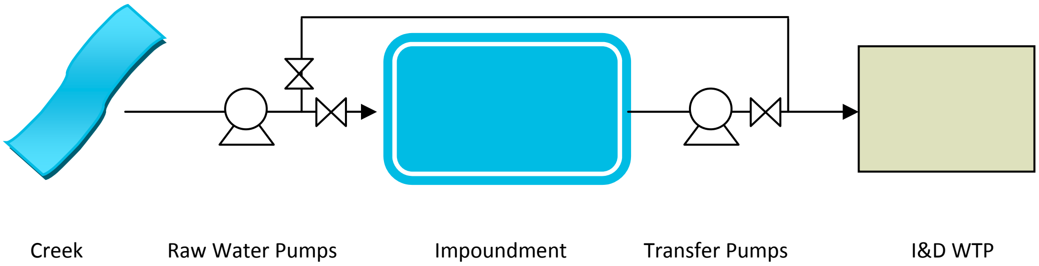


Figure 6-4: Schematic arrangement of raw water impoundment

The raw water pumps would normally run unless the chloride concentration in the Savannah River were above some pre-determined threshold, or the reservoir were full. If the chloride concentration exceeded the threshold, but the reservoir were empty (excluding the bottom 20% or so which is needed for sediment storage and minimum capacity), the raw water pumps could be run at a reduced rate to supply only enough water for plant production. This operating logic is summarized in **Figure 6-5** using the firm raw water pumping capacity of 75 mgd and the maximum plant production of 62.5 mgd. Firm pumping capacity is the capacity with the facility's largest pump out of service. The use of firm capacity for design purposes is standard engineering practice, and is required by the Georgia Environmental Protection Division's *Minimum Standards for Public Water Systems,* Section 9.4.1 (2000). The use of plant design capacity for sizing this mitigation option is required by the Water Quality Certification letter for the SHEP project, issued to USACE by the State of Georgia, and is consistent with standard engineering practice.

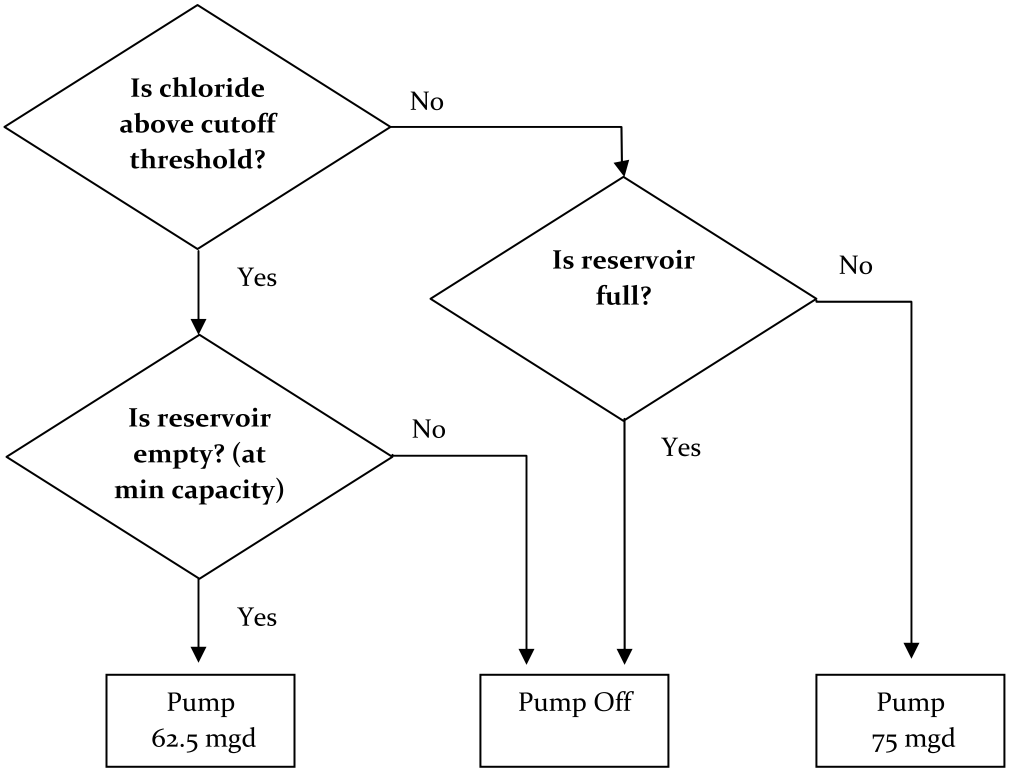


Figure 6-5: Pump Operating Rules

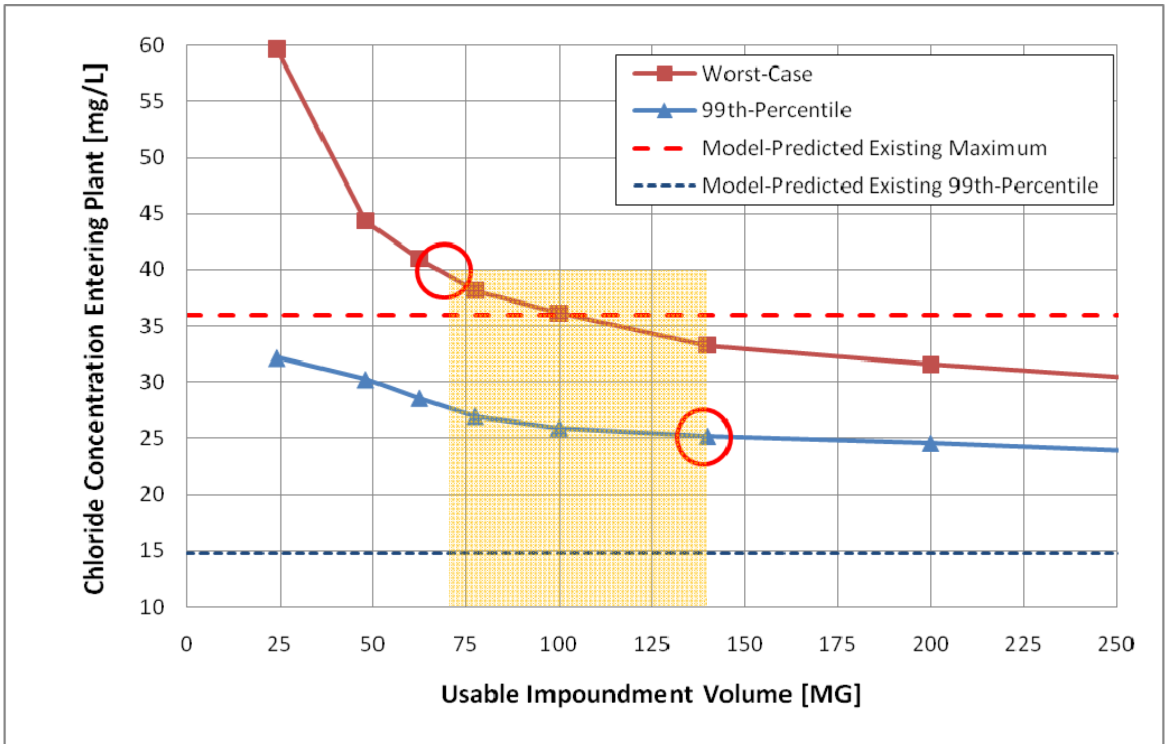
Sizing Considerations

The extent to which the impoundment could prevent the need for pumping during extreme chloride events depends greatly on the difference between the raw water pumping capacity and plant production. Consider that if the two were equal, the reservoir could still average out fluctuations in concentration, but could never be used without the raw water pumps operating. In contrast, if there is a large excess of raw water pumping capacity relative to demand by the plant, then the raw water pumps can be shut down for a period of time each day while the accumulated water in the impoundment feeds the plant.

A series of statistical analyses were used to determine the appropriate size for a raw water impoundment for the I&D WTP given the existing constraints of 62.5 mgd plant capacity and 75 mgd firm raw water pumping capacity. Based on the bench-scale testing results, it is clear that chloride concentrations as low as 25 mg/L have an adverse impact on lead corrosion, so initially the goal was to find the impoundment size that would limit the maximum chloride entering the plant to 25 mg/L. Due to the capacity constraints described above, a 480 million gallon (MG) usable volume would be required. An impoundment of this volume was deemed infeasible both due to cost and size.

An alternate performance goal was established to limit the chloride entering the plant to 40 mg/L in the worst-case and 25 mg/L 99 percent of the time. These values were chosen for several reasons. First, as discussed in Section 6.1.1, 40 mg/L is the chloride concentration at which the LRAA for THMs in the distribution system can be expected to reach the MCL, potentially triggering a regulatory violation. Second, keeping chloride below 25 mg/L was our target for lead corrosion control as noted above. Third, under existing conditions the maximum hourly chloride concentration predicted by the model in Abercorn Creek is approximately 36 mg/L (see section 4.4.2) and the maximum grab sample is 28 mg/L. Therefore, an impoundment that limits the chlorides entering the plant to 40 mg/L or less should protect against excessive THM formation and provide nearly comparable water quality during worst-case events to current conditions. It should be noted that the 99th-percentile chloride concentration entering the plant would still increase by 50-100% over the range of impoundment sizes that were considered, but these concentrations would not be appreciably higher than the historic maxima predicted by the model.

Figure 6-6 illustrates the usable impoundment volume that is required to limit the maximum and 99th-percentile chloride concentration entering the plant to various values ranging from 20 to 60 mg/L. The red curve shows the worst-case or maximum concentration while the blue curve shows the 99th percentile value. The dashed red and blue lines indicate the model-predicted maximum and 99th percentile chloride under existing conditions, respectively. Red circles indicate the smallest usable impoundment volumes that satisfy the two performance criteria established above.



Raw water pumping capacity: 75 mgd Water Plant Production: 62.5 mgd
Based on 2001-2009 river flows and 5ft deepening / mitigation 6A model results
Assumes 20% Unused Volume in Reservoir

Figure 6-6: Relationship between usable impoundment volume and the chloride concentration entering the I&D WTP. The dashed red and blue lines indicate the model-predicted maximum and 99th-percentile hourly chloride concentration under existing conditions, respectively. Each data point represents the concentration achieved when the impoundment is operated at the optimal pumping cutoff concentration, which varies by size. The pumping cutoff concentration is discussed further in Section 8. Red circles indicate the minimum impoundment volumes needed to limit the maximum concentration to 40 mg/L and the 99th-percentile concentration to 25 mg/L, respectively. The shaded region represents the range of volumes recommended for consideration.

As shown in the figure, the maximum chloride concentration entering the plant can be limited to 40 mg/L with a usable impoundment volume of approximately 72 MG. To satisfy the 2nd criterion of 25 mg/L for the 99th-percentile value, a much larger volume of approximately 140 MG is required. Note, however, that the 99th-percentile curve has a very shallow slope over the 70 – 140 MG range. As such, doubling the impoundment volume results in only a 3 mg/L decrease in 99th-percentile chloride concentration. For this reason, a volume on the lower end of the range is recommended, as this would be adequate to satisfy the 40 mg/L maximum criterion and still limit the 99th percentile chloride to 28 mg/L, which is equal to the existing measured maximum concentration.

To further evaluate the impoundment volume, a slightly more restrictive criterion was imposed. It was noted earlier that an impoundment would reduce chloride concentration in two ways – first by averaging out fluctuations in concentration during the tidal cycle, and second by allowing the raw water pumps to be shut down. If, in the course of an extreme drought, the impoundment goes empty (reaches its minimum volume), it cannot perform the second of these functions, limiting the options available to operations staff. Raw water pumping must continue all the time, even when chlorides are extremely high. To address this possibility, **Figure 6-7** shows the minimum usable impoundment volume that is required to limit the maximum chloride concentration entering the plant to 40 mg/L without going empty (reaching its minimum storage volume). The volume required is shown for plant flow rates ranging from 50 mgd to the plant capacity of 62.5 mgd.

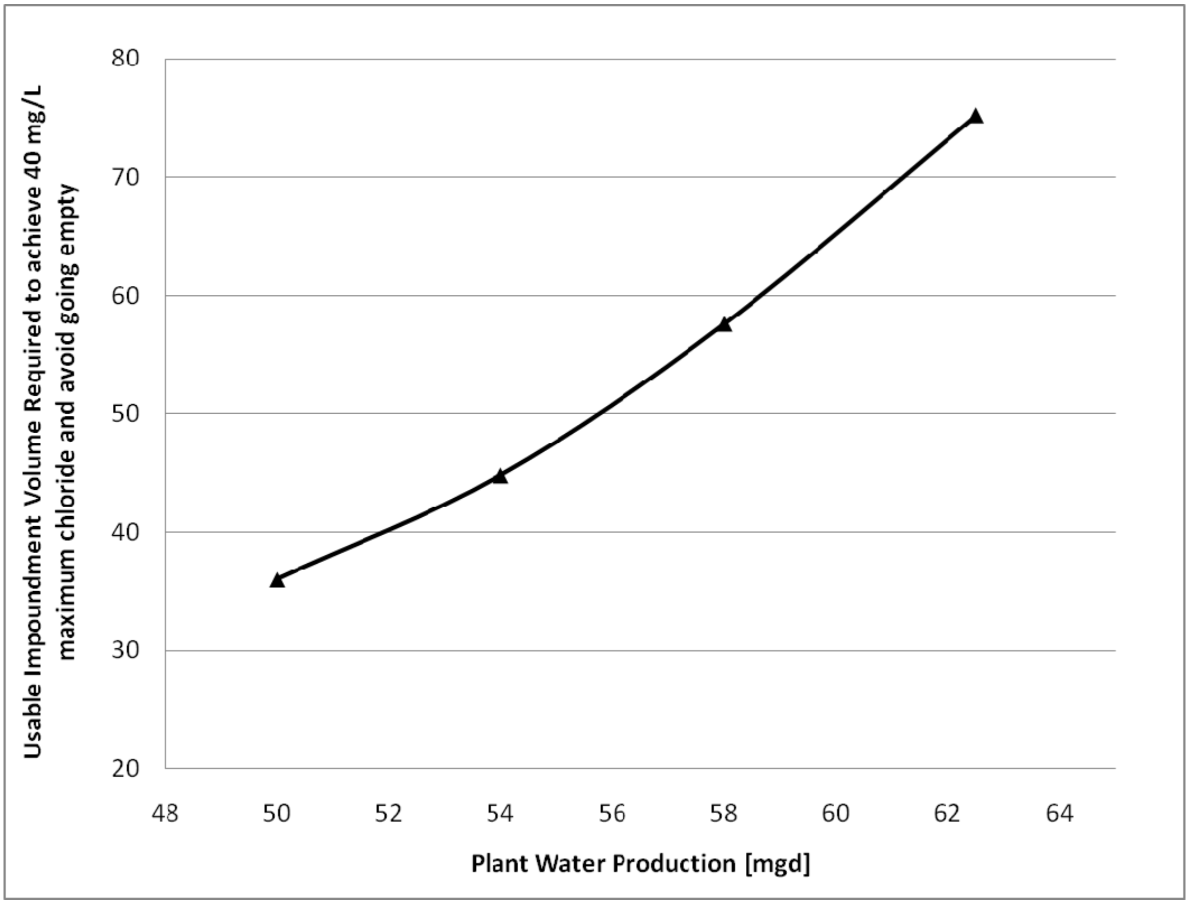


Figure 6-7: Usable impoundment volume required to limit maximum chloride concentration entering plant to 40 mg/L without reaching minimum storage capacity.

As shown, a usable volume of 75 MG is required at the plant design capacity of 62.5 mgd.

These results must be interpreted with a few qualifications. First, this analysis is based on simulated chloride concentrations using historical river flows from 2001-2009. Although this period included an extreme drought, changing climate patterns may mean that future river flows are different from this relatively short period of record. Second, these results assume that each impoundment is operated at its optimum pumping cutoff threshold concentration. The pumping cutoff is the threshold chloride concentration at which the raw water pumps are shut down (e.g. do not pump if chloride in the river exceeds 75 mg/L), and is discussed further in Section 8. However, in actual operation the impoundment cannot be expected to be operated at the optimum at all times, due to time delays between chloride measurements, operator decisions, and actually turning off the raw water pumps.

Because of these uncertainties, the recommended usable impoundment volume is 77.5 MG. The additional 2.5-MG above the required 75-MG volume provides 1 hour of reaction time at a plant flow of 62.5 mgd to account for the need to check chloride levels, make decisions and turn on or off pumps. The additional volume will have a minimal impact on capital costs due to economies of scale, discussed below.

The City of Savannah conducted a separate analysis using different methodology, but also found that a usable raw water impoundment capacity in the range of 75 to 80 million gallons (MG) would be adequate to limit the chloride concentration entering the plant to under 40 mg/L in all cases.

Preliminary Layout

Based on the above considerations, a preliminary layout of the impoundment and associated facilities was prepared. The impoundment should be located as close as practical to the existing raw water pipelines and to the I&D WTP. For the purposes of this analysis, it was assumed that the impoundment would be located on Parcel 3 of the Savannah River International Trade Park, near State Highway 21 and I-95, which satisfies both criteria.

A preliminary layout of the facility is presented in **Figure 6-8**. To provide redundancy at the tie-in points, two 36" influent and two 36" effluent pipelines would connect the impoundment to the respective raw water pipelines. Since the impoundment can be bypassed for redundancy, the use of one pipe each way under the railroad is assumed. This arrangement will allow the impoundment to remain in operation if one of the raw water lines must be shut down for maintenance or repair. A pump station containing four vertical turbine pumps will convey flow out of the impoundment and back into the raw water lines for transmission to the I&D WTP. A mechanical reservoir mixer in the center of the impoundment will help maintain oxygen levels throughout the pond's depth, reducing the likelihood of taste and odor issues associated with algae growth. A powdered activated carbon (PAC) silo and feed system will be installed on the influent pipelines, to be used on an intermittent basis during severe taste and odor episodes. A 24" drain pipe can be used to empty the impoundment during cleaning by drawing water from the very bottom of the basin into the pump station.

Provisions will need to be made for trenchless construction across the CSX Railroad right of way in between the proposed site and the existing raw water lines. The details of this crossing would need to be determined after performing a detailed geotechnical survey of the area and discussing the crossing with the Railroad.

Figure 6-9 and 6-10 show the proposed grading of the impoundment and a cross section view of the berms, respectively. An emergency spillway is provided on the north side of the impoundment to prevent overtopping in the event of a pump failure. Access roads would be constructed around the entire perimeter of the impoundment crest to facilitate access for maintenance, etc.

Cost

The estimated cost for the raw water impoundment described above is **$30.0 million**. This opinion of probable costs is detailed in **Table 6-5,** and assumes that 20% of the total impoundment volume is unusable. If the volume of the final design results in a greater unusable volume, then the required total reservoir size and associated costs will be larger. Alternatively, two 38.8-MG usable volume ponds (48.5 MG total volume each) could be constructed instead of one larger pond, in order to facilitate maintenance by allowing one to be taken out of service. It is estimated that construction of two ponds would cost approximately $3.1 million more than the single pond option due to the extra berm that would be required.

Table 6-4 provides a comparison of the costs of the options described above.

Table 6-4: Summary of Raw Water Impoundment Alternative Costs

Usable Volume	Total Volume	No. of Ponds	Estimated Capital Cost
77.5 MG	97 MG	1	$30.0 million
38.8 MG	48.5 MG	2	$33.1 million

GENERAL NOTES:

1. **ALL INFLUENT, OUTLET, AND DRAIN PIPES UNDER RAW WATER IMPOUNDMENT SHALL BE ENCASED IN CONCRETE WITHIN IMPOUNDMENT AND BENEATH EMBANKMENT TO A POINT 20 FT. OUTSIDE TOE OF SLOPE.**
2. **THE LOCATION OF EXISITNG PROPERTY LINES, ROADS, PIPELINES, AND RAILROAD TRACKS IS APPROXIMATE AND FOR INFORMATION PURPOSE ONLY.**
3. **ELEVATIONS REFER TO THE NORTH AMERICAN VERTICAL DATUM OF 1988 (NAVD88).**

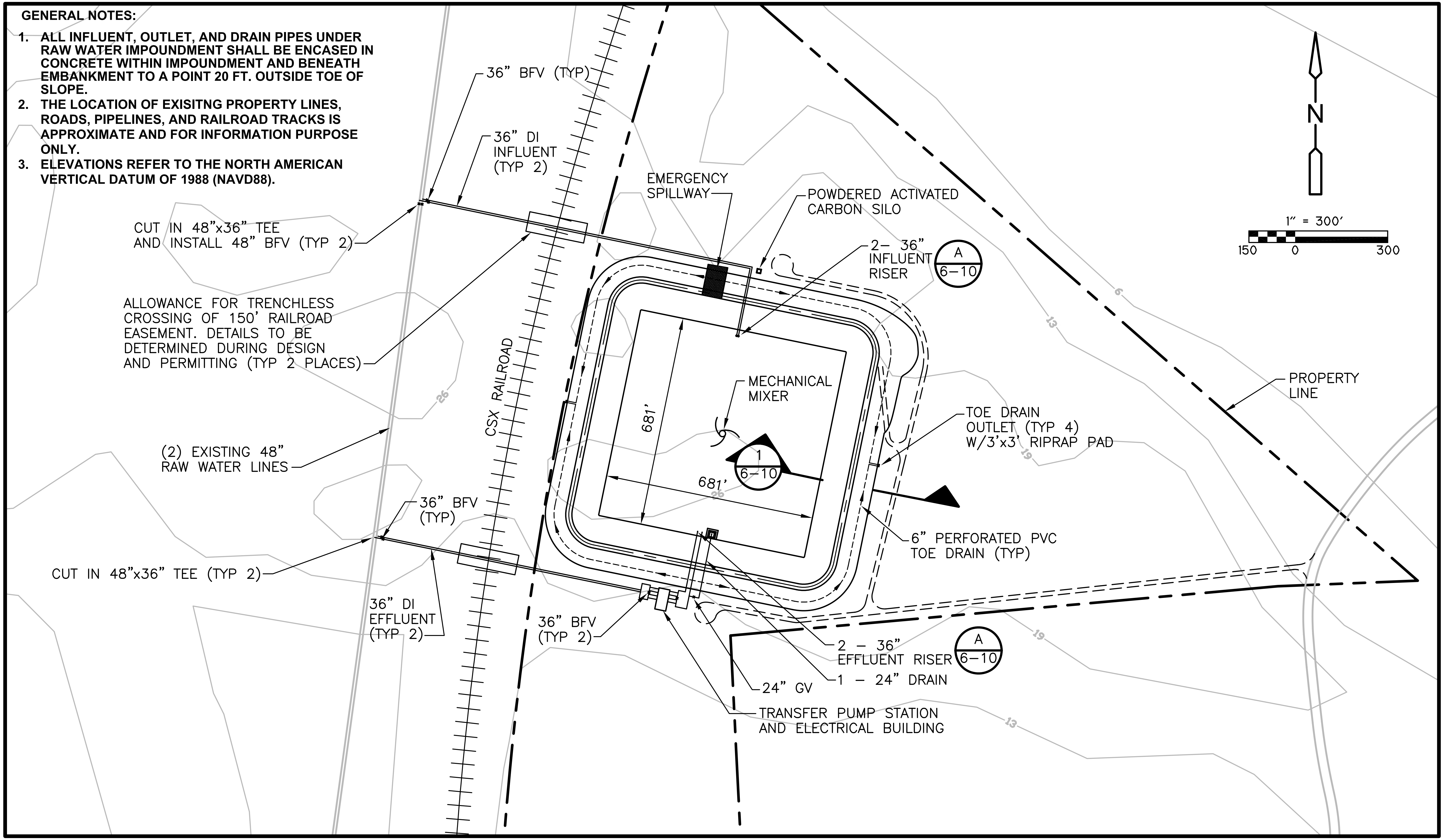


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Figure No. 6-8
Preliminary Raw Water Impoundment Site Layout
November 2011

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GENERAL NOTES:

1. **THE LOCATION OF EXISITNG PROPERTY LINES, ROADS, PIPELINES, AND RAILROAD TRACKS IS APPROXIMATE AND FOR INFORMATION PURPOSE ONLY.**
2. **ELEVATIONS REFER TO THE NORTH AMERICAN VERTICAL DATUM OF 1988 (NAVD88).**

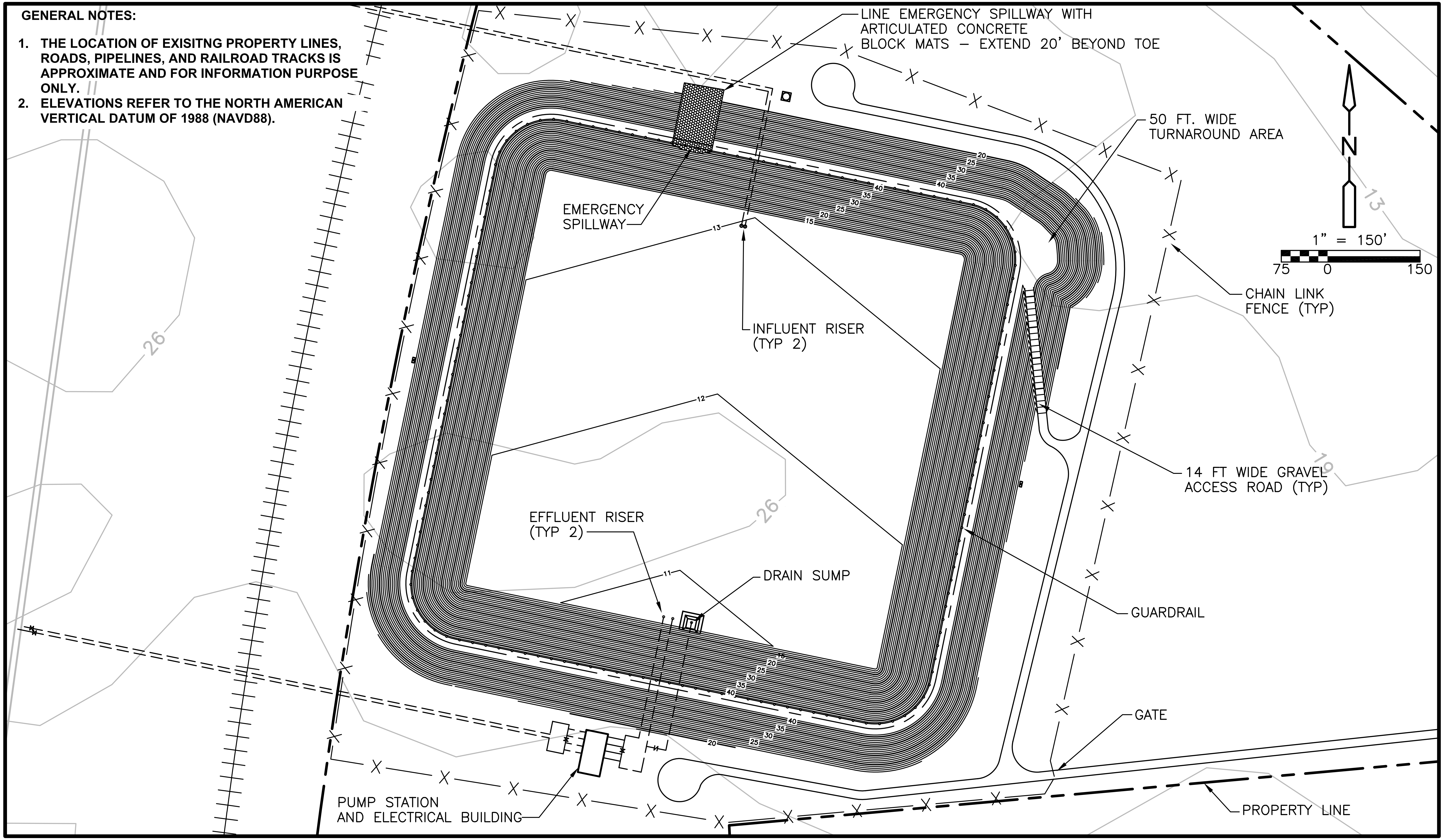

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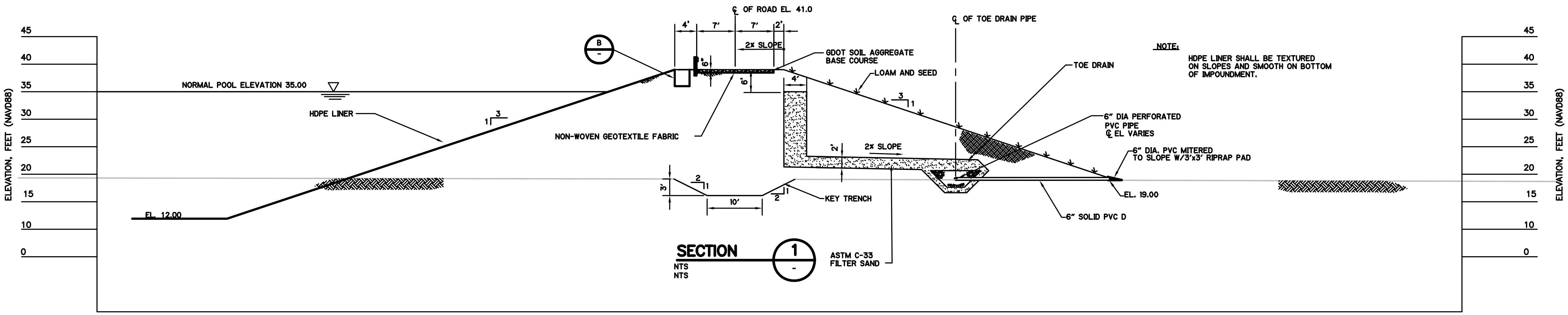
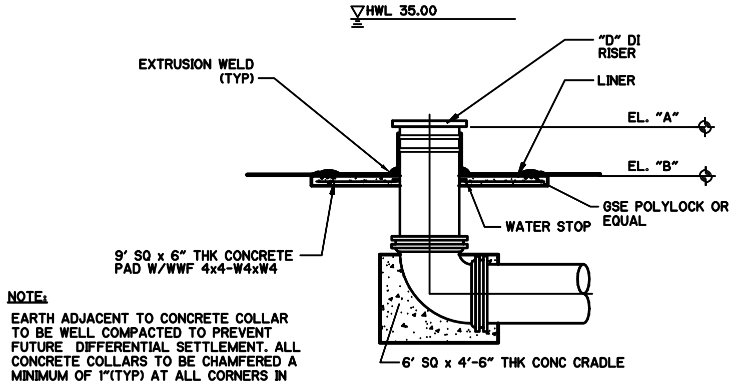
Figure No. 6-9
Preliminary Raw Water Impoundment Grading
November 2011



SECTION 1
NTS
NTS



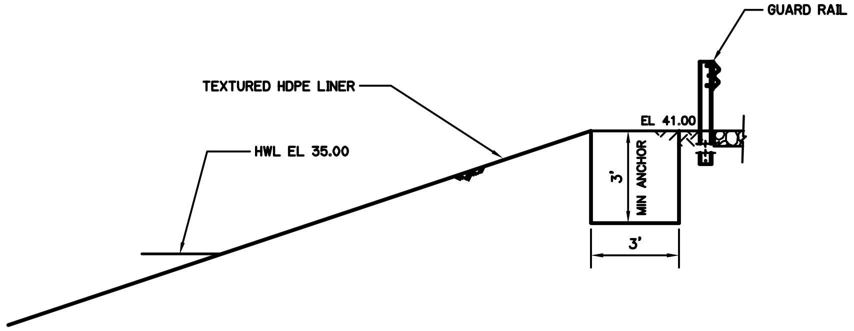
NOTE:
EARTH ADJACENT TO CONCRETE COLLAR TO BE WELL COMPACTED TO PREVENT FUTURE DIFFERENTIAL SETTLEMENT. ALL CONCRETE COLLARS TO BE CHAMFERED A MINIMUM OF 1"(TYP) AT ALL CORNERS IN CONTACT WITH LINER.

INFLUENT AND EFFLUENT RISER

DETAIL A
NTS 6-8

"D" FLANGED DI RISER WITH SS SCREEN WITH 1/2" DIA. BARS 6" SQUARE OPENINGS (TYP – OUTLETS ONLY)

DESCRIPTION	DIA. (IN.)	A (FT.MSL)	B (FT.MSL)
OUTLET	36	14.50	11.00
OUTLET	36	14.50	11.00
INFLUENT	36	16.50	13.00
INFLUENT	36	16.50	13.00



HDPE LINER ANCHOR

DETAIL B
NTS –

GENERAL NOTES:

1. ALL INFLUENT, OUTLET, AND DRAIN PIPES UNDER RAW WATER IMPOUNDMENT SHALL BE ENCASED IN CONCRETE WITHIN IMPOUNDMENT AND BENEATH EMBANKMENT TO A POINT 20 FT. OUTSIDE TOE OF SLOPE.

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Figure No. 6-10
Preliminary Raw Water Impoundment Section And Details
November 2011

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Table 6-5: Opinion of Probable Cost for 77.5 MG (usable) / 97 MG (total) Raw Water Impoundment

ITEM	UNIT COST	QUANTITY		ITEM COST[a]	CONTINGENCY[b]	TOTAL COST
Land[c]	$55,000	35	AC	$1,930,000	n/a[b]	$1,930,000
LAND SUBTOTAL				**$1,930,000**	**n/a**	**$1,930,000**
Water Storage-Ponds & Site work						
Fill/Earthwork	$18.82	286,000	CY	$5,390,000	$1,347,500	$6,737,500
HDPE Liner	$1.36	725,000	SF	$990,000	$247,500	$1,237,500
Toe Drain	$55.41	17,900	CY	$1,000,000	$250,000	$1,250,000
Site Piping, Valves, and Accessories	$538	5,750	LF	$3,100,000	$775,000	$3,875,000
Trenchless Crossing of Railroad Track	$3,195.95	300	LF	$960,000	$240,000	$1,200,000
Concrete-encased Influent and Effluent Piping	$175	500	LF	$90,000	$22,500	$112,500
Mechanical Mixing System	$90,297	1	EA	$100,000	$25,000	$125,000
Clear and Grub	$7,294	35	AC	$260,000	$65,000	$325,000
Access Roads	$1.45	112,500	SF	$170,000	$42,500	$212,500
Chain Link fencing and gate	$52.16	4,600	LF	$240,000	$60,000	$300,000
Seeding	$4,935.53	15	AC	$80,000	$20,000	$100,000
Re-pump Station						
Pumps with VFD's and cans (400 hp,21 mgd each)	$655,823	4	EA	$2,630,000	$657,500	$3,287,500
Pump Can Concrete, Excavation, & Backfill	$824	40	CY	$40,000	$10,000	$50,000
1 MW Standby Generator with Fuel Storage	$513,486	1	EA	$520,000	$130,000	$650,000
Pump Station and Electrical Building	$315	2,400	SF	$760,000	$190,000	$950,000
Pump Station Electrical & Instrumentation	$1,133,036	1	LS	$1,140,000	$285,000	$1,425,000
Electrical Service[d]	$500,000	1	LS	$500,000	n/a[b]	$500,000
Valves	$16,295	14	EA	$230,000	$57,500	$287,500
Piping Allowance	$94,420	1	LS	$100,000	$25,000	$125,000
Powdered Activated Carbon System						
Silo and Feed Equipment	$822,641	1	EA	$830,000	$207,500	$1,037,500
Installation, piping, etc	$231,443	1	LS	$240,000	$60,000	$300,000
Testing, Commissioning, Monitoring	$57,034	6	MO	$350,000	$87,500	$437,500
Mobilization / Demobilization	$58,597	1	LS	$60,000	$15,000	$75,000
FACILITIES SUBTOTAL				$19,780,000	$4,820,000	$24,600,000
PLANNING, ENGINEERING & DESIGN (7%)				$1,380,000	$345,000	$1,725,000
SUPERVISION & ADMIN-CONSTRUCTION MGMT (6%)				$1,190,000	$298,000	$1,488,000
GEOTECHNICAL & LINER TESTING ALLOWANCE				$200,000	$50,000	$250,000
CONSTRUCTION SUBTOTAL				**$22,550,000**	**$5,513,000**	**$28,063,000**
TOTAL COST FOR 1-77.5 MG (USABLE) IMPOUNDMENT				**$24,480,000**	**$5,513,000**	**$29,993,000**

[a] Item costs rounded up to the nearest $10,000 for planning purposes. All costs are given in 2011 dollars.

[b] Construction contingency is calculated as 25% of eligible item costs. Contingency was not added to direct costs to the City.

[c] Unit land cost is a placeholder until a specific site can be identified. Land costs do not include easements that may be required to connect the impoundment to existing raw water lines. Construction contingency was not added to land cost because this is a direct cost to the City.

[d] Estimate provided by Georgia Power. Construction contingency was not added because this is a direct cost to the City.

Estimated operations and maintenance costs for the proposed raw water impoundment are given in **Table 6-6.**

Table 6-6: Opinion of Probable Operations & Maintenance Costs

Item	Quantity	Unit	Unit Cost[b]	Total Cost
Transfer Pumping Power Cost	3,058,000	kWh	$0.06	$184,000
Spare Parts	1	LS	$20,000	$20,000
Seals, lubricants, tools	1	LS	$3,000	$3,000
Operator/Mechanic	½	FTE	$25,000	$12,500
Liner Replacement (amortized over 20 years)[a]	1	LS	$199,000	$199,000
Sediment Removal (amortized over 10 years)	1	LS	$87,000	$87,000
TOTAL				**$506,000**
15-year Present Worth[a]				**$5,250,000**

[a] Amortization and present worth calculations use a 5% discount rate
[b] All costs are given in 2011 dollars

Alternate Project Depths

Recommended impoundment sizes for four alternate harbor deepening scenarios were determined using the same methodology described above. The results of this analysis are documented in **Appendix J. Table 6-7** summarizes the recommended sizes.

Table 6-7: Recommended Impoundment Size and Estimated Cost for Alternate Harbor Deepening Scenarios

Harbor Deepening Scenario	2ft 6B	3ft 6A	4ft 6A	5ft 6A	6ft 6A
Recommended Usable Volume, MG	22.5	30	46.5	77.5	120
Total Volume, MG	28	38	58	97	150
Probable Construction Cost, $M	$24,333,000	$25,143,000	$26,883,000	$29,993,000	$34,073,000

As indicated in the table, the raw water impoundment contains considerable economies of scale due to the large fixed costs associated with the pump station, PAC silo, and influent and effluent piping. Moreover, because of the shape of the embankments used to construct it, the incremental costs of additional impoundment volume are minimal. **Figure 6-11** illustrates the relationship between usable impoundment volume and estimated capital cost. As shown, roughly one half of the total cost is independent of volume, and the marginal cost of increasing to a larger reservoir volume is relatively small. For example, increasing the impoundment volume by more than 50% from 46.5 MG to 77.5 MG increases the capital costs by only 12%.

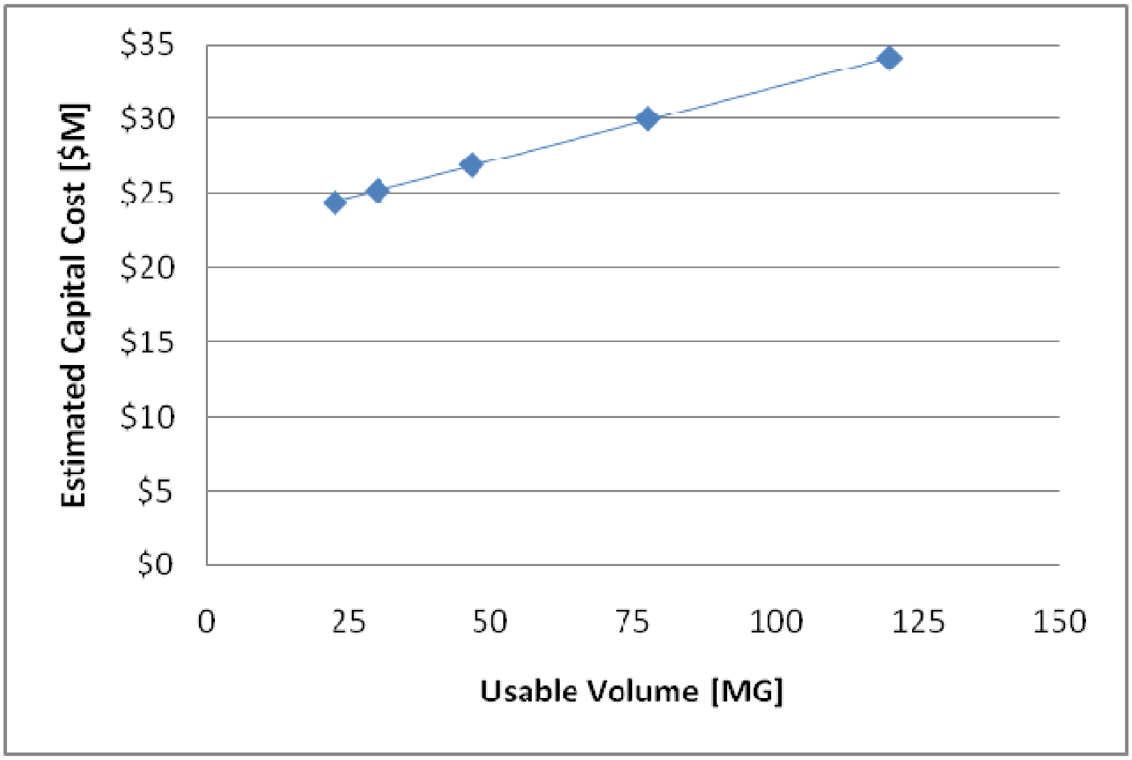


Figure 6-11: Economies of scale for raw water impoundment

Low-head Dam or Sill

A low-head water control or sill structure (dam) constructed across Abercorn Creek downstream of the existing City of Savannah raw water intake is another alternative to reduce the potential for salt water intrusion occurring during periods of low flows and high tides. The dam structure would be constructed 0.5 mile to 1 mile downstream of the existing intake and incorporate a central core/cut-off wall that is relatively impermeable to reduce the potential for backflow of salt water towards the intake during lower tide levels in the river. The dam would be “run of the river” and overtop during normal to high river flows. The dam crest elevation would be set above the intake elevation and provide some freeboard above the anticipated low tide levels. Although this alternative can reduce the potential for salt water intrusion, it will require significant permitting efforts through the USACE and Georgia Department of Natural Resources (Environmental Protection and Safe Dams). The project would also need to demonstrate that the new structure would not adversely impact flood levels along the river, aquatic species, etc. Modeling would be needed to verify that a single dam would suffice and to provide guidance on the proper location based on where the channel narrows.

Based on the extensive amount of permitting and potential issues anticipated for this option, all parties agreed that further analysis and cost estimating of this alternative was not necessary for the purposes of this study.

Section 7
Summary and Recommendations

7.1 Summary of Findings

Bench-scale testing using City of Savannah raw water combined with seawater was used to simulate the effect of harbor deepening on treated water quality with respect to corrosion, formation of disinfection byproducts (DBPs), and chemical treatability. Higher chloride concentrations in the range expected to result from harbor deepening caused significant increases in DBP formation, chlorine demand, and lead corrosion, and moderate increases in iron corrosion and total organic carbon (TOC). Coagulant demand was not appreciably affected by the percentage increases in seawater evaluated.

Under the existing treatment regime, increased chlorides would likely make it difficult or impossible for the City to comply with drinking water regulations for disinfection byproducts and lead.

Numerous alternatives exist for mitigating these impacts and ensuring continued protection of public health and compliance with regulations. These alternatives can be broadly categorized as modifications to adapt the treatment process to increased seawater or measures that avoid increased seawater in the source water.

The results of the bench-scale study indicate that neither the existing corrosion inhibitor nor pH adjustment will consistently control lead and iron corrosion to the extent required. Adapting the treatment process to accommodate the high chlorides that may be encountered after harbor deepening would require costly modification and multiple steps to address both corrosion and DBP impacts. The most suitable treatment alternative for removing seawater ions is membrane treatment, which was previously studied by others and estimated to cost in excess of $60 million, and would require further testing to confirm its impact on water quality. All parties at the July progress meeting agreed that there was no interest in pursuing membrane treatment further.

An alternate approach is to dampen the chloride concentrations to the plant through the construction of a raw water impoundment. An impoundment would smooth tidal fluctuations in chloride concentration and provide storage so that pumping during high tide could be avoided. Such a facility would stabilize source water quality and simplify plant operations while mitigating the impact of chlorides on both lead corrosion and DBPs. Similarly, a new upstream supplemental intake could be used to avoid the seawater spikes from the harbor deepening. The latest cost estimate for the upstream supplemental intake is $35.9 million. As such, construction of the raw water impoundment appears to be the least-cost mitigation strategy for protecting drinking water quality.

7.2 Recommendations

Recommended Alternative

Raw Water Impoundment

- One pond
- 77.5 MG usable volume
- Stabilizes source water quality to plant
- Allows avoidance of pumping during high tide
- Simplifies plant operations

CDM recommends that one raw water impoundment with a usable volume of 77.5 million gallons (MG) be constructed in order to stabilize and reduce the chloride concentration pumped to the plant, or that the supplemental intake further upstream be constructed. This impoundment volume was selected based on the existing firm raw water pumping capacity of 75 mgd, and is adequate to keep the chloride concentration entering the plant below 30 mg/L 99% of the time, with a worst-case concentration of 40 mg/L based on historic chloride concentrations and the model predicted chloride concentrations provided. Independent analysis by the City of Savannah using a different methodology suggested a nearly identical impoundment size. The agreement between the two modeling efforts lends additional support to the recommended impoundment size presented here.

The same effect could be achieved with a smaller impoundment if the raw water pumping capacity could be increased, but the impoundment is preferred at this time based on discussion with City staff, because of space constraints in the existing intake structure, the need to save future pumping for future capacity, and most notably because the economy of scale found for the raw water impoundment with re-pump station suggested that further reduction in impoundment size would not offer savings large enough to justify the additional capital expense for raw water pumps. One reservoir is recommended since the City can treat river water during non-drought seasons to allow taking the reservoir out of service for maintenance. The total volume of the impoundment should be approximately 20% greater than the 77.5 MG usable volume, for a total volume of approximately 97 MG. This extra volume is needed in order to allow for sediment accumulation and minimum water storage.

The proposed impoundment could be constructed in the vicinity of the I&D Plant. Cost estimates of the proposed impoundment are presented below based on recent pricing for similar projects with which CDM has experience. The estimated capital cost of the recommended alternative is **$30.0 million** for a 77.5-MG usable volume impoundment, and is broken down in more detail in **Table 7-1**. If two impoundments are constructed instead of one, the estimated cost is increased by $3.1 million, hence the City agreed to the use of one impoundment in the interest of compromise and moving the project forward. The estimated 15-year present worth of operations and maintenance expenses is **$5.25 million**.

Table 7-1: Estimated Capital Cost of one 77.5-MG (usable volume) Raw Water Impoundment

Item	Cost[a]	Contingency[b]	Total Cost
Land[c]	$1,930,000	n/a[b]	$1,930,000
LAND SUBTOTAL	**$1,930,000**	**n/a**	**$1,930,000**
Water Storage Ponds & Site Work	$12,380,000	$3,095,000	$15,475,000
Transfer Pump Station	$5,920,000	$1,355,000[b]	$7,275,000
Powdered Activated Carbon Silo	$1,070,000	$267,500	$1,337,500
Testing, Commissioning, Monitoring	$350,000	$87,500	$437,500
Mobilization / Demobilization	$60,000	$15,000	$75,000
FACILITIES SUBTOTAL	$19,780,000	$4,820,000	$24,600,000
Planning, Engineering & Design (7%)	$1,380,000	$345,000	$1,725,000
Supervision & Admin-Construction Management (6%)	$1,190,000	$298,000	$1,488,000
Geotechnical & Liner Testing Allowance	$200,000	$50,000	$250,000
CONSTRUCTION SUBTOTAL	**$22,550,000**	**$5,513,000**	**$28,063,000**
TOTAL COST (One 77.5-MG Impoundment)	**$24,480,000**	**$5,513,300**	**$29,993,000**
15-YEAR PRESENT WORTH OPERATIONS AND MAINTENANCE COST[d]			**$5,250,000**

[a] Item costs rounded up to the nearest $10,000 for planning purposes. All costs are given in 2011 dollars.

[b] Construction contingency is calculated as 25% of eligible item costs. Contingency was not added to the cost of providing electrical service to the site or to land, as these are direct costs to the City.

[c] Unit land cost is a placeholder until a specific site can be identified. Land costs do not include easements that may be required to connect the impoundment to existing raw water lines. Construction contingency was not added to land cost because this is a direct cost to the City.

[d] 5% discount rate

The results of the bench-scale study and source water quality modeling by Tetratech were used to develop operational guidelines for plant staff. These guidelines will assist in operating the impoundment and in making adjustments to chemical treatment as the chloride concentration fluctuates. The guidelines are provided in the next section

Section 8
Guidance for Operational Adjustments to Respond to Increased Percentage of Seawater

8.1 Chemical Considerations

The results of this study have shown that the presence of seawater can increase the chlorine demand by 50-75%. In addition, the more seawater contained in the raw water, the greater the potential to form DBPs. Although the coagulant demand for turbidity removal is not significantly affected, it may be advisable to increase the coagulant dose during high chloride events (>20 mg/L reaching the plant) in order to improve TOC removal. Feeding PAC prior to an impoundment would also help with TOC removal. Reducing TOC in the water is a reliable way to mitigate both the increased chlorine demand and the higher DBP formation potential.

Increased vigilance for leaks due to corrosion of iron or steel pipes and pinhole leaks in copper piping is advisable, particularly during and after a prolonged drought where chloride concentrations are consistently elevated. In addition, distribution system water quality should be monitored carefully for changes that may indicate corrosion. Besides increases in dissolved metals, increases in alkalinity, pH, or hardness in the system can be associated with dissolution of cement linings as a result of high chloride levels.

Continued optimization of corrosion control may be helpful as well. For example, continue exploring options with the corrosion inhibitor suppler that increase the percentage of orthophosphate in the product.

8.2 Raw Water Impoundment Operation

Construction of the recommended raw water impoundment would allow operations staff to make decisions about when to pump raw water, and thereby allow control over the source water quality entering the plant. This section provides guidelines on how to maximize the benefit of a raw water impoundment and keep the influent chloride concentration as low as possible. It is recommended that a remote, on-line chloride analyzer or other means of monitoring seawater percentage be installed at the raw water intake to facilitate these decisions.

8.2.1 Routine (non-drought) Operation

The ratio of water plant production to raw water pumping capacity is an indication of how much of the time (e.g. hours per day) the raw water pumps must operate on a sustained or continuous basis. The firm raw water pumping capacity of the I&D plant is 75 mgd, and the maximum water production is 62.5 mgd. With these values, the pumps must run 62.5/75 = 83% of the time, or 20 hours each day, in order to supply adequate water to the plant. This implies that they can only be shut down for 4 hours each day, or 2 hours during each 12-hour tidal cycle. If they run less than 20 hours per day, the storage level in the impoundment will gradually drop.

During routine operations, it is desirable to keep the reservoir as full as possible to provide a buffer against extreme events. Therefore, when chlorides are elevated, it is recommended to plan to turn the pumps off for at least the 2 hours surrounding peak high tide each tidal cycle.

8.2.2 Management of High-Chloride Events

A "high chloride event" is defined as a period of time during which the chloride concentration at the intake continuously exceeds some pre-determined cutoff threshold. During periods of low river flow (drought), the reservoir can be used to mitigate the impact of these events on plant operations. The raw water impoundment would reduce chloride concentration entering the plant in two ways. The first would be to average out the chloride concentrations throughout the day or tidal cycle. The second, subject to the cutoff concentration and the rate of water production, would be the ability to turn off the pumps during the worst 2 hours (more hours when plant is not at capacity) and thereby avoid pumping the highest chloride concentrations. The key operational parameter is a selection of an appropriate cutoff concentration.

Modeling data suggest that after harbor deepening, the median duration of a high-chloride event may be 3 to 6 hours, with worst-case durations as high as 12 hours, depending on the threshold concentration. **Figure 8-1** shows the maximum, median, and 95th percentile event durations over the period analyzed for chloride cutoff concentrations ranging from 20 to 70 mg/L chloride.

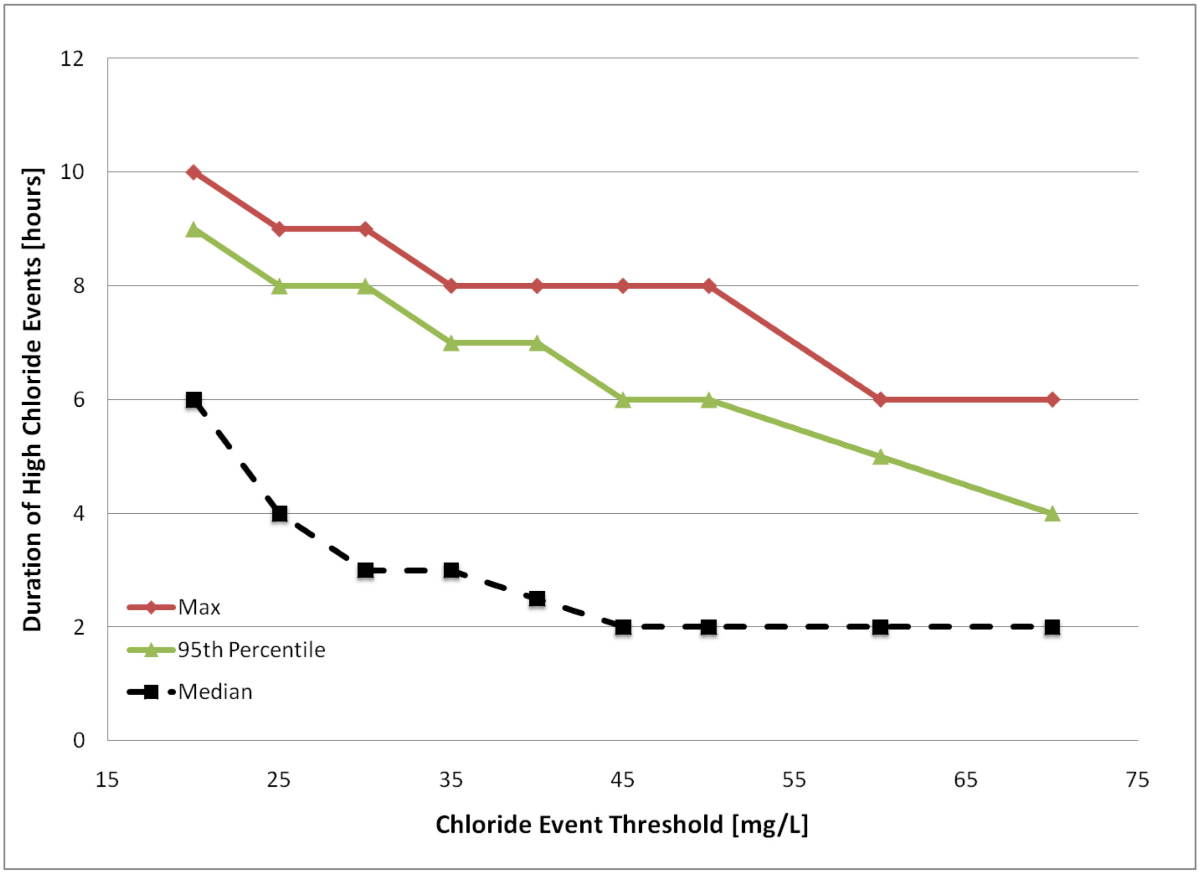


Figure 8-1: Duration of high-chloride events at various cutoff threshold concentrations.

Because the pumps can only be shut down for 2 hours each tidal cycle on a sustained basis and most of these events are longer than that, it will be necessary to rely on stored water in the impoundment if high chlorides are to be avoided. As the graph shows, the higher cutoff concentrations imply shorter event durations. Choosing a higher pumping cutoff effectively increases the opportunities available for filling up the reservoir.

Figure 8-2 shows the impact of choosing different pumping cutoff concentrations on the 99th-percentile chloride concentration entering the plant for water production rates of 50 mgd and 62.5 mgd. At the plant capacity of 62.5 mgd (solid line), the raw water impoundment is capable of keeping the chloride concentration entering the plant below 30 mg/L if operated at a cutoff of 40-60 mg/L.

If water production is decreased to 50 mgd, the optimum cutoff range shifts downward to 30 – 50 mg/L, and the 99th-percentile concentration entering the plant is reduced by approximately 5 mg/L. The cutoff can be decreased because lowering water production increases the gap between raw water pumping capacity and demand, allowing the reservoir to be filled faster. A similar effect would be observed if the raw water pumping capacity could be increased to 94 mgd, or if total pumping capacity could be used during severe drought, instead of limiting to firm capacity.

The optimum cutoff concentrations, indicated by the yellow arrows, represent the ideal tradeoff between the two impoundment functions—averaging of chloride concentration and avoiding pumping the highest chlorides—for each water production rate.

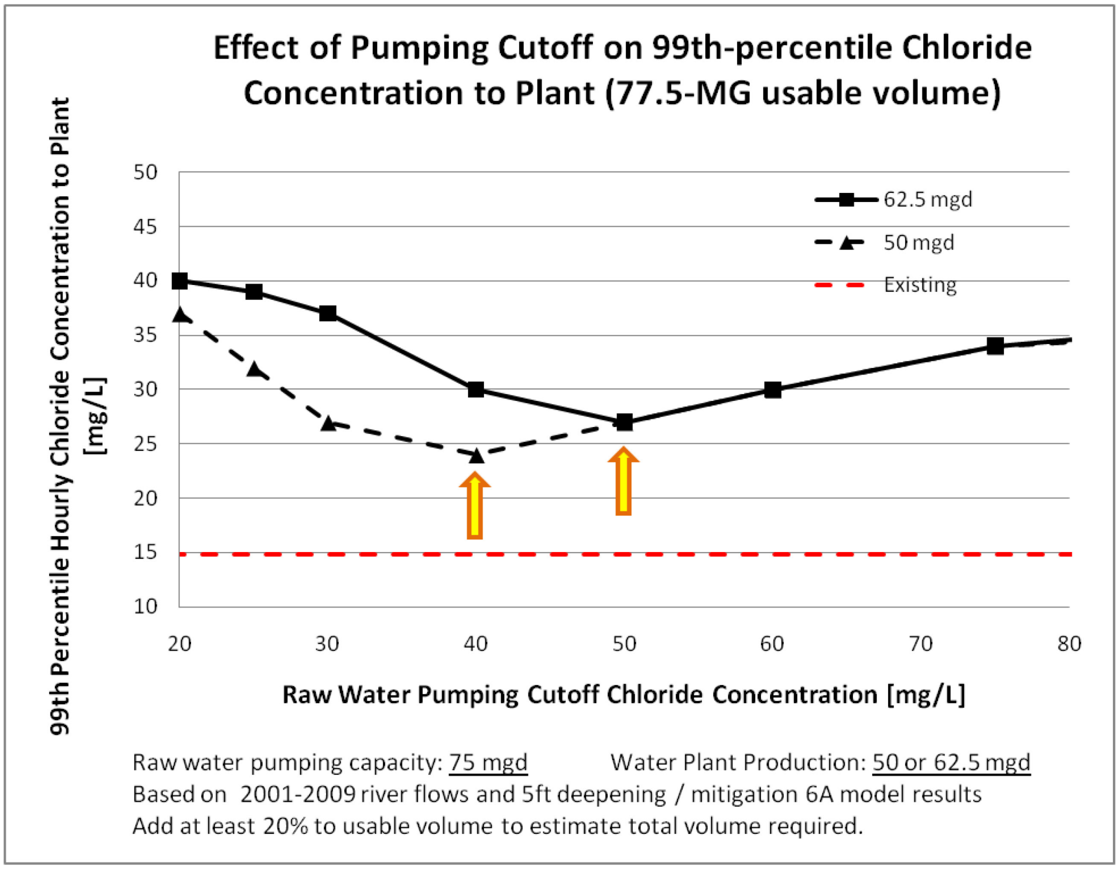


Figure 8-2: Effect of pumping cutoff chloride concentration and water production rate on 99th-percentile chloride concentration entering the Savannah I&D Plant. The model-predicted 99th-percentile chloride concentration under current conditions is shown as a red dashed line. Optimum cutoff concentrations are indicated by the yellow arrows.

Extreme Drought

The above plot shows that when operated with a cutoff concentration of 30-50 mg/L, the raw water impoundment will be able to limit the chloride concentration entering the plant to below 30 mg/L in all but the most extreme circumstances. During extreme drought a slightly different operational approach is recommended.

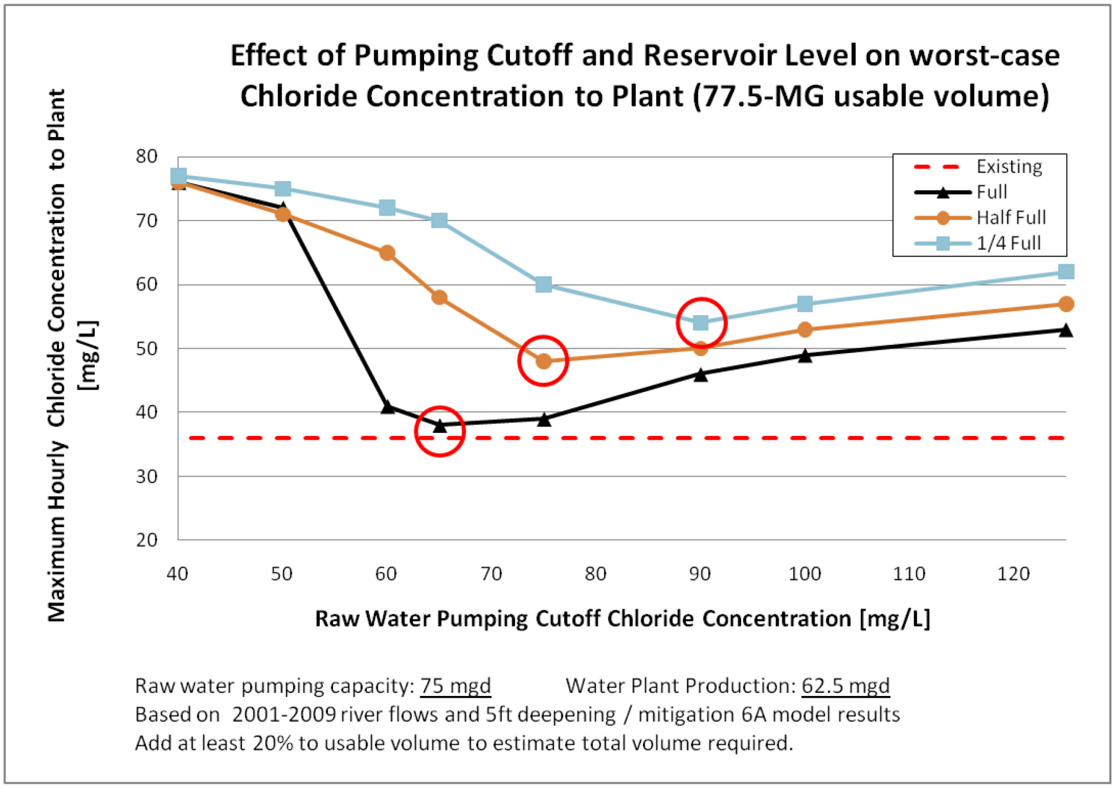
Simulations during the 2008 drought indicate that had the harbor been deepened, there may have been high chloride events greater than 2 hours long for as many as 39 consecutive days, depending on the threshold concentration. Without either an increase in raw water pumping capacity or a reduction in water production, there would be no choice but to pump during periods of very high chloride concentration, since it would be impractical to size the impoundment for more than a few days storage. As such, the pumping cutoff should be gradually increased in order to keep the reservoir from going empty. **Table 8-1** shows the consecutive days of high chloride events at various cutoff concentrations.

Table 8-1: Consecutive days with high-chloride events exceeding the threshold concentration for more than 2 hours

Cutoff Concentration	25 mg/L	30 mg/L	35 mg/L	40 mg/L	50 mg/L	75 mg/L
Days	39	37	24	12	10	4

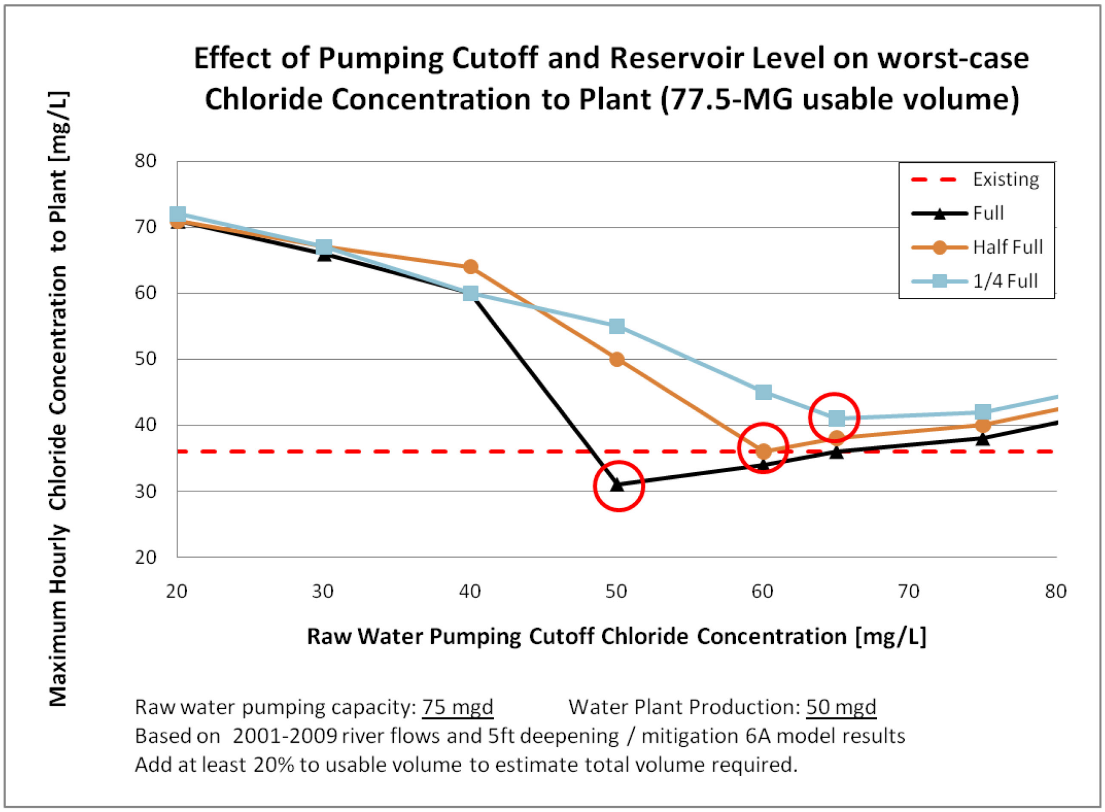
Figures 8-3 and **8-4** show the worst-case (maximum) chloride concentrations entering the plant through the recommended 77.5-MG (usable volume) raw water impoundment at various pumping cutoff chloride concentrations. Each plot shows three curves, representing the reservoir at full capacity (97 MG total), half-full of usable volume (58 MG total), and one quarter full of usable volume (38 MG total). The maximum chloride under current conditions is shown as a dashed red line. For each reservoir level, the pumping cutoff concentration resulting in the lowest chloride concentration entering the plant is circled in red.

The first plot shows a water production rate of 62.5 mgd; the second shows the same information if the plant were to be operated at 50 mgd during the extreme drought. As noted above, reducing the water demand or increasing raw water pumping capacity would improve the ability to avoid pumping during chloride spikes.



Raw water pumping capacity: 75 mgd Water Plant Production: 62.5 mgd
Based on 2001-2009 river flows and 5ft deepening / mitigation 6A model results
Add at least 20% to usable volume to estimate total volume required.

Figure 8-3: Effect of pumping cutoff chloride concentration on worst-case chloride concentration to the Savannah I&D Plant at 62.5 mgd water production. The dashed red line indicates the model-predicted maximum concentration under existing conditions; red circles indicate the optimum cutoff concentration for each reservoir level.



Raw water pumping capacity: 75 mgd Water Plant Production: 50 mgd
Based on 2001-2009 river flows and 5ft deepening / mitigation 6A model results
Add at least 20% to usable volume to estimate total volume required.

Figure 8-4: Effect of pumping cutoff chloride concentration on worst-case chloride concentration to the Savannah I&D Plant at 50 mgd water production. The dashed red line indicates the model-predicted maximum concentration under existing conditions; red circles indicate the optimum cutoff concentration for each reservoir level.

The most obvious trend evident in the plots is that the optimum pumping cutoff concentration increases as the usable reservoir volume is drawn down. Moreover, there are clear operational advantages to choosing a relatively high chloride cutoff concentration during an extreme drought. The optimum cutoff concentration depends on the reservoir level, and the plant flow. At 62.5 mgd water production, it varies between 65 mg/L and 90 mg/L; for 50 mgd water production, between 50 mg/L and 65 mg/L.

Although raising the pumping cutoff in order to lower the chloride entering the plant may be counterintuitive, higher cutoff concentrations effectively increase the opportunities for filling the reservoir, making it less likely to go empty. An empty reservoir forces pumping at undesirable times (e.g. in the middle of an event), so allowing slightly higher chloride concentrations to be pumped in to keep the reservoir full prevents extremely high concentrations from having to be pumped later on. In an extreme drought event, it is recommended that the pumping cutoff be gradually increased as the reservoir volume drops. Doing so should prevent a situation in which operations staff are forced to pump during a high chloride event because the reservoir is nearly empty.

Finally, reducing the plant production to 50 mgd lowers the worst-case chloride concentration by approximately 8- 10 mg/L. This fact reinforces the point made earlier that a larger gap between raw water pumping capacity and demand improves the performance of the impoundment.

8.2.3 Suggested Operation

In summary, the following guidelines are suggested for maximizing the benefit of the impoundment:

1. During non-drought conditions, keep the reservoir full.
2. During mild drought conditions, operate with a cutoff in the range of 30-50 mg/L, depending on water production rate. Use Figure 8-2 as a guide. If the reservoir is not able to be kept full, transition to the severe drought rules stated below.
3. During severe drought conditions, begin with a raw water chloride pumping cutoff of 40-60 mg/L. If drought conditions persist, continue to increase the cutoff up to a maximum of 75 mg/L chloride. Use the figures in this section as a guide to manage increases in cutoff as the impoundment is drawn down.

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Appendix A

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Appendix B

Bench Testing Progress Memo

Georgia Department of Natural Resources
2 MLK, Jr. Drive, S.E., East Floyd Tower, Atlanta, Georgia 30334
Mark Williams, Commissioner
F. Allen Barnes, Director
Environmental Protection Division

Reply To:
Drinking Water Program
Suite 1362, East Floyd Tower
2 MLK, Jr. Drive, S.E.
Atlanta, Georgia 30334

May 13, 2011

Mr. William B. Dowbiggin, P.E., BCEE
Camp Dresser & McKee Inc.
5400 Glenwood Ave., Suite 300,
Raleigh NC 27612

RE: Exhibit A and Testing Plan for Seawater Effect Study
Savannah - I & D Filtration Plant Water System, WSID# 0510004
Chatham County

Dear Mr. Dowbiggin:

The Drinking Water Program of the Environmental Protection Division (EPD) hereby concurs with Exhibit A (April 1, 2011) and the Testing Plan for Seawater Affect Study (May 13, 2011) that were submitted by Camp Dresser & McKee Inc. contingent upon the following conditions:

1. The jar testing procedure shall simulate full-scale plant operation as closely as possible.
2. The final results of the bench-scale tests and Draft Report shall be submitted to EPD for review and comment.

This concurrence is valid for one year from the date of this letter. If the study has not begun by that date, the Division may choose to reevaluate the project with regard to the Rules and Regulations in effect at that time. If you have any questions, please feel free to contact me at the number below.

Sincerely,

Kirk A. Chase

Kirk A. Chase
Unit Manager
Drinking Water Program
(404) 657-8283

cc: Heath Loyd, Director, Water Supply and Treatment Department, Water Resources Bureau
Jeff Larson, ABC, WPB
Brad Addison, PM, WPB DWP

-----Original Message-----

From: Kirk Chase [mailto:Kirk.Chase@dnr.state.ga.us]

Sent: Wednesday, June 01, 2011 3:20 PM

To: Dowbiggin, William

Cc: Jeff Larson; Pete Zorbanos; <Sawyer John

Subject: Fwd: Fw: bench testing memo - Savannah

Mr. Dowbiggin,

Comment #1 in the EPD Drinking Water Program's letter dated May 13, 2011 (attached) has been satisfactorily addressed by the Memorandum prepared by CDM on the Relationship of Bench-Scale Results to Full-Scale Treatment.

The EPD Drinking Water Program hereby concurs with the refined jar testing procedure and approves the City of Savannah and CDM to begin detailed bench testing on the effects of seawater concentration on disinfection byproduct formation and corrosion.

Once complete, the final results of the bench-scale tests and Draft Report must be submitted to the EPD Drinking Water Program for review and comment.

Please let me know if you have any questions.

Kirk Chase

Unit Manager

Environmental Protection Division

Drinking Water Program

2 MLK, Jr. Drive S.E.

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Atlanta, GA 30334

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CDM

Memorandum

To: *Jeff Larson, Georgia Environmental Protection Division*

From: *Bill Dowbiggin*

Date: *May 26, 2011*

Subject: *Relationship of Bench-scale Results to Full-Scale Treatment*

As it is urgent that the Seawater Effects Study of Savannah, GA water begin as soon as possible, this memorandum is being issued to update all concerned parties on CDM's progress in refining the bench-scale testing procedures to reasonably match full-scale parameters such as turbidity and total organic carbon (TOC).

The past few weeks have focused on the development and refinement of bench-scale testing procedures that will simulate full-scale treatment as closely as practicable, recognizing that there will always be some differences between water quality generated under laboratory conditions and that in the actual plant distribution system. The purpose of bench-scale testing is to identify trends and comparative differences in water quality from changes to the chemical treatment regime.

Study Impacts

The objective of the Seawater Effects Study is to understand the impacts of increased percentage of seawater in the raw water supply by measuring three major water quality impacts:

- Coagulant demand and coagulation treatability
- Formation of disinfection by-products (DBPs)
- Treated water corrosivity

As such, it is desirable that bench-scale treatment of plant raw water yield similar coagulant demand, corrosivity, and DBP levels as full-scale treatment in order to provide a meaningful baseline for comparison. Preliminary testing has been conducted to gauge the extent to which this is the case.

Coagulant Demand and Jar Testing Performance

Numerous jar tests have been conducted over the last several weeks in an effort to match the efficacy of full-scale treatment. Procedural details such as the type of jar, the mixing speed and time, settling time, polymer addition, method of selecting the optimal coagulant dose, and type of filter have all been investigated and refined. **Table 1** shows the preliminary results of the three most recent jar tests, which were all conducted using the same procedure. This memo will be updated as soon as the remaining results for the 5/24 jar test becomes available.

Table 1: Summary of recent jar testing data

	5/24/11		**5/20/11**		**5/19/11**		**Average**	
	Plant	**Jar Test**	**Plant**	**Jar Test**	**Plant**	**Jar Test**	**Plant**	**Jar Test**
Alum Dose	27 mg/L	27 mg/L	28 mg/L	28 mg/L	35 mg/l	35 mg/l	**30 mg/L**	**30 mg/L**
Raw Turbidity (NTU)	8.40	8.40	10.10 [a]	10.10	15.96	14.20	**11.49**	**10.90**
Settled Turbidity (NTU)	Pending	0.47	0.71	0.47	0.70	0.61	**0.71**	**0.52**
% Removal	*Pending*	*94%*	*93%*	*95%*	*96%*	*96%*	***94%***	***95%***
Filtered Turbidity (NTU)	Pending	0.08	0.07	0.08	0.06	0.09	**0.07**	**0.08**
% Removal	*Pending*	*99%*	*99%*	*99%*	*99%*	*99%*	***99%***	***99%***
Raw pH	6.9	6.9	7.3 [a]	7.3	6.7	7.2	**7.0**	**7.1**
Settled pH	Pending	6.6	6.8 [b] / 6.2 [c]	6.5	6.2 [c]	6.6	**6.5**	**6.6**
Filtered pH	Pending	6.7	6.2	6.9	6.1	6.9	**6.2**	**6.8**
Raw TOC (mg/L)	2.8	2.8	2.00	2.1	4.8	5.0	**3.2**	**3.3**
Settled TOC (mg/L)	2.3	1.6	1.0	0.7	1.6	2.9	**1.6**	**1.7**
% Removal	*18%*	*43%*	*50%*	*67%*	*67%*	*42%*	***45%***	***51%***
Filtered TOC (mg/L)	2.1	1.7	1.1	no data	1.6	2.7	**1.6**	**2.2**
% Removal	*25%*	*39%*	*45%*	*no data*	*67%*	*46%*	***46%***	***n/a***

[a] Assumed equal to the value measured in laboratory

[b] Measured in laboratory before chlorination.

[c] Measured by plant staff after chlorination.

As shown in the table, the bench-scale protocol achieves very similar levels of turbidity removal to full-scale treatment. Turbidity removal is shown graphically in **Figure 1.**

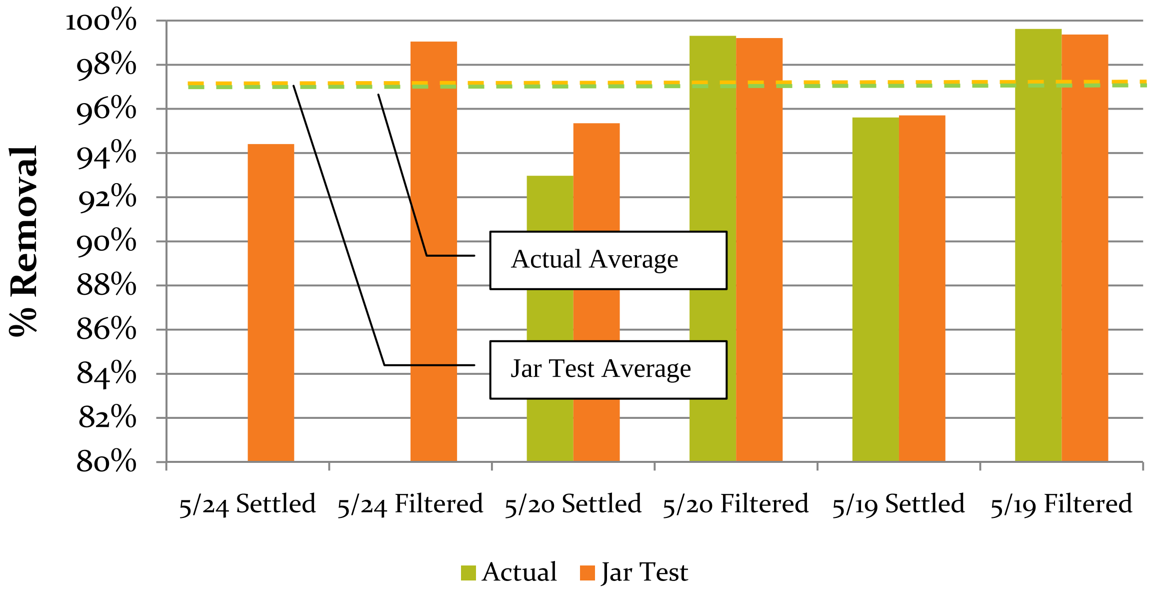
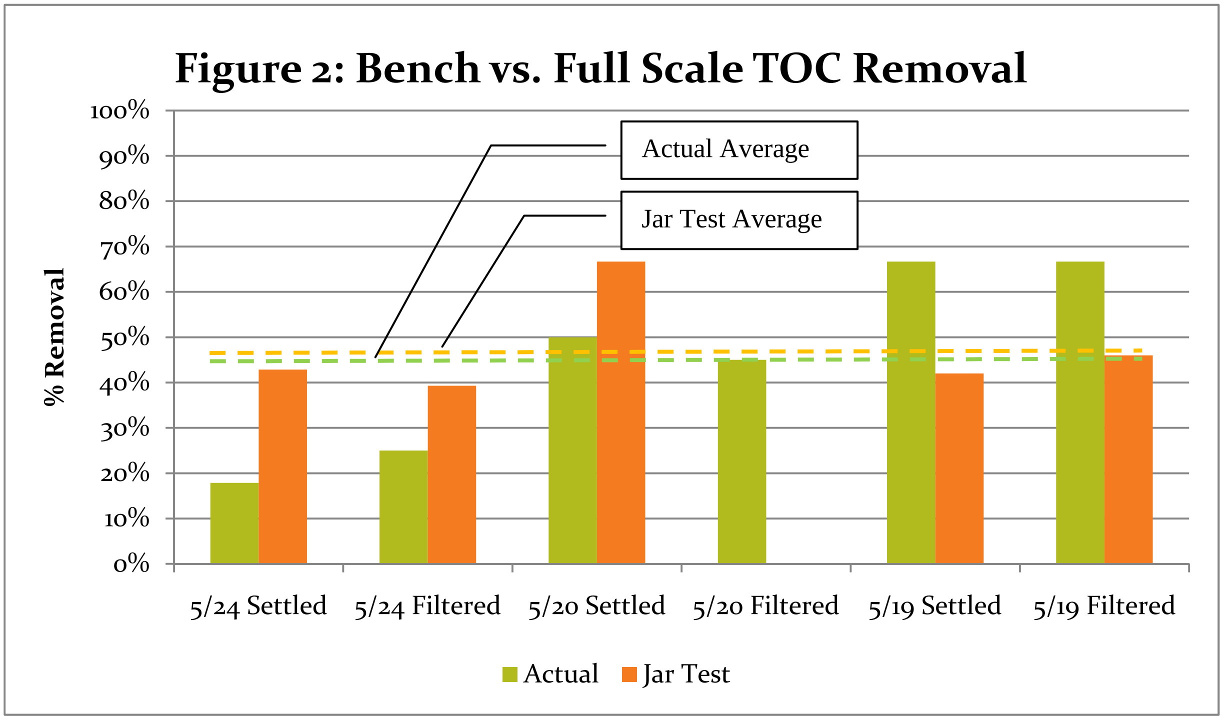
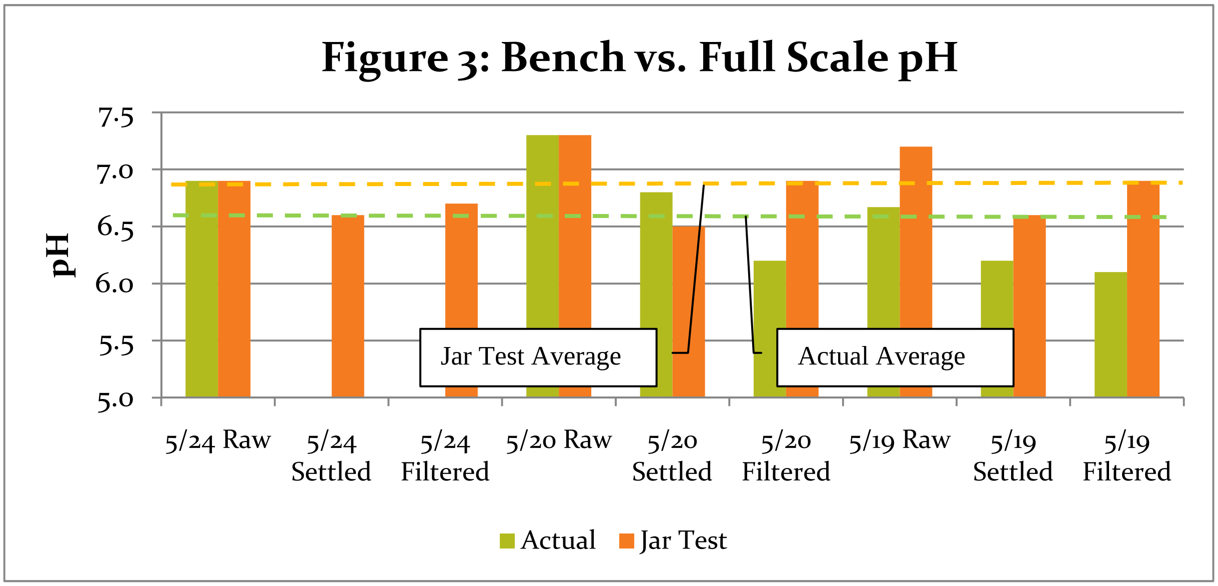


Figure 1: Bench vs. Full Scale Turbidity Removal

Jar testing achieved 39%-46% TOC removal, which appears to be somewhat more consistent than the range seen at full-scale (25%-67%). However, as raw water quality changes, jar testing appears to react differently than the full-scale process, e.g. the jar tests with lower TOC removal were not consistently associated with lower full-scale TOC removal. This finding is shown in **Figure 2.** There is support from the literature to suggest that differences in CO_2 release, discussed below, can account for significant differences in TOC removal between bench- and full-scale treatment (Tseng and Edwards, 1999). Figures 1 and 2 show that this type of data varies both full-scale and bench-scale, but the average of the conditions is reasonably close.

Finally, the settled and filtered water pH appears to be consistently higher at bench scale than at full scale, as shown in **Figure 3**. Two factors account for the discrepancy. First, the plant routinely measures settled water pH after chlorine is added. The gaseous chlorine used at the plant acts as an acid and lowers the pH somewhat. Thus in order to compare "apples to apples,"the full-scale pH must be measured prior to chlorine addition (this was done on 5/20). Second, plant staff performed measurements of dissolved CO_2 on both plant- and lab-treated waters and found that there was significantly less CO_2 in the lab-treated water. This occurs because the surface area to volume ratio of water in the jar testing apparatus is much greater than that in the plant's basins, allowing for more release of the gas.





In order to gauge the impact of chlorine addition on bench-treated water pH, the chlorine residual, pH, and dose of lime required to adjust the pH to the target were compared for filtered water from jar testing and a sample of plant filtered water. The results are shown in **Table 2.**

Table 2: Comparison of lime doses required to achieve target pH

	Before Chlorination and pH Adjustment		After Chlorination and pH Adjustment		Lime Solution Added
	Chlorine Residual	pH	Chlorine Residual	pH	
Jar Test	0.0 mg/L	6.89	1.5 mg/L	7.28	3.1 mL
Plant	0.4 mg/L	6.34	1.6 mg/L	7.28	10 mL

As shown in the table, the addition of chlorine does lower pH as expected, but does not account for the entire pH discrepancy between bench- and plant-treated water. As such, a greater lime dosage is required to adjust the plant-treated water to the target final pH than the bench-treated water.

Based on this information, CDM will revise the testing procedure to use floating styrofoam covers on the jars in order to minimize gas transfer with the atmosphere. This measure should improve the consistency of both pH and TOC removal between bench- and full-scale. The lime dose will be coordinated with the dose actually fed in the plant, while further adjustment of pH to the target will be made with carbonic acid (CO_2) if necessary.

Disinfection By-Product Formation

Plant staff have indicated that the vast majority of DBPs in the I&D system form inside the clearwell at the plant, with a detention time of approximately 12 hours. To further evaluate the bench-scale test protocol, samples of bench-treated water were chlorinated and held for 12-hours to measure the quantity of trihalomethanes (THMs) and haloacetic acids (HAAs) that form under laboratory conditions. Plant filtered water was also chlorinated using the same procedure as the bench-treated water. This will allow us to compare the extent to which the bench-scale treatment protocol yields similar DBP concentrations to full-scale treatment under the simulated distribution system conditions used in this study. The results of these measurements are expected early next week, and will be compared to DBP measurements taken from the clearwell at a time that corresponds to the same raw water matrix treated in the laboratory.

It is not expected that the DBP levels generated under laboratory conditions will match those in the plant clearwell exactly. Fluctuations in temperature and detention time (due to changing water demand) and effects of the clearwell and pipe walls are impossible to re-create at laboratory scale. By extension, the THM and HAA concentrations measured in the full study cannot be used to predict actual levels that may result from treatment changes.

Rather, they will provide a comparative basis for evaluating alternate treatments relative to the current regime.

This memo will be updated as soon as the DBP formation results become available.

Corrosivity

Corrosion takes place entirely in the distribution system, where detention time, wall effects, and temperature are even less consistent than the clearwell. Much like the DBPs, corrosion testing is not intended to predict metals concentrations in the actual system, but rather to provide a relative comparison to current treatment practice that will offer insight into the impact of seawater percentage on corrosion.

Preliminary testing with respect to corrosivity is not feasible due to the one-time use nature of the exposure containers and the long timescales involved in the reactions.

Conclusions and Recommendations

Due to the dynamic water quality characteristics of Savannah River water and the very nature of laboratory-scale testing, it is infeasible to expect the results of this study to exactly match the performance of current treatment or to predict the outcome of future changes in treatment with a high degree of precision. Preliminary testing of the refined jar testing and filtration protocol has shown that it achieves comparable removal of TOC and turbidity to full-scale treatment; although it does not respond in precisely the same way to changes in raw water quality. Similar removal of TOC and turbidity is important for subsequent corrosion and DBP studies, and we believe this protocol, with revisions as noted in this memo, will yield water of comparable quality for these purposes.

Given the urgency of the study, we recommend proceeding using the testing protocol (with modifications described in this memo), pending review of the DBP formation results early next week. We are confident that this testing procedure will yield a wealth of useful information about the impacts of increased seawater percentage, as intended. However, it is vital to the success of this project that all interested parties understand and agree that the conclusions which can be drawn from a laboratory study are primarily comparative in nature, which is consistent with the purpose of the study—to compare the impact of increased seawater concentration under different treatment conditions. Please concur that the bench vs. full scale correspondence is acceptable to proceed with testing.

Schedule

Provided that the DBP results do not raise further concerns, corrosion testing can begin during the first week of June. The proposed schedule for the remaining project is as follows:

5/31 – 7/15:	Initiate testing and corrosion exposure
Mid July:	Workshop with plant staff on preliminary findings, options, and conclusions
Late July:	Draft Report
Early August:	Final Report

References

Tseng, Tai and Edwards, Mark. "Predicting Full-Scale TOC Removal" *Journal of the American Water Works Association* 91:4 (1999).

cc: Hope Moorer, Georgia Ports Authority

Appendix C

Bench-Scale Disinfection Byproduct Memo

Memorandum

To: *Bill Dowbiggin*

From: *Ryan Kingsbury*

Date: *July 11, 2011*

Subject: *Preliminary Bench-scale vs. Full-Scale Disinfection by Products Results*

This memo supplements the progress memo issued May 26th with the results of the preliminary disinfection by products (DBPs) testing.

Plant staff have indicated that the vast majority of DBPs in the I&D system form inside the clearwell at the plant, which has a detention time of approximately 12 hours. To further evaluate the bench-scale test protocol, triplicate samples of bench-treated water (raw and 150 mg/L chloride spike) were chlorinated to a residual of 2.0 mg/L free chlorine and held for 12-hours to measure the quantity of trihalomethanes (THMs) and five haloacetic acids (HAAs) that formed under laboratory conditions. Plant filtered water was also chlorinated using the same procedure as the bench-treated water. Finally, the DBP concentrations in the plant clearwell were measured for comparison to the bench-scale results. The results are summarized in **Table 1** below.

As shown, the THM and HAA5 concentrations in the bench-treated plant raw waters are similar to those measured in the plant clearwell, indicating that the laboratory conditions chosen for this test are a good approximation of full-scale treatment conditions. Moreover, the triplicate raw waters all have very similar DBP concentrations, indicating that the results are reproducible. The same is true for the triplicate 150 mg/L chloride blends. The 150 mg/L chloride blends produced nearly twice the quantity of DBPs seen in the raw water. The higher DBP production also resulted in greater chlorine demand and lower residuals at the end of the incubation period, as shown in the table.

Bench-scale chlorination of the plant filtered water produced significantly higher THM and HAA5 concentrations than were observed either in the clearwell or the bench-treated raw waters. This result was not expected, but may be related to the fact that plant water receives some additional chlorine prior to filtration.

Table 1: Comparison of Bench-scale and Full-scale DBP Concentrations

Sample		Chlorine Residual after Incubation (mg/L)	pH after Incubation	THM (μg/L)	HAA5 (μg/L)
Bench-Treated Plant Raw Water	A	1.11	7.14	37	22
	B	1.11	7.22	38	18
	C	1.16	7.37	40	19
Bench-Treated Plant Raw Water with 150 mg/L Chloride	A	0.64	7.35	82	15
	B	0.59	7.34	81	14
	C	0.67	7.35	81	15
Plant Filtered Water		0.95	7.31	61	36
Plant Clearwell (full scale)		No data	No data	36	22

Figure 1 and **Figure 2** illustrate the THM and HAA5 concentrations, respectively, that resulted from this experiment. The colored sections of each bar represent individual THM or HAA species. Chloroform (CHCl3), bromodichloromethane (CHBrCL2), dibromochloromethane (CHBr2Cl), and bromoform (CHBr3) for THMs and chloroacetic (CAA), dichloroacetic (DCAA), trichloroacetic (TCAA), bromoacetic (BAA), and dibromoacetic acids (DBAA) for the HAAs. In both figures the individual species are stacked in order of increasing bromine content, with the most bromine-containing species at the top of each bar. Note that in this preliminary testing only the 5 regulated HAA species were measured. In full testing all 9 species, including the HAA species with the most bromine, will be measured.

As shown in the figures, the degree of bromine incorporation was significantly higher in the 150 mg/L chloride blend. In addition, the overall quantity of THMs increased because the brominated THMs have higher molecular weights than their chlorine-containing counterparts. The total quantity of HAA5 decreased, most likely because the unmeasured, more bromine-containing HAA species comprised a greater fraction of the HAAs formed. It is expected that when all 9 species are measured, the total HAA concentration in the chlorinated seawater blends will be elevated as is the case with the THMs. Both the increase in bromine-containing species and the overall increase in DBPs are consistent with expectations and can be attributed to the elevated bromide concentration in the seawater blend.

Figure 1: Trihalomethane Concentrations

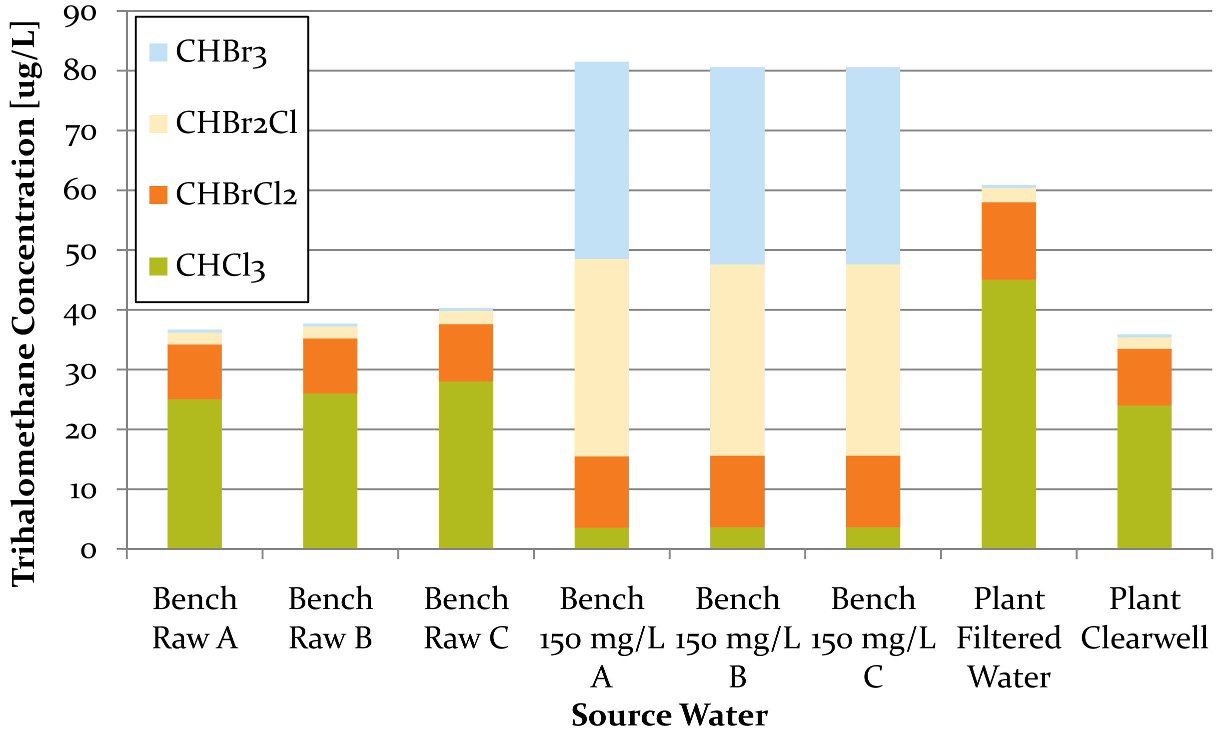
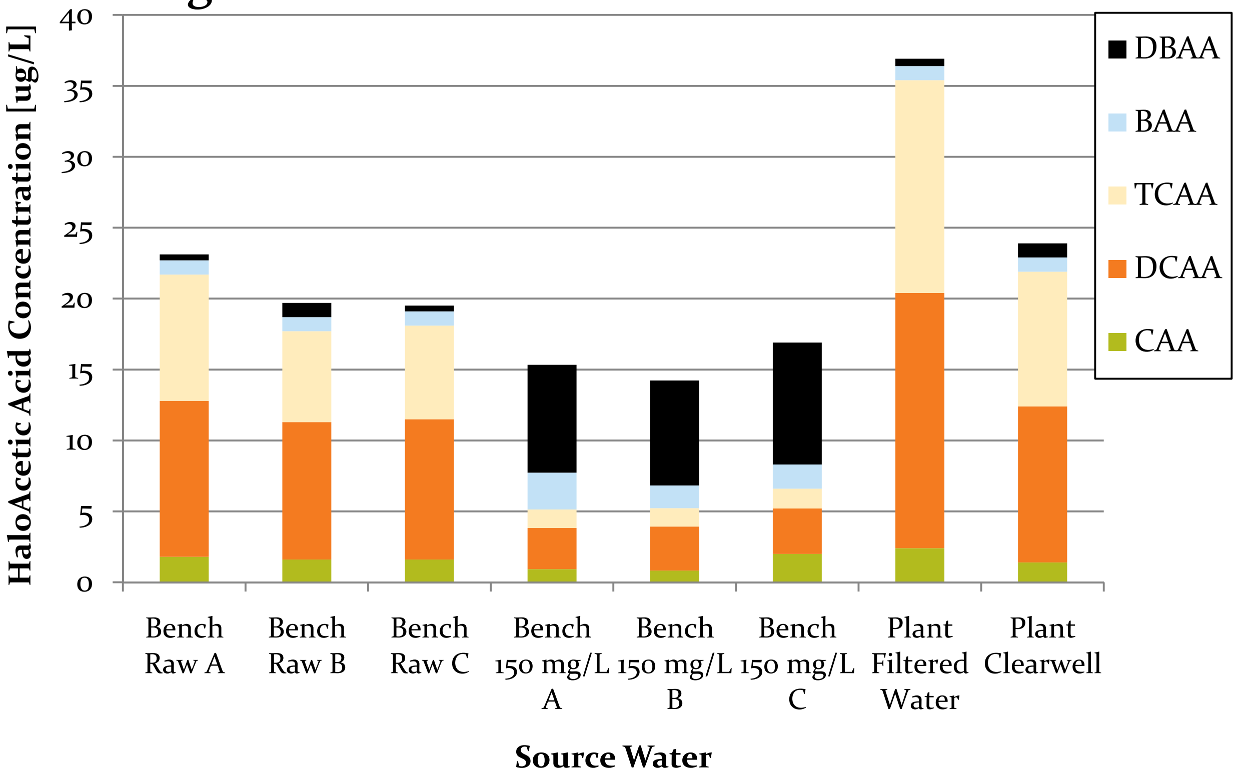


Figure 2: Haloacetic Acid Concentrations



As noted previously, it is not expected that the DBP levels generated under laboratory conditions will match those in the plant clearwell exactly. Fluctuations in temperature and detention time (due to changing water demand) and effects of the clearwell and pipe walls are impossible to re-create at laboratory scale. However, as the above data show, the laboratory results appear to approximate full-scale concentrations reasonably well. It can be inferred that the impact of increased seawater percentage on the bench-scale results (e.g. more bromine-containing DBPs) would be observed at full-scale as well.

Appendix D

Bench-Scale Testing Plan

CDM

Memorandum

To: *City of Savannah, Georgia*

From: *CDM*

Date: *June 16, 2011*

Subject: *Testing Plan for Seawater Effect Study*

This bench-scale study is being conducted in order to determine the potential impact that increased seawater intrusion into the City of Savannah's Water Treatment Plant may have on treated water corrosivity and disinfection byproduct (DBP) formation. Increased chloride concentrations could potentially impact compliance with the lead and copper rule. Increased concentrations of organic matter, chloride and bromide along with a potential pH change could impact compliance with the disinfectants and disinfection byproducts rule.

Current Treatment

The City of Savannah's Water Treatment Plant draws surface water from the Savannah River. The Water Treatment Plant (WTP) employs a conventional coagulation / flocculation / sedimentation / filtration process using flocculation aid polymer and aluminum sulfate as the coagulant. Free chlorine is used for primary disinfection, while free chlorine or chloramines provide a residual in the distribution system. The City uses sodium hexametaphosphate at a dose of approximately 0.75 mg/L to inhibit corrosion.

Historical data from 2003 to the present indicate that the following water quality characteristics, shown in **Table 1,** are typical of the raw water at the plant.

Table 1: Historical Raw Water Quality Characteristics

Parameter	Range[1]
pH	6.0 – 6.8
Alkalinity	13- 29 - mg/L as $CaCO_3$
Turbidity	10-40 NTU
Hardness	18 -31 mg/L as $CaCO_3$
Chloride	5.5 – 14.2 mg/L

[1] Range of monthly average values from 2003-2010

Water Quality Test Conditions

A total of 64 distinct water quality conditions for corrosion will be tested in this study. These conditions comprise factorial combinations of 5 chloride concentrations, 3 pH levels, 2 types of disinfectant, and 2 corrosion inhibitor doses. Two additional pH levels will be tested on two selected water matrices, bringing the total to 64. Existing treatment conditions are used as a base case for each parameter, which are then varied based on anticipated treatment changes resulting from increased seawater intrusion. **Table 2** summarizes the conditions being tested.

Table 2: Summary of Water Quality Conditions

Chloride	pH	Disinfectant	Corrosion Inhibitor
Existing (10 mg/L)	Existing[1] (7.3 ± 0.15)	Free Chlorine (2.0 ± 0.2 mg/L)	Existing (0.75 mg/L)
25 mg/L	7.5 ± 0.15[2]		
50 mg/L	7.8 ± 0.15	Chloramines (~1.2 mg/L)[4]	Existing + 0.75 mg/L
75 mg/L	7.9 ± 0.15[3]		
150 mg/L (Sensitivity Test)	8.3 ± 0.15		

[1] Target finished water pH, according to plant staff.

[2] 25 mg/L and 50 mg/L with free chlorine and existing inhibitor only.

[3] 50 mg/L and 75 mg/L with free chlorine and existing inhibitor only.

[4] Chloramines will be formed using procedures identical to full-scale treatment. Exact residual will be measured after formation but plant staff and data indicate that 1.2 mg/L is typical.

Plumbing Material Test Conditions

Each of the 64 water matrices described above will be exposed to two different plumbing materials using specially-made exposure containers. The containers are:

- 60-mL glass jars containing a copper coupon galvanically connected to lead solder
- 35-mL sections of PVC pipe with mild steel coupons affixed to one end

Testing on lead/copper solder unions will be conducted in triplicate, while testing on the mild steel coupons will be conducted in duplicate, for a total of 192 jars and 128 pipe segments, respectively. Samples will be collected from each material on a weekly basis, as described in the Procedures section below.

Procedures

Water will be exposed to the plumbing materials in batch using a "fill and dump" procedure two times per week. The frequency of the fill and dump is intended to simulate the worst-case time of exposure to these plumbing materials in a typical residence or commercial building. Samples will be collected for laboratory analysis during one of these cycles each week. The study will continue for 6 weeks.

The sections below detail the procedures for the preparation of seawater blends, water treatment, sample collection, and laboratory analysis.

Preparation of Seawater Blends (Initial Setup and Testing)

1. Collect approximately 5 gal of estuarine water from the Savannah River just upstream of its junction with the Atlantic Ocean. Preferably collect from a bridge or boat to avoid near-shore effects.

2. Analyze an aliquot of this water for chloride, conductivity, and total organic carbon (TOC).

3. Based on the results, spike 20-L samples of raw water from the plant intake with appropriate quantities of estuarine water to achieve 25, 50, 75, and 150 mg/L chloride, for a total of four 20-L blends. The 150 mg/L chloride concentration is twice the maximum predicted daily average value, but will be analyzed as a sensitivity test. Preferably use raw water collected between high and low tide.

4. Perform jar testing with alum on each of the four blends and on unblended raw water. Use the following procedure, which is intended to simulate full-scale treatment as closely as possible:

    - Place 2L of water in each of 6 square beakers
    - Add coagulant and begin 1minute of rapid mix at 90 rpm
    - Add polymer during rapid mix
    - Measure pH and add lime as needed to maintain pH above 5.3
    - After 1 min rapid mix ends, turn down mixer speed for staged flocculation
    - Mix for 5 min at 60 rpm (G=55 sec^{-1}), 5 min at 30 rpm (G=23 sec^{-1}), and 5 min at 15 rpm (G=18 sec^{-1}). Turn off mixer.
    - Allow to settle 30+ minutes

    Measure the TOC and turbidity of the supernatant in each jar. Document the final pH of each blend, polymer dose, alum dose, and % removal of TOC and turbidity.

5. Prepare ~20L of the four seawater blends and unblended raw water. Perform coagulation on each using the optimal coagulant dose and the same procedures as used for jar testing, but allow the water to settle until the turbidity of the supernatant is

approximately equal to the full-scale settled water turbidity (about 90 minutes). Filter the supernatant through glass microfiber filters pre-rinsed with 500-mL of deionized (DI) water. The objective of this set of tests is to simulate full-scale treatment.

6. Analyze each filtered water blend for chloride, bromide, sulfate, TOC, UV absorbance at 254nm, alkalinity, total- and ortho-phosphate, lead, copper, and iron. Repeat these analyses for blends prepared during the last week of the study. The objective of this set of tests (and the simulated distribution testing in Step 7) is to evaluate the impact of seawater intrusion on water quality, relative corrosivity, and the efficacy of full-scale treatment.

7. Separate three 1-L samples each of the *treated* raw water. Adjust the pH of the three samples to existing, existing+0.5, and existing+1.0 (see Table 2). Take 1-L samples of the 75 mg/L and 150 mg/L chloride blend and adjust pH to existing. Send to the laboratory for simulated distribution system (SDS) testing under the conditions specified in **Table 3**. Analyze for four trihalomethanes (THMs) and nine haloacetic acids (HAAs).

Table 3: Conditions for Simulated Distribution System Testing

Free Chlorine Residual	Temperature	Incubation Time
2.0 ± 0.2 mg/L	25° C	24 hours

Note that although the above parameters are related to actual conditions in the distribution system, the purpose of the simulated distribution system testing is to provide a *comparison* of DBP formation among the different water matrices. It is not expected to predict actual DBP concentrations due to fluctuations in temperature, variable water age, different pipe materials, and other factors that cannot be replicated in the laboratory.

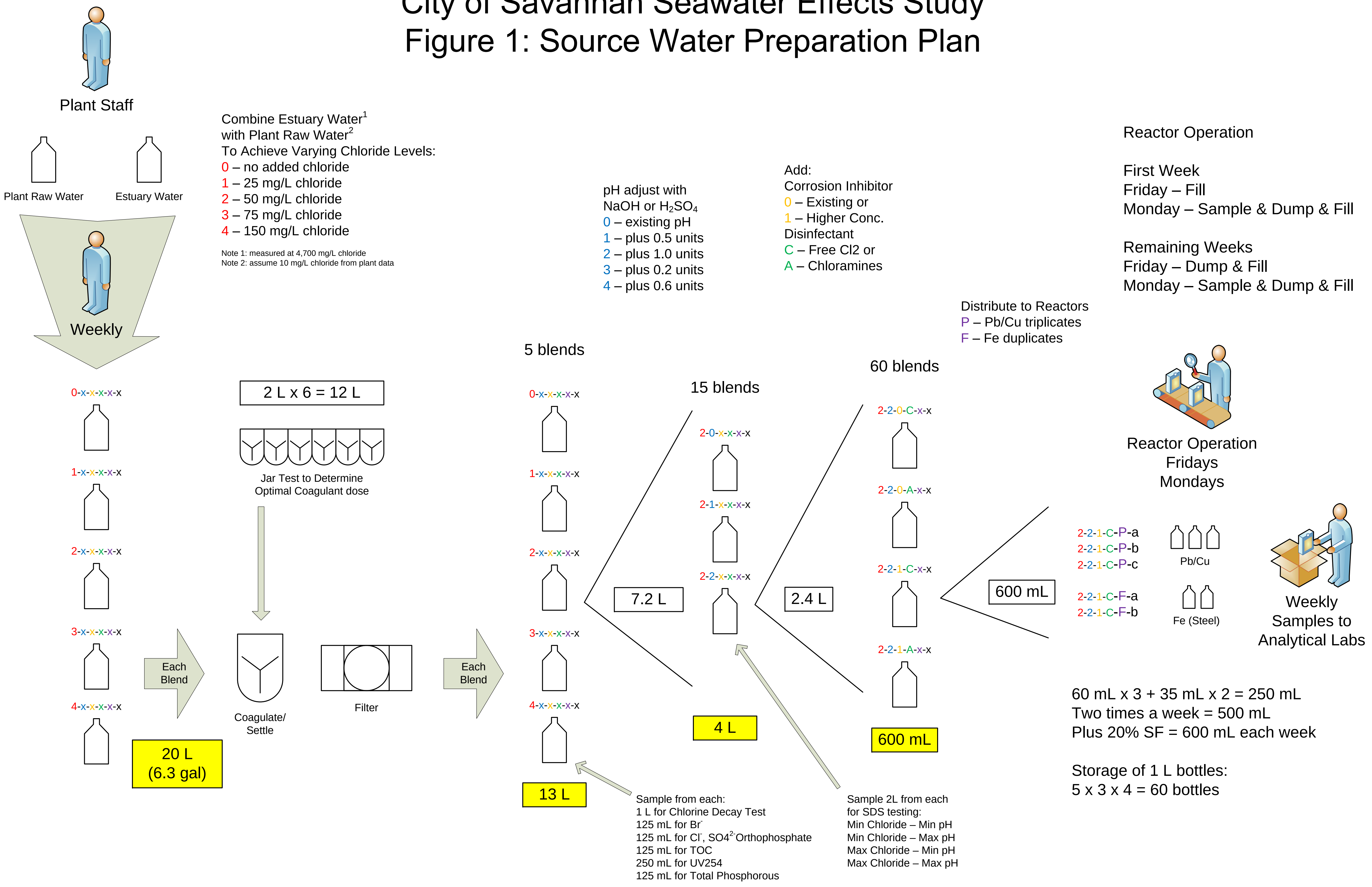
8. Treat the remaining volume of each of the filtered waters for use during the first week of study by following steps 3 – 6 below.

Water Treatment (to be performed weekly)

The water matrices exposed to the plumbing materials will be prepared fresh every week according to procedures shown schematically in **Figure 1**. These procedures are described in detail below.

1. Determine the required chemical amounts to achieve target inhibitor and disinfectant doses for the different water matrices (see Table 1). Prepare stock solutions of each chemical. Withdraw chlorine stock solution from the plant's educator system and measure its strength.

City of Savannah Seawater Effects Study
Figure 1: Source Water Preparation Plan



Plant Staff

Plant Raw Water

Estuary Water

Weekly

Combine Estuary Water[1]
with Plant Raw Water[2]
To Achieve Varying Chloride Levels:
0 – no added chloride
1 – 25 mg/L chloride
2 – 50 mg/L chloride
3 – 75 mg/L chloride
4 – 150 mg/L chloride

Note 1: measured at 4,700 mg/L chloride
Note 2: assume 10 mg/L chloride from plant data

0-x-x-x-x-x
1-x-x-x-x-x
2-x-x-x-x-x
3-x-x-x-x-x
4-x-x-x-x-x

20 L
(6.3 gal)

Each Blend

2 L x 6 = 12 L

Jar Test to Determine
Optimal Coagulant dose

Coagulate/
Settle

Filter

Each Blend

pH adjust with
NaOH or H_2SO_4
0 – existing pH
1 – plus 0.5 units
2 – plus 1.0 units
3 – plus 0.2 units
4 – plus 0.6 units

5 blends

0-x-x-x-x-x
1-x-x-x-x-x
2-x-x-x-x-x
3-x-x-x-x-x
4-x-x-x-x-x

13 L

7.2 L

Sample from each:
1 L for Chlorine Decay Test
125 mL for Br^-
125 mL for Cl^-, $SO4^{2-}$Orthophosphate
125 mL for TOC
250 mL for UV254
125 mL for Total Phosphorous

Add:
Corrosion Inhibitor
0 – Existing or
1 – Higher Conc.
Disinfectant
C – Free Cl2 or
A – Chloramines

15 blends

2-0-x-x-x-x
2-1-x-x-x-x
2-2-x-x-x-x

4 L

2.4 L

Sample 2L from each
for SDS testing:
Min Chloride – Min pH
Min Chloride – Max pH
Max Chloride – Min pH
Max Chloride – Max pH

Distribute to Reactors
P – Pb/Cu triplicates
F – Fe duplicates

60 blends

2-2-0-C-x-x
2-2-0-A-x-x
2-2-1-C-x-x
2-2-1-A-x-x

600 mL

600 mL

Reactor Operation

First Week
Friday – Fill
Monday – Sample & Dump & Fill

Remaining Weeks
Friday – Dump & Fill
Monday – Sample & Dump & Fill

Reactor Operation
Fridays
Mondays

2-2-1-C-P-a
2-2-1-C-P-b
2-2-1-C-P-c

Pb/Cu

2-2-1-C-F-a
2-2-1-C-F-b

Fe (Steel)

Weekly
Samples to
Analytical Labs

60 mL x 3 + 35 mL x 2 = 250 mL
Two times a week = 500 mL
Plus 20% SF = 600 mL each week

Storage of 1 L bottles:
5 x 3 x 4 = 60 bottles

2. Prepare 20L of one seawater blend by adding the appropriate quantity of seawater to plant raw water. Preferably withdraw plant raw water between high and low tide. Perform coagulation and filtration using the optimal conditions identified above.

3. Divide the blend into 4-L and 6-L portions. Add chlorine to achieve the desired dose, shown in Table 2, to the 4-L portion. If necessary, adjust the pH of both portions to match that of the full-scale filtered water (pH ~6.5) by bubbling CO_2. Allow both containers to incubate at room temperature for 12 hours.

4. After 12 hours, check the chlorine residual in the 4-L container and boost to 1.0 mg/L if lower. Add ammonium hydroxide at a Cl2:NH3 weight ratio of 2.2:1, per standard plant operations. Add chlorine to the 6-L portion to achieve a 2.0 mg/L residual.

5. Divide each 4-L and 6-L portion into three aliquots. Make remaining adjustments to the three target pHs using lime and carbonic acid (if necessary).

6. Using a graduated cylinder, divide each pH-adjusted sample into two 600-mL aliquots, placing each in a 1-L reagent bottle, for a total of twelve. Add corrosion inhibitor as indicated in Table 2. Label each bottle to indicate its treatment according to the coding scheme shown in **Figure 2.** Preferably associate color-coded tape or markings with at least some of the variables to minimize human error.

Figure 2: Sample Coding Scheme

```
0 - 0 - 1 - C - P -  a

^    ^    ^    ^    ^    ^
|    |    |    |    |    Duplicate/Triplicate
|    |    |    |    Material
|    |    |    Disinfectant
|    |    Inhibitor Concentration
|    pH
Chloride Blend
```

Above Example Indicates:
Existing Cl, Existing pH, higher inhibitor,
Free Cl2, pb/cu sample, first triplicate

Constituent Codes

Chloride		pH	
0	Existing	0	Existing
1	25 mg/L	1	+ 0.5 units
2	50 mg/L	2	+ 1.0 unit
3	75 mg/L	*3*	*+ 0.2 units*
4	150 mg/L	*4*	*+ 0.6 units*

Inhibitor		Disinfectant	
0	Existing	C	Free Cl2
1	Higher	A	Chloramine

Material		Duplicate/Triplicate	
P	Pb/Cu	a	first
F	Fe	b	Second
		c	Third

7. Rinse the intermediate containers. Repeat steps 2 through 6 for the other four seawater blends. Using similar procedures, but adjusting volumes as needed, prepare 600 mL of each of the four "extra pH" matrices noted in Table 2.

Exposure Testing and Sample Collection

Each water matrix will be continuously exposed to the plumbing materials using purpose-built exposure jars. Water in each jar will be changed twice per week (Mon/Fri), and samples from each jar at the time of the change will be composited and sent for laboratory analysis every week. All exposed water will be collected and analyzed so that mass balance calculations can be performed at the end of the study. Sampling procedures are diagrammed in **Figure 3** and described in detail below.

1. Prepare and label all exposure jars according to the coding scheme shown in Figure 2. Preferably associate color-coded tape or markings with at least some of the variables to minimize human error.

2. (First week only.) Fill each exposure jar with the matching water from the 1-L sample bottles prepared in the previous section. Store the 1-L bottles in coolers after filling is complete.

3. Prepare sample containers for each water matrix labeled according to Figure 2 with a sharpie. Add 2.0 mL of 10% nitric acid to each of the iron sample containers and 3.5 mL to each of the lead/copper sample containers using an automatic pipet. **Use appropriate protective measures including gloves, goggles, and a lab coat when handling the acid.**

4. Twice per week (Mon/Fri), manually dump water from each of the exposure jars. All dumped water is to be composited into the appropriate container; DO NOT DISCARD ANY WATER FROM THE JARS. During the first and last week, dump each replicate exposure jar into a separate container. During the other weeks, combine the water from each of the three lead/copper triplicates into one container, and from each of the two steel duplicates into another. In all cases, combine water dumped Monday and Friday into the same container. **NOTE: the sample jars contain nitric acid as a preservative. Take care not to dump out the acid and use appropriate personal protective equipment.**

5. Refill sample containers with the appropriate treated water matrix (Mon /Fri each week). Remove the 1-L sample bottles from the coolers the night before each fill/dump cycle to allow them to reach room temperature.

6. Store the composite sample containers in the designated area until picked up for analysis by the lab courier.

City of Savannah Seawater Effects Study
Figure 3: Sampling Plan

Combine Estuary Water[1]
with Plant Raw Water[2]
To Achieve Varying Chloride Levels:
0 – no added chloride
1 – 25 mg/L chloride
2 – 50 mg/L chloride
3 – 75 mg/L chloride
4 – 150 mg/L chloride

Note 1: measured at 4,700 mg/L chloride
Note 2: assume 10 mg/L chloride from plant data

pH adjust with
NaOH or H_2SO_4
0 – existing pH
1 – plus 0.5 units
2 – plus 1.0 units
3 – plus 0.2 units
4 – plus 0.6 units

Add:
Corrosion Inhibitor
0 – Existing or
1 – Higher Conc.

Add:
Disinfectant
C – Free Cl2 or
A – Chloramines

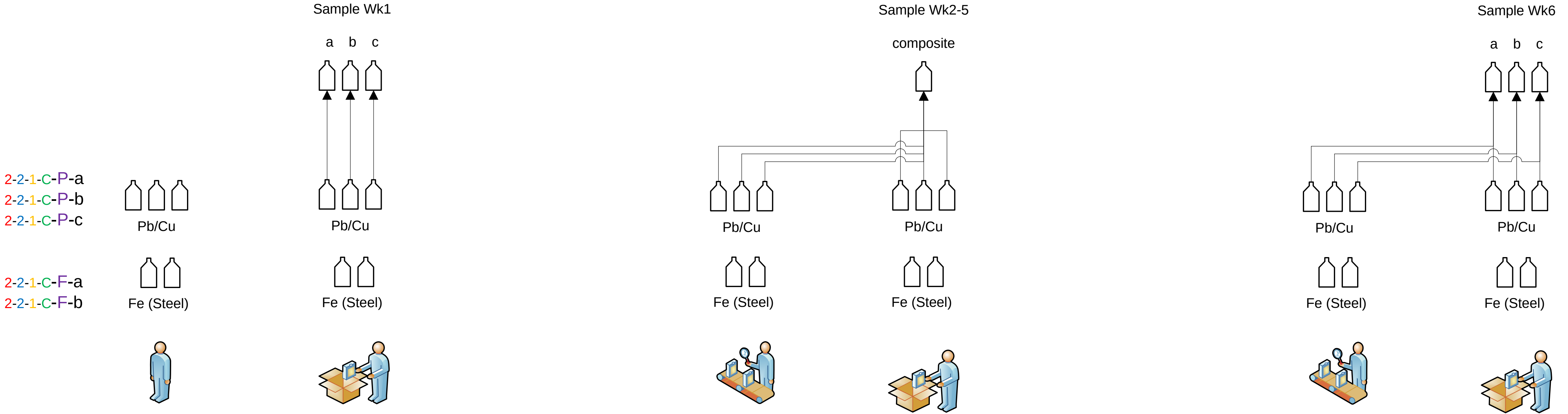
1 L bottles
60 Matrices
Prepared Weekly

Distribute to Reactors
P – Pb/Cu triplicates
F – Fe duplicates

First Week
Friday – Fill
Monday – Sample & Dump & Fill

Middle Weeks
Friday – Dump & Fill
Monday – Sample & Dump & Fill

Sixth Week
Friday – Dump & Fill
Monday – Sample & Dump



Week 1
Friday

Prepare
Reagents
600 mL

Source Water
Samples to
Analytical
Lab

Set up
Reactors
Fill

Week 1
Monday

Reactor
Dump
& Fill

Reactor
Samples to
Analytical
Lab

Week 2-5
Friday

Prepare
Reagents
600 mL

Reactor
Dump
& Fill

Week 2-5
Monday

Reactor
Dump
& Fill

Reactor
Samples to
Analytical
Lab

Week 6
Friday

Prepare
Reagents
600 mL

Source Water
Samples to
Analytical
Lab

Reactor
Dump
& Fill

Week 6
Monday

Reactor
Dump

Reactor
Samples to
Analytical
Lab

Laboratory Analysis

Table 4 presents a listing of the samples to be analyzed at the laboratory throughout the study. Testing for corrosion products (metals) will be performed every week. Note that samples for the replicate exposure jars will be analyzed separately during the first and last round of sampling, but will be composited during the other rounds of sampling. Water quality testing of the treated seawater blends (prior to pH adjustment or chemical addition) will be performed twice (near the beginning and the end of the study) to provide confirmation that source water quality remained constant. SDS testing will be performed once at the beginning of the study.

Table 4: Laboratory Samples

Analyte	No. of Waters	No. of Samples per Week per water	Duration (weeks)	Waters to be Analyzed
Lead and Copper	64	1	4**	All treated, exposed waters
Lead and Copper (triplicate)	64	3	2*	All treated, exposed waters (+ all triplicates)
Iron	64	1	4**	All treated, exposed waters
Iron (duplicate)	64	2	2*	All treated, exposed waters (+ all duplicates)
Lead and Copper	5	1	2	Filtered seawater blends only
Iron	5	1	2	Filtered seawater blends only
Chloride	5	1	2	Filtered seawater blends only
Bromide	5	1	2	Filtered seawater blends only
Sulfate	5	1	2	Filtered seawater blends only
Total Organic Carbon	5	1	2	Filtered seawater blends only
UV Abosrbance at 254nm	5	1	2	Filtered seawater blends only
Orthophosphate	5	1	2	Filtered seawater blends only
Total Phosphate	5	1	2	Filtered seawater blends only
THM4	5	2	1	Treated waters: ambient, 75 mg/L, and 150 mg/L chloride at existing pH, ambient chloride at existing pH, +0.5, +1.0 only, duplicate for each
HAA9	5	2	1	Treated waters: ambient, 75 mg/L, and 150 mg/L chloride at existing pH, ambient chloride at existing pH, +0.5, +1.0 only, duplicate for each

* Triplicate / duplicate analysis will be performed only during the first and last round of sampling. Triplicates/duplicates will be composited during the other rounds.

** If metals concentrations are relatively stable after the first 3 weeks, one or two weeks of intermediate sampling may be omitted to save cost and labor.

Special procedures must be followed for metals testing. Based on input from Dr. Marc Edwards at Virginia Tech, the analytical laboratory will be directed to perform strong acid digestions of all metals samples associated with our study, as described in Standard Methods 3030D and E. This procedure ensures that all the metal in the sample, including particulates, will be captured in the analysis. It is critical to capture all the metal in the samples in order to be able to perform mass balance calculations on the resulting data. However, the strong acid digestion is a slight departure from the standard USEPA Method 200.8, for which the laboratory is officially certified. The EPA method calls for this type of digestion only if the turbidity of the sample is >1. Based on Dr. Edwards' extensive experience with metals measurements, documentation in Standard Methods, and support from the literature (Triantafyllidou, Parks, and Edwards, 2007; Parks et al., 2004) we feel that exceeding the minimum requirements of the EPA method in this instance is justified.

References

Standard Methods for the Examination of Water and Wastewater, 20th Ed. American Public Health Association, American Water Works Association, Water Environment Federation publication. APHA, Washington D.C.

Parks, Jeffrey L. et al. "Determination of total chromium in environmental water samples," *Water Research* 38 (2004), 2827-2838.

Triantafyllidou, Simoni, Parks, Jeffrey, and Edwards, Mark. "Lead articles in Potable Water," *Journal of the American Water Works Association* 99, no. 6 (2007), 107-117.

Appendix E

Water Quality Data Summary

City of Savannah, GA
Seawater Effects Study
Water Quality Data Summary

Water Matrix	Chloride mg/L	Bromide ug/L	Sulfate mg/L	CSMR -	TOC mg/L	UV254 1/cm	SUVA L/mg-m	Lead ug/L	Copper ug/L	Iron ug/L	Ortho-phosphate mg/L	Total Phos-phorous mg/L
Blend 0												
Week 1	10	63	13	0.77	2.8	0.140	5.00	<1.5	7.1	1400	0.087	<0.1
Week 2	10	49	26	0.38	1.8	0.025	1.39	<1.5	<5	<100	<0.05	<0.1
Week 3	16	59	27	0.59	1.8	0.026	1.44	<1.5	5.1	<100	<0.05	<0.1
Week 4	12	42	31	0.39	2.3	0.031	1.35	<1.5	<5	<100	<0.05	<0.1
Week 5	11	38	27	0.41	1.8	0.026	1.44	<1.5	<5	<100	<0.05	<0.1
Week 6	10	49	27	0.37	2	0.073	3.65	<1.5	<5	<100	<0.05	<0.1
Average	*12*	*50*	*25*	*0.49*	*2.1*	*0.054*	*2.38*	*0*	*2*	*233*	*0*	*0*
Std. Dev.	*2*	*10*	*6*	*0.16*	*0.4*	*0.046*	*1.57*	*0*	*3*	*572*	*0*	*0*
Blend 1												
Week 1	23	100	14	1.64	3	0.150	5.00	<1.5	6	1100	0.086	<0.1
Week 2	23	95	28	0.82	1.9	0.026	1.37	<1.5	<5	<100	<0.05	<0.1
Week 3	29	100	29	1.00	1.8	0.031	1.72	<1.5	<5	<100	<0.05	<0.1
Week 4	25	92	32	0.78	2.4	0.036	1.50	<1.5	<5	<100	<0.05	<0.1
Week 5	25	85	29	0.86	1.9	0.018	0.95	<1.5	<5	<100	<0.05	<0.1
Week 6	24	100	29	0.83	2	0.027	1.35	<1.5	<5	<100	<0.05	<0.1
Average	*25*	*95*	*27*	*0.99*	*2.2*	*0.048*	*1.98*	*0*	*1*	*183*	*0*	*0*
Std. Dev.	*2*	*6*	*6*	*0.33*	*0.5*	*0.050*	*1.50*	*0*	*2*	*449*	*0*	*0*
Blend 2												
Week 1	47	190	17	2.76	2.9	0.140	4.83	<1.5	7.1	1100	0.085	<0.1
Week 2	45	180	31	1.45	1.8	0.027	1.50	<1.5	<5	<100	<0.05	<0.1
Week 3	54	190	33	1.64	1.9	0.077	4.05	<1.5	<5	<100	<0.05	<0.1
Week 4	49	170	36	1.36	2.3	0.042	1.83	<1.5	<5	<100	<0.05	<0.1
Week 5	49	160	32	1.53	2	0.015	0.75	<1.5	<5	<100	<0.05	<0.1
Week 6	46	170	33	1.39	1.8	0.032	1.78	<1.5	<5	<100	<0.05	<0.1
Average	*48*	*177*	*30*	*1.69*	*2.1*	*0.056*	*2.46*	*0*	*1*	*183*	*0*	*0*
Std. Dev.	*3*	*12*	*7*	*0.54*	*0.4*	*0.046*	*1.60*	*0*	*3*	*449*	*0*	*0*
Blend 3												
Week 1	69	280	21	3.29	3.3	0.140	4.24	<1.5	8.5	1100	0.078	<0.1
Week 2	68	260	35	1.94	1.9	0.031	1.63	<1.5	<5	<100	<0.05	<0.1
Week 3	75	260	36	2.08	2	0.027	1.35	<1.5	<5	<100	<0.05	<0.1
Week 4	74	230	40	1.85	2.4	0.033	1.38	<1.5	<5	<100	<0.05	<0.1
Week 5	73	240	36	2.03	2.1	0.021	1.00	<1.5	<5	<100	<0.05	<0.1
Week 6	68	240	36	1.89	2	0.033	1.65	<1.5	<5	<100	<0.05	<0.1
Average	*71*	*252*	*34*	*2.18*	*2.3*	*0.048*	*1.87*	*0*	*1*	*183*	*0*	*0*
Std. Dev.	*3*	*18*	*7*	*0.55*	*0.5*	*0.046*	*1.18*	*0*	*3*	*449*	*0*	*0*
Blend 4												
Week 1	140	470	30	4.67	3.2	0.130	4.06	1.6	10	960	0.065	<0.1
Week 2	130	480	43	3.02	2.2	0.029	1.32	<1.5	<5	<100	<0.05	<0.1
Week 3	140	490	47	2.98	2.2	0.027	1.23	<1.5	<5	<100	<0.05	<0.1
Week 4	140	460	50	2.80	2.7	0.037	1.37	<1.5	<5	<100	<0.05	<0.1
Week 5	140	480	45	3.11	2.2	0.019	0.86	<1.5	<5	<100	<0.05	<0.1
Week 6	140	470	46	3.04	2.2	0.028	1.27	<1.5	<5	<100	<0.05	<0.1
Average	*138*	*475*	*44*	*3.27*	*2.5*	*0.045*	*1.69*	*0*	*2*	*160*	*0*	*0*
Std. Dev.	*4*	*10*	*7*	*0.69*	*0.4*	*0.042*	*1.18*	*1*	*4*	*392*	*0*	*0*

---

* Values below detection limit are evaluated as 0 for averaging purposes

Appendix F

Metal Corrosion Data Summary

Notes for Interpreting the Metal Corrosion Data

Samples are listed according to their reactor label, which follow the coding scheme below:

Sample Coding Scheme

```
0  -  0  -  1  -  C  -  P  -  a

^     ^     ^     ^     ^     ^
|     |     |     |     |     Duplicate/Triplicate
|     |     |     |     Material
|     |     |     Disinfectant
|     |     Inhibitor Concentration
|     pH
Chloride Blend
```

Above Example Indicates:
Existing Cl, Existing pH, higher inhibitor,
Free Cl2, pb/cu sample, first triplicate

Constituent Codes

Chloride		pH	
0	Existing	0	Existing
1	25 mg/L	1	+ 0.5 units
2	50 mg/L	2	+ 1.0 unit
3	75 mg/L	*3*	*+ 0.2 units*
4	150 mg/L	*4*	*+ 0.6 units*

Inhibitor		Disinfectant	
0	Existing	C	Free Cl2
1	Higher	A	Chloramine

Material		Duplicate/Triplicate	
P	Pb/Cu	a	First
F	Fe	b	Second
		c	Third

Notes

1. During week 1, a number of samples were flagged with a “B” indicating that lead was detected in both the sample and the laboratory blank. The lab did not offer any explanation as to why this may have been the case. However, the levels of lead detected in the samples were orders of magnitude greater than those detected in the blanks. Therefore, this issue was not considered to impact the findings. Moreover, Week 1 data was excluded from subsequent analysis for reasons explained in Section 5.5.3.

2. The replicate samples (“a” and “b” reactors for iron and “a” “b” and “c” reactors for lead and copper) were composited together during weeks 2 through 5 of the study. These composite results are reported only once in the data table and are listed with the “a” reactors.

3. During week 6, a number of samples were misplaced by the lab before they could be analyzed. These are indicated with an “N.”

4. One sample during week 1 was deemed an outlier and excluded from analysis. This measurement indicated no lead detected, but both replicates and all other lead samples contained significant concentrations. These are indicated with an “O.”

5. Two measurements from week 6 were deemed outliers and were excluded from analysis. Both had lead levels higher than the week 1 measurement and more than 10x greater than both of their other replicates during week 6. This is indicated with an “O.”

City of Savannah Seawater Effects Study

Metals Corrosion Data Summary

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O Outlying data point excluded from analysis

Reactor Label						Week 1 - 6/6/2011			Week 2 - 6/13/2011			Week 3 - 6/20/2011			Week 4 - 6/27/2011			Week 5 - 7/5/2011			Week 6 - 7/15/2011			Average		
						Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L
0	0	0	C	F	a			23000			21000			18000			17000			31000			17000			21167
0	0	1	C	F	a			25000			20000			20000			22000			26000			22000			22500
0	0	0	A	F	a			33000			18000			18000			22000			20000			13000			20667
0	0	1	A	F	a			31000			19000			16000			20000			23000			15000			20667
0	1	0	C	F	a			26000			23000			22000			26000			41000			20000			26333
0	1	1	C	F	a			23000			21000			27000			29000			25000			16000			23500
0	1	0	A	F	a			34000			23000			21000			21000			23000			16000			23000
0	1	1	A	F	a			31000			27000			24000			26000			26000			14000			24667
0	2	0	C	F	a			22000			23000			25000			30000			27000			24000			25167
0	2	1	C	F	a			21000			27000			23000			19000			21000			15000			21000
0	2	0	A	F	a			29000			20000			23000			19000			22000			19000			22000
0	2	1	A	F	a			26000			22000			23000			24000			26000			15000			22667
1	0	0	C	F	a			24000			22000			23000			32000			28000			19000			24667
1	0	1	C	F	a			27000			19000			19000			28000			24000			23000			23333
1	0	0	A	F	a			910			21000			22000			24000			29000			16000			18818
1	0	1	A	F	a			21000			18000			19000			23000			23000			13000			19500
1	1	0	C	F	a			20000			29000			23000			25000			32000			21000			25000
1	1	1	C	F	a			21000			20000			25000			32000			33000			17000			24667
1	1	0	A	F	a			22000			25000			19000			23000			30000			14000			22167
1	1	1	A	F	a			27000			23000			25000			23000			22000			16000			22667
1	2	0	C	F	a			23000			21000			28000			30000			31000			21000			25667
1	2	1	C	F	a			17000			23000			27000			32000			24000			24000			24500
1	2	0	A	F	a			29000			27000			20000			29000			30000			17000			25333
1	2	1	A	F	a			29000			26000			23000			31000			28000			19000			26000
2	0	0	C	F	a			16000			28000			28000			32000			34000			18000			26000
2	0	1	C	F	a			26000			25000			25000			32000			29000			23000			26667
2	0	0	A	F	a			31000			27000			22000			24000			29000			22000			25833
2	0	1	A	F	a			28000			25000			23000			26000			31000			17000			25000
2	1	0	C	F	a			26000			29000			31000			26000			32000			21000			27500
2	1	1	C	F	a			24000			20000			26000			24000			31000			18000			23833
2	1	0	A	F	a			39000			27000			25000			22000			24000			19000			26000
2	1	1	A	F	a			32000			28000			22000			28000			28000			17000			25833
2	2	0	C	F	a			21000			32000			32000			26000			40000			23000			29000

City of Savannah Seawater Effects Study

Metals Corrosion Data Summary

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O Outlying data point excluded from analysis

Reactor Label						**Week 1 - 6/6/2011**			**Week 2 - 6/13/2011**			**Week 3 - 6/20/2011**			**Week 4 - 6/27/2011**			**Week 5 - 7/5/2011**			**Week 6 - 7/15/2011**			**Average**		
						Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L
2	2	1	C	F	a			17000			28000			28000			27000			31000			22000			25500
2	2	0	A	F	a			35000			31000			23000			28000			35000			22000			29000
2	2	1	A	F	a			30000			31000			25000			28000			32000			16000			27000
3	0	0	C	F	a			21000			32000			27000			28000			20000			20000			24667
3	0	1	C	F	a			25000			29000			26000			26000			26000			17000			24833
3	0	0	A	F	a			27000			30000			23000			27000			29000			21000			26167
3	0	1	A	F	a			16000			36000			25000			27000			30000			18000			25333
3	1	0	C	F	a			16000			31000			22000			25000			28000			21000			23833
3	1	1	C	F	a			25000			27000			27000			28000			31000			21000			26500
3	1	0	A	F	a			28000			38000			25000			24000			27000			18000			26667
3	1	1	A	F	a			28000			28000			26000			28000			33000			19000			27000
3	2	0	C	F	a			21000			27000			29000			27000			30000			19000			25500
3	2	1	C	F	a			27000			30000			26000			25000			29000			24000			26833
3	2	0	A	F	a			25000			33000			27000			27000			31000			20000			27167
3	2	1	A	F	a			26000			25000			24000			32000			35000			22000			27333
4	0	0	C	F	a			36000			33000			30000			28000			25000			18000			28333
4	0	1	C	F	a			22000			30000			26000			26000			27000			24000			25833
4	0	0	A	F	a			37000			29000			27000			22000			25000			15000			25833
4	0	1	A	F	a			32000			30000			31000			29000			24000			22000			28000
4	1	0	C	F	a			27000			33000			28000			29000			26000			21000			27333
4	1	1	C	F	a			31000			30000			30000			26000			32000			24000			28833
4	1	0	A	F	a			29000			28000			26000			27000			27000			19000			26000
4	1	1	A	F	a			33000			26000			29000			29000			26000			25000			28000
4	2	0	C	F	a			31000			27000			27000			32000			32000			20000			28167
4	2	1	C	F	a			28000			24000			27000			28000			28000			26000			26833
4	2	0	A	F	a			36000			33000			26000			28000			31000			21000			29167
4	2	1	A	F	a			38000			36000			24000			31000			31000			19000			29833
3	4	0	C	F	a			31000			26000			33800			23000			33000			20000			27800
2	3	0	C	F	a			16000			24000			24000			28000			37000			17000			24333
2	4	0	C	F	a			20000			25000			27000			25000			33000			19000			24833
1	3	0	C	F	a			20000			16000			26000			25000			24000			24000			22500
0	0	0	C	P	a	12000 B	1100		3200	430		2200	1200		1000	1600		760	1500		570	490		3288 B	1053	
0	0	1	C	P	a	8100	2800		5600	240		3000	360		2600	320		1700	380		200	470		3533	762	

City of Savannah Seawater Effects Study

Metals Corrosion Data Summary

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						Lead ug/L		Copper ug/L		Iron ug/L		Lead ug/L		Copper ug/L		Iron ug/L		Lead ug/L		Copper ug/L		Iron ug/L		Lead ug/L		Copper ug/L		Iron ug/L		Lead ug/L		Copper ug/L		Iron ug/L		Lead ug/L		Copper ug/L		Iron ug/L		Lead ug/L		Copper ug/L		Iron ug/L	
0	0	0	A	P	a	24000	B	1900				2600		1300				1100		1900				770		2200				500		2500				140		1000				4852	B	1800			
0	0	1	A	P	a	19000		2000				6200		380				1400		390				900		310				480		470				300		350				4713		650			
0	1	0	C	P	a	15000		1300				5600		100				1700		220				1300		420				600		620				530		1500				4122		693			
0	1	1	C	P	a	15000		2900				3600		120				1000		200				630		330				530		440				270		430				3505		737			
0	1	0	A	P	a	22000		670				5300		220				2200		240				2000		110				990		380				320		390				5468		335			
0	1	1	A	P	a	21000		1200				10000		170				3500		130				1400		130				1400		280				1000		150				6383		343			
0	2	0	C	P	a	6800		640				5300		94				1300		120				1400		770				740		1000				360		2400				2650		837			
0	2	1	C	P	a	31000	B	3000				5600		180				1500		110				1000		160				590		280				430		800				6687	B	755			
0	2	0	A	P	a	38000	B	2400				11000		310				2400		120				1700		160				1200		280				600		1600				9150	B	812			
0	2	1	A	P	a	6600	B	5600				2700		300				770		140				570		650				370		1600				170		1100				1863	B	1565			
1	0	0	C	P	a	17000	B	1700				7200		97				2500		81				2000		450				1500		930					N		N			6040	B N	652	N		
1	0	1	C	P	a	28000		1600				13000		70				4200		50	U			4100		80				1800		70					N		N			10220	N	374	U N		
1	0	0	A	P	a	3800	B	1100				6900		410				2200		310				1600		820				1700		1200					N		N			3240	B N	768	N		
1	0	1	A	P	a	28000		1700				8300		240				3200		150				3500		90				2400		79					N		N			9080	N	452	N		
1	1	0	C	P	a	11000		590				10000		140				3500		93				2300		130				1800		740					N		N			5720	N	339	N		
1	1	1	C	P	a	27000		1100				21000		270				3000		110				1600		240				1200		650				1700		340				9250		452			
1	1	0	A	P	a	11000		730				9000		220				1800		110				2100		160				1400		630					N		N			5060	N	370	N		
1	1	1	A	P	a	15000		1200				6200		330				2600		200				2700		390				840		740				990		780				4722		607			
1	2	0	C	P	a	6400	B	1000				14000		120				2700		63				1900		74				1300		120				590		990				4482	B	395			
1	2	1	C	P	a	11000		950				12000		110				4000		120				1900		170				1300		340				280		1200				5080		482			
1	2	0	A	P	a	26000	B	750				14000		270				6200		100				2400		100				1900		290				1000		69				8583	B	263			
1	2	1	A	P	a	14000		920				7400		100				2600		92				1000		160				600		530				510		370				4352		362			
2	0	0	C	P	a	21000		1700				14000		200				2900		150				2600		390				1600		940				780		1600				7147		830			
2	0	1	C	P	a	9300		390				17000		190				5100		110				3000		210				2200		170				2500		660				6517		288			
2	0	0	A	P	a	67000		14000				9300		180				3600		130				3600		84				2800		370				890		2700				14532		2911			
2	0	1	A	P	a	13000		840				10000		280				2900		170				2800		120				2100		150				2700		680				5583		373			
2	1	0	C	P	a	9900	B	1100				15	U	50	U			3900		73				2500		120				1400		130				2900		110				3436	BU	264	U		
2	1	1	C	P	a	42000		1300				15000		270				4600		91				2300		140				2500		930				2700		180				11517		485			
2	1	0	A	P	a	22000		1100				9700		360				3800		1200				2400		1100				1900		1100				4000		110				7300		828			
2	1	1	A	P	a	8400		460				17000		120				4800		93				2700		300				1100		210				1100		210				5850		232			
2	2	0	C	P	a	28000		740				32000		290				4700		50	U			3300		50	U			2000		50	U			2200		1400				12033		430	UUU		
2	2	1	C	P	a	15000		2200				17000		1400				5900		110				2300		130				1300		560				710		1700				7035		1017			
2	2	0	A	P	a	14000		640				18000		210				6900		84				2200		190				1500		170				1800		110				7400		234			

City of Savannah Seawater Effects Study

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						Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L
2	2	1	A	P	a	19000	1500		19000	180		3900	64		4600	90		3400	550		3200	170		8850	426	
3	0	0	C	P	a	19000 B	1600		14000	59		4300	50 U		2800	65		3500	370		1000	940		7433 B	514 U	
3	0	1	C	P	a	12000 B	1500		15000	210		5800	76		1800	150		1000	400		410	2300		6002 B	773	
3	0	0	A	P	a	15000 B	1200		17000	150		5900	61		4300	130		4200	160		5100	350		8583 B	342	
3	0	1	A	P	a	23000 B	940		16000	110		5700	50 U		3000	55		2700	50 U		1500	130		8650 B	223 U U	
3	1	0	C	P	a	20000	680		12000	110		6400	72		3700	59		2800	390		1000	1000		7650	385	
3	1	1	C	P	a	40000 B	1300		12000	92		3400	59		2100	120		2100	380		4900	67		10750 B	336	
3	1	0	A	P	a	12000 B	710		13000	230		5500	90		2900	100		1700	710		1300	640		6067 B	413	
3	1	1	A	P	a	15000 B	1600		6900	170		2500	140		1400	180		64	31		410	320		4379 B	407	
3	2	0	C	P	a	31000	800		29000	110		7300	87		4500	51		3300	50 U		3600	54		13117	192 U	
3	2	1	C	P	a	30000	680		17000	140		4200	51		3500	75		2100	100		2900	53		9950	183	
3	2	0	A	P	a	34000	2600		16000	150		6600	90		3400	42		2700	50 U		3200	57		10983	498 U	
3	2	1	A	P	a	7900	600		18000	99		4000	50 U		2700	50 U		270	5 U		5000	120		6312	154 UUU	
4	0	0	C	P	a	48000	1300		28000	140		10000	110		6600	55		8300	180		66000 O	2100 O		20180 O	357 O	
4	0	1	C	P	a	29000	1000		19000	160		9300	51		6500	43		5400	50 U		3500	24		12117	221 U	
4	0	0	A	P	a	17000	2400		11000	160		3200	89		3200	67		180	27		820	1600		5900	724	
4	0	1	A	P	a	8500	1800		9600	240		5800	160		3800	88		280	23		1500	240		4913	425	
4	1	0	C	P	a	49000	1500		20000	240		7900	66		5300	59		5000	50 U		4300	88		15250	334 U	
4	1	1	C	P	a	29000	1300		13000	170		9200	170		5500	120		7000	77		6300	96		11667	322	
4	1	0	A	P	a	41000	1600		18000	170		7500	50 U		4100	50 U		290	6.4		3300	61		12365	323 UU	
4	1	1	A	P	a	27000	940		10000	130		5500	68		4300	55		300	11		3700	63		8467	211	
4	2	0	C	P	a	48000	1600		21000	97		19000	76		9400	68		4000	75		3900	120		17550	339	
4	2	1	C	P	a	19000 B	1800		19000	160		11000	58		8400	59		6300	50 U		5000	31		11450 B	360 U	
4	2	0	A	P	a	24000 B	990		9400	56		4000	54		3900	63		280	5 U		2900	53		7413 B	204 U	
4	2	1	A	P	a	26000 B	1000		17000	120		5900	57		5600	110		360	31		6100	83		10160 B	234	
3	4	0	C	P	a	16000	910		20000	160		7800	51		4900	49		4200	53		4700	84		9600	218	
2	3	0	C	P	a	8200	1500		11000	300		4600	110		2200	150		2500	960		2500	99		5167	520	
2	4	0	C	P	a	17000	1100		12000	120		5400	66		4500	57		6900	61		7200	110		8833	252	
1	3	0	C	P	a	27000	410		22000	130		4900	73		3200	93		2900	640		1200	1800		10200	524	
0	0	0	C	F	b			25000															18000			21500
0	0	1	C	F	b			19000															17000			18000
0	0	0	A	F	b			24000															12000			18000
0	0	1	A	F	b			32000															17000			24500

City of Savannah Seawater Effects Study

Metals Corrosion Data Summary

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						Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L
0	1	0	C	F	b			24000															13000			18500
0	1	1	C	F	b			20000															16000			18000
0	1	0	A	F	b			36000															13000			24500
0	1	1	A	F	b			31000															14000			22500
0	2	0	C	F	b			23000															20000			21500
0	2	1	C	F	b			18000															14000			16000
0	2	0	A	F	b			26000															22000			24000
0	2	1	A	F	b			32000															9800			20900
1	0	0	C	F	b			22000															22000			22000
1	0	1	C	F	b			21000															17000			19000
1	0	0	A	F	b			22000															17000			19500
1	0	1	A	F	b			18000															11000			14500
1	1	0	C	F	b			13000															19000			16000
1	1	1	C	F	b			19000															16000			17500
1	1	0	A	F	b			33000															16000			24500
1	1	1	A	F	b			30000															11000			20500
1	2	0	C	F	b			21000															20000			20500
1	2	1	C	F	b			24000															22000			23000
1	2	0	A	F	b			34000															18000			26000
1	2	1	A	F	b			28000															17000			22500
2	0	0	C	F	b			21000															16000			18500
2	0	1	C	F	b			23000															18000			20500
2	0	0	A	F	b			24000															15000			19500
2	0	1	A	F	b			27000															15000			21000
2	1	0	C	F	b			17000															18000			17500
2	1	1	C	F	b			22000															21000			21500
2	1	0	A	F	b			30000															15000			22500
2	1	1	A	F	b			39000															10000			24500
2	2	0	C	F	b			21000															16000			18500
2	2	1	C	F	b			21000															13000			17000
2	2	0	A	F	b			32000															19000			25500
2	2	1	A	F	b			25000															17000			21000
3	0	0	C	F	b			26000															21000			23500

City of Savannah Seawater Effects Study

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						Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L
3	0	1	C	F	b			23000															21000			22000
3	0	0	A	F	b			26000															16000			21000
3	0	1	A	F	b			25000															17000			21000
3	1	0	C	F	b			19000															17000			18000
3	1	1	C	F	b			20000															16000			18000
3	1	0	A	F	b			100 U															14000			7050 U
3	1	1	A	F	b			24000															19000			21500
3	2	0	C	F	b			16000															15000			15500
3	2	1	C	F	b			27000															25000			26000
3	2	0	A	F	b			24000															18000			21000
3	2	1	A	F	b			36000															21000			28500
4	0	0	C	F	b			23000															22000			22500
4	0	1	C	F	b			26000															21000			23500
4	0	0	A	F	b			32000															24000			28000
4	0	1	A	F	b			35000															21000			28000
4	1	0	C	F	b			20000															19000			19500
4	1	1	C	F	b			26000															22000			24000
4	1	0	A	F	b			27000															19000			23000
4	1	1	A	F	b			34000															21000			27500
4	2	0	C	F	b			29000															25000			27000
4	2	1	C	F	b			33000															22000			27500
4	2	0	A	F	b			32000															15000			23500
4	2	1	A	F	b			29000															22000			25500
3	4	0	C	F	b			28000															15000			21500
2	3	0	C	F	b			27000															15000			21000
2	4	0	C	F	b			36000															17000			26500
1	3	0	C	F	b			13000															15000			14000
0	0	0	C	P	b	10000 B	1700														360	2400		5180 B	2050	
0	0	1	C	P	b	15000	930														1000	570		8000	750	
0	0	0	A	P	b	6000 B	4900														440	3100		3220 B	4000	
0	0	1	A	P	b	14000	1100														240	1300		7120	1200	
0	1	0	C	P	b	13000	2500														11000	5400		12000	3950	
0	1	1	C	P	b	20000	2500														490	350		10245	1425	

City of Savannah Seawater Effects Study

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						Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L
0	1	0	A	P	b	39000	1900														520	410		19760	1155	
0	1	1	A	P	b	36000	9600														970	460		18485	5030	
0	2	0	C	P	b	20000	1200														480	1200		10240	1200	
0	2	1	C	P	b	34000 B	1500														16000	8800		25000 B	5150	
0	2	0	A	P	b	8600 B	2600														N	N		8600 B N	2600 N	
0	2	1	A	P	b	14000 B	4600														420	610		7210 B	2605	
1	0	0	C	P	b	20000 B	1400														N	N		20000 B N	1400 N	
1	0	1	C	P	b	28000	1800														N	N		28000 N	1800 N	
1	0	0	A	P	b	8700 B	2000														N	N		8700 B N	2000 N	
1	0	1	A	P	b	9700	1300														N	N		9700 N	1300 N	
1	1	0	C	P	b	13000	1100														N	N		13000 N	1100 N	
1	1	1	C	P	b	8200	1300														1500	100		4850	700	
1	1	0	A	P	b	9400	990														930	1600		5165	1295	
1	1	1	A	P	b	11000	800														600	440		5800	620	
1	2	0	C	P	b	7700 B	870														2700	170		5200 B	520	
1	2	1	C	P	b	13000	1300														1200	140		7100	720	
1	2	0	A	P	b	10000 B	4100														530	620		5265 B	2360	
1	2	1	A	P	b	25000	1600														770	1400		12885	1500	
2	0	0	C	P	b	20000	710														2200	1200		11100	955	
2	0	1	C	P	b	21000	790														1200	3000		11100	1895	
2	0	0	A	P	b	9400	1300														4500	110		6950	705	
2	0	1	A	P	b	4800	850														1100	2200		2950	1525	
2	1	0	C	P	b	31000 B	1600														4600	950		17800 B	1275	
2	1	1	C	P	b	17000	3800														550	2600		8775	3200	
2	1	0	A	P	b	21000 B	1400														3600	75		12300 B	738	
2	1	1	A	P	b	16000	690														590	1100		8295	895	
2	2	0	C	P	b	22000	1200														3000	830		12500	1015	
2	2	1	C	P	b	31000	1100														1700	2300		16350	1700	
2	2	0	A	P	b	21000	2800														1000	1300		11000	2050	
2	2	1	A	P	b	38000	690														5400	80		21700	385	
3	0	0	C	P	b	17000 B	510														2500	55		9750 B	283	
3	0	1	C	P	b	27000 B	3400														1600	800		14300 B	2100	
3	0	0	A	P	b	15000 B	630														2500	2400		8750 B	1515	

City of Savannah Seawater Effects Study

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						Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L
3	0	1	A	P	b	27000 B	1000														4700	120		15850 B	560	
3	1	0	C	P	b	16000	930														1500	1300		8750	1115	
3	1	1	C	P	b	8600 B	1600														410	2600		4505 B	2100	
3	1	0	A	P	b	2.7 BO	9.7 O														6000	1500		6000 BO	1500 O	
3	1	1	A	P	b	26000 B	1500														1300	1500		13650 B	1500	
3	2	0	C	P	b	36000	1500														2800	53		19400	777	
3	2	1	C	P	b	15000	3000														990	1000		7995	2000	
3	2	0	A	P	b	15000	920														4400	130		9700	525	
3	2	1	A	P	b	13000	970														4400	76		8700	523	
4	0	0	C	P	b	50000	1400														4400	61		27200	731	
4	0	1	C	P	b	36000	840														3800	30		19900	435	
4	0	0	A	P	b	14000	1100														4500	140		9250	620	
4	0	1	A	P	b	6400	920														1000	770		3700	845	
4	1	0	C	P	b	28000	1300														5000	54		16500	677	
4	1	1	C	P	b	18000	810														6100	56		12050	433	
4	1	0	A	P	b	16000	800														4300	97		10150	449	
4	1	1	A	P	b	8200	790														740	430		4470	610	
4	2	0	C	P	b	20000	830														4800	77		12400	454	
4	2	1	C	P	b	23000 B	1100														5100	68		14050 B	584	
4	2	0	A	P	b	29000 B	610														4400	30		16700 B	320	
4	2	1	A	P	b	30000 B	1800														3500	210		16750 B	1005	
3	4	0	C	P	b	6300	380														5200	50		5750	215	
2	3	0	C	P	b	16000	810														2400	720		9200	765	
2	4	0	C	P	b	19000	630														5200	180		12100	405	
1	3	0	C	P	b	19000	1100														2000	500		10500	800	
0	0	0	C	P	c	8900 B	2100														270	1000		4585 B	1550	
0	0	1	C	P	c	15000	1300														1900	73		8450	687	
0	0	0	A	P	c	14000 B	1500														350	1600		7175 B	1550	
0	0	1	A	P	c	8900	760														270	1000		4585	880	
0	1	0	C	P	c	20000	930														480	270		10240	600	
0	1	1	C	P	c	8900	960														130	480		4515	720	
0	1	0	A	P	c	7100	650														1400	54		4250	352	
0	1	1	A	P	c	13000	870														240	540		6620	705	

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						Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L
0	2	0	C	P	c	17000	1000														31000 O	1200		17000 O	1100	
0	2	1	C	P	c	11000 B	1800														940	290		5970 B	1045	
0	2	0	A	P	c	45000	2100														N	N		45000 N	2100 N	
0	2	1	A	P	c	18000 B	1500														380	1900		9190 B	1700	
1	0	0	C	P	c	20000 B	1500														N	N		20000 B N	1500 N	
1	0	1	C	P	c	16000	840														N	N		16000 N	840 N	
1	0	0	A	P	c	17000 B	1800														N	N		17000 B N	1800 N	
1	0	1	A	P	c	18000	1100														N	N		18000 N	1100 N	
1	1	0	C	P	c	42000	2500														N	N		42000 N	2500 N	
1	1	1	C	P	c	25000	1400														1000	2500		13000	1950	
1	1	0	A	P	c	12000	1400														1500	2300		6750	1850	
1	1	1	A	P	c	7500	4400														630	1200		4065	2800	
1	2	0	C	P	c	8500 B	860														3100	260		5800 B	560	
1	2	1	C	P	c	39000	2500														1700	1700		20350	2100	
1	2	0	A	P	c	19000 B	1800														1000	190		10000 B	995	
1	2	1	A	P	c	10000	1100														450	1300		5225	1200	
2	0	0	C	P	c	9300	1700														1100	2000		5200	1850	
2	0	1	C	P	c	18000	790														6700	200		12350	495	
2	0	0	A	P	c	12000	580														2200	53		7100	317	
2	0	1	A	P	c	13000	1000														2800	140		7900	570	
2	1	0	C	P	c	20000 B	1000														1500	1700		10750 B	1350	
2	1	1	C	P	c	25000	1000														2500	75		13750	538	
2	1	0	A	P	c	8500 B	3800														520	3200		4510 B	3500	
2	1	1	A	P	c	14000	940														3600	950		8800	945	
2	2	0	C	P	c	26000	350														3500	110		14750	230	
2	2	1	C	P	c	14000	1100														1500	630		7750	865	
2	2	0	A	P	c	15000	780														2000	230		8500	505	
2	2	1	A	P	c	7800	1800														850	1500		4325	1650	
3	0	0	C	P	c	32000	1400														4900	230		18450	815	
3	0	1	C	P	c	21000 B	470														2800	78		11900 B	274	
3	0	0	A	P	c	15000 B	820														4300	150		9650 B	485	
3	0	1	A	P	c	19000 B	520														4900	57		11950 B	289	
3	1	0	C	P	c	16000	770														3000	140		9500	455	

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						Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Copper ug/L	Iron ug/L
3	1	1	C	P	c	31000 B	2300														1800	830		16400 B	1565	
3	1	0	A	P	c	6800 B	470														2600	1600		4700 B	1035	
3	1	1	A	P	c	8300 B	1100														540	1100		4420 B	1100	
3	2	0	C	P	c	33000	2500														3700	58		18350	1279	
3	2	1	C	P	c	29000	590														2400	34		15700	312	
3	2	0	A	P	c	14000	430														3400	51		8700	241	
3	2	1	A	P	c	23000	590														3100	28		13050	309	
4	0	0	C	P	c	30000	1200														5400	230		17700	715	
4	0	1	C	P	c	19000	1100														3900	68		11450	584	
4	0	0	A	P	c	11000	1000														2100	40		6550	520	
4	0	1	A	P	c	23000	1000														3900	73		13450	537	
4	1	0	C	P	c	25000	740														3300	61		14150	401	
4	1	1	C	P	c	20000	770														3900	60		11950	415	
4	1	0	A	P	c	15000	880														3900	95		9450	488	
4	1	1	A	P	c	18000	820														2900	39		10450	430	
4	2	0	C	P	c	43000	1300														3900	280		23450	790	
4	2	1	C	P	c	22000 B	1200														5100	79		13550 B	640	
4	2	0	A	P	c	22000 B	390														7100	220		14550 B	305	
4	2	1	A	P	c	20000 B	1100														6200	360		13100 B	730	
3	4	0	C	P	c	6300	1400														2600	1200		4450	1300	
2	3	0	C	P	c	6900	1800														1100	2500		4000	2150	
2	4	0	C	P	c	12000	670														6900	57		9450	364	
1	3	0	C	P	c	13000	1200														3200	160		8100	680	

Appendix G

Post-Exposure Analysis Memo

CDM

Memorandum

To: *Bill Dowbiggin*

From: *Ryan Kingsbury*

Date: *August 15, 2011*

Subject: *Post-Exposure Analysis of Savannah Plumbing Materials*

This memorandum documents the results of post-exposure analysis conducted for quality control purposes following completion of bench-scale corrosion testing for the Savannah Seawater Effects Study.

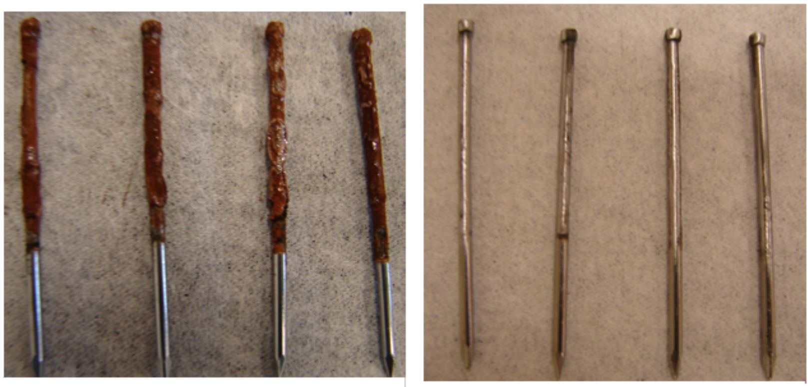
Two analyses were performed. First, all the mild steel coupons were returned to Virginia Tech for weighing on a microbalance. Each coupon was weighed prior to the start of the study so that the total weight loss after corrosion exposure could be determined. Second, plastic sample containers were analyzed to confirm that there were no significant quantities of metals sorbed to the walls.

Mild Steel Coupon Weighing

Iron generally corrodes at a somewhat faster rate than lead or copper, and therefore it is possible to draw meaningful conclusions from the weight loss of an iron or steel coupon over the course of a relatively short-duration study such as this one. The weight loss provides a more direct measurement of the rate of corrosion that is less prone to error than dissolved iron measurement.

Procedure

Each of the coupons was dried in an oven for approximately 24 hours. Each coupon was then weighed on a microbalance both before and after removal of scale (rust). **Figure 1** shows the appearance of typical coupons before and after scale removal.



Before Removal

After Removal

Figure 1: Mild steel coupons before and after scale removal

Results

Table 1 (at the end of this memo) contains the measured weight loss data for each steel coupon. **Figure 2** shows the impact of chloride concentration and pH on the rate of iron corrosion as measured by weight loss. This figure is identical to Figure 5-11 of the report except that the measurements are based on weight loss rather than dissolved iron concentration.

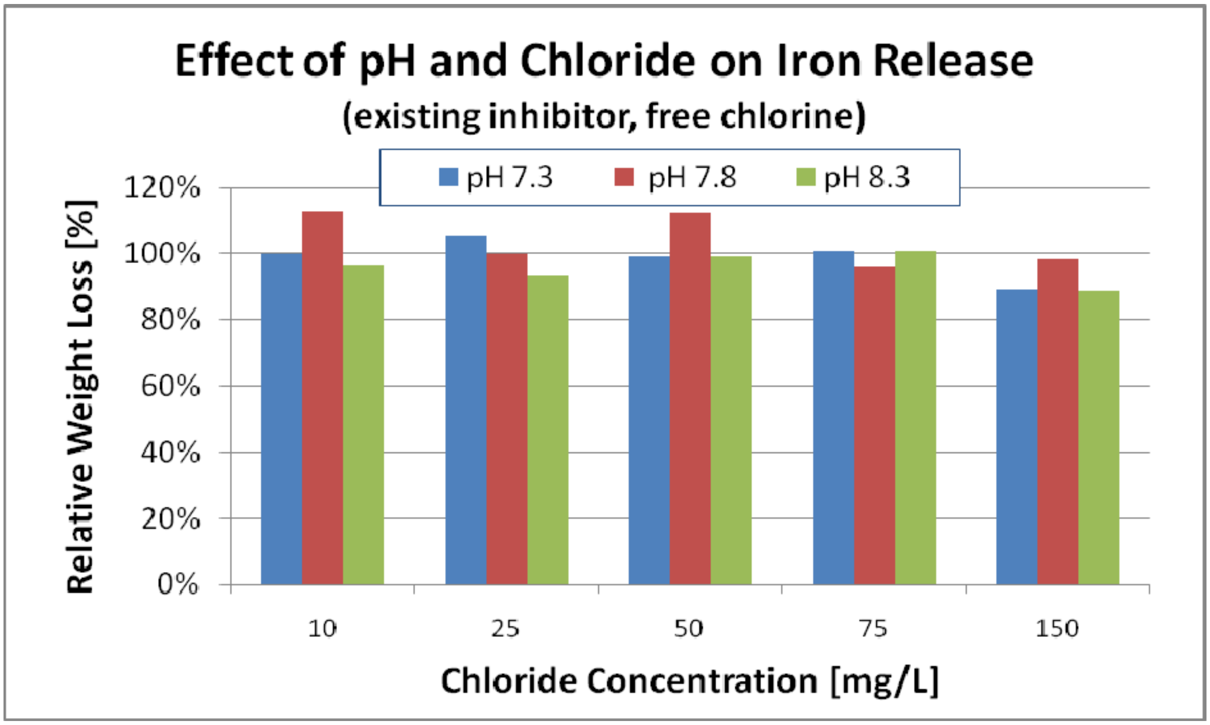


Figure 2: Relationship between pH, chloride concentration, and iron corrosion. Data shown represent the average weight loss of duplicate coupons in the existing inhibitor, free chlorine test condition. Concentrations are normalized to the baseline scenario (existing chloride, pH, and inhibitor).

As shown, neither increased chloride concentration nor increased pH had a significant impact on the iron corrosion rate. Figure 5-11 suggested the possibility of slight increases in iron due to chloride, but these data indicate no increase at all.

Similar plots were prepared to evaluate each of the other test conditions (inhibitor dose and chlorine vs. chloramines) on iron corrosion. Neither variable had any significant effect on the corrosion rate as measured by weight loss. These findings are entirely consistent with previously reported data.

Sample Container Digestion

Samples of exposed water that were "dumped" between laboratory analyses were stored in plastic sample containers for approximately 4 days before being analyzed. During storage, it is possible that some metal sorbed to the walls of these containers or precipitated and was therefore not captured by the dissolved metals analysis. Strong acid preservative was added to all containers prior to filling them with sample in order to prevent these occurrences, but post-exposure analysis was performed on ten selected containers to confirm that no significant amount of metal was lost. The containers selected were those containing water quality conditions judged to be most favorable to precipitation. If significant levels of metal had been found in these ten bottles, the remaining sample containers would have been analyzed.

Procedure

At the conclusion of the study, the selected containers were sent to Virginia Tech to be analyzed by "in-bottle digestion." This procedure involved adding concentrated nitric acid to each bottle and heating to 55 °C for approximately 3 days in order to drive any metal that might be present into solution. Then the bottle contents were analyzed for dissolved metals in similar fashion to other analyses in this study.

Results

Table 2 summarizes the results of this analysis for lead and copper; **Table 3** shows similar results for iron. In each table, the metal recovered by digestion is compared with the metal released into solution during the study. This value was calculated by summing up the measured aqueous concentration times sample volume over the course of the study. As shown, the metal recovered from the containers represented less than 0.5% of the lead, 1.5% of the copper, and 2.5% of the iron released and measured during the course of the study. As such, sorption of metals to the containers was judged to be insignificant and the remaining sample containers were not analyzed.

Table 2: Summary of Metals Leaching from Sample Containers

Container ID	Metal Recovered from Container [mg]	Metal Released During Study [mg]	Metal Recovered / Metal Released [%]
Lead			
020APa	0.005	6.588	0.08%
120APa	0.003	6.180	0.05%
220APa	0.014	5.328	0.26%
320APa	0.017	7.908	0.22%
420APa	0.018	5.338	0.35%
Copper			
020APa	0.003	0.584	0.48%
120APa	0.002	0.189	1.30%
220APa	0.001	0.168	0.34%
320APa	0.001	0.359	0.18%
420APa	0.001	0.147	0.45%
Iron			
020Afa	0.168	9.24	1.82%
120AFa	0.108	10.64	1.01%
220Afa	0.096	12.18	0.78%
320AFa	0.109	11.41	0.95%
420AFa	0.275	12.25	2.25%

Impact on Study Findings

Post-exposure analysis did not raise any new issues or call into question any of the major findings of the study. Mild steel weight loss measurements suggested that chloride and pH had virtually no effect on iron corrosion. This finding is slightly different from the dissolved metal results, which indicated a slight increase in corrosion with chloride concentration. With respect to the effect of inhibitor dose and disinfectant, weight loss measurements were in agreement with dissolved metal results.

The quantity of unaccounted-for metal sorbed to the sample containers appeared to be insignificant in comparison with the total quantity released, indicating that the dissolved metal measurements presented in the report accurately represent the corrosion rate.

Table 1: Mild Steel Coupon Weighing Results

(Page 1 of 3)

Reactor Label						Coupon Weight (g)			Weight Loss (g)
						Initial	Final, With Scale	Final, Without Scale	
0	0	0	A	F	a	0.5205	0.5185	0.4982	0.0223
0	0	0	A	F	b	0.5181	0.5166	0.4959	0.0222
0	0	0	C	F	a	0.5172	0.5129	0.4949	0.0223
0	0	0	C	F	b	0.5209	0.5125	0.5000	0.0209
0	0	1	A	F	a	0.5145	0.5165	0.4980	0.0165
0	0	1	A	F	b	0.5195	0.5116	0.4958	0.0237
0	0	1	C	F	a	0.5199	0.5119	0.4979	0.0220
0	0	1	C	F	b	0.5220	0.5170	0.4998	0.0222
0	1	0	A	F	a	0.5210	0.5173	0.4976	0.0234
0	1	0	A	F	b	0.5210	0.5191	0.4964	0.0246
0	1	0	C	F	a	0.5239	0.5141	0.5006	0.0233
0	1	0	C	F	b	0.5237	0.5193	0.5008	0.0229
0	1	1	A	F	a	0.5182	0.5090	0.4977	0.0205
0	1	1	A	F	b	0.5178	0.5139	0.4945	0.0233
0	1	1	C	F	a	0.5184	0.5133	0.4950	0.0234
0	1	1	C	F	b	0.5088	0.4984	0.4824	0.0264
0	2	0	A	F	a	0.5097	0.5060	0.4894	0.0203
0	2	0	A	F	b	0.5244	0.5183	0.5042	0.0202
0	2	0	C	F	a	0.5174	0.5066	0.4963	0.0211
0	2	0	C	F	b	0.5209	0.5132	0.4987	0.0222
0	2	1	A	F	a	0.5242	0.5157	0.5016	0.0226
0	2	1	A	F	b	0.5230	0.5186	0.5023	0.0207
0	2	1	C	F	a	0.5183	0.5136	0.4967	0.0216
0	2	1	C	F	b	0.5209	0.5162	0.4998	0.0211
1	0	0	A	F	a	0.5190	0.5149	0.4953	0.0237
1	0	0	A	F	b	0.5168	0.5131	0.4925	0.0243
1	0	0	C	F	a	0.5227	0.5196	0.4978	0.0249
1	0	0	C	F	b	0.5236	0.5168	0.5012	0.0224
1	0	1	A	F	a	0.5212	0.5159	0.5001	0.0211
1	0	1	A	F	b	0.5179	0.5083	0.4952	0.0227
1	0	1	C	F	a	0.5217	0.5117	0.4999	0.0218
1	0	1	C	F	b	0.5202	0.5151	0.4955	0.0247
1	1	0	A	F	a	0.5203	0.5161	0.4978	0.0225
1	1	0	A	F	b	0.5228	0.5213	0.4965	0.0263
1	1	0	C	F	a	0.5233	0.5147	0.5009	0.0224
1	1	0	C	F	b	0.5217	0.5141	0.4993	0.0224
1	1	1	A	F	a	0.5211	0.5186	0.5006	0.0205
1	1	1	A	F	b	0.5230	0.5120	0.5015	0.0215
1	1	1	C	F	a	0.5134	0.5031	0.4915	0.0219
1	1	1	C	F	b	0.5206	0.5110	0.4984	0.0222
1	2	0	A	F	a	0.5180	0.5111	0.4966	0.0214
1	2	0	A	F	b	0.5219	0.5134	0.5011	0.0208
1	2	0	C	F	a	0.5214	0.5126	0.5002	0.0212
1	2	0	C	F	b	0.5211	0.5112	0.4969	0.0242

Table 1: Mild Steel Coupon Weighing Results

(Page 2 of 3)

Reactor Label						Coupon Weight (g)			Weight Loss (g)
						Initial	Final, With Scale	Final, Without Scale	
1	2	1	A	F	a	0.5196	0.5101	0.4973	0.0223
1	2	1	A	F	b	0.5212	0.5138	0.4982	0.0230
1	2	1	C	F	a	0.5200	0.5104	0.4981	0.0219
1	2	1	C	F	b	0.5229	0.5114	0.5036	0.0193
1	3	0	C	F	a	0.5235	0.5209	0.5020	0.0215
1	3	0	C	F	b	0.5209	0.5178	0.4993	0.0216
2	0	0	A	F	a	0.5162	0.5063	0.4934	0.0228
2	0	0	A	F	b	0.5120	0.5098	0.4906	0.0214
2	0	0	C	F	a	0.5174	0.5077	0.5012	0.0162
2	0	0	C	F	b	0.5203	0.5114	0.4985	0.0218
2	0	1	A	F	a	0.5202	0.5103	0.5031	0.0171
2	0	1	A	F	b	0.5214	0.5126	0.5031	0.0183
2	0	1	C	F	a	0.5109	0.5033	0.4896	0.0213
2	0	1	C	F	b	0.5222	0.5131	0.4996	0.0226
2	1	0	A	F	a	0.5226	0.5158	0.5014	0.0212
2	1	0	A	F	b	0.5184	0.5096	0.4978	0.0206
2	1	0	C	F	a	0.5129	0.5054	0.4909	0.0220
2	1	0	C	F	b	0.5224	0.5137	0.5006	0.0218
2	1	1	A	F	a	0.5210	0.5107	0.5028	0.0182
2	1	1	A	F	b	0.5197	0.5145	0.4982	0.0215
2	1	1	C	F	a	0.5194	0.5132	0.4952	0.0242
2	1	1	C	F	b	0.5215	0.5154	0.4960	0.0255
2	2	0	A	F	a	0.5194	0.5127	0.5031	0.0163
2	2	0	A	F	b	0.5232	0.5163	0.5051	0.0181
2	2	0	C	F	a	0.5198	0.5135	0.4971	0.0227
2	2	0	C	F	b	0.5226	0.5115	0.5006	0.0220
2	2	1	A	F	a	0.5234	0.5129	0.5016	0.0218
2	2	1	A	F	b	0.5239	0.5147	0.5032	0.0207
2	2	1	C	F	a	0.5198	0.5132	0.4986	0.0212
2	2	1	C	F	b	0.5209	0.5137	0.4983	0.0226
2	3	0	C	F	a	0.5210	0.5147	0.4990	0.0220
2	3	0	C	F	b	0.5201	0.5135	0.4992	0.0209
2	4	0	C	F	a	0.5123	0.5036	0.4922	0.0201
2	4	0	C	F	b	0.5194	0.5156	0.4989	0.0205
3	0	0	A	F	a	0.5218	0.5113	0.5001	0.0217
3	0	0	A	F	b	0.5204	0.5144	0.4991	0.0213
3	0	0	C	F	a	0.5234	0.5193	0.5022	0.0212
3	0	0	C	F	b	0.5230	0.5167	0.5024	0.0206
3	0	1	A	F	a	0.5245	0.5173	0.5043	0.0202
3	0	1	A	F	b	0.5087	0.5027	0.4884	0.0203
3	0	1	C	F	a	0.5211	0.5123	0.4999	0.0212
3	0	1	C	F	b	0.5175	0.5141	0.4941	0.0234
3	1	0	A	F	a	0.5203	0.5106	0.4990	0.0213
3	1	0	A	F	b	0.5178	0.5126	0.4963	0.0215

Table 1: Mild Steel Coupon Weighing Results
(Page 3 of 3)

Reactor Label						**Coupon Weight (g)**			**Weight Loss (g)**
						Initial	**Final, With Scale**	**Final, Without Scale**	
3	1	0	C	F	a	0.5216	0.5195	0.4987	0.0229
3	1	0	C	F	b	0.5162	0.5179	0.4930	0.0232
3	1	1	A	F	a	0.5178	0.5080	0.4992	0.0186
3	1	1	A	F	b	0.5236	0.5129	0.5018	0.0218
3	1	1	C	F	a	0.5158	0.5071	0.4936	0.0222
3	1	1	C	F	b	0.5234	0.5168	0.5030	0.0204
3	2	0	A	F	a	0.5182	0.5124	0.4974	0.0208
3	2	0	A	F	b	0.5209	0.5099	0.4993	0.0216
3	2	0	C	F	a	0.5200	0.5089	0.5011	0.0189
3	2	0	C	F	b	0.5215	0.5123	0.5013	0.0202
3	2	1	A	F	a	0.5211	0.5131	0.5018	0.0193
3	2	1	A	F	b	0.5219	0.5121	0.5018	0.0201
3	2	1	C	F	a	0.5112	0.5036	0.4898	0.0214
3	2	1	C	F	b	0.5236	0.5100	0.5005	0.0231
3	4	0	C	F	a	0.5203	0.5125	0.4989	0.0214
3	4	0	C	F	b	0.5186	0.5133	0.4967	0.0219
4	0	0	A	F	a	0.5203	0.5157	0.4993	0.0210
4	0	0	A	F	b	0.5217	0.5093	0.5009	0.0208
4	0	0	C	F	a	0.5209	0.5156	0.4978	0.0231
4	0	0	C	F	b	0.5186	0.5076	0.4998	0.0188
4	0	1	A	F	a	0.5183	0.5124	0.5001	0.0182
4	0	1	A	F	b	0.5211	0.5137	0.5015	0.0196
4	0	1	C	F	a	0.5197	0.5127	0.5013	0.0184
4	0	1	C	F	b	0.5201	0.5145	0.4991	0.0210
4	1	0	A	F	a	0.5172	0.5097	0.4957	0.0215
4	1	0	A	F	b	0.5199	0.5154	0.4988	0.0211
4	1	0	C	F	a	0.5183	0.5105	0.4987	0.0196
4	1	0	C	F	b	0.5212	0.5096	0.5006	0.0206
4	1	1	A	F	a	0.5236	0.5166	0.5001	0.0235
4	1	1	A	F	b	0.5212	0.5149	0.5020	0.0192
4	1	1	C	F	a	0.5184	0.5095	0.4954	0.0230
4	1	1	C	F	b	0.5210	0.5121	0.5005	0.0205
4	2	0	A	F	a	0.5205	0.5124	0.4977	0.0228
4	2	0	A	F	b	0.5238	0.5165	0.5030	0.0208
4	2	0	C	F	a	0.5211	0.5139	0.5005	0.0206
4	2	0	C	F	b	0.5246	0.5136	0.5048	0.0198
4	2	1	A	F	a	0.5186	0.5132	0.4977	0.0209
4	2	1	A	F	b	0.5102	0.5005	0.4906	0.0196
4	2	1	C	F	a	0.5172	0.5090	0.4982	0.0190
4	2	1	C	F	b	0.5131	0.5050	0.4928	0.0203

Appendix H

Historical Lead and Copper Sampling Data

City of Savannah
Lead and Copper Rule Sampling Data

Sampling Date	April 2001		April 2001 (continued)	September 2002		September 2003		September 2004		September 2006		September 2008	
	Summary		Summary	Summary		Summary		Summary		Summary		Summary	
No. of sites sampled	30			30		30		30		30		29	
No. of sites exceeding Action Level	2			3		0		2		0		2	
Site IDs exceeding Action Level	13, 19, 45, 51, 61,66		(see summary at left)	18, 64, 65		n/a		39, 56		n/a		13, 56	
Maximum lead / copper concentration, µg/L	29	380		47	570	5.4	440	190	530	7.3	330	260	890
90th Percentile lead/copper concentration, µg/L	5.2	230		7.1	370	4.3	350	4.7	270	3.2	260	3.3	350

NOTES:
1. Sites exceeding the action level are shaded red.
2. Lead Action Level = 15 µg/L
3. Copper Action Level = 1300 µg/L
4. Sites 48, 50, 56, 64, and 65 are located in the domestic system, treated with chloramines. All others are located within the industrial system which is treated with free chlorine.

Individual Site Data			Individual Site Data (continued)			Individual Site Data			Individual Site Data			Individual Site Data			Individual Site Data			Individual Site Data		
Site ID	Lead µg/L	Copper µg/L	Site ID	Lead µg/L	Copper µg/L	Site ID	Lead µg/L	Copper µg/L	Site ID	Lead µg/L	Copper µg/L	Site ID	Lead µg/L	Copper µg/L	Site ID	Lead µg/L	Copper µg/L	Site ID	Lead µg/L	Copper µg/L
2	0	0	44	4	25	2	0	0	2	2.5	180	2	0	210	2	0	110	2	0	44
3	0	140	45	20	45	3	2.5	280	3	2.5	160	3	0	95	3	2.5	77	3	0	54
4	0	60	46	2.9	0	4	3.7	120	4	2.5	64	4	2.5	53	4	2.5	78	4	0	45
5	2.5	220	47	5	54	17	2.5	51	17	2.5	43	12	2.5	180	12	2.7	240	12	2.7	29
6	2.5	54	48	0	0	18	39	400	18	2.8	110	13	0	270	13	0	260	13	26	220
7	5.2	100	49	0	160	20	4.1	97	20	0	25	17	0	0	17	0	0	17	2.5	890
11	11	76	50	0	120	22	0	350	21	4.3	390	18	3.8	47	18	2.5	130	18	0	760
12	2.5	200	51	92	380	23	0	100	22	0	210	20	12	160	20	0	0	20	0	350
13	29	150	52	4.6	190	28	2.5	29	23	2.5	52	21	2.5	330	21	2.5	260	21	3.5	260
14	5.6	340	53	0	0	29	0	0	33	2.5	73	22	0	130	22	0	56	22	0	75
17	0	62	54	0	250	33	2.5	96	34	0	0	23	0	34	23	0	25	23	0	0
18	2.5	240	55	3.7	910	34	0	0	35	0	0	33	2.5	83	33	0	90	33	0	90
19	22	25	56	2.5	240	35	0	0	38	0	42	34	0	0	34	0	0	34	0	0
20	0	110	57	0	73	38	0	70	39	4	45	35	0	0	35	0	0	35	2.5	0
21	3.7	0	58	0	110	39	2.5	35	48	2.5	0	38	0	32	38	0	0	38	0	0
22	0	230	59	9.7	27	46	4	25	50	2.5	99	39	40	120	39	7.3	33	39	2.7	37
23	0	56	60	2.5	31	48	0	0	53	0	0	48	0	0	48	0	0	48	0	0
26	4.7	0	61	70	410	50	2.5	180	54	0	220	50	3.1	110	50	0	90	50	2.5	76
27	0	0	62	2.5	460	53	0	0	55	4.8	440	53	0	0	53	0	0	53	0	0
28	2.5	25	63			54	0	320	56	2.5	330	54	0	67	54	0	160	54	0	130
29	0	25	64	0	42	56	2.5	410	57	0	29	55	4.4	330	55	3.1	310	55	3.2	320
33	0	47	65	0	25	57	0	99	58	0	160	56	190	530	56	2.5	180	56	260	410
34	0	0	66	56	150	58	0	180	62	2.5	280	57	0	42	57	0	0	57	0	95
35	0	0	67	0	480	62	2.5	370	64	3.9	40	58	0	130	58	0	120	58	0	170
37	4.3	0	68	2.5	0	64	32	130	65	5.4	68	62	2.5	220	62	0	210	62	0	120
38	0	69	69	0	99	65	47	250	67	2.5	410	64	2.5	49	64	3.8	41	64	2.5	100
39	0	38	70	4.9	710	67	0	570	68	2.5	0	65	2.5	38	65	3.2	0	65	3.3	51
41	13	140	71	9.3	340	68	3.4	0	69	5.3	350	68	0	0	68	0	0	68	0	0
42	4.8	92	72	3.2	0	69	7.1	240	73	2.5	0	69	4.7	0	69	3.7	260	74	0	110
43	7.8	380	73	0	0	74	0	340	74	0	270	74	0	170	74	0	330			
			74	0	520															

Appendix I

USACE Comments and Responses

Consolidated Comments on CDM Draft report

CDM responses appear in red.

USACE counter responses appear in blue.

City of Savannah responses appear in green.

Comments are separated into 3 categories: A. Concerns, B. Questions and Suggestions for Clarification, and C. Typos

A. Concerns

1. Page ES-1 - States significant increase in DBP formation. From bench scale results it appears the increase in TTHMs could be described as significant, however the increase in HAAs were not significant and even less when looking at the regulated forms. Need to differentiate the HAAs between regulated (HAA5) and unregulated (HAA9) forms.
   Will modify description as appropriate. ***Comment resolved.***

2. Page ES-2 - States the raw water pumping capacity is 75 MGD. From the previous review meeting it was stated the raw water pumping capacity was 100 MGD. From discussion with John Sawyer, it was determined that the 75 mgd firm rate is based on the design assumption of 1 pump outage. Study needs to address the potential of an additional backup pump at the Abercorn Creek plant, which would impact impoundment size.
   Increased raw water pumping capacity would potentially allow the impoundment to be smaller but would add capital cost at the intake structure. Further study would be required to determine whether this approach would be more cost-effective than a larger impoundment. ***Comment resolved.***

3. Table 5-4 – Add HAA5 to the table. Agree it's good to look at the HAA9, however HAA5 is what is currently regulated and should be shown.
   Will modify table. ***Comment resolved.***

4. Table 5-5 - The total THM and HAA9 are n/a for all the chloramines samples? Isn't that the sample set that is supposed to best represent the residential system?
   Chloramines do not form significant quantities of regulated DBPs. The DBPs in the residential system are due to reactions with free chlorine in the plant clearwell. The DBP testing using free chlorine simulates these conditions, in which water is treated with free chlorine for approximately 12 hours in the clearwell before ammonia is added. ***Comment resolved.***

5. Table 6-7 - Raw water storage pond/s recommended acquisition site is that same one owned by GPA that we apprised in 2008. That appraisal involved coordination with GPA. This proposal is for a much smaller site and used a value of $15,000 per acre compared to our $55,000 per acre from our 2008 appraisal. How was this value per acre determined?
   The unit land cost was not intended for the specific parcel mentioned in previous studies but is a placeholder number based on CDM's cost estimating knowledge of the area. Will revise using $55,000 per acre. It was agreed 12 Aug 2011 GPA would provide updated land values after coordinating with their real estate staff and recent economic conditions could have considerably reduced the 2008 value. Incorporation of GPA's $55,000 per acre cost updated with an explanation of any changes will resolve the comment.

6. Figures 8-2 – 8-12 - Very little difference shown between 72 and 80 MG reservoir, and actually not a great difference with 48 mg reservoir. Is there any reason to justify an 80 MG reservoir; is it possible to view 60 or 62.5 MG reservoir under the same modeling scenarios as it correlates to 1 day of storage?
   Ideally the impoundment would allow chloride concentration entering the plant to be kept below 30 mg/L at all times (per City). This does not appear feasible, but Figure 8-4 shows a significant additional benefit to increasing size from 48 to the range of 72-80 MG as it allows for operation at a lower pumping cutoff concentration and keeps the worst-case chloride lower. Figure 8-2 shows a small added benefit of 80 MG over 72 MG in that the worst-case concentration can be kept near 40 mg/L for a broader range of pumping cutoffs. It was agreed 12 Aug 2011 GPA figures would be modified and added for clarification and additional reservoir sizes added to the analysis for comparison. Incorporation of this information will resolve the comment.

7. Appendix F - It appears there are a significant number of samples that had Pb detections in the blank. Any explanation, and was this considered in the impact analysis?
   During week 1 there was some lead detected above the detection limit in the blanks used for analysis. The lab has offered no explanation, but the levels of lead detected in the blanks were orders of magnitude lower than those measured in the samples. As such, this contamination was not considered to impact the findings. Note also that Week 1 data were excluded from analysis of corrosion impacts for reasons explained in Section 5.5.3. It was agreed 12 Aug 2011 the City of Savannah would provide additional historical Pb and other water quality parameter testing results to CDM and CDM would then incorporate this info (including any necessary analysis of historical water quality results) into the final report. CDM would also include an explanation for

the Pb shown in the samples. Incorporation of this information will resolve the comment.

B. Questions and Suggestions for Clarification

1. Section 1.3 - it would be helpful to add more detail to this section to clearly understand the plant's operation. More detail on how the process differs between the industrial users and the residential users and the percentages of use for each group would be very helpful to the reader.
   This information is provided in Section 4.1, but will be added to Section 1.3 as well.
   Comment resolved.

2. Section 1.3 - Is the clearwell used for the residential system and the industrial system? It is stated that the majority of the DBP formation is in the clearwell prior to distribution in a later section, but it isn't clear if this is for the industrial users or the residential system. Is it the same for both?
   Will clarify. Only the residential system has a clearwell. It was agreed 12 Aug 2011 CDM would incorporate a description of the WTP distribution system into the final report. Incorporation of this information will resolve the comment.

3. Section 3.3 - Were the concentrations shown for bromides in the last sentence measured or determined from a typical or known relationship of bromide to chloride concentrations?
   These were measured from the seawater blends prepared in the course of the study.
   Comment resolved

4. Page 4-2 - Given the wide swings in pH in the distribution system, has the City considered doing alkalinity adjustment to increase buffering capacity?
   Unknown; City to comment. Awaiting info. Alkalinity, as a pre-treatment process, is adjusted as needed for proper coagulation. The adjustment is completely dependent upon incoming raw water quality. To a lesser degree, alkalinity is again increased in the finished water basically as a by-product of final pH adjustment. However, the amount of finished water pH adjustment necessary at any given time is directly related to the specific chemical dosages necessary to treat the raw water quality which changes continuously. The finished water pH leaving the plant is therefore, also a continuously changing value.

   The changes in pH within the distribution system itself are negligible. What is changing continuously is the pH of the finished water entering the distribution system from the treatment process. Thus at any point in time the pH of the water throughout the distribution system will vary.

5. Section 4.3.2- Are these four sites the only LRAA sites for TTHMs? It is interesting that there is only one site for residential use monitored and 3 sites for industrial use. Is that

based on the percentage of treated water for each system? Is there a theory on why the OAT site generally has the highest LRAA?
It is our understanding that these are the current DBP monitoring sites. City to comment. ***Awaiting info.*** ***At the time that the original Disinfection/Disinfection By-Product (D/DBP) Rule became effective, the I&D system served industrial customers almost exclusively. Under the D/DBP Rule it was required for the system to have 4 sample sites. 1 site near the plant, 1 site representing the longest residence time (determined by the lowest average chlorine residual), and 2 sites representing the average detention time within the system. When Travis Field was taken off groundwater and added to the surface water system, Georgia EPD required that we move the sample site from the plant to the point of longest residence time within the Travis Field system. This was in part based on the percentages of water used by each system. Under the stage 2 D/DBP Rule (effective in 2012), Savannah will be required to add 2 to 4 additional sites, most of which will not be in the original industrial system.***

Chlorine residual is a function of chlorine demand and residence time. Likewise, TTHMs are a function of naturally occurring organic matter (NOM), chlorine concentration and chlorine contact time. The longer free chlorine is allowed to be in contact with any existing NOM the higher the TTHM levels will become. The water demand at OAT is relatively low thus providing an extended residence time. The long residence time allows TTHM levels in to increase. It is precisely this general relationship between lowest chlorine residual and high TTHM formation potential, that federal and state regulations use as a basis for selecting the TTHM sites.

6. Page 5-19 and 5-22 - Change language to say there was significant increase in THMs and slight or moderate increase in HAAs and distinguish between HAA5 and HAA9.
Will modify language. ***Comment resolved***

7. Section 5 Charts – Please indicate the regulated value for HAA5 and THM. As in the previous comment, expand the charts to include both HAA5 and HAA9, since only HAA5 can be compared to regulated values.
Will modify charts. ***Comment resolved***

8. Chapter 5 - was there anything to report in regards to the weighing of the coupons before/after the study?
Post-exposure data was received after the draft report was issued. A summary will be prepared and attached to the final report as an appendix. Post-exposure analysis did not raise any significant issues or change the findings presented in the draft report.
Comment resolved.

9. Page 5-12 and figures 5-7 and 5-8- what is the chloride to sulfate mass ratio and why is that an important indicator for metal release?
The CSMR is described in Section 2.4.1.3 of the report. The ratio of chloride to sulfate in the water plays a key role in determining what solid phase species control the

solubility of lead, and therefore can have a major impact on lead leaching. Adding such as explanation to the report would resolve this comment.

10. Figure 5-16- since there are so few data points it would be helpful to know if this effect is typical and expected.
    Increased chlorine demand is consistent with expectations based on the reduced removal and increased hydrophilic character of the TOC, shown in Figure 5-5. Will clarify language. Comment resolved.

11. Figure 5-17- is this figure for the chloramine or free chlorine samples? How do the THM and HAA speciation vary between the disinfectant methods?
    Chloramine samples were not tested for DBPs as chloramines form negligible quantities of regulated DBPs. All DBP testing employed free chlorine, as described in section 5.4.2. Will clarify language. Comment resolved.

12. Page 6-2 - Chloramines/change in location of the ammonia feed point should be discussed more for DBP compliance. We realize that this does not solve the corrosion issue, but feel the report could put some more emphasis on the cost effective solutions for managing DBPs.
    Strategies for improving DBP compliance are discussed in section 6-5. Based on CDM's experience optimization of disinfection (e.g. change in feed point) is not likely to reduce DBP formation to the degree needed to ensure compliance with regulations given the increased chlorides. Adding such as explanation to the report would resolve this comment.

13. Page 6-4 - MIEX should not be listed as treatment option for corrosion control, it should be in section 6.2.2 as a treatment option for DBPs, as stated it can increase chlorides. Perhaps mention a chloride specific ion exchange resin as an advanced treatment option.
    Will move to the appropriate section. Comment resolved.

14. Table 6-2 would argue that reducing contact time could be effective at reducing DBPs by itself assuming adequate contact time could be maintained for CT (this table refers to only treatment for DBPs).
    Agree; will clarify language on this point. Further study would be required to determine the extent to which contact time could be reduced without compromising CT, as discussed in section 6.2.2. Nevertheless, based on CDM's experience we feel it is unlikely that this solution would reduce DBP formation to the degree needed to ensure compliance with regulations given the increased chlorides. Comment resolved.

15. Table 6-4- suggest using a flowchart to show pump operations. Table format is a little confusing.
    Will comply. Comment resolved.

16. Table 6-6 Does the transfer pumping power costs take into account potential reduction in raw water pumping costs (assuming they operate on VFDs) due to the shorter distance to pump to the reservoir than the WTP?
    No; this was not considered since the location of the impoundment is still uncertain.
    Comment resolved.

17. Section 7.2 - impoundment size determination is mentioned here (and on pg 6-10) based on methodologies/models by CDM and the City. Could those be discussed in greater detail to show how the impoundment size was determined and what calculations were used?
    Will clarify language on this point. Comment resolved.

18. Section 8.1 - would the chemical considerations be necessary in addition to the raw water impoundment?
    Yes. During extreme drought or other high-seawater periods, elevated chloride levels may reach the plant in spite of the impoundment. As such, it is advisable to be prepared to respond as described in Section 8.1. Comment resolved.

19. Figures 8-2 to 8-5 - clarify values used for maximum chloride concentration and 99th percentile.
    Please clarify this question. Comment resolved during 12 Aug 2011 discussions.

20. Section 8.2.3- raw water pumping cut-offs were suggested at 30-50 for severe droughts and 20-40 for mild droughts. How were those values determined? Please clarify.
    Will clarify with reference to Figure 8-3 and 8-5. Comment resolved.

21. Tables on 8-4 and 8-5 are difficult to understand. Perhaps axis could be renamed for clarity.
    Will rename axis after discussion with all parties. It was agreed 12 Aug 2011 CDM would simplify tables (possibly use more, simpler tables). Comment resolved.

22. Additionally with adding potentially smaller reservoirs, could the possibility of increasing groundwater flows during periods of high chlorides with the understanding these withdrawals would be reduced during periods of lower chlorides for no overall net increase in groundwater withdrawal be investigated? This approach is being considered with a lot of utilities in Florida as alternative water supplies are being investigated.
    We understand from the City that there would be a number of issues such as with EPD and the State if groundwater use were to be increased. It was agreed 12 Aug 2011 the City would provide evidence of this transition away from coastal groundwater supply. This concept is not viable for two primary reasons. 1) In June 2006, the Georgia EPD released the "Coastal Georgia Water & Wastewater Permitting Plan for Managing Salt Water Intrusion". This plan and subsequent special conditions for all municipal groundwater systems, required that existing permits for each system be rewritten and include, among other things, a reduction in total groundwater withdrawal to the

system's 2004 actual pumping volume. With an average demand of approximately 25 MGD and a revised permit capacity of 23.53 MGD, Savannah is already supplementing groundwater needs with surface water. In addition, a special committee appointed by Governors Perdue of Georgia and Sanford of South Carolina is currently studying the options related to further reductions in groundwater withdrawals so as to reduce current saltwater intrusion into the aquifer. The proposed swapping of groundwater and surface water as suggested would be in complete contradiction to the permitting plan. In addition, the uncertainties of future frequency, magnitude, and duration of high chloride periods would make for an unmanageable condition from both the operation and regulatory perspective. 2) Adequately sized and located distribution system piping and pressure booster facilities necessary to transmit water in the required volumes does not currently exist between the surface water and groundwater systems.

23. Table 6-7 - Are there any costs/plans for the easements required to tie the line into the existing waterline?
    These easements were not explicitly considered in the cost estimate. Adding a statementto the final report that easements were not included in the estimate would resolve this comment.

24. Section 6 Could a brief analysis of adding greater raw water pumping and smaller ponds be added? Are rental pumps an option to be considered in such an analysis? For what reasons does the City not wish to increase raw water pumping?
    See response to comment A.2. Comment resolved.

25. Section 8 - Can an analysis showing how often the raw water storage pond/s would be used and for how many hours be added?
    All flow to the plant would pass through the impoundments at all times, as described on page 6-10. During high chloride events pumping would be shut off and the level in the impoundment would be drawn down to supply the plant. Figure 8-1 shows the amount of time that the pumps would ideally be shut down for different chloride pumping concentrations. Comment resolved during 12 Aug 2011 discussions.

26. Appendix F - Why is there no Pb and Cu data for weeks 2-5 for a large number of samples (pp. 45-50)? I thought the "averages" were for weeks 4, 5, and 6 to account for equilibration time? Can we see the original lab report?
    As explained in the testing protocol (Appendix D), replicate samples were analyzed separately only on weeks 1 and 6. During the remaining weeks replicate samples were composited. These composite measurements are shown only once in the table. CDM would be happy to provide copies of the original lab reports. Comment resolved during 12 Aug 2011 discussions.

C. Typos

Will correct as appropriate. Comments resolved.

1. Table of Contents – Page number for 3.1.1 should be 3-1 instead of 2-1.
2. Figure 4-4- legend should be corrected to read Mitigation 6A
3. Table 5-3- Check bromide units, should it be micrograms/L?
4. Page 5-19- check figure numbering, text seems to describe figure 5-16 not 5-14.
5. Page 5-20- check figure numbering, text seems to describe figures 5-17 and 5-18. Also, last sentence I believe "chlorine-containing" should be "chloride-containing".
6. Page 6-3- misspelled word – "som" should be "some".
7. Table 6-5- table is not consistent with preceding text. No. of ponds column needs to be verified. Also, a parenthesis is missing after MG in first sentence on same page.
8. Page 6-11, 3rd paragraph, 4th word - change from "if" to "in".

USACE Comments to CDM Amended Final Draft Report

November 2011

CDM Responses appear in red.

1. Page 2-7, Section 2.3.2.1 - "Utilitys'" should be spelled "Utilities'"

Revised as requested.

2. Page 6-9, Figure 6-4 - The process schematic is not consistent with valves and pumps as shown in Figure 6-8. On Figure 6-4, there should also be a valve shown at the inlet to the pond; and the transfer pumps should be upstream of the confluence with the bypass line, on the pipeline just downstream of the pond.

Revised figure as requested.

3. Page 6-15, Figure 6-8 - Would it not be more economical to have both the influent and effluent pipelines cross the railroad at the same location? Since additional effort will be made during design phase to locate other potential sites for the impoundment, it is not necessary to make this change at this time. The comment is made for future consideration.

Acknowledged.

4. Page 8-1, Section 8.2 - It would be helpful in the description of Impoundment Operation to include a paragraph addressing data needed to make timely decisions regarding pump and valve operation. Clearly the City operator cannot wait until chloride levels are measured at the treatment plant to make operational decisions, because there is about a 6-hour travel time for raw water in the pipeline, not including residence time in the proposed pond. What date will be required - and what data would be helpful - to make these decisions?

Added the following statement to Section 8.2: "It is recommended that a remote, on-line chloride analyzer or other means of monitoring seawater percentage be installed at the raw water intake to facilitate these decisions."

Appendix J

Recommended Impoundment Size for Alternate Depths

SUMMARY OF ALTERNATE DEPTH ANALYSIS

The recommended impoundment volume for four additional harbor deepening scenarios (2ft 6B, 3ft 6A, 4ft 6A, 6ft 6A) was determined using the same procedures outlined in Section 6.2.3 of the report. The recommended volumes for each depth are shown in the table and chart below. The chart also shows (on the right hand axis) the maximum chloride concentration *in the river* for each scenario. The following steps summarize the procedure used:

1. Modeled chloride concentration data for each scenario was used to generate performance graphs showing the impact of usable impoundment volume on the maximum and 99th-percentile chloride concentration reaching the plant. These graphs are shown on the following pages.
2. Volumes were selected based on two performance criteria: limit the maximum chloride concentration entering the plant to 40 mg/L and limit the 99th percentile concentration to 25 mg/L. The minimum volumes satisfying each of these criteria are circled in red on the performance graphs. As noted in the report, in cases where meeting the second criterion would require a large volume increase, but only reduce the 99th percentile concentration by 2-3 mg/L, the criterion was relaxed from 25 mg/L to the existing maximum concentration of 28 mg/L.
3. The selected volumes were checked to make sure they did not go empty during worst-case conditions and were increased as necessary.
4. A 2.5-MG buffer to allow for operator reaction time was added to each selected volume

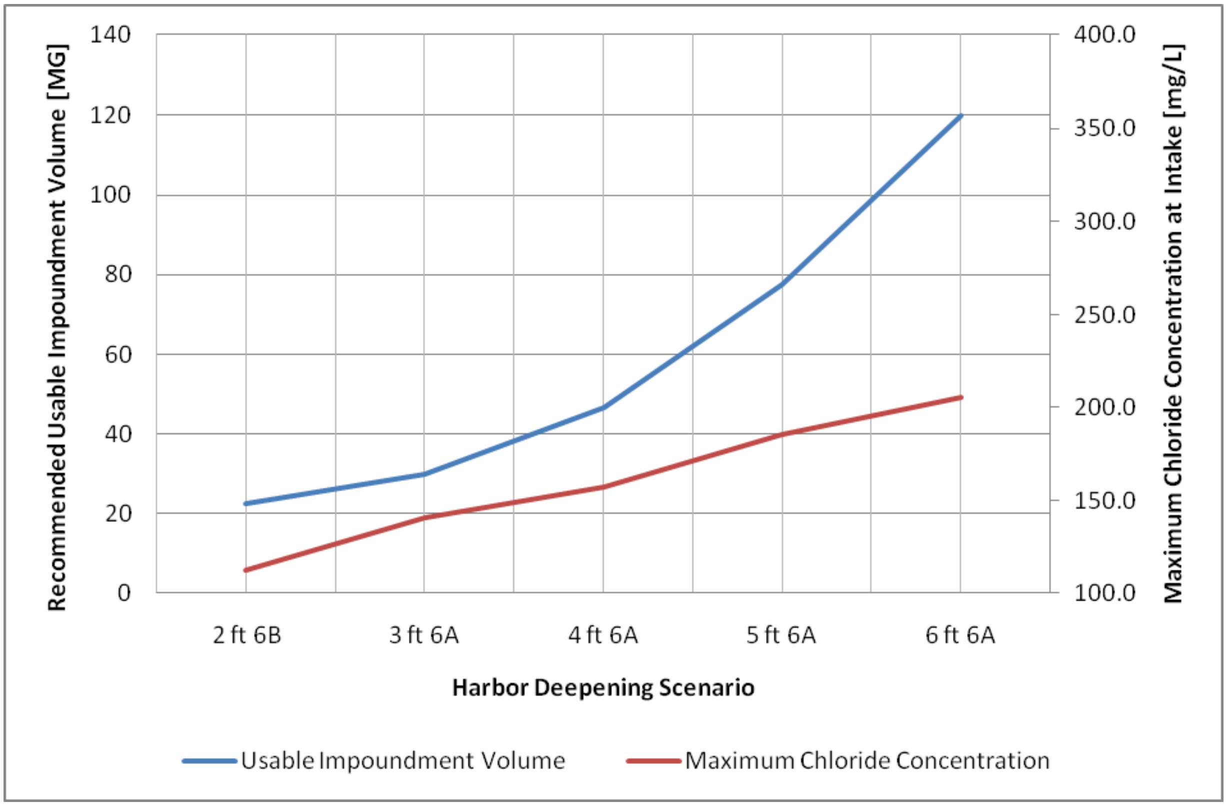
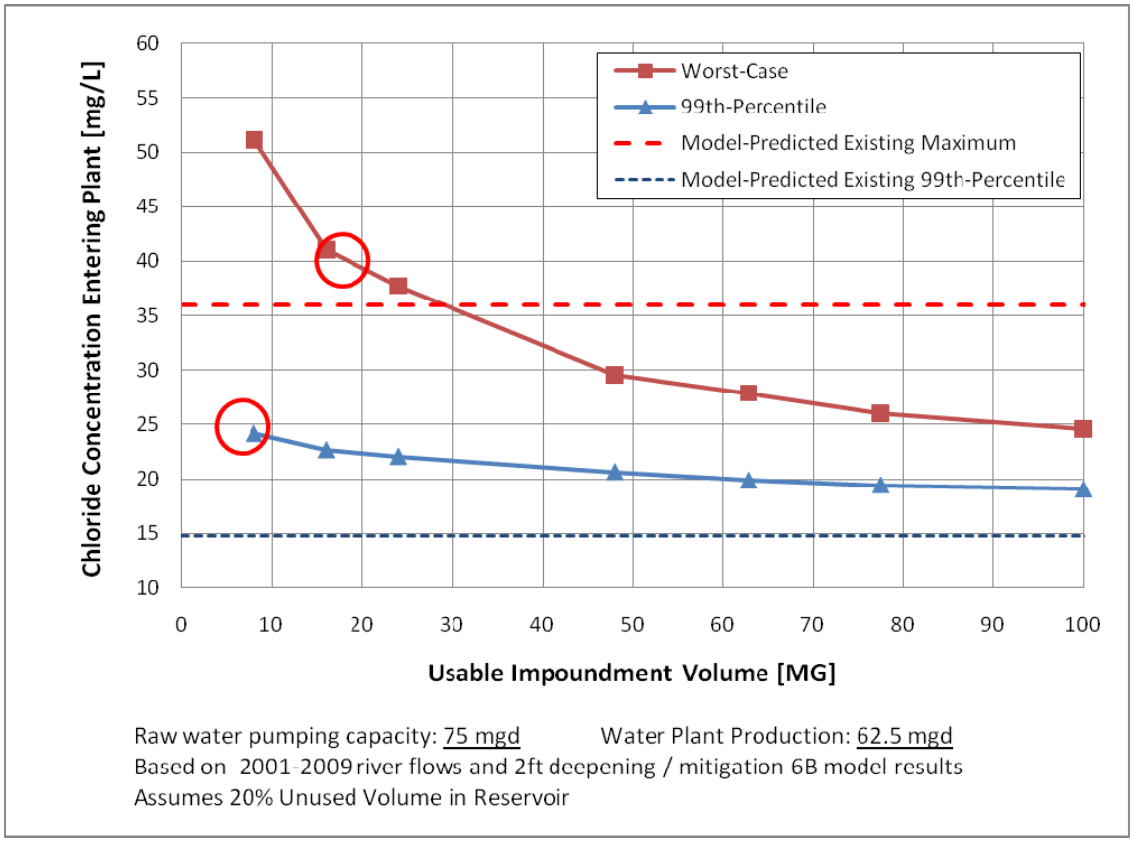


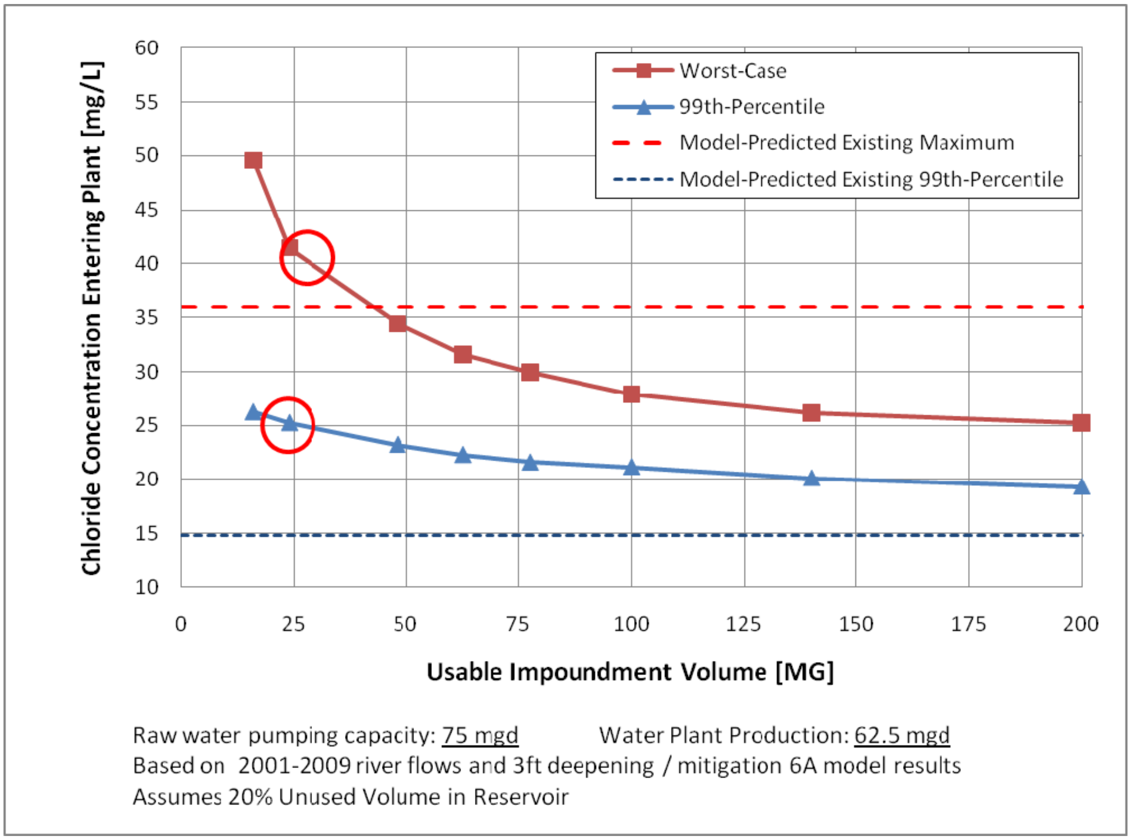
Figure 1: Recommended usable impoundment volume and maximum chloride concentration at the intake location for each scenario

Table 1: Recommended usable impoundment volumes for each depth					
Depth scenario	2ft 6B	3ft 6A	4ft 6A	5ft 6A	6ft 6A
Recommended usable impoundment volume, MG	22.5	30	46.5	77.5	120.0



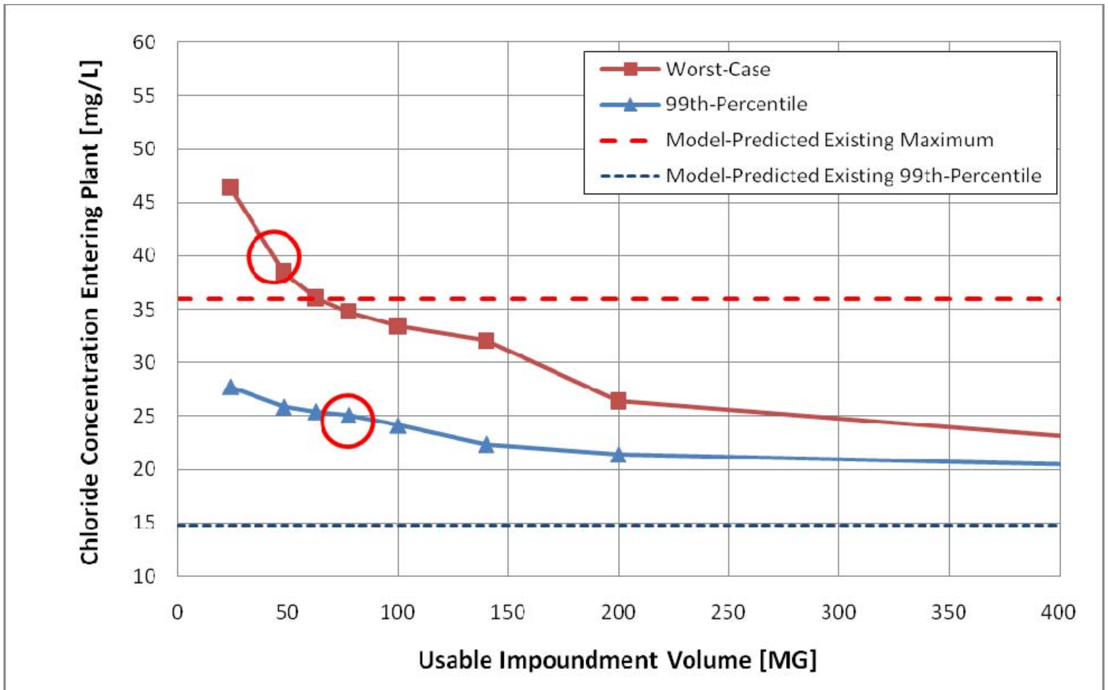
Raw water pumping capacity: 75 mgd Water Plant Production: 62.5 mgd
Based on 2001-2009 river flows and 2ft deepening / mitigation 6B model results
Assumes 20% Unused Volume in Reservoir

Figure 2: Reservoir performance for 2-ft Depth, Mitigation 6B Scenario. The 40 mg/L maximum criterion controls.



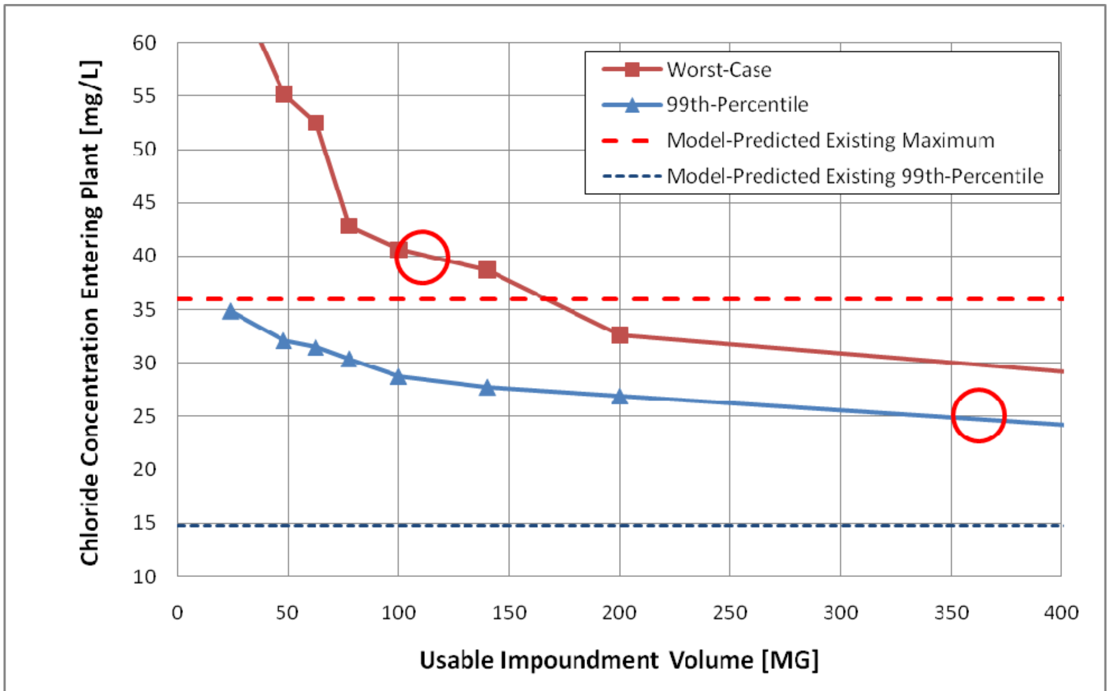
Raw water pumping capacity: 75 mgd Water Plant Production: 62.5 mgd
Based on 2001-2009 river flows and 3ft deepening / mitigation 6A model results
Assumes 20% Unused Volume in Reservoir

Figure 3: Reservoir performance for 3-ft Depth, Mitigation 6A Scenario. The 40 mg/L maximum criterion controls.



Raw water pumping capacity: 75 mgd Water Plant Production: 62.5 mgd
Based on 2001-2009 river flows and 4ft deepening / mitigation 6A model results
Assumes 20% Unused Volume in Reservoir

Figure 4: Reservoir performance for 4-ft Depth, Mitigation 6A Scenario. The 40 mg/L maximum criterion controls.



Raw water pumping capacity: 75 mgd Water Plant Production: 62.5 mgd
Based on 2001-2009 river flows and 6ft deepening / mitigation 6A model results
Assumes 20% Unused Volume in Reservoir

Figure 5: Reservoir performance for 6-ft Depth, Mitigation 6A Scenario. The 99th-percentile criterion of 25 mg/L (relaxed to 28 mg/L) controls.