FINAL, REV 1

BENCH-SCALE TESTING TECHNICAL MEMORANDUM

Water Quality Assessment –
City of Santa Cruz Water Department
& Soquel Creek Water District

B&V PROJECT NO. 197086

PREPARED FOR

City of Santa Cruz

AUGUST 1, 2018

BLACK & VEATCH

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Acronyms and Abbreviations

CCPP	Calcium Carbonate Precipitation Potential
CCT	Corrosion Control Treatment
City	City of Santa Cruz
CSMR	Chloride-to-Sulfate Mass Ratio
District	Soquel Creek Water District
GHWTP	Graham Hill Water Treatment Plant
GW	Ground Water
SW	Surface Water

1.0 Introduction

1.1 BACKGROUND

The City of Santa Cruz (City) have entered into a pilot agreement with Soquel Creek Water District (District) to sell excess winter water supply from the City's surface water treatment plant. Currently, the District's water supply source is a number of groundwater wells, whereas the majority of the City's supply is from various surface waters and supplemented by a few groundwater wells within its service area. As a proactive step prior to introducing a new water supply into the District's distribution system, the water agencies evaluated potential water quality impacts from the change in source waters as part of the City of Santa Cruz Intertie Blending Analysis desktop study completed in 2016, which prompted the need for demonstration testing and lead to this Water Quality Assessment . This Assessment was aided by pipe scale analysis and included bench-scale corrosion testing to rapidly screen multiple corrosion control treatments under controlled conditions so as to evaluate water quality parameters and quantify their effect on corrosion and metals release.

Winter water quality data for the City between November and March from 2012 to 2015 were analyzed from distribution system sample stations SS 105 (corner of Gross Road and 41st avenue) and SS 119 (corner of Marnell Avenue and Morrissey Blvd) as they are the closest to the O'Neill Ranch intertie at the intersection of 41st Avenue and Soquel Drive and therefore are anticipated to be the most representative of the water reaching the intertie. The City's Graham Hill Water Treatment Plant (GHWTP) data were used in cases where distribution system data were unavailable. Both the City and the District use free chlorine to provide a disinfectant residual in the distribution system.

A summary of parameters that influence corrosion and metals scale release are provided below in Table 1, where winter water quality data were analyzed for November to March from 2012 to 2015. A detailed explanation for the water quality data in Table 1 is provided in the City of Santa Cruz Intertie Blending Analysis Technical Memorandum (2016).As shown in Table 1, the City water has a Calcium Carbonate Precipitation Potential (CCPP) of -7 in the winter, whereas the CCPP of the District's water in Service Area 1 is +7. The City's CCPP by itself would indicate a tendency to dissolve any calcium carbonate based scale present in the District's system. However, the City adds orthophosphate, a phosphate-based corrosion inhibitor to its water, which indicates that the CCPP does not completely describe the tendency for precipitation or dissolution of calcium carbonate scales.

Orthophosphate combines with various metals found in distribution systems and plumbing materials to form compounds that are insoluble and thereby precipitate and form a coating on the pipe wall surfaces. For this reason, the addition of orthophosphate minimizes the potential for corrosion and other metals release to occur and it is added to many systems to prevent lead release. The effect on corrosion control and metals release from the addition of orthophosphate was studied as part of the bench-scale testing.

Table 1   Wintertime (November to March) Water Quality from District and City

| | DISTRICT | | | | | | CITY | |
| | SERVICE AREA 1 | | SERVICE AREA 2 | | SERVICE AREA 3 | | CITY[1] | |
PARAMETER	AVERAGE	RANGE	AVERAGE	RANGE	AVERAGE	RANGE	AVERAGE	RANGE
Alkalinity	196	157-254	242	197-288	175	149-205	131	92-194
Calcium	72	34-110	38	21-59	29	14-36	50	48-51
Chloride	49	25-88	41	31-53	26	18-39	25	19-30
Magnesium	21	14-25	29	16 - 50	31	21-40	9	9 - 10
CCPP[2]	7		5		-1		-7	
Orthophosphate (as P)[4]	.02	ND-.075	.04	ND-.09	0.2	0.15-0.34	0.2	0.1-0.3
pH	7.5	7.0–8.1	7.6	7.1-8.1	7.7	7.2-8.1	7.4	7.1-7.7
Sulfate	101	42-180	68	46-99	28	15-43	77	64-92
CSMR[3]	0.5		0.6		0.9		0.3	
Total Dissolved Solids	477	300-638	411	332-492	282	191-357	262	255-258

[1] **Data from SS 105,119, or GHWTP effluent as available**
[2] **Calcium Carbonate Precipitation Potential (CCPP) results using Water!Pro modeling software. Results modeled for average conditions only**
[3] **Chloride to Sulfate Mass Ratio**
[4] **P = phosphorous**

The District has the opportunity to adjust the City's water chemistry at the intertie between the City's system and the District's system to prevent upsetting the pipe scale in the District's system that could result in metals release. The bench-scale testing included conditions that simulate alternative water treatment conditions that should minimize the disturbance to the District's system if deemed necessary.

1.2   SPECIFIC GOALS OF BENCH-SCALE TESTING

The specific goals for bench-scale testing include the following:

- Examine the relative aggressiveness of the City's water and the District's water towards harvested galvanized iron pipe, harvested asbestos cement pipe, and new copper pipe with lead solder.
- Screen multiple treatment conditions to determine the impact of adjusting the water chemistry of either the District's wells, or of the City's water at the intertie location.
- Establish the need for future pipe loop testing, and which treatment alternatives could be further tested with pipe-loop testing.

2.0   Bench-Scale Corrosion Testing

2.1   OVERVIEW

The goal of bench-scale corrosion testing is to compare the effects of different water qualities towards metals release and corrosion of pipe surfaces from the materials known to be present in the District's system. The bench-scale testing was composed of the following:

- Metal wire testing.
- Metal coupon testing.
- Scale analysis.

The metal wire testing assessed the corrosivity to new or aged galvanized iron pipe using zinc wires to represent new galvanized iron pipe and iron wires to represent aged galvanized iron pipe where the galvanized coating is no longer present.

The metal coupon testing was conducted using both new pipe and harvested pipe from the District's distribution system and it provided information with regards to the aggressiveness of the current water source and potential treatment conditions as well as their impact on metals release and corrosion of pipe surfaces.

The scale analysis was conducted on the harvested pipe and it involved examining the composition of metals within the scale and other defining characteristics, which allowed for both qualitative and quantitative interpretation of the scale on the interior of pipes harvested from the District's distribution system.

2.2   METAL COUPON SELECTION

Metal coupon testing used short pipe sections or small pieces of larger pipes (i.e., coupons) of common materials present in the District's distribution system or within premise plumbing to help determine how specific corrosion control treatments (CCTs) and alternating source waters will affect the release of metals and the corrosion of pipe walls. To better simulate anticipated full scale effects in the District's system, harvested galvanized pipe, harvested asbestos cement pipe, and new copper pipe with lead solder were used for testing.

2.3   WATER TREATMENT CONDITIONS

The water treatment conditions were chosen based on the knowledge of metals solubility and the effect of corrosion inhibitors such as orthophosphate under different water chemistries. The water in the District's system will alternate seasonally as the District will receive water from the City during the winter months only. It was important to represent the effect of alternating water sources as part of the bench-scale testing as this could affect the corrosion potential within the piping materials. There is the possibility for some blending of source waters within the distribution system, but based on previous studies, the worst case conditions typically involve switching sources rather than blending. Therefore, this study chose to look at the potential worst case condition of alternating sources.

Currently, the City adds 0.5-0.6 mg/L of orthophosphate as phosphorous (P) to the finished surface water (SW) as a corrosion inhibitor, but a conservative value of 0.2 mg/L was selected for bench-scale testing based on the water quality data provided in Table 1 and explained in more detail in the City of Santa Cruz Intertie Blending Analysis Technical Memorandum (2016). The District does not use corrosion inhibitors due to their water's positive CCPP. The District could potentially add orthophosphate year-round to their groundwater (GW) prior to introducing it to their distribution system as a way to prepare the piping materials to receive the City's water in the winter that already includes the corrosion inhibitor. This scenario was examined during bench-scale testing (i.e., C2 and C7 in Table 2).

Similarly, the District could adjust the pH of the City's water at the intertie before it enters the District's system. If the pH of the City's water was increased to 7.8 it would result in a CCPP of approximately 3.5 based on the City's average winter water conditions displayed in Table 1. Testing this scenario will determine if pH adjustment can compensate for the District's water not having a corrosion inhibitor.

The seven water conditions that were evaluated in bench-scale testing are outlined below in Table 2 with the description of the water condition and the full scale representation of each testing condition.

Table 2   Water Conditions for Metal Coupon Bench-Scale Testing (7 water conditions)

WATER CONDITION	WATER DESCRIPTION	FULL SCALE REPRESENTATION
C1	GW at pH 7.5	Experimental control; current District water quality conditions
C2	GW at pH 7.5 with the addition of orthophosphate	If orthophosphate is added to the District's GW wells
C3	SW at pH 7.2 with the addition of orthophosphate	SW that would enter the District's system at the low end of the normal pH range
C4	SW at pH 7.8 with the addition of orthophosphate	SW that would enter the District's system with a higher pH (either adjusted or at the high end of the normal range)
C5	Alternating between C1 and C3	Impact on District's system from alternating between City water at the low end of the normal pH range and District GW
C6	Alternating between C1 and C4	Impact on District's system from alternating between City water with high pH and District GW
C7	Alternating between C2 and C3	Impact on District's system from alternating between City water with low pH and District GW treated with orthophosphate

The full methodology including the results and analysis of the bench-scale testing can be found in Appendix A.

3.0 Conclusions

The bench-scale testing was successful at providing comparable results for a number of treatment alternatives (i.e., adjust the City's SW pH at the intertie with the District, add orthophosphate to the District's GW) as well as alternating conditions to simulate the proposed seasonal change in source water. In regards to the relative aggressiveness of the City's water and the District's water towards harvested galvanized iron pipe, harvested asbestos cement pipe, and new copper pipe with lead solder, the bench-scale testing showed the following:

WIRE TESTING

■ Wire testing demonstrated that GW conditions had similar or higher corrosivity to pure Zn or Fe wires, compared to SW conditions.

ASBESTOS CEMENT COUPON TESTING

■ The asbestos cement coupons showed no concern for calcium dissociation, even for the alternating conditions that experienced switches in source waters.

COPPER PIPE WITH LEAD SOLDER COUPON TESTING

■ Copper pipe with lead solder coupons displayed statistically similar results for copper release for all examined water conditions.

■ When comparing alternating conditions (C5 versus C6) for copper pipe with lead solder coupons, the lower SW pH 7.2 (C5) appeared to help with maintaining low lead levels and minimized the spike in lead and copper when switching to GW.

■ Copper pipe with lead solder coupons had more stable low levels of lead leaching when orthophosphate was added to GW, but the benefit was not statistically different from the baseline GW.

GALVANIZED IRON COUPON TESTING

■ Galvanized iron pipe coupons had similar ranges of water turbidity among all examined water conditions, but the most constant low levels of turbidity resulted from switching between SW at pH 7.2 and GW at pH 7.5 (C5).

■ Manganese leaching from the scale of galvanized iron pipe coupons for all treated conditions was similar to or lower than baseline GW at pH 7.5 (C1).

■ Galvanized iron pipe coupons had consistently low levels of iron leaching for all conditions throughout the 10 weeks of exposure.

■ Significant phosphorous uptake was only observed with the galvanized iron pipe coupons (as expected), and the uptake decreased over time as the orthophosphate reacted with the pipe surface to form a passivating layer.

■ Additional testing with galvanized iron pipe coupons confirmed that phosphorous was still present in the water after two weeks of contact with SW at pH 7.2 containing 0.2 mg/L orthophosphate as P.

4.0 Recommendations

This assessment of the City's water and the District's water towards harvested galvanized iron pipe, harvested asbestos cement pipe, and new copper pipe with lead solder indicates the following;

■ Alternating between the current District's GW and the typical City's SW at pH 7.2 (C5) performed equal to or better than the baseline GW (C1) especially in regards to decreasing lead and iron release.

■ Similar results to those displayed for condition 5 (alternating between the current District's GW and the typical City's SW at pH 7.2) are expected if the City's SW pH ranges from 7.0 to 7.6.

■ Adjusting the SW to pH 7.8 was not beneficial as it resulted in spikes in both lead and copper when the source was switched to GW at pH 7.5 for the alternating condition C6 as well as increased iron leaching.

■ Adding orthophosphate to the GW was able to preserve slightly lower lead levels when comparing the alternating conditions (C7 versus C5), but the minimal benefit is not worth the expense when the lead levels for C5 are already lower than the baseline GW (C1).

The recommendations based on the conclusions of bench-scale testing are as follows:

■ Pipe-loop testing is not recommended based on the positive bench-scale testing results for alternating condition C5 (current District's GW and the typical City's SW at pH 7.2) because the results do not show a need to adjust water chemistry at the intertie or within the District's system.

■ Proceed with the implementation plan to introduce the City's SW within a pH range of 7.0 to 7.6 to an isolated portion of the District's distribution system, where the implementation plan includes coordination with the California Division of Drinking Water (DDW) to determine the number and location for compliance monitoring sites, additional sampling sites for the District to monitor water quality, a customer notification plan, and distribution system flushing.

■ The results of bench-scale testing showed minimal aesthetic concerns for the proposed full-scale condition, but a proactive customer notification plan should be implemented to alert customers in the isolated portion of the District's distribution system of the proposed seasonal change in source water and the possibility for water quality changes that could include the following: discoloration, taste, odor, and turbidity.

■ Businesses or individuals that could be susceptible to water quality changes should be alerted of the seasonal switch in water sources, and this could include hospitals, daycare facilities, nursing homes, dialysis patients, and food or beverage production facilities.

■ The portion of the District's distribution system that will receive the City's water via the intertie should be isolated prior to receiving the City's water so that full-scale baseline water quality monitoring can be conducted. Water quality monitoring should continue after the City's water is introduced to the isolated portion of the District's system.

■ Water quality monitoring in the isolated portion of the District's system should continue through at least one year of the seasonal source water changes between the City's water and the District's water to validate the results of bench-scale testing.

Appendix A.   Proactive Water Pipe Corrosion Investigation in Santa Cruz, California

Proactive Water Pipe Corrosion Investigation in Santa Cruz, California

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1. INTRODUCTION

Utilities considering changing source waters or alternating between different sources or making changes to the treatment process that will affect the finished water's chemistry must understand and prepare for the impacts that those changes could have on the distribution system and ultimately the water quality at customer taps. An abrupt change in water quality can cause both aesthetic-based and health-based water quality issues, as previously formed protective pipe scale could be destabilized from a new water source (Tang et al., 2018; Sheehan, 2016).

The City of Fresno, CA historically used groundwater (GW) sources and started to deliver surface water (SW) to their water systems in 2004. In 2016, Fresno, with wide use of galvanized iron pipe (GIP), received more than 2000 reports of water quality concerns due to problems arising from iron (Fe) pipe surfaces as the zinc (Zn) coating containing up to 2% lead (Pb) by weight was depleted (Sheehan, 2016; Tang et al., 2018). Likewise, in the recent high-profile Flint water crisis, Pb contamination and legionella outbreak in Flint, MI were caused by a switch of source waters and a lack of appropriate corrosion control strategy (Kelsey, et al., 2017; Rhoads et al., 2017). The plumbing corrosion issues in Flint were exacerbated by the switch from sulfate-based coagulants to chloride-based coagulants, increasing the chloride-to-sulfate mass ratio and therefore copper: lead solder joint galvanic corrosion (Davis et al., 2016; Edwards and Triantafyllidou, 2007).

To minimize water corrosivity to Pb-containing materials, the Lead and Copper Rule under Environmental Protection Agency (EPA) Clean Water Act of 1991 requires corrosion control strategies be implemented and optimized for water systems (EPA, 1991a). Addition of orthophosphate is a commonly used corrosion control strategy, and it can prevent contaminants from entering into water by forming a protective layer inside the pipe scale (Edwards and McNeill, 2002; McNeill and Edwards, 2002; Benjamin, 1990).

The Soquel Creek Water District, CA (District) is planning to buy winter water supply from the City of Santa Cruz, CA (City). The District historically used GW sources with a typical high alkalinity of 175-250 mg/L as $CaCO_3$ at water pH 7.5-7.7. The District has been in compliance with the Lead and Copper Rule, despite not using a corrosion inhibitor. Lead solder joints that were used to connect copper pipes are present in old homes built before 1986 when lead solders were officially banned in the United States. The City treats SW with conventional processes at the Graham Hill Water Treatment Plant (GHWTP) and the finished water has moderate alkalinity of 100-140 mg/L as $CaCO_3$ at water pH of 7.2-7.8. The City adds 0.2 mg/L of orthophosphate as P to the finished water as a corrosion inhibitor, but the District does not use corrosion inhibitors due to their water's positive calcium carbonate precipitation potential. The difference in water characteristics and use of corrosion inhibitors of the two water sources raised concerns about potential water pipeline corrosion and re-equilibration issues, as some homes in the District will experience an alternating scenario between virtually 100% GW and 100% SW, because there is little chance of blending these two water sources according to hydraulic models.

Thus, before delivering SW to the District pipeline system, both the City and District wanted to proactively investigate pipe and plumbing corrosion in response to a change of water sources. The objectives of this study are to 1) examine the corrosivity of GW and SW to extreme conditions of GIPs, 2) quantify the water turbidity, calcium (Ca) and metal release from harvested GIPs, asbestos cement pipes and copper: lead solder joints under different water qualities, and 3) explore corrosion control strategies at various water quality scenarios.

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2. EXPERIMENTAL APPROACH

Two phases of experiments were conducted, including 1) examining the corrosivity of GW and SW to new and aged GIPs and 2) investigating water corrosion potential to harvested pipes with pre-existing scale and plumbing fixtures under different GW, SW and alternating scenarios. The experiment approach was adapted from Tang et al., 2018 with modifications as described below.

2.1 Phase 1: Examine the Corrosivity of GW and SW

2.1.1 Zinc and iron wire glass jar apparatus

Iron (>99.9% Fe) and zinc (>99.95% Zn) wire (2 mm diameter [d]; 5.7 cm long) within ±3% by weight was epoxied (Loctite Super Glue Plastics Bonding System with Activator) to the center of 125 mL glass jar lids (Fig. 1). Pure Zn wires represent the inside of new GIPs where the protective Zn coating is 100% present. Pure Fe wires represent very aged GIP with Fe surfaces where the protective Zn coating has been completely depleted.

2.1.2 Testing water conditions

The finished SW from the City (i.e., SW from the GHWTP after filtration but prior to the addition of orthophosphate or disinfectant) and GW from the Opal Cliff sample station in the District system were shipped to Virginia Tech. The actual concentrations for each parameter of GW and SW were determined upon arrival at Virginia Tech and an average level of each parameter is presented in Table 1. In total, six water conditions were examined (Table 2).

Table 1. Typical (average) water quality for GW from the District and SW from the City during testing.

Parameter	GW	SW
pH	7.5	7.2/7.8
Alkalinity (mg/L as $CaCO_3$)	176	109
Silica (mg/L as SiO_2)	60.0	20.0
Calcium Hardness (mg/L as $CaCO_3$)	206	110
Total Hardness (mg/L as $CaCO_3$)	297	148
Chloride (mg/L)	63.8	19.9
Sulfate (mg/L)	123	61.4
Chloride to Sulfate Mass Ratio[l]	0.52	0.32
Buffering Intensity	0.56	0.63/0.2
Free Chlorine (mg/L)	0.5	1.0

[l]chloride to sulfate mass ratio>0.5 indicates a corrosive water to galvanic corrosion.

Table 2. Summary of testing conditions in Phase 1 and Phase 2.

Testing Phase		Condition	Water Description	Scenario Representation to Examine the Corrosivity of
Phase 1		R1	SW, pH 7.2	SW at low pH without corrosion control in the City
		R2	SW, pH 7.8	SW at high pH without corrosion control in the City
	Phase 2	C1	GW, pH 7.5	Current baseline GW condition present in the District
		C2	GW, pH 7.5, 0.2 mg/L OP as P	Baseline GW in the District with potential OP treatment
		C3	SW, pH 7.2, 0.2 mg/L OP as P	Current SW at low water pH in the City
		C4	SW, pH 7.8, 0.2 mg/L OP as P	Current SW at high water pH in the City
		C5	Alternating between C1 and C3	Potential alternating condition between baseline GW and SW at low pH
		C6	Alternating between C1 and C4	Potential alternating condition between baseline GW and SW at high pH
		C7	Alternating between C2 and C3	Potential alternating condition between baseline GW with orthophosphate treatment and SW at low pH
OP=orthophosphate; GW=groundwater SW=surface water; City=Santa Cruz; District=Soquel Creek Water District				

2.1.3 Water quality maintenance

All water conditions were tested in triplicate and mixed on a shaker table (MaxQ3000) at a speed of 100 rpm for 8 weeks. In order to investigate the role of disinfection, for the first three weeks, all water conditions were not disinfected; for the remaining five weeks, the GW conditions were treated with 0.5 ± 0.2 mg/L free chlorine and SW conditions with 1.0 ± 0.2 mg/L free chlorine as confirmed on a HACH DR 2700. The water pH for each condition was adjusted to the target pH within ±0.2 unit. The water pH was achieved by adding carbon dioxide (CO_2) or 0.1M sodium hydroxide as confirmed by a pH meter (Model Oakton 11 series).
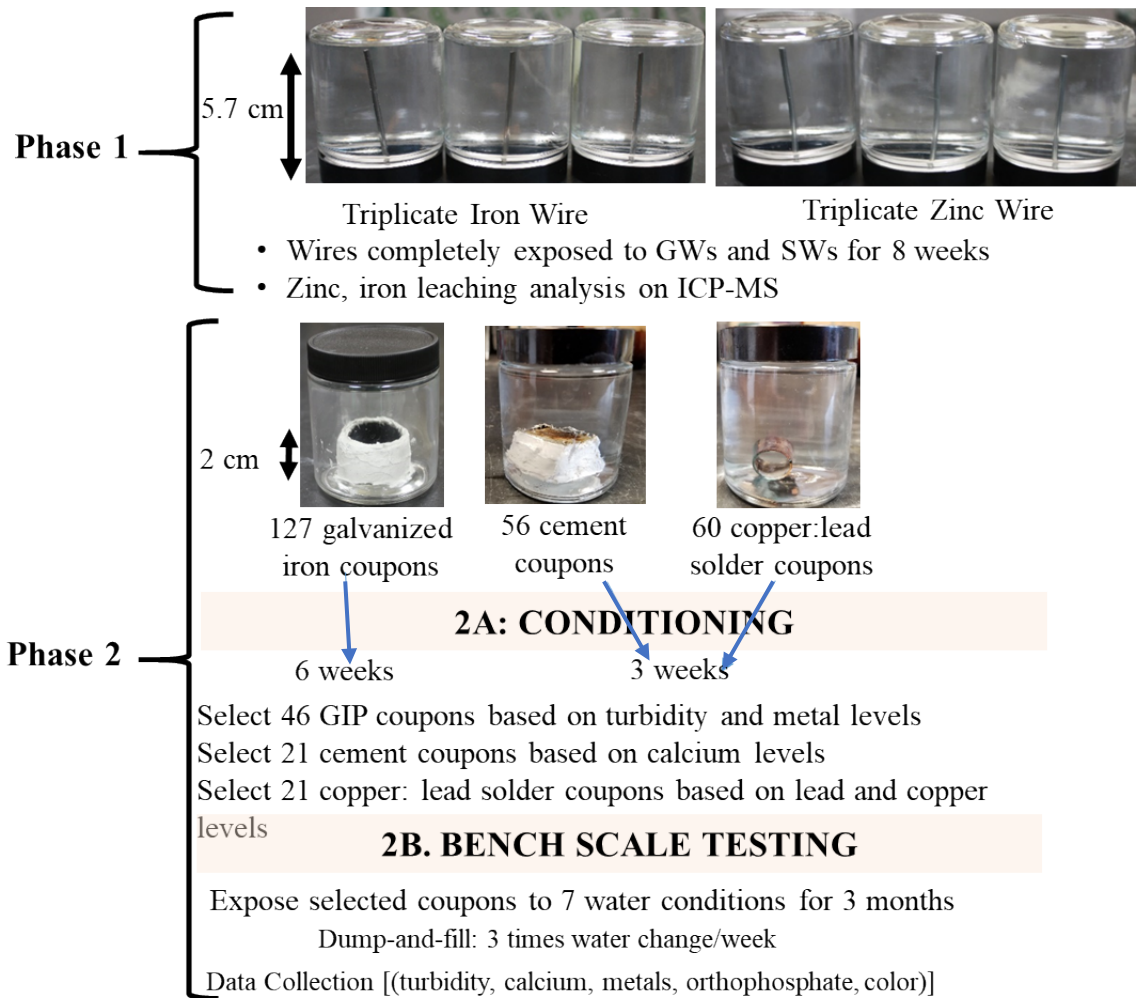
Figure 1. Illustration of two bench scale studies including wire tests (Phase 1) and galvanized iron pipe (GIP), asbestos cement pipe and copper: lead solder joint tests.

2.1.4 Water sample collection and processing

A dump-and-fill protocol was conducted three times per week (Tuesday, Thursday and Saturday) to replace the water in each jar with freshly made SW or GW every 2-3 days. Visible changes in water clarity were sometimes recorded and photographed every 2-3 days. Fe and Zn concentrations were measured on a weekly basis via a Thermo Electron X-Series Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) by collecting 10 mL aliquots from each glass jar after complete mixing. The 10 mL aliquots were acidified with 2% v/v concentrated nitric acid and digested for a minimum of 16 hours before analysis according to Standard Method 3125-B (APHA, AWWA&WEF 1998). For data quality assurance and quality control, blanks and spikes of known concentrations were measured every 10-15 samples.

2.2 Phase 2: Explore Water Corrosion Potential

2.2.1 Pipe coupon jar preparation

Galvanized iron and asbestos cement pipe coupons:

Aged GIPs and asbestos cement pipes in service were harvested by the District and sent to Virginia Tech. To avoid disturbance to the pipe interior scale, the GIPs were filled with a GW that was flowing in these pipes historically and the two ends were closed with rubber stoppers during the shipment to Virginia Tech. The two ends of asbestos cement pipes were wrapped with plastic and not filled with water.

Upon arrival at Virginia Tech, the interior scale from each pipe was visually observed and photographed. As GIP is a very complicated plumbing material with highly variable surfaces, the composition of GIP interior scale was examined for elemental composition via X-Ray Fluorescence (XRF) (Innov-X Systems Alpha SeriesTM) and environmental scanning electron microscope with an attached X-ray energy dispersive system (ESEM/EDS). The composition of the interior scale gives insight into potential contaminants leaching into water.

In total, 127 GIP coupons (2 cm long) and 56 asbestos cement pipe coupons (approximately 2 cm x 2 cm) were generated in a construction lab. The exterior surfaces and cutting edges of the coupons were coated and covered with PC·11 epoxy to ensure water interaction with the interior surface only, simulating water contact in the water distribution system. All GIP and asbestos cement pipe coupons were then epoxied to the bottom of a 125 mL glass jar. During the cutting and gluing process, the interior scale of each coupon was kept wet with the GW from Phase 1.

Copper: lead solder coupons:

The inner surface of sixty 3/8" (0.95 cm) copper coupling were applied with 50:50 Pb:Tin (Pb:Sn) solder (Alpha 13505) using a propane torch, recreating essential features of a galvanic connection present in old homes built before 1986 (EPA, 1991). All copper:lead solder coupons were submerged in 1 mM sodium hydroxide for five minutes and then rinsed with deionized water three times. Afterwards, all copper: lead solder coupons were exposed to a 125 mL NSF 61 testing water (pH 8.5±0.5, alkalinity 500±25 mg/L as $CaCO_3$) for three days before conditioning.

2.2.2 Conditioning

All 127 GIP coupons were exposed to the finished GW from Phase 1 for 6 weeks and all 56 asbestos cement pipe coupons and 60 copper: lead solder coupons for 3 weeks, with the aim at restoring any scale disrupted during extraction and shipment to Virginia Tech. A "dump-and-fill" protocol was conducted three times per week to expose the coupons to fresh GW every 2-3 days. Water turbidity was measured on a turbidimeter (model Lamotte 2020we) and metal (Fe, manganese [Mn] and Zn) levels leaching from the scale were quantified on ICP-MS. Both turbidity and metal leaching data were used for grouping at the end of 6-week conditioning. Meanwhile, Ca, Pb and Cu were measured on ICP-MS at the end of 3-week conditioning to select and group asbestos cement and copper: lead solder coupons.

2.2.3 Bench-scale testing

Selected asbestos cement, copper: lead solder and GIP coupons were exposed to seven water conditions (i.e., two GW, two SW, and three alternating conditions) for 3 months (Table 2). Each alternating condition was conducted by switching between one SW and one GW every month, to simulate the actual alternating scenario that would occur in the District. The grouping of each material was based on results

in the conditioning phase. The water pH for each condition was adjusted with injection of CO_2 or 0.2M NaOH as confirmed by a pH meter (Model Oakton 11 series). The orthophosphate corrosion inhibitor stock was sent from the City and maintained at 0.2 mg/L orthophosphate as P as confirmed by ICP-MS. A control condition with only epoxy was added to examine leaching of inorganics (Ca, Pb, Cu, Mn, Fe and Pb) from epoxy using four waters (C1-C4). A "dump-and-fill" protocol was conducted three times per week. All glass jars were placed on a shaker table (MaxQ3000) at 100 rpm to ensure complete mixing. The water turbidity, metal analyses and color were measured based on the schedule in Table A2. For conditions treated with orthophosphate, the uptake of orthophosphate by coupon scale was also monitored throughout the 3-month exposure.

2.3 Data Analysis

All statistics were conducted in RStudio (version 3.3.2). A p value of <0.05 with an alpha value (α) of 0.05 was selected to determine the statistical significance. Non-parametric statistics including Wilcoxon test and Kruskal Wallis test were used to compare the mean ranks for non-normally distributed data (Dalgaard, 2008). The Spearman's test was used to examine the correlation between metals (Fe, Zn, Pb) and turbidity.

3. RESULTS

3.1 Phase 1. Examine the Corrosivity of GW and SW

The Zn and Fe wires were exposed to six water conditions for 8 weeks (Table 2), with no disinfectant the first three weeks and chlorine the remaining five weeks. The color change and metal leaching were recorded with detailed discussion as below.

3.1.1 Zinc wire testing

Over the course of the 8-week experiment, the color in each jar remained clear for every 2-3 days of exposure with various Zn levels leaching into the six water conditions (Figure 2). Overall, the average zinc concentrations for untreated SW at low pH of 7.2 (R1), SW at high pH of 7.8 (R2) and current baseline GW condition in the District (C1) were 4.9-7.8 mg/L, 1.7-2.6 mg/L and 3.6-6.1 mg/L, respectively. Without orthophosphate treatment, the corrosivity of baseline GW in the District as indicated by Zn leaching was significantly lower than the untreated SW at pH 7.2 (Wilcoxon test, $p=6.1 \times 10^{-9}$) and higher than that at pH 7.8 (Wilcoxon test, $p=6.2 \times 10^{-14}$).

Orthophosphate (0.2 mg/L as P) was added to the current SW in the City as a corrosion control treatment. With orthophosphate treatment, the average Zn leaching throughout the 8 weeks of testing for GW at pH 7.5 (C2), SW at pH 7.2 (C3) and SW at pH 7.8 (C4) was 3.0-4.4 mg/L, 3.7-5.5 mg/L and 1.7-2.1 mg/L, respectively. Compared to baseline GW (C1) in the District, adding orthophosphate to baseline GW (C2) did significantly reduce Zn release (Wilcoxon test, $p=2.1 \times 10^{-5}$) and the potential new SW source from the City induced similar (C1 versus C3, Wilcoxon test, $p>0.05$) or significantly less (C1 versus C4, Wilcoxon test, $p=3.1 \times 10^{-9}$) Zn leaching as well. Therefore, SW at pH 7.2-7.8 generally showed less corrosivity to pure Zn wires representing new GIP, relative to baseline GW.

Figure 2. Average zinc leaching from zinc wire testing during 8 weeks of exposure. The photos at bottom showed color change in representative samples for its corresponding testing condition at week 3. The error bar denotes a 95% confidence interval. OP= 0.2 mg/L orthophosphate as P.

3.1.2 Iron wire testing

In contrast, during 8 weeks of exposure, the color in each iron wire jar changed after every 2-3 days of exposure, with a reduction in iron levels over time (Figure 3). The average iron levels for untreated SW at low pH of 7.2 (R1), SW at high pH of 7.8 (R2) and baseline GW condition in the District (C1) at week 1 were 14.7 mg/L, 20.7 mg/L and 14.4 mg/L, respectively, reducing to 1.0 mg/L, 2.9 mg/L and 1.8 mg/L after 8 weeks of exposure. Without orthophosphate treatment, the corrosivity of baseline GW in the District as indicated by iron leaching was statistically similar to the untreated SW at pH 7.2 and pH 7.8 (Kruskal Wallis, $p > 0.05$).

With orthophosphate treatment, the average Fe leaching for GW at pH 7.5 (C2), SW at pH 7.2 (C3), SW at pH 7.8 (C4) was reduced from 12.8-17.4 mg/L to 1.1-1.5 mg/L. Compared to baseline GW (C1), adding orthophosphate to GW (C2) or introducing SW with low and high pH (C3 and C4) induced similar Fe leaching (Kruskal Wallis, $p > 0.05$), indicating similar water corrosivity for GW and SW sources.

It is worth noting that higher natural silica (often used as a corrosion inhibitor) in GW (60 mg/L as SiO_2) versus SW (20 mg/L as SiO_2) had an ability to "hide" visible color from iron as shown previously (Rushing et al., 2003). Particularly for C2 and C3 at week 3 in Figure 3, the similar amount of Fe level in water induced very discolored SW but very clear GW.
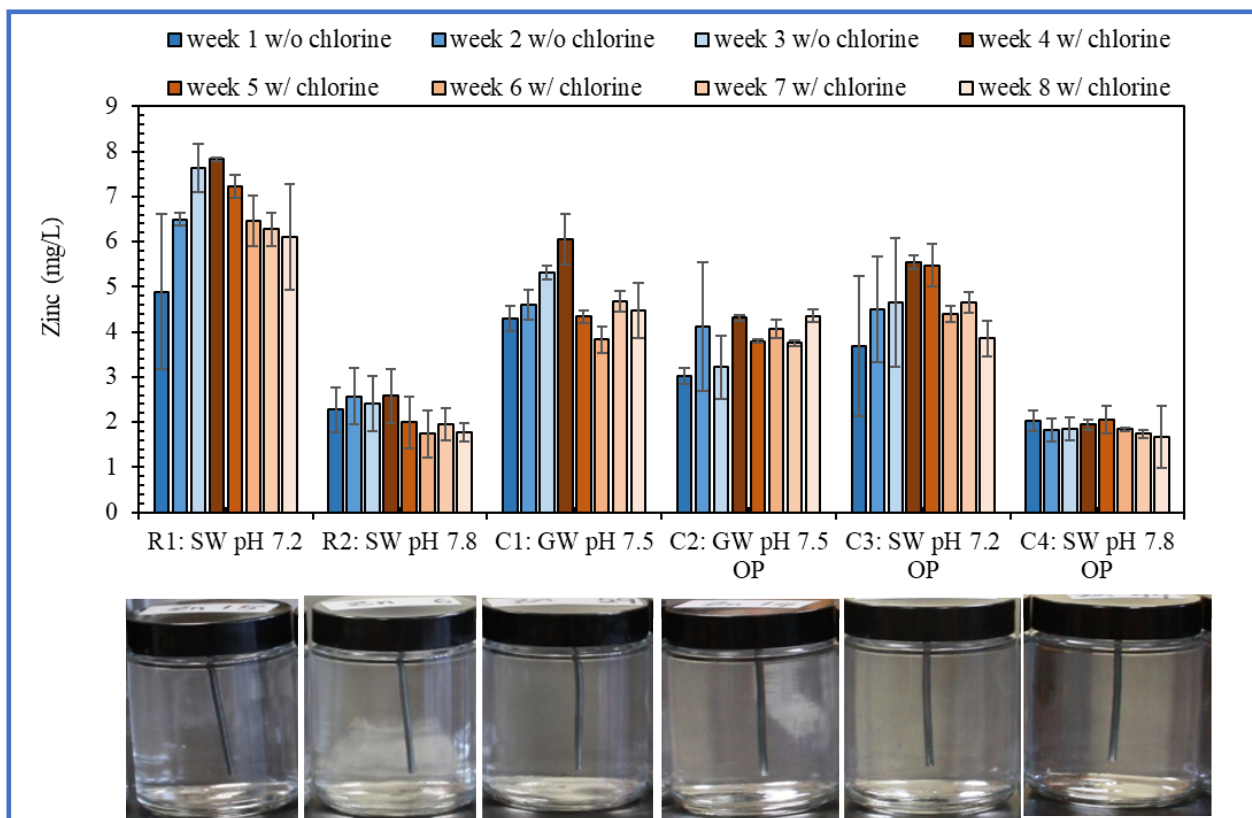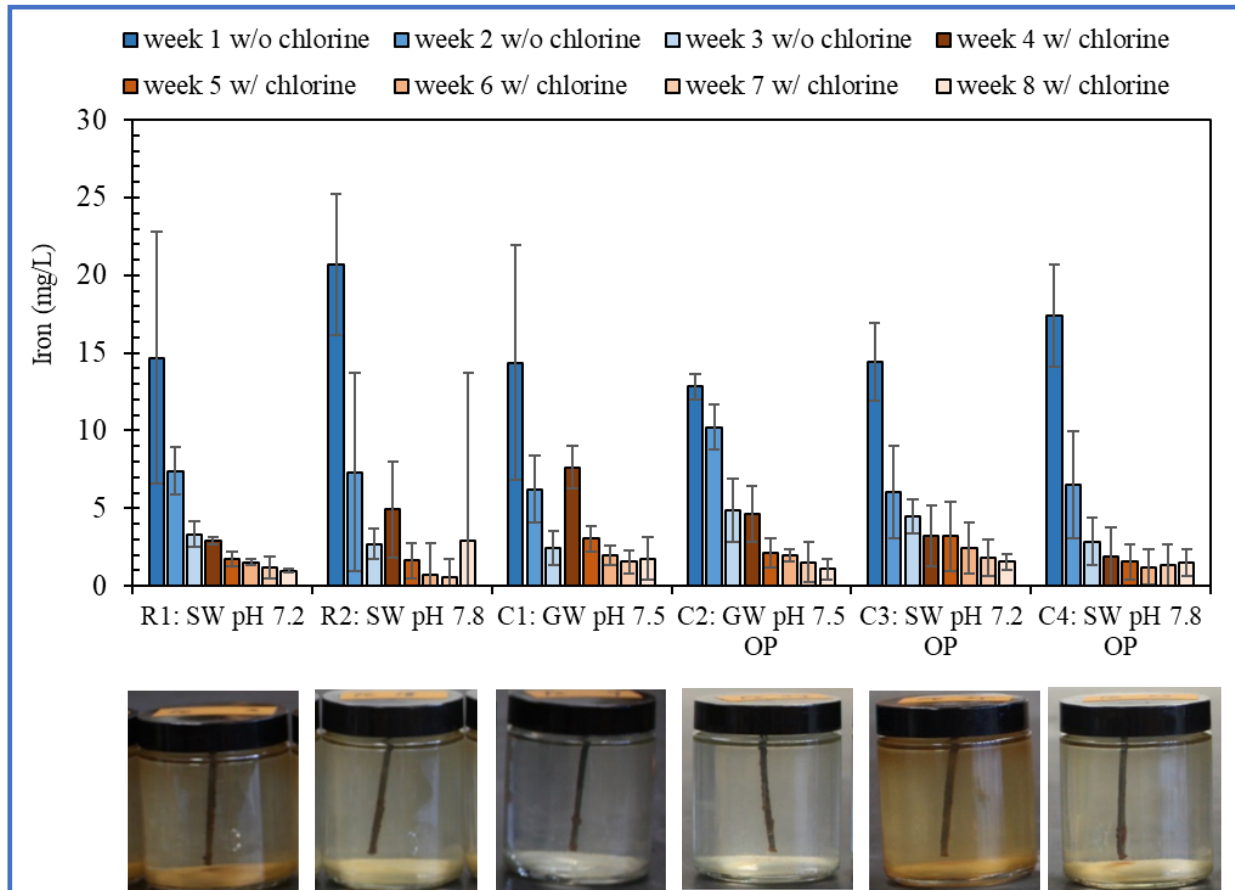

Figure 3. Average iron leaching from iron wire testing during 8 weeks of exposure. The photos at bottom showed color change in representative samples for its corresponding testing condition at week 3. The error bar denotes a 95% confidence interval. OP= 0.2 mg/L orthophosphate as P.

3.2 Phase 2A. Conditioning

After Phase 1 testing, GIP and asbestos cement pipe coupons made from harvested pipe in the District and laboratory made copper: lead solder joint coupons were conditioned with a commonly used GW from the District for up to 6 weeks.

3.2.1. Grouping of asbestos cement pipe coupons

Twenty-one asbestos cement pipe coupons were selected and three coupons were grouped into each water condition based on Ca levels after 3 weeks of conditioning, as asbestos cement coupons tend to leach out calcium hydroxide, resulting in an increase of water pH and hardness (Tang et al., 2013). The selected 21 coupons had an average Ca concentration of 98.6±0.4mg/L, with the lowest and highest at 98.1 mg/L and 99.4 mg/L, respectively (Table A2). The grouped ACP coupons for each of the seven conditions had statistically similar calcium concentrations (Table A3) (Kruskal Wallis test, p>0.05). These average

calcium concentrations were similar to the level (100 mg/L) in the original GW, indicating a relatively inert interior scale in the harvested asbestos cement pipe from the District.

3.2.2   Grouping of copper: lead solder coupons

Twenty-one copper: lead solder coupons were selected and three coupons were grouped into each condition based on relative deviations (RSD=100*standard deviation/average) of Cu and Pb levels after 3 weeks of conditioning (Table A3). The selected 21 coupons had average Cu of 990±182 µg/L and average lead of 28.5±6.1 µg/L, with RSD at 18.4% and 21.4%, respectively. The RSD for these selected 21 coupons was considered acceptable and normal based on our experience. The grouped coupons for each of the seven conditions had similar average Cu levels of 867-1016 µg/L (Kruskal Wallis test, p>0.05) and Pb levels of 27.8-29.1 µg/L (Kruskal Wallis test, p>0.05).

3.2.3 Grouping of GIP coupons

Based on scale analysis, the interior scale of the selected two GIPs contained 45-55% manganese (Mn), 14-27% iron (Fe), and 25-27% zinc (Zn) on XRF and 37-42% Mn, 5-14% Fe, and 11-12% Zn as measured by ESEM/EDS (Table A4). Additionally, during the first two weeks of exposure, water turbidity was correlated with Fe (Spearman's, $p<2.2x10^{-16}$, rho=0.66) and Mn (Spearman's, $p=8.0x10^{-5}$, rho=0.34), but not correlated with Zn (Spearman's, p>0.05), indicating that Fe and Mn were the main contributors to water turbidity or water clarity. At the end of six weeks of conditioning, thirty-five GIP coupons with the highest turbidity were selected for monitoring aesthetic issues (Table A5). All 127 GIP coupons leached out less than 300 µg/L (secondary maximum contaminant level) of Fe and up to 492 µg/L of manganese into water. As manganese concentrations of more than 50 µg/L causes aesthetic water issues and fixture staining (EPA 1991b; Tobiason et al., 2016; Brandhuber et al., 2015), manganese instead of Fe was used for selecting 21 GIP coupons containing high Mn levels and monitored as a complementary standard (Table A5).

The 35 GIP coupons selected based on water turbidity had an average level of 0.32 NTU, with the lowest and highest had 0.19 NTU and 0.72 NTU, respectively. Five GIP coupons were grouped into each water condition and the average water turbidity for each of the seven water conditions was similar at 0.29-0.37 NTU (Kruskal Wallis test, p>0.05).

Similarly, for the 21 GIP coupons based on Mn levels, the average Mn was 101.6 µg/L, with the lowest and highest at 29 µg/L and 491.7 µg/L. Three GIP coupons were grouped into each water condition and the average manganese level for each of the seven water conditions was also statistically similar at 72.5-211.9 µg/L, due to the large variability (Kruskal Wallis test, p>0.05).

3.3   Phase 2B. Bench Scale Testing

The 13-week bench scale testing examined water corrosivity of seven testing conditions to asbestos cement pipe coupons, copper: lead solder coupons and GIP coupons. The results for each testing material are presented in the following sections.

3.3.1   Control Conditions

In order to validate that there was no Ca, Cu, Pb, Fe, and Mn leaching from the epoxy control condition (with any pipe material) as indicated by Tang et al., 2018, each control condition was executed for each testing water (C1-C4) throughout the 13-week testing (Figure 4). In these control water conditions, the water color remained clear and there was non-detectable Ca (<50 µg/L), Cu (<1 µg/L), Pb (<1 µg/L), Fe (<10 µg/L) and Mn (<1 µg/L) in each water collected after water change.
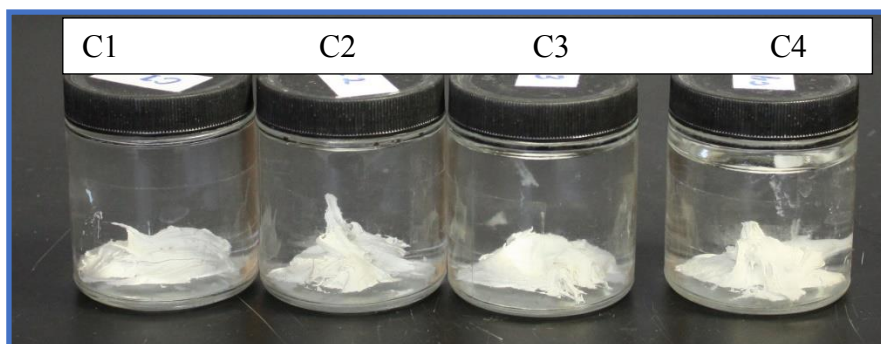
Figure 4. Control conditions for C1-C4 waters in contact with only epoxy but no pipe coupons during 13-week testing.

3.3.2 Asbestos cement pipe coupons

The major concern with asbestos cement coupons was the leaching potential of Ca from the cement, into water under different sources and treatment options. More leaching of Ca indicates increased corrosion of this infrastructure asset. As the City and the District shipped water to Virginia Tech once every few weeks, the calcium concentrations in GW varied from 44.4-108.4 mg/L whereas Ca levels in SW were relatively constant at 38.1-55.1 mg/L (Figure A1). To take GW variability into account, the Ca in collected water after water change was compared to the control water collected from the jar with only epoxy (Figure 5). In summary, the Ca levels in water for seven testing conditions were almost the same as those in the control waters, indicating very little leaching of Ca ion from (or Ca precipitation on) the asbestos cement pipe scale. This result was consistent with visual perception of the water, which remained clear throughout the testing (Figure 5).

As orthophosphate inhibitor was an important option to evaluate for controlling water corrosivity, orthophosphate uptake was also monitored. There was very little uptake of orthophosphate by asbestos cement pipe scale as indicated by similar levels of P between control waters and testing waters (Figure A2). Therefore, all the tested source waters, with or without orthophosphate treatment, did not seem to indicate significant problems relative to performance of the asbestos cement pipe scale.
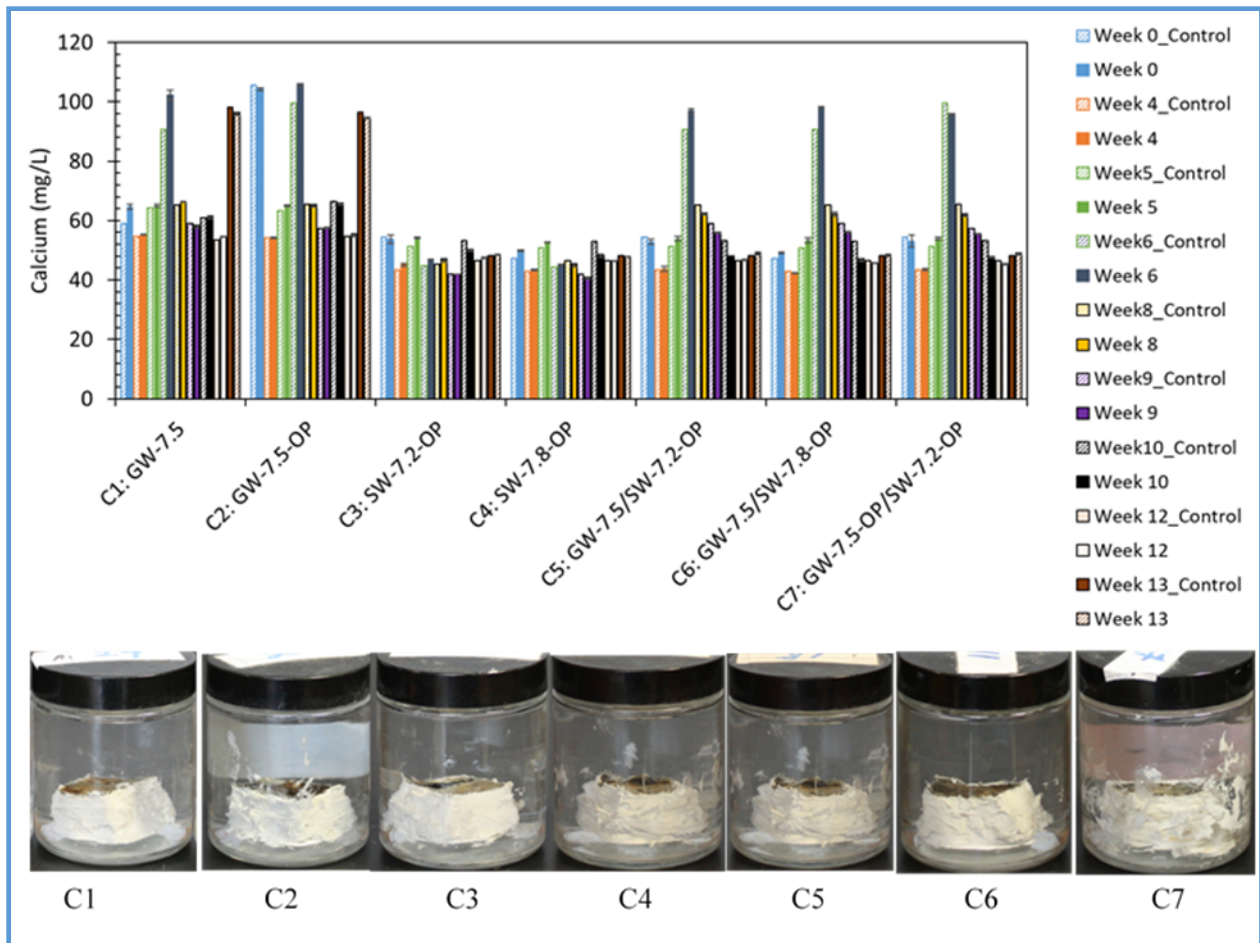
Figure 5. Calcium levels in seven testing waters for asbestos cement pipe coupons and representative photos for each testing condition after 2 days of exposure or right before water change. The error bar indicates a 95% confidence interval. The source water was switched in the alternating conditions (C5-C7) in the following order: GW for weeks 0-5, SW for weeks 6-9, and GW for weeks 10-13.

3.3.3   Copper: lead solder coupons

The Cu and Pb leaching from the copper: lead solder coupons were monitored throughout the 13-week exposure (Figure 6). The Cu and Pb levels for the conditioning phase and for C1 represented the baseline levels in the current District. The philosophy was that if the Cu and Pb levels in the other six testing conditions (C2-C7) were significantly higher than that in C1 over time, the water represented by that test condition could potentially induce copper:lead solder galvanic corrosion problems, and associated concerns with Cu and/or Pb. Overall, the Cu levels for all testing conditions were relatively constant throughout the testing and Pb levels gradually reduced over time. At the end of testing, the average Cu leaching for current (C1) and potential water conditions (C2-C7) of the District were 802 µg/L and 773-1040 µg/L, respectively. Though there were variations, the Cu levels amongst C1-C7 were statistically similar (Kruskal Wallis, p>0.05). Similarly, the average Pb leaching was 4.8-14.1 µg/L for potential water conditions C2-C7, statistically similar to that (20.6 µg/L) for baseline GW (C1) (Kruskal Wallis, p>0.05).

During weeks 6, 8 and 9 for alternating condition C6, there was a spike in both Cu and Pb greater than the Cu and Pb values for the baseline GW when the source water switched from SW at pH 7.8 with orthophosphate to GW at pH 7.5. The Pb and Cu levels decreased to low levels again after switching back to SW at pH 7.8 with orthophosphate. When comparing C5 versus C6, the lower SW pH 7.2 (C5) appeared to help with maintaining low Pb levels, though there was no statistical difference. Adding orthophosphate to GW (C2 versus C1) appeared to be slightly beneficial in limiting lead release, but the results were not statistically different. Therefore, adding orthophosphate to GW is probably not worth the resources. Additionally, there was very little uptake of orthophosphate by copper: lead solder joints in testing waters compared to control waters (Figure A3).

All of the above discussed results indicate that pH adjustment of SW was not beneficial for controlling water corrosivity to copper: lead solder joints. The C5 results indicated that alternating between the baseline GW and the current City's SW at pH 7.2 resulted in lower Pb release and similar Cu release when compared to the baseline GW (C1). Adding orthophosphate to GW might be beneficial for maintaining low Pb leaching from the coupons, but it is not necessary at this time since the C5 results without orthophosphate added to the GW performed better than the baseline GW (C1) and there was no statistical difference between C2 and C1.
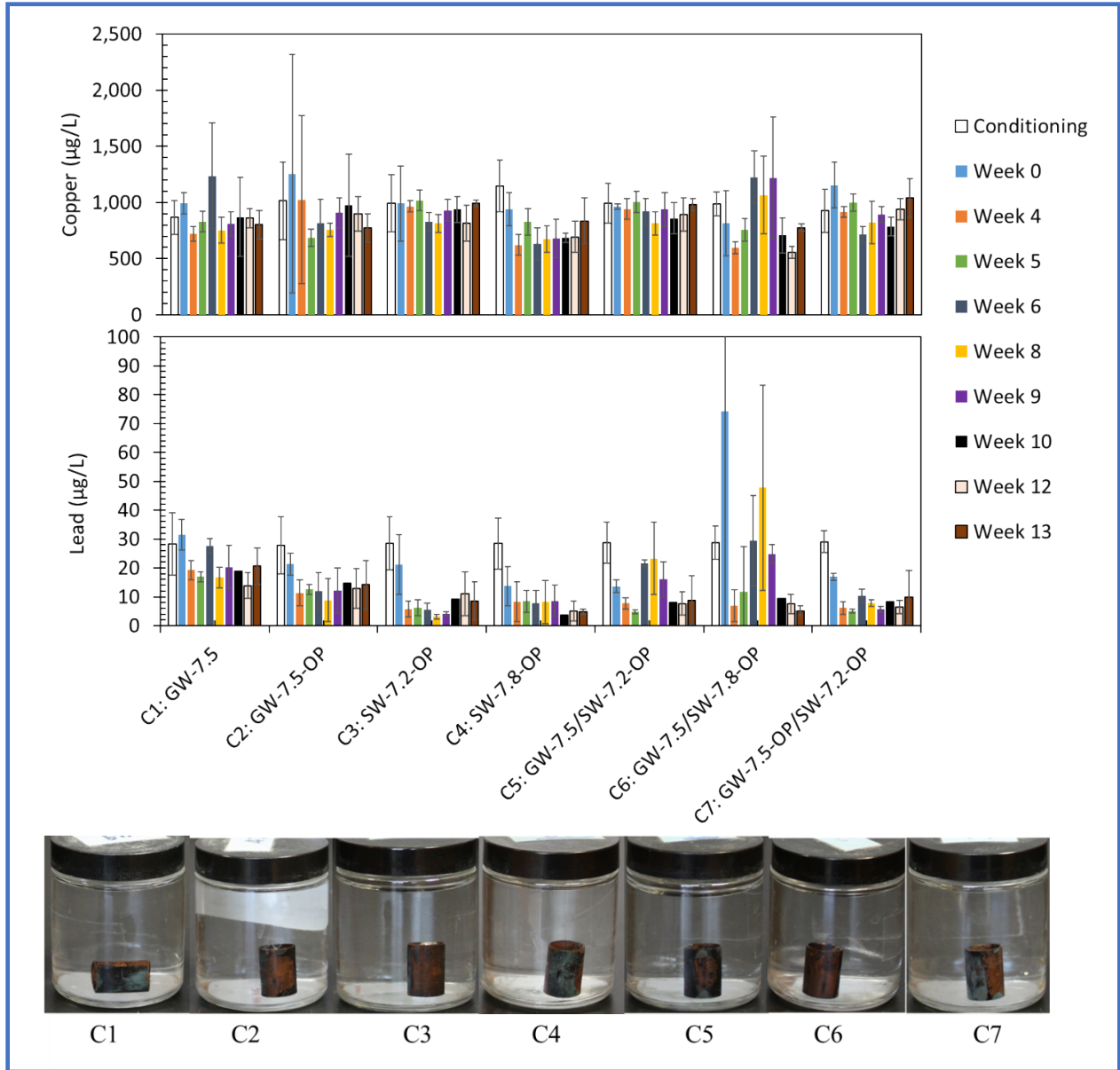
Figure 6. Copper and lead levels in seven testing waters for copper:lead solder joints and representative photos for each testing condition after 2 days of exposure or right before water change. The error bar indicates a 95% confidence interval. The coupons were exposed to GW at pH 7.5 (C1) during conditioning. The source water was switched in the alternating conditions (C5-C7) in the following order: GW for weeks 0-5, SW for weeks 6-9, and GW for weeks 10-13.

3.3.4 GIP coupons

Water turbidity, Mn and Fe leaching from GIP coupons were monitored throughout the 13-week testing. Water turbidity was an indicator for water clarity and was mainly a result of Mn and Fe in water in this case. Specifically, average water turbidity for each testing condition was low and less than 0.51 NTU. Water turbidity did vary to a large extent as indicated by the large error bars, resulting in overall statistically similar turbidity for all testing conditions (Kruskal Wallis, $p > 0.05$) (Figure 7). However, water turbidity for SW at lower pH 7.2 (C5 versus C6) seemed to be relatively more stable at maintaining a low turbidity. Regardless, the overall turbidity was very low versus what we previously encountered during similar testing (3.2-37 NTU) in Fresno, CA. This suggested that fewer problems should be anticipated from introducing SW from the City to the District, given the scale on existing GIP in the District's water systems (Tang et al., 2018).

However, in the District's GIP scale, we also observed relatively high amounts of Mn (up to 47% in Table A4) and the possible release of Mn from GIP scale could be concerning. At the end of conditioning, up to 334 µg/L Mn leached into water, which was 6.6 times the EPA secondary standard (50 µg/L). During the bench scale testing, the Mn leaching gradually decreased over time and there were rare spikes of Mn in water. The only exception was for SW at pH 7.2 with orthophosphate (C3) at week 12, potentially caused by sporadic detachment of GIP scale. The general trend was that introduction of SW or new treatment in GW (C2-C7) was statistically similar to the baseline GW condition (C1) (Kruskal Wallis, $p > 0.05$), showing similar corrosivity between both source waters and between the various treatment options.

The Fe leaching based on 10 weeks of monitoring was relatively low and generally less than the aesthetic standard of 0.3 mg/L (Figure A4). At the end of testing, the average Fe was less than 81 µg/L, and 43% of water samples contained non-detectable levels of Fe (< 10 µg/L). The Fe leaching detected from the District's GIP scale, was not at a level requiring corrosion control specifically targeting GIP corrosion in this case (EPA, 2007).

In contrast to asbestos cement pipe and copper: lead solder joints, there was 15-67% uptake of orthophosphate by GIP scale (Figure A5). The relatively high uptake raises the question whether GIP scale would deplete the 0.2 mg/L orthophosphate as P when the City's SW is delivered to the District through miles of GIP before getting to customers' taps. Therefore, a 2-week orthophosphate depletion test was conducted by filling three jars from C1 and three jars from C3 with SW at pH 7.2 with 0.2 mg/L orthophosphate as P. The testing aimed at evaluating the uptake before entering the District's water system (C3) and after entering the District's water system (C1). Our testing showed a 60-82% uptake of orthophosphate in these two scenarios, even after an extreme 2-week stagnation time within the pipe, indicating that some orthophosphate residual would normally persist in the water.

Overall, the above results showed that adding orthophosphate to GW had little beneficial impact for lowering water corrosivity, and that the 0.2 mg/L orthophosphate as P in SW would not be depleted before reaching the District's home taps.
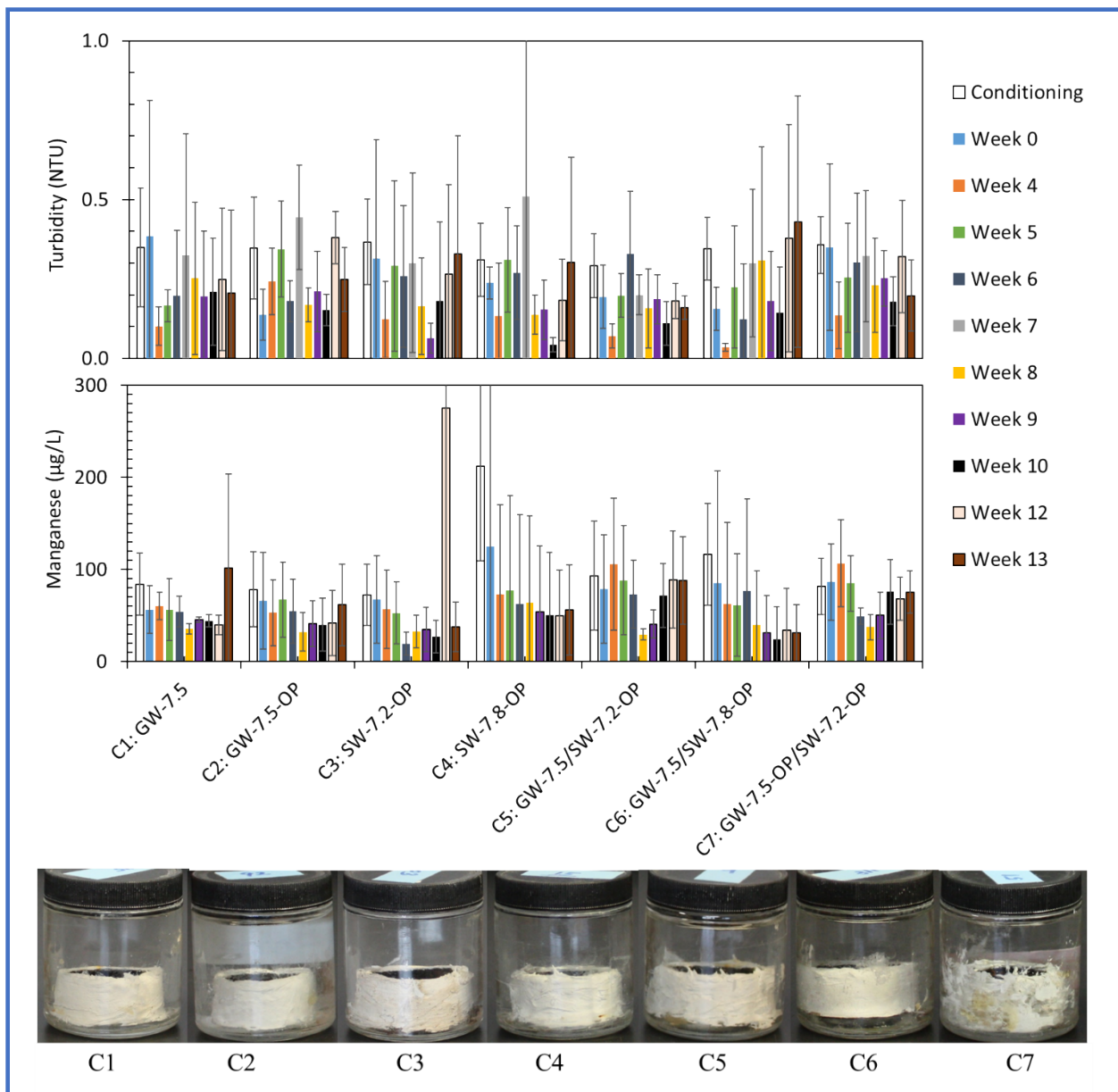
Figure 7. Water turbidity and manganese levels in seven testing waters for galvanized iron pipe coupons and representative photos for each testing condition after 2 days of exposure or right before water change. The error bar indicates a 95% confidence interval. The coupons were exposed to GW at pH 7.5 (C1) during conditioning. The source water was switched in the alternating conditions (C5-C7) in the following order: GW for weeks 0-5, SW for weeks 6-9, and GW for weeks 10-13.

4 KEY FINDINGS AND RECOMMENDATIONS

The wire testing and bench scale testing generated the following key findings:

- GW conditions showed similar or higher corrosivity to pure Zn or Fe wires, compared to SW conditions.
- Asbestos cement pipe coupons had very little release of Ca into water and little uptake of orthophosphate for all examined water conditions.
- Copper: lead solder joints had statistically similar levels of Cu leaching for all examined water conditions.
- Copper: lead solder joints had more stable low levels of Pb leaching with added orthophosphate to GW, but the benefit was not statistically different from the baseline GW.
- Copper: lead solder joints had relatively more stable Cu and Pb leaching when exposed to SW at pH 7.2.
- When comparing alternating conditions (C5 versus C6) with copper: lead solder joints, the lower SW pH 7.2 (C5) appeared to help with maintaining low Pb levels and minimized the spike in Pb and Cu when switching to GW.
- Copper: lead solder joints had very little uptake of orthophosphate.
- GIP coupons had similar ranges of water turbidity among all examined water conditions.
- GIP coupons had more constant low levels of water turbidity when exposed to SW at pH 7.2.
- Adding orthophosphate to GW did not show a clear benefit in reducing water turbidity for GIP.
- Mn leaching for all treated conditions was similar to or lower than baseline GW at pH 7.5.
- GIP coupons had constantly low levels of Fe leaching throughout the 10 weeks of exposure.
- GIP scale had 15-67% orthophosphate uptake during 2-3 days of exposure.
- GIP did not completely deplete 0.2 mg/L orthophosphate after 2 weeks of exposure.

Based on our wire and bench scale testing, we recommend that adjusting SW pH to 7.8 is not beneficial for controlling potential corrosion issues from GIP, asbestos cement pipe and copper: lead solder joints in the District. There is little benefit of adding orthophosphate to GW for controlling discoloration from GIP in the District. That being said, it is important to manage customer expectations in relation to GIP pipe performance, because this antiquated material does not meet modern expectations in terms of providing water free of discoloration. The pre-existing Mn deposits on the pipe could detach and cause some reports of discoloration. A letter communicating these expectations to the homeowners is recommended to notify them of the expected changes in water, expectation of some discolored water events, and likely noticeable changes in taste and aesthetics of the new water supply. Additionally, distribution and sentinel home sampling sites, can be frequently monitored, to proactively detect water quality changes before (baseline) and after the water change. A program to respond promptly to consumer reports of water quality concerns, record them and analyze data for trends, should also be in place.

5 ACKNOWLEDGEMENTS

undergraduate research assistants Hisyam Mohsin and Rusty Rouillier for their help with setting up the experiments and conducting water changes.

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Appendix

Table A1. Water sampling, analysis and testing condition schedule.

Water Sampling and Analysis Schedule				Testing Condition Schedule			
Time	Tues	Thurs	Sat	Testing Condition	Feb.-Mar.	Mar.-Apr.	Apr.-May
February				C1	GW-7.5	GW-7.5	GW-7.5
Week 0	6-Feb	8-Feb	10-Feb	C2	GW-7.5-OP	GW-7.5-OP	GW-7.5-OP
Week 1	13-Feb	15-Feb	17-Feb	C3	SW-7.2-OP	SW-7.2-OP	SW-7.2-OP
Week 2	20-Feb	22-Feb	24-Feb	C4	SW-7.8-OP	SW-7.8-OP	SW-7.8-OP
Week 3	27-Feb	1-Mar	3-Mar	C5	SW-7.2-OP	GW-7.5	SW-7.2-OP
March				C6	SW-7.8-OP	GW-7.5	SW-7.8-OP
Week 4	6-Mar	8-Mar	10-Mar	C7	SW-7.2-OP	GW-7.5-OP	SW-7.2-OP
Week 5	13-Mar	*15-Mar*	17-Mar				
Week 6	20-Mar	22-Mar	24-Mar				
Week 7	27-Mar	29-Mar	31-Mar				
April							
Week 8	3-Apr	5-Apr	7-Apr				
Week 9	10-Apr	*12-Apr*	14-Apr				
Week 10	17-Apr	19-Apr	21-Apr				
Week 11	24-Apr	26-Apr	28-Apr				
May							
Week 12	1-May	3-May	5-May				
Week 13	8-May	10-May					
	Turbidity+Fe, Mn, Pb, Cu, Ca, P						
	Turbidity only						
Dates in bold for switching water source							
Color measurement on 17-Mar and 14-Apr.							

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Table A2. Grouping of the selected 21 asbestos cement pipe coupon (AC) jars based on calcium levels.

Testing Condition	Calcium (mg/L)				
	Replicate 1	Replicate 2	Replicate 3	Average	95% confidence interval
C1	AC 29	AC 24	AC 4		
	98.1	98.5	99.4	98.7	0.7
C2	AC 14	AC 20	AC 13		
	98.2	98.5	99.4	98.7	0.7
C3	AC 9	AC 2	AC 7		
	98.2	98.5	99.1	98.6	0.5
C4	AC 19	AC 18	AC 21		
	98.2	98.6	99.0	98.6	0.5
C5	AC 31	AC 16	AC 32		
	98.4	98.6	98.8	98.6	0.2
C6	AC 15	AC 11	AC 38		
	98.4	98.7	98.8	98.6	0.2
C7	AC 23	AC 17	AC 3		
	98.5	98.7	98.8	98.6	0.2

Table A3. Grouping of the selected 21 copper:lead solder coupon (LS) jars based on copper and lead levels.

Testing Condition	Metal (µg/L)	Replicate 1	Replicate 2	Replicate 3	Average	95% confidence interval
		LS 7	LS 49	LS 3		
	Copper	713.3	943.9	943.9	867.0	150.7
C1	Lead	20.6	25.3	38.9	28.3	10.8
		LS 57	LS 41	LS 27		
	Copper	779.1	909.1	1,361.0	1,016.4	345.6
C2	Lead	20.6	25.4	37.5	27.8	9.8
		LS 26	LS 13	LS 58		
	Copper	774.7	1,223.0	982.8	993.5	253.9
C3	Lead	21.1	27.1	37.1	28.5	9.2
		LS 4	LS 23	LS 60		
	Copper	1,261.0	1,269.0	913.0	1,147.7	230.0
C4	Lead	21.4	27.2	36.8	28.5	8.8
		LS 11	LS 38	LS 16		
	Copper	943.8	864.8	1,166.0	991.5	176.7
C5	Lead	23.1	27.6	35.5	28.7	7.1
		LS 6	LS 32	LS 21		
	Copper	987.2	891.0	1,083.0	987.1	108.6
C6	Lead	23.2	29.9	33.2	28.8	5.7
		LS 47	LS 17	LS 1		
	Copper	1,050.0	731.2	997.1	926.1	193.3
C7	Lead	25.3	30.0	31.9	29.1	3.8

Table A4. ESEM/EDS and XRF galvanized iron pipe interior scale composition analysis.

ESEM/EDS composition on a normalized mass percent (%)										
Pipe	Replicate	C	O	Al	Si	S	Cl	Ca	Mn	Fe	Zn
Pipe 1	1	58.88	28.35	0.58	1.68	0.46	0.29	0.37	0.82	8.58	-
	2	60.49	24.51	0.69	2.06	0.51	0.28	0.41	1.43	9.62	-
	3	70.37	20.19	1.01	0.97	0.73	0.58	0.54	1.17	4.44	-
	Average	63.25	24.35	0.76	1.57	0.57	0.38	0.44	1.14	7.55	-
	Std	6.22	4.08	0.22	0.55	0.14	0.17	0.09	0.31	2.74	-
Pipe 2	1	2.58	15.79	-	1.13	-	-	3.92	55.56	7.44	13.58
	2	5.74	28.23	-	1.22	-	-	1.87	33.06	16.61	13.26
	3	11.91	31.80	-	2.83	-	-	2.13	22.79	19.06	9.48
	Average	6.74	25.27	-	1.73	-	-	2.64	37.14	14.37	12.11
	std	4.75	8.40	-	0.96	-	-	1.12	16.76	6.13	2.28
Pipe 3	1	7.30	38.59	-	0.27	-	-	2.98	39.08	1.81	9.97
	2	17.75	7.68	-	0.24	-	-	1.66	47.22	11.67	13.78
	3	24.03	20.02	-	0.20	-	-	2.68	40.83	1.86	10.36
	Average	16.36	22.10	-	0.24	-	-	2.44	42.38	5.11	11.37
	std	8.45	15.56	-	0.04	-	-	0.69	4.28	5.68	2.10

XRF composition on a normalized mass percent (%)								
Pipe	Replicate	Fe	Mn	Ni	Pb	Ti	W	Zn	Bi
Pipe 1	1	3.52	0.99	ND	0.02	-	-	0.04	0.02
	2	3.52	0.97	0.01	0.02	-	-	0.04	0.02
	3	3.45	1.00	0.01	0.02	-	-	0.04	0.02
	Average	3.50	0.99	0.01	0.02	-	-	0.04	0.02
	Std	0.04	0.02	0.00	0.00	-	-	0.00	0.00
Pipe 2	1	27.92	44.17	-	1.20	-	2.35	24.36	-
	2	26.47	45.23	-	1.16	-	2.04	25.09	-
	3	27.06	44.44	-	1.27	-	2.77	24.46	-
	Average	27.15	44.61	-	1.21	-	2.39	24.64	-
	Std	0.73	0.55	-	0.06	-	0.37	0.40	-
Pipe 3	1	13.84	54.84	-	0.82	0.45	2.43	27.63	-
	2	14.36	54.74	-	0.94	0.46	2.31	27.20	-
	3	13.95	55.58	-	0.98	0.38	2.45	26.65	-
	Average	14.05	55.05	-	0.91	0.43	2.40	27.16	-
	Std	0.27	0.46	-	0.08	0.04	0.08	0.49	-

Note that pipe 1 was excluded for generating coupons due to little presence of contaminants in the scale.

XRF analysis could not detect light elements including carbon, oxygen, silicon and calcium.

Table A5. Grouping of the selected 46 galvanized iron pipe coupon (GIP) jars based on water turbidity and manganese levels.

Testing Condition	Parameter	Replicate 1	Replicate 2	Replicate 3	Replicate 4	Replicate 5	Replicate 6	Replicate 7	Average Turbidity	95% Confidence Interval (CI)	Average Mn	95% CI
		GIP60	GIP67	GIP48	GIP45	GIP65	GIP69	GIP8				
	Turbidity (NTU)	0.19	0.22	0.32	0.3	0.7	0.18	0.15	0.35	0.19		
C1	Mn (µg/L)	15.9	9.4	13.9	4.8	108.2	64.0	80.0			84.1	25.3
		GIP59	GIP92	GIP95	GIP19	GIP111	GIP125	GIP122				
	Turbidity (NTU)	0.19	0.64	0.26	0.3	0.22	0.14	0.17	0.35	0.16		
C2	Mn (µg/L)	16.0	7.6	12.1	27.5	47.9	150.8	36.3			78.3	71.3
		GIP117	GIP113	GIP103	GIP90	GIP57	GIP42					
	Turbidity (NTU)	0.20	0.32	0.58	0.23	0.26	0.16		0.37	0.13		
C3	Mn (µg/L)	7.5	7.6	12.6	44.5	53.0	119.9				72.5	46.7
		GIP58	GIP74	GIP100	GIP15	GIP109	GIP62	GIP80				
	Turbidity (NTU)	0.2	0.24	0.27	0.53	0.25	0.15	0.15	0.31	0.12		
C4	Mn (µg/L)	13.0	4.3	5.0	7.3	491.7	35.9	29.0			211.9	300.1
		GIP94	GIP11	GIP29	GIP50	GIP35	GIP119					
	Turbidity (NTU)	0.42	0.24	0.27	0.2	0.46	0.13		0.29	0.10		
C5	Mn (µg/L)	6.9	17.5	5.9	147.4	86.4	45.5				93.1	58.0
		GIP124	GIP126	GIP78	GIP118	GIP37	GIP85	GIP86				
	Turbidity (NTU)	0.21	0.46	0.28	0.43	0.25	0.17	0.14	0.35	0.10		
C6	Mn (µg/L)	7.7	19.4	4.1	4.2	40.1	276.7	32.0			116.3	157.3
		GIP49	GIP116	GIP56	GIP51	GIP33	GIP44					
	Turbidity (NTU)	0.25	0.29	0.21	0.43	0.43	0.19		0.36	0.09		
C7	Mn (µg/L)	26.5	8.1	37.1	89.3	118.4	8.0				81.6	88.4

Represent five GIP coupons selected for monitoring of turbidity in bench scale testing

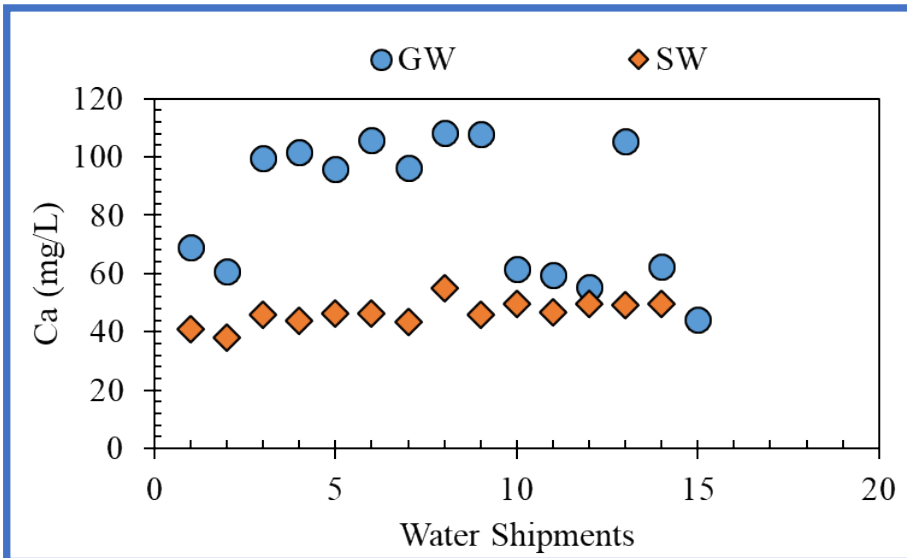Represent three GIP coupons selected for monitoring of manganese in bench scale testing

Figure A1. There was variability for calcium (Ca) concentration in each set of shipped GW whereas the Ca in SW was relatively constant.
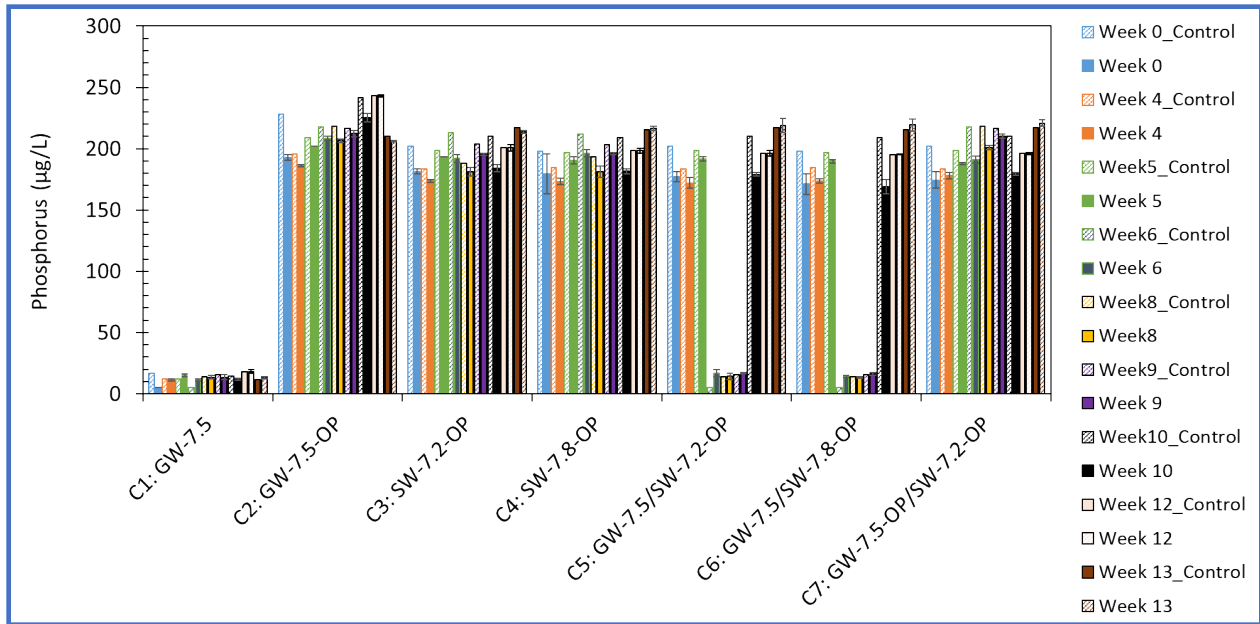
Figure A2. Phosphorus levels representing presence of orthophosphate in water for asbestos cement coupon testing. The error bar indicated a 95% confidence interval. The source water was switched in the alternating conditions (C5-C7) in the following order: GW for weeks 0-5, SW for weeks 6-9, and GW for weeks 10-13.
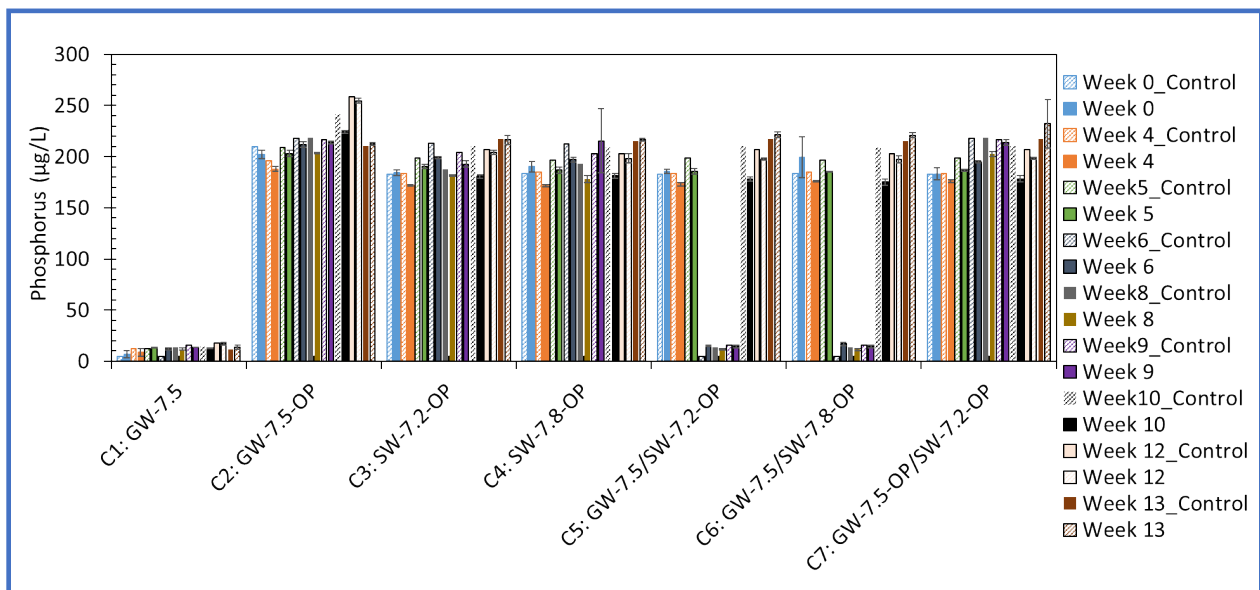

Figure A3. Phosphorus levels representing presence of orthophosphate in water for copper: lead solder coupon testing. The error bar indicated a 95% confidence interval. The source water was switched in the alternating conditions (C5-C7) in the following order: GW for weeks 0-5, SW for weeks 6-9, and GW for weeks 10-13.
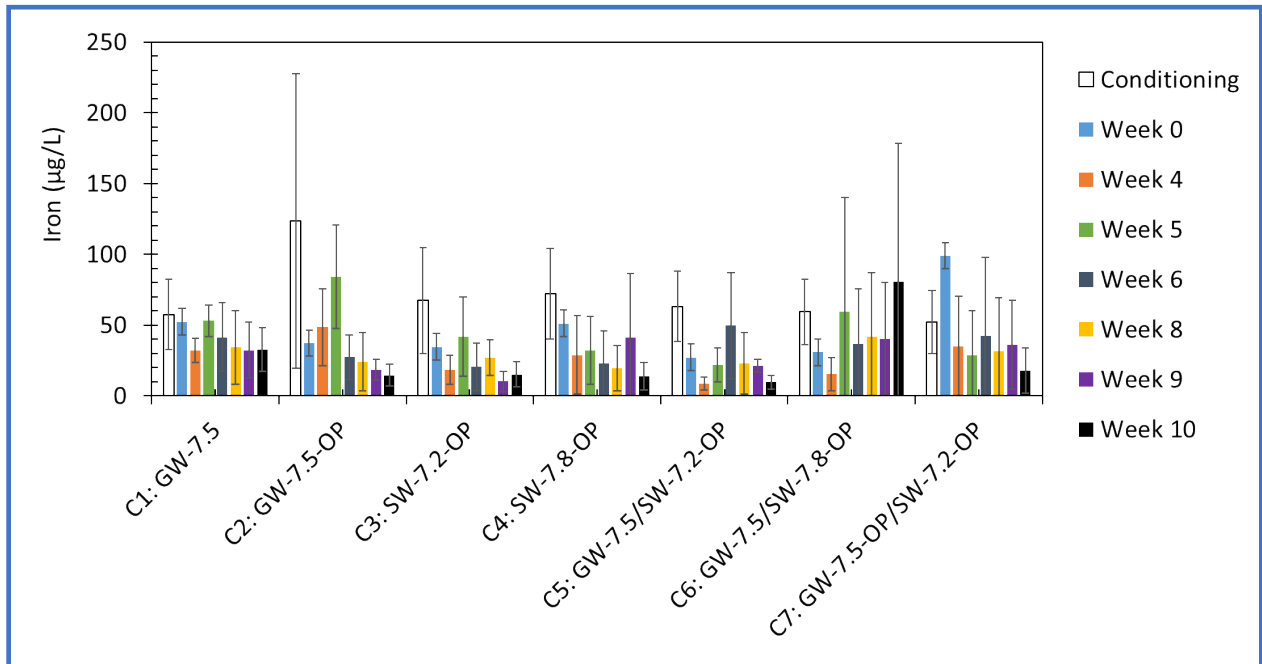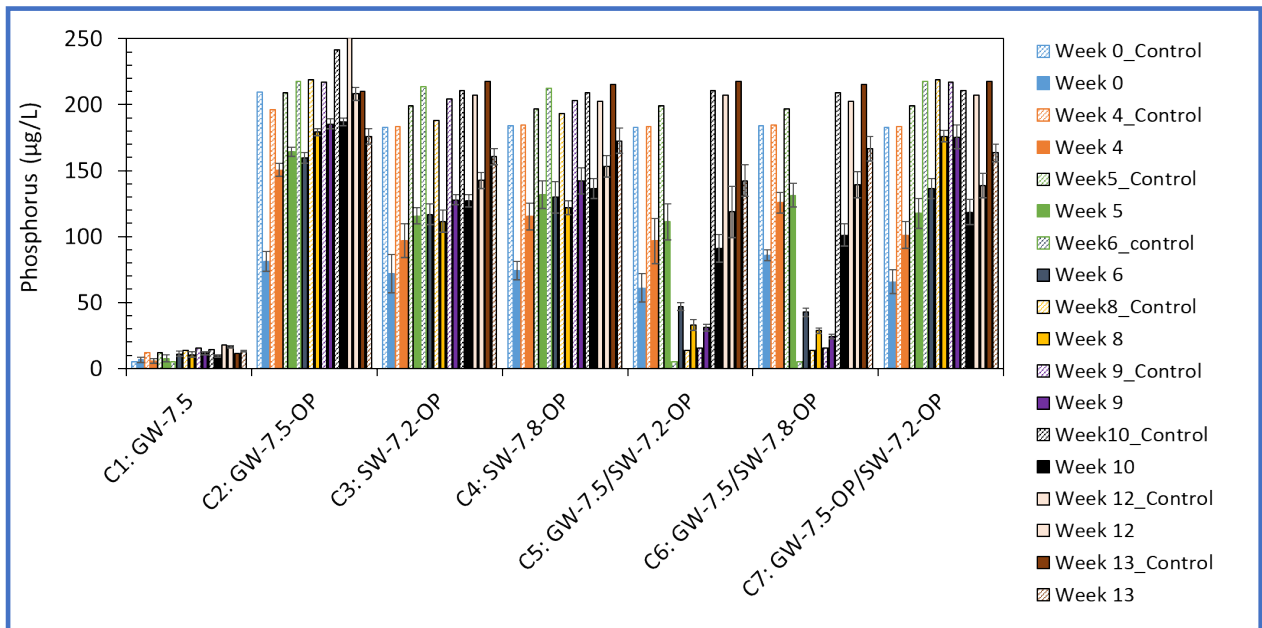
Figure A4. Iron levels in water for galvanized iron pipe coupon testing. The error bar indicated a 95% confidence interval. The coupons were exposed to GW at pH 7.5 (C1) during conditioning. The source water was switched in the alternating conditions (C5-C7) in the following order: GW for weeks 0-5, SW for weeks 6-9, and GW for week 10.

Figure A5. Phosphorus levels representing orthophosphate in water for galvanized iron pipe coupon testing. The error bar indicated a 95% confidence interval. The source water was switched in the alternating conditions (C5-C7) in the following order: GW for weeks 0-5, SW for weeks 6-9, and GW for weeks 10-13.
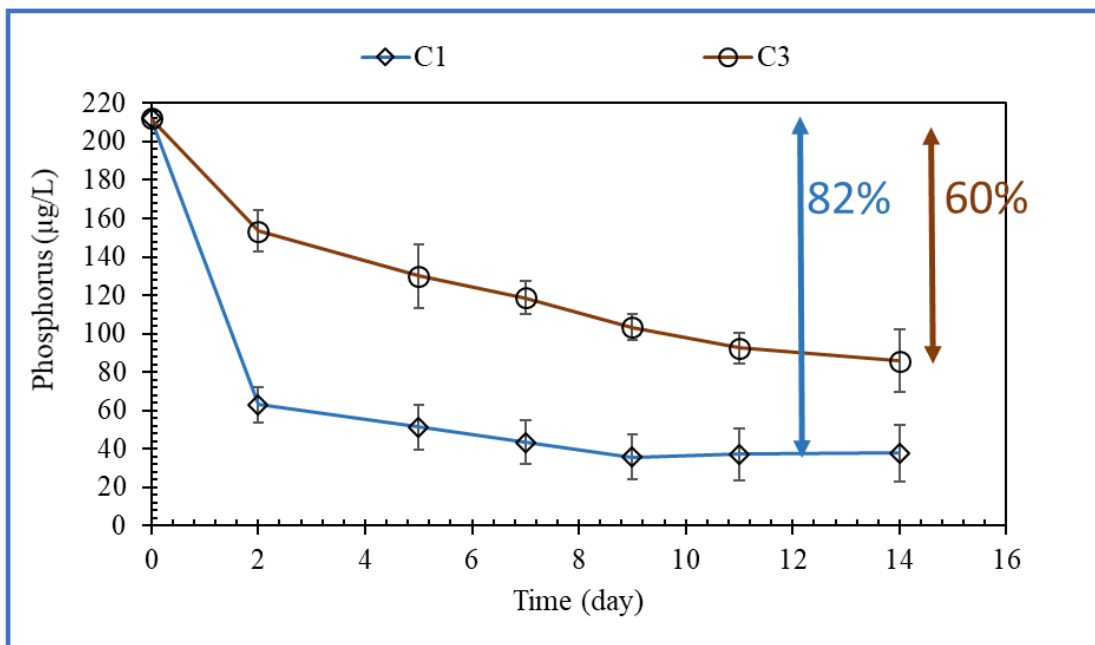
Figure A6. Two-week orthophosphate depletion test with three glass jars from C1 and three glass jars from C3, after the bench scale testing. These six jars were filled with SW at pH 7.2 with 212 μg/L orthophosphate as P at day 0 and 10 mL aliquots from each jar were collected for phosphorus analysis on ICP-MS during the course of the 2-week test. The error bar indicated a 95% confidence interval.
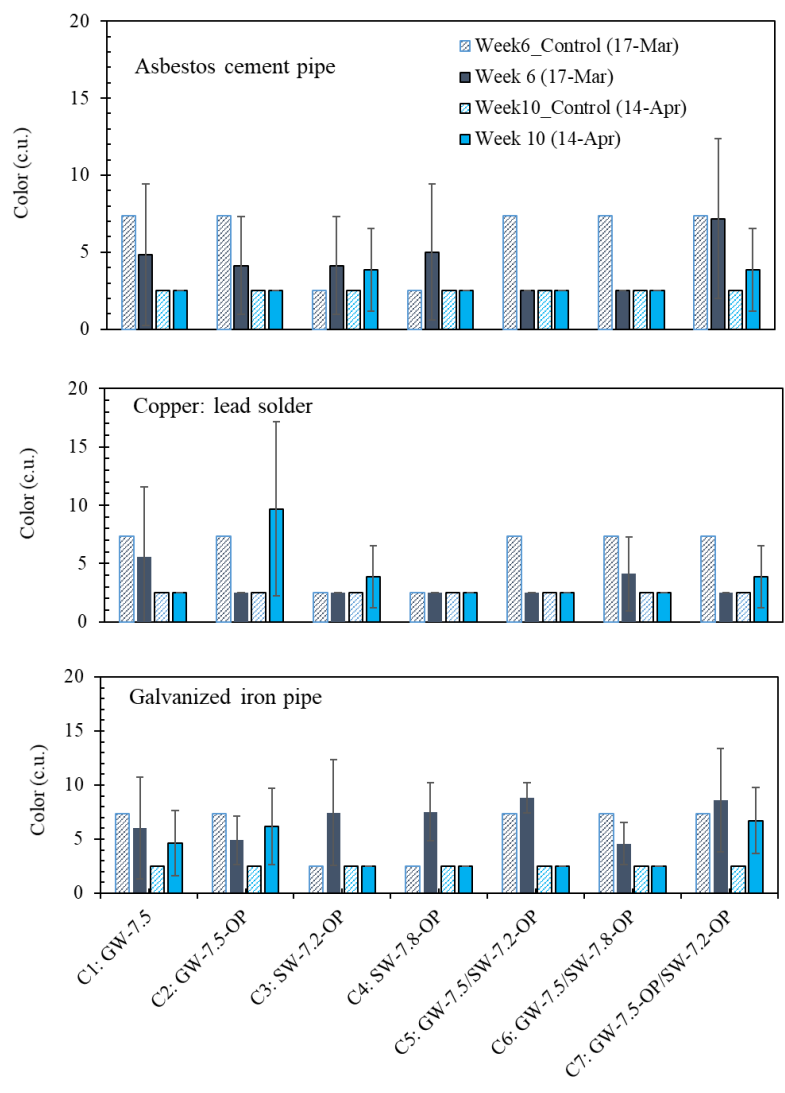
Figure A7. Color measurements on 17-Mar and 14-Apr right after source water changes. Week 6 and week 10 represent the two dates. Visual comparisons of color were included throughout the report, and the results of color measurements are included for reference.