FINAL

Terry Ranch Water Supply Inspection Activities Water Quality Evaluation

Prepared for

Greeley Water and Sewer Department, Colorado

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List of Abbreviations

μg/L	micrograms per liter
ACP	asbestos cement pipe
AI	Aggressiveness Index
AL	action level
ASR	aquifer storage and recovery
CCPP	calcium carbonate precipitation potential
CCR	Colorado Code of Regulations
CCS	corrosion control study
CCT	corrosion control treatment
CDPHE	Colorado Department of Public Health and Environment
CIP	cast iron pipe
CML	cement mortar lining
CSMR	chloride-to-sulfate mass ratio
DBP	disinfection byproduct
DIC	dissolved inorganic carbon
DIP	ductile iron pipe
DO	dissolved oxygen
EIS	Environmental Impact Statement
EQ	equalization tank
fps	foot per second
IX	ion exchange
LCR	Lead and Copper Rule
LCRR	Lead and Copper Rule Long-Term Revisions
LCRWG	Lead and Copper Rule Working Group
LR	Larson Ratio
LSI	Langelier Saturation Index
MCL	maximum contaminant level
MG	million gallons
mg/L	milligrams per liter
MGD	million gallons per day
MIC	microbiologically-induced corrosion
MSWSP	Milton Seaman Water Supply Project
ND	not detected
NDWAC	National Drinking Water Advisory Committee
OCCT	optimal corrosion control treatment
ORP	oxidation reduction potential
PAC	powder activated carbon
Pb(II) scales	lead carbonate scales
Pb(IV) scales	lead oxide scales
$Pb_3(CO_3)_2(OH)_2$	hydrocerussite
$PbCO_3$	cerussite
PEX	cross-linked polyethylene
PRV	pressure-reducing valves
PVC	polyvinyl chloride
RI	Ryznar Saturation Index
TCR	Total Coliform Rule
TDS	total dissolved solids
THM	trihalomethane
TM	Technical Memorandum
TOC	total organic carbon
TR	Terry Ranch
U.S. EPA	United States Environmental Protection Agency
WQP	water quality parameters
WTP	water treatment plant

Executive Summary

The Greeley Water & Sewer Department of the City of Greeley (Greeley) currently distributes surface water treated by the Bellvue Water Treatment Plant (WTP) and the Boyd Lake WTP. Greeley is developing an aquifer storage and recovery (ASR) program in the Upper Laramie Aquifer underlying the Terry Ranch (TR) land parcels to develop reliable and resilient water supplies. Before introducing water from the TR wells into the potable distribution system, it will be treated for radionuclides using a highly-selective uranium absorptive media, also called single-use ion exchange (IX) media. The introduction of a new water source into an existing distribution system can significantly change a water system's chemistry and trigger various challenges including corrosion and metal release. For this reason, the Lead and Copper Rule (LCR) requires water systems to undertake corrosion control studies (CCS) when changing water sources or implementing long-term water treatment changes to evaluate the potential for increase lead and/or copper corrosion. This Technical Memorandum (TM) presents the tasks that were conducted to evaluate the effect of the TR wells on Greeley's existing distribution system when TR's groundwater will blend with surface water treated by the Bellvue and Boyd WTPs. The following three scenarios were examined:

1. Each individual water sources independently, including water from the TR wells;
2. Blend of water treated by the Bellvue WTP and Terry Ranch wells; and
3. Blend of water treated by the Bellvue and Boyd Lake WTPs and Terry Ranch wells.

Potential challenges, as well as options to mitigate those challenges, are identified and discussed. This TM also includes a cursory assessment of chlorine residuals throughout the existing distribution system and whether booster chlorination stations may be needed once the TR groundwater is introduced into the existing distribution system.

Results and findings obtained during this evaluation are summarized here:

- The lead and copper concentrations measured at customer taps during the most recent samplings indicate that cuprosolvency and plumbosolvency are currently well-controlled in Greeley's service area. Isolated occurrences of high lead concentrations (including concentrations above the lead Action Level of 0.015 mg/L) have been observed at certain customer taps. Although these do not warrant changing Greeley's corrosion control treatment (CCT) and can be handled directly with the customers of these properties, under the Long-Term Revisions to the Lead and Copper Rule (LCRR), water systems in this position will need to initiate actions, conduct additional sampling, and reach out to the affected customers.
- Because the Bellvue WTP tends to form different lead mineral scales than Greeley's other water supplies, the existing lead scales could be disturbed when water from the TR wells will be introduced the distribution system. However, Greeley's system is already experiencing seasonal changes in water source when the Boyd Lake WTP is online in summertime, without widespread lead or copper releases. Therefore, it is unlikely that the addition of the TR wells will exacerbate current conditions.
- With regards to copper corrosion, water treated by the Bellvue WTP is not corrosive towards copper, but water treated by the Boyd Lake WTP can be corrosive at its lower pH range. Some of the analyses indicated that water from the TR wells, if used alone without blending, would also be corrosive towards copper unless a corrosion inhibitor is used. However, the corrosion indices calculated do not support this observation. Before proposing an alternative CCT strictly to control

potential copper release, additional water quality data should be collected from the TR wells to resolve the conflicting trends observed. Water from the TR wells will not be as corrosive towards copper upon blending with water treated by the Bellvue WTP or Boyd Lake WTP.

- The overall blend of TR well water shows that under certain conditions, the TR wells may be aggressive towards cement-mortar lined pipes and asbestos-cement pipes. However, these conditions are similar or better than those calculated in water treated by the Bellvue and Boyd Lake WTPs, suggesting that the introduction of TR well water into the existing distribution system is not likely change the aggressiveness of the water distributed by Greeley, and may even decrease it. Moreover, Greeley's distribution system contains very little cement-base materials (only a few percent of the transmission mains and less than 1 percent of the distribution system pipes).

Analyses conducted suggest that a change in CCT is not warranted, however, it was noted that the low pH of the water treated by the Boyd Lake WTP compared to the Bellvue WTP and future TR wells leads to significant pH variations in the distribution system. Increasing pH at the effluent of the Boyd Lake WTP would improve water quality, decreases the water's aggressiveness, reduce the corrosiveness of the water towards copper pipes, and limit changes in pH in the distribution system. Before increasing pH at the effluent of the Boyd Lake WTP, the consequences of this change would need to be evaluated more comprehensively, including effect on disinfectant stability, trihalomethane (THM) formation potential, and others.

This TM also includes a cursory assessment of chlorine residuals throughout the existing distribution system and whether booster chlorination stations may be needed once the TR groundwater is introduced into the existing distribution system. Results suggest that optimizing the use of the 23rd Street Booster Station and Reservoir or an upstream reservoir could help re-establish chlorine residual in the southeastern part of the distribution system where chlorine residual is lower. A booster chlorination station at the Gold Hill Tank, where water from the TR wells is expected to connect with the existing distribution system, may also help Greeley maintain a sufficient chlorine residual throughout its service area. Because booster chlorination stations also increase disinfection byproduct (DBP) concentrations, the overall impact would need to be examined in bench-scale tests.

Section 1

Introduction

The Greeley Water & Sewer Department of the City of Greeley (Greeley) currently distributes surface water treated by the Bellvue Water Treatment Plant (WTP) and the Boyd Lake WTP. Greeley evaluated several strategies to develop reliable and resilient water supplies and has narrowed in on aquifer storage and recovery (ASR). ASR will allow for the use of the Upper Laramie Aquifer underlying the Terry Ranch (TR) land parcels for groundwater supply and storage of surface water treated by the Bellvue and Boyd Lake WTPs. This project (known as the Terry Ranch Project) will be developed in several milestones, with the last phases expected for Year 2100. Before introducing water from the TR wells into the potable distribution system, it will be treated for radionuclides (mainly radon, uranium, and gross alpha particles) using a highly-selective uranium absorptive media, also called single-use ion exchange (IX). Detailed information can be found in the Draft Technical Memorandum titled *Terry Ranch Water Supply Project - Treatment Concept Design* and dated of November 16, 2020.

The introduction of a new water source into an existing distribution system can significantly change a water system's chemistry and trigger various challenges including corrosion, metal release, disinfectant decay, increases in disinfection byproduct (DBP) formation, and many others. For this reason, the Lead and Copper Rule (LCR) requires water systems to undertake corrosion control studies (CCS) when changing water sources or implementing long-term water treatment changes to evaluate the potential for increase lead and/or copper corrosion. The LCR also requires Primacy Agencies (for Greeley, the Primacy Agency is the Colorado Department of Public Health and Environment, CDPHE) to review and approve the addition of a new source or long-term change in water treatment before it is implemented by water systems. Primacy Agencies may require systems to resume Standard Monitoring for LCR compliance (i.e., collect two samplings per year at a greater number of sites) or take other appropriate steps such as increasing WQP monitoring or re-evaluating their corrosion control treatment (CCT) before implementing the proposed changes.

This Technical Memorandum (TM) presents the tasks that were conducted to evaluate the effect of the TR wells on Greeley's existing distribution system when TR's groundwater will blend with surface water treated by the Bellvue and Boyd WTPs. This evaluation is important because the introduction of groundwater from the TR wells will represent a new water source and the TR treatment process will represent a long-term change in water treatment strategy, and any changes in water quality can impact the stability of the system's corrosion scales. In this evaluation, the following three scenarios were examined:

1. Each individual water sources independently, including water from the TR wells;
2. Blend of water treated by the Bellvue WTP and Terry Ranch wells; and
3. Blend of water treated by the Bellvue and Boyd Lake WTPs and Terry Ranch wells.

Potential challenges, as well as options to mitigate those challenges, are identified and discussed. This TM also includes a cursory assessment of chlorine residuals throughout the existing distribution system and whether booster chlorination stations may be needed once the TR groundwater is introduced into the existing distribution system.

This desktop evaluation of water quality was conducted as part of Work Order 6 under the Contract for Owner's Advisory Services associated with the Milton Seaman Water Supply Project (MSWSP) Environmental Impact Statement (EIS).

1.1 Organization of the Desktop Corrosion Control Study Report

The following outlines the sections of this TM:

- Section 1: Introduction and organization of the TM;
- Section 2: Background information on the current LCR, corrosion and metal release, and corrosion control options;
- Section 3: Description of Greeley's water system, including current water sources and WTPs, future water source from the TR wells, and distribution system;
- Section 4: Corrosion control evaluation, including lead and copper concentrations, water quality, corrosion tendencies, corrosion indices, and CCT;
- Section 5: Disinfectant residual under the current conditions and expected conditions;
- Section 6: Conclusions and recommendations;
- Section 7: Limitations; and
- Section 8: References.

The report is supported by Appendix A, which presents a detailed background on corrosion including impact of corrosion on different distribution system materials, effect of water quality indicators, corrosion indices, and importance of hydraulic conditions. Information on corrosion control strategies including pH and alkalinity adjustment, and phosphate- and silicate-based agents is also presented.

Section 2

Background Information

This section introduces the current LCR, presents technical information about corrosion and metal release in general, and describes corrosion control options available to water systems.

2.1 Lead and Copper Rule

For Colorado water systems, the LCR is described in Title 5 of the Colorado Code of Regulations, Series 1002 Water Quality Control Commission, Regulation No. 11 – Colorado Primary Drinking Water Regulations (5 CCR 1002-11), and more specifically in Section 11.26.

The main purpose of the LCR is to protect public health by minimizing lead and copper levels in drinking water, primarily by reducing water corrosivity. Recognizing that lead and copper are rarely present in raw water sources but instead come from pipes, fittings, and fixtures of service lines and premise plumbing, the requirements of the LCR include sampling at customer taps instead of utility-owned portions of the water system. The LCR is a treatment technique, meaning it relies on Action Levels (ALs) for lead and copper instead of maximum contaminant levels (MCLs), and may require monitoring of water quality parameters (WQPs) to assess compliance. The ALs are the following:

- Lead: 90th percentile of tap water samples less than 0.015 mg/L or 15 µg/L (i.e., no more than 10 percent of the samples can exceed 0.015 mg/L for lead);
- Copper: 90th percentile of tap water samples less than 1.3 mg/L (i.e., no more than 10 percent of the samples can exceed 1.3 mg/L for copper).

Exceedances of these ALs or WQPs may trigger actions that water systems must implement to decrease lead and copper concentrations at customer taps. These actions may include implementing CCT, source water monitoring and/or treatment, public education, and lead service line replacement.

For lead and copper samples collected from customer taps, samples consist of first-draw samples, i.e., one liter of water that has stood motionless in the plumbing system for at least six hours. Unless otherwise advised by their Primacy Agency, water systems on Standard Monitoring must conduct two samplings per year at customer taps: between January 1 and June 30, and again between July 1 and December 31. Systems on Reduced Monitoring can collect samples once per three years during the months of June, July, August, or September. The numbers of lead, copper and WQP samples are based on population served. Systems on Standard Monitoring must collect twice as many customer tap samples as systems on Reduced Monitoring. Greeley was on Reduced Monitoring with triennial samplings at 50 customer taps until 2017. Following the lead crisis in Flint, MI, CDPHE required Greeley to sample for lead and copper annually at the Reduced Monitoring number of taps, i.e., 50.

The LCR requires large water systems serving more than 50,000 people (which includes Greeley) to optimize their CCT; this includes monitoring for lead and copper at customer taps, and WQPs at taps and distribution system entry points for one year to allow the Primacy Agency, i.e., CDPHE, to designate an adequate treatment for each system. In the current LCR, the WQPs are specific to corrosion control and may include the following parameters: pH, alkalinity, orthophosphate (when an inhibitor containing a phosphate compound is used), silica (when an inhibitor containing a silicate compound is used), calcium, conductivity and water temperature. In July 1998, CDPHE assigned a wide range of pH (7.0 to 8.9) and alkalinity (20 to 125 mg/L $CaCO_3$) to represent optimal corrosion control treatment (OCCT) for Greeley. According to CDPHE's letter of July 1998, WQP must be monitored at the distribution system entry points every two weeks, and at distribution system sites twice per six months.

The LCR has undergone several revisions since its original publication in 1991. More recently, the Long-Term Revisions to the Lead and Copper Rule (LCRR) were published by the U.S. Environmental Protection Agency (USEPA) as a final regulation on January 15, 2021. The LCRR aims at reducing lead exposure in drinking water with a focus on the most at-risk communities. The following presents the main areas of change brought by the LCRR:

1. Identifying the areas most impacted;
2. Strengthening drinking water treatment requirements;
3. Aggressively replacing lead service lines;
4. Increasing sampling reliability;
5. Improving risk communication; and
6. Protecting children in schools and child-care facilities.

The current LCR includes three options to control corrosion in distribution systems: 1) alkalinity and pH adjustments; 2) calcium hardness adjustment, and 3) addition of a phosphate- or silicate-based corrosion inhibitor. The LCRR eliminates the calcium hardness adjustment option, recognizing that calcium carbonate ($CaCO_3$) scales do not effectively passivate lead or copper piping. The LCRR also specifies that orthophosphate- or silicate-based corrosion inhibitors should be used, recognizing that polyphosphates do not offer protection against lead or copper release.

2.2 Corrosion and Metal Release

Corrosion is an electrochemical interaction between a metal surface (e.g., a pipe wall) and water. While it is important to understand and control corrosion, metal release into the water is the process that drives drinking water regulations and presents the greatest risks to public health. Pipe scales that build up on the metal surface are also important, and can include two types of compounds: 1) passivating films that form when pipe material and water react directly with each other; and 2) deposited scales that form when substances in the water (e.g., iron, manganese, aluminum, calcium) precipitate or sorb to, and then build up on the pipe surface. Appendix A presents detailed information about corrosion.

Erosion of pipe internal surfaces and linings is a phenomenon that differs from metal corrosion, as explained further in Appendix A. It derives from aggressive waters, and mainly affects cement-mortar lined pipes and asbestos-cement pipes. These pipes are composed of various calcium-based compounds that can dissolve in aggressive waters.

Many factors influence corrosion, sometimes in conflicting ways. Distribution system materials play an essential role in the process, and water that may be passivating for one material may be corrosive for another. Likewise, many water quality parameters need to be considered when examining the corrosiveness of a water source, and changes in water quality (from the use of a different water supply or change in treatment process) can also exacerbate corrosion and metal release. These complexities form the rationale that was used to develop indices of corrosion and aggressiveness, such as the Langelier Saturation Index (LSI), the Chloride-to-Sulfate Mass Ratio (CSMR), and others. Lastly, distribution system hydraulic conditions such as water velocity, water usage and flow direction also influence corrosion. Appendix A provides detailed information about each factor responsible for corrosion and metal release.

2.2.1 Lead Corrosion Control Theory

When assessing water quality data for lead release or plumbosolvency, it is beneficial to assess the mechanism controlling lead concentrations in customers' service lines and premise plumbing. Brown et al. (2013) summarized three primary mechanisms for lead corrosion control:

- pH and alkalinity adjustment to form passivating lead carbonate scales (Pb(II) mineral scales);
- Maintenance of a high oxidation reduction potential (ORP) to form passivating lead oxide scales (Pb(IV) mineral scales); and
- Addition of a chemical corrosion inhibitor such as orthophosphate- or silicate-based compounds.

The potential for Greeley to rely on these mechanisms to control lead in its distribution system is discussed in Section 4.3.1.1.

Because drinking water always contain some alkalinity, lead carbonates are important lead minerals found in drinking water distribution systems. When only the pH and carbonate concentrations are considered, there are two forms of lead carbonate minerals that predominate under water quality conditions that are typically encountered in drinking water: cerussite ($PbCO_3$) and hydrocerussite ($Pb_3(CO3)_2(OH)_2$). These minerals form under different conditions: hydrocerussite is the dominant lead carbonate when pH is high or the dissolved inorganic carbon (DIC) concentration is low, while cerussite is more prevalent when DIC concentration is higher and pH is lower. The approximate domains of the two minerals are shown in Figure 2-1. In general, hydrocerussite is more stable than cerussite and is the form of lead carbonate that can lead to the lowest overall theoretical lead solubilities. Hydrocerussite tends to dissolve at pH below approximately 8.5, unless DIC concentrations are low. Cerussite is less stable and can be more prone to sloughing, leading to lead release, when water quality is not favorable to its production. However, in distribution systems with relatively low amounts of lead-bearing plumbing materials (which is expected in Greeley's system), either form of lead carbonate, i.e., cerussite or hydrocerussite, can effectively control plumbosolvency if water quality conditions are stable. Thus, one of the key elements to limit lead corrosion and release is to maintain stable water quality and distribution conditions, which preserve the stability of the passivating lead carbonate minerals and limit plumbosolvency. If water quality conditions change such that the dominant mineral form is no longer thermodynamically favorable, the water system may experience increases in lead as one mineral scale dissolves and the other forms.

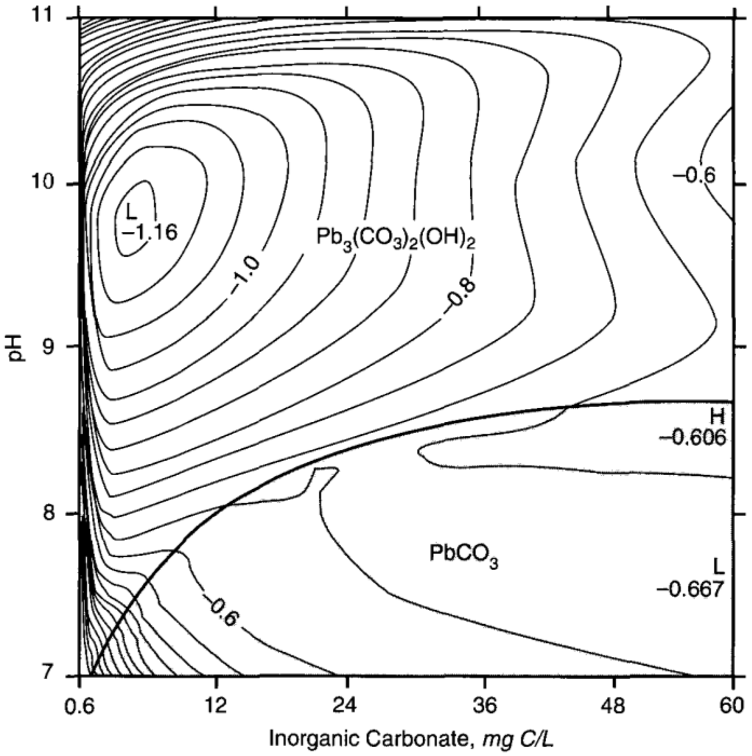


Figure 2-1. Contour Diagram of Theoretical Lead Carbonate Solubility

This diagram represents a pure system with varying hydrogen ion and carbonate species concentrations, at 25°C and I=0.005 mol/L. Concentration units are log (mg Pb/L). Local high and low points are identified with "H" and "L", respectively. The boundary line position between the domains of the lead carbonate minerals is approximate.
Source: AwwaRF and TZW (1996)

2.2.2 Copper Corrosion Control Theory

Copper piping, which is commonly used for both service lines and premise plumbing, is most vulnerable to corrosion when it is newly installed. That is because, over time, copper pipe naturally forms a scale of insoluble minerals that 'passivate' the pipe by isolating the bulk water from the metallic pipe wall. These scales typically manifest as duplex films, with a thin layer of the semiconductor cuprite ($Cu_2O_{(s)}$) in contact with the metal pipe wall, overlain with a porous layer of relatively insoluble cupric salts such as malachite ($Cu_2CO_3(OH)_{2(s)}$) or tenorite ($CuO_{(s)}$) (Schock and Lytle, 2011). However, the formation of malachite and tenorite is relatively slow; prior to formation of these minerals, copper corrosion is controlled by the metastable cupric hydroxide ($Cu(OH)_2(s)$)], which is more soluble. Prior to formation of malachite or tenorite, high DIC water may lead to rapid carbonate complexation that can disrupt the formation of the cuprite underlayer, leading to increased copper corrosion. Therefore, except at high pH values, high DIC concentrations that may be protective of iron piping may actually be aggressive to new copper piping. This is shown in Figure 2-2, which delineates between water conditions that were considered corrosive and noncorrosive towards copper. Water quality conditions that fall in the grey shaded area of Figure 2-2 are considered to be corrosive towards copper unless a corrosion inhibitor such as orthophosphate (identified as PO_4 in Figure 2-2) is used.

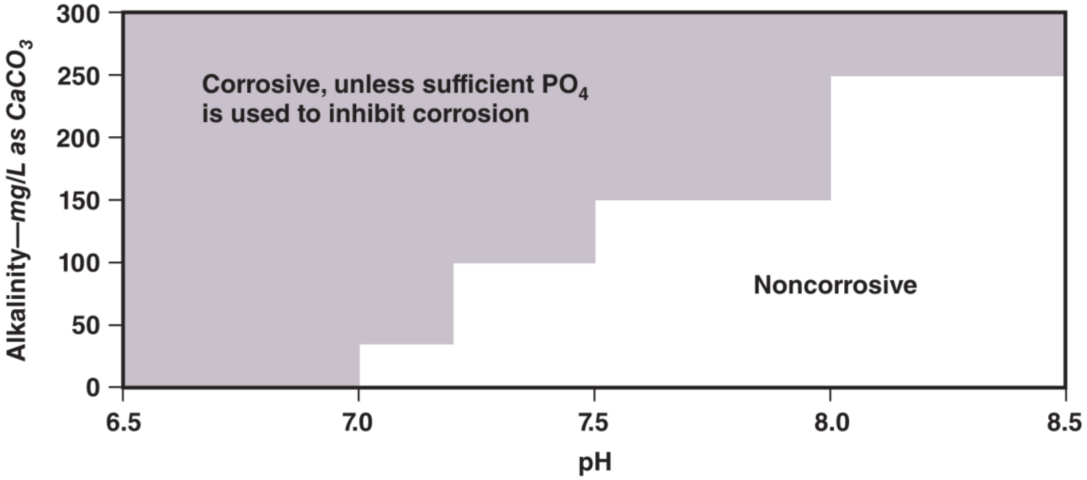


Figure 2-2. Conditions that are Corrosive to Copper as Defined by the Lead and Copper Rule Working Group (LCRWG) of the National Drinking Water Advisory Committee (NDWAC)

Source: Roth et al. (2016)

In addition to the general corrosion of copper piping described above, copper piping can be vulnerable to pitting corrosion. Although pitting corrosion has been studied by many researchers, the mechanisms controlling pitting are not currently well understood. Partially, this is because there are multiple factors that can cause pitting, complicating analysis. In general, it has been demonstrated that high pH water (pH 9) with low DIC concentrations (5 to 10 mg/L as C) and low free chlorine residuals can result in copper pitting (Lytle and Schock, 2008). Chloride and sulfate may also impact pitting corrosion. Historically, chloride was considered to be the most important ion when considering pit formation and sulfate was not thought to be a factor. However, research by Edwards et al. (1994) suggests that there is a temporal factor to the influence of chloride and sulfate on pitting corrosion; chloride was found to initially increase corrosion yet lead to the formation of passivating scales over time, while sulfate was found to initially have no impact on copper corrosion but increased copper corrosion over time, presumably by modifying the scale minerology away from passivating scales.

2.3 Corrosion Control Options

The selection of a corrosion control strategy needs to consider water quality, as well as distribution system materials and hydraulic conditions. If corrosion control is deemed necessary, the general approaches that can be used are the following:

- Alkalinity and pH adjustment, which affects DIC concentration; or
- Use of corrosion inhibitors to form less soluble metal compounds (e.g., carbonates, silicates, or phosphates) that adhere to the inner pipe walls.

Calcium hardness adjustment that increases $CaCO_3$ precipitation is often practiced to protect cement-based pipes, but it does not directly affect corrosion of lead, copper or galvanized materials. Appendix A presents detailed information about corrosion control strategies.

If a corrosion inhibitor is deemed necessary, its dosage needs to be carefully determined using laboratory, bench and/or pilot tests, pipe racks, pipe-loop or metal coupon tests, with appropriate monitoring methods.

Section 3

Description of the Water System

In addition to serving the City of Greeley, the Greeley Water & Sewer Department also serve the municipalities of Windsor, Milliken and Evans, which represent approximately 15 percent of Greeley's water demand according to Greeley's 2003 *Water Master Plan*. In 2016, approximately 96,500 people received water from Greeley. Population passed the 100,000 mark to reach approximately 108,000 people in 2017.

3.1 Current Water Sources

Greeley's water sources include direct river diversions, unit ownership in two projects, high mountain reservoirs, shares in several irrigation companies, and opportunities for exchanges with neighboring entities (Figure 3-1). More specifically, Greeley's drinking water originates from surface water from four river basins: Cache la Poudre River, Laramie River, Big Thompson River, and Colorado River. These water sources are retained in six high-mountain reservoirs located in the Poudre Basin, namely Barnes Meadow, Comanche, Hourglass, Peterson, Milton Seaman, and Twin Lake. Greeley also uses a plains reservoir system that consists in three lakes (Boyd Lake, Lake Lovel, and Horseshoe Lake) to provide storage to meet summer demands. In addition, Greeley can store a portion of its allocation of the Colorado Big-Thompson (C-BT) Project in Lake Granby, Horsetooth Reservoir and Carter Lake to meet water demand. Greeley also owns a portion of the Windy Gap Project. Water from the C-BT and Windy Gap transmountain Projects originates from the Upper Colorado River Basin.

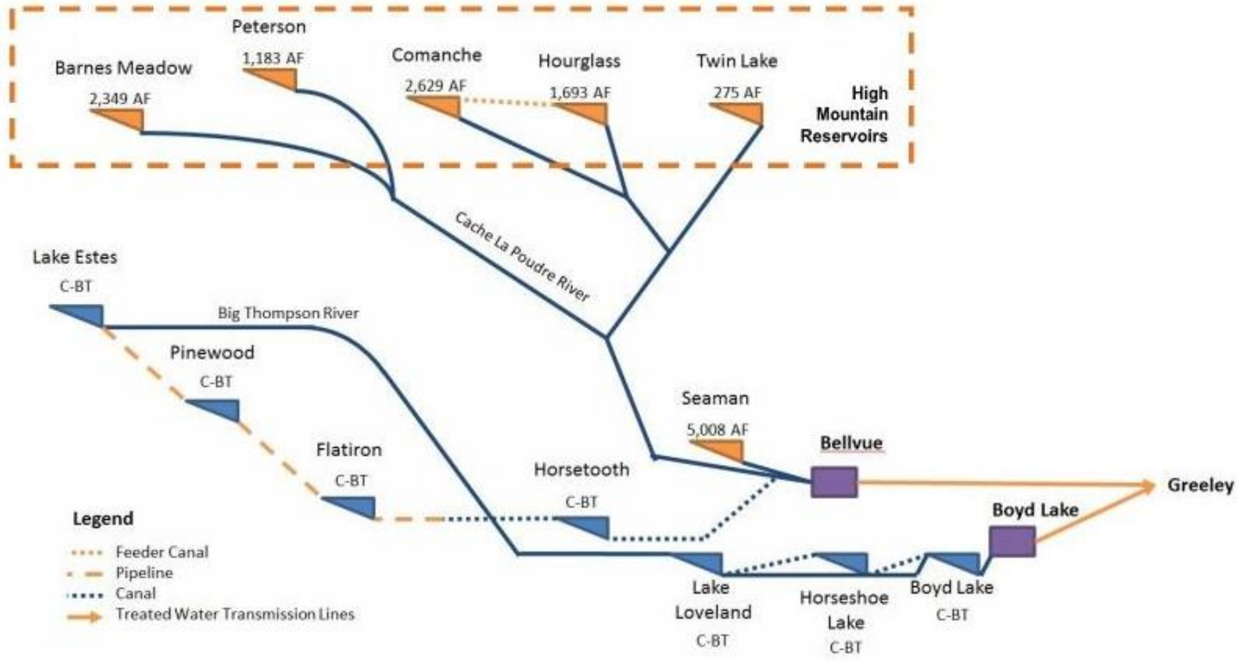


Figure 3-1. Greeley Water Resources

Source: City of Greeley –Production Rate Summary and System Review Technical Memorandum (2016)

3.2 Existing Water Treatment Plants

Greeley owns and operates two drinking water treatment plants (WTPs): the Boyd Lake WTP located east of Loveland, and the Bellvue WTP located north of Fort Collins.

3.2.1 Bellvue Water Treatment Plant

The Bellvue WTP was established in 1907 and operates year around. It is supplied by high-quality surface water from the six high-mountain reservoirs described in Section 3.1, as well as the Laramie-Poudre Tunnel Project, the C-BT Project, and the Windy Gap Project.

The Bellvue WTP has a design capacity of 32 million gallons per day (MGD), but limitations from the transmission pipes leaving the plant restricts the capacity to 22.6 MGD, according to the 2016 *Production Rate Summary and System Review Technical Memorandum*. Following raw water settling ponds, chlorine dioxide is added to decrease DBP formation and oxidize iron and manganese. Chemical addition includes powdered activated carbon (PAC) when needed, and chlorine and soda ash (sodium carbonate) before rapid mixing. In the rapid mixer, alum, a polymer, and caustic soda (sodium hydroxide) are added. Following flocculation on plate settlers and sedimentation, chlorine, a filter aid polymer and caustic soda are added before filtration. Disinfection is performed with free chlorine. Caustic soda is used to increase pH to 7.7 to 7.8 and control corrosion in the distribution system.

3.2.2 Boyd Lake Water Treatment Plant

The Boyd Lake WTP was established in 1964 and typically operates from April to October each year. It is supplied by surface water from the C-BT Project, the Windy Gap Project, and the three lakes of the plains reservoir system described in Section 3.1. Greeley operators adjust the water source blend to reach an alkalinity of 30 mg/L as $CaCO_3$, and preferably 40 to 45 mg/L.

The Boyd Lake WTP has an approved capacity of 40 MGD, conditional on maintaining effluent water quality, but aging infrastructure and raw water quality have limited the capacity to approximately 32 MGD (according to the 2016 *Production Rate Summary and System Review Technical Memorandum*). Like the Bellvue WTP, water is treated using a conventional process that begins with raw water settling ponds, followed by chlorine dioxide to inactivate microorganisms and improve tastes and odors, coagulation with alum and a cationic polymer in a rapid mixer, flocculation (a PAC slurry is added at one of the flocculation basins), sedimentation in tube settlers, addition of a cationic polymer and chlorine, and filtration on dual media. Disinfection is performed with free chlorine. Like the Bellvue WTP, caustic soda is used to increase pH to 7.2 to control corrosion in the distribution system.

3.3 Greeley's Distribution System

From the WTPs, treated water is delivered to Greeley through 153 miles of transmission pipelines, 14 inches in diameter and greater. The summary of pipe materials presented in Table 3-1 indicates that the majority of the transmission pipes are made of steel, with small amounts of cast iron pipes (CIP) and ductile iron pipes (DIP).

From the Bellvue WTP to Greeley, two transmission pipelines with a combined capacity of 20 MGD (according to the 2003 *Water Master Plan*) distribute water by gravity. One of the transmission pipelines is predominantly 27 inches in diameter, and splits into two 20-inch pipes. The second transmission pipeline leaves the Bellvue WTP at 38 inches in diameter and decreases to 30 inches and then 27 inches (its predominant size) until it reaches Greeley. A number of customers are served directly from these transmission lines.

From the Boyd Lake WTP, two transmission pipelines provide water to Greeley: a 27-inch diameter pipeline and a 34-inch pipeline. The combined capacity is 40 MGD according to the 2003 *Water Master Plan*. As opposed to the Bellvue WTP transmission pipelines, water from the Boyd Lake WTP is pumped through the transmission pipelines to reach Greeley.

Greeley's distribution system consists of four pressure zones interconnected by pump stations and pressure-reducing valves (PRVs), as illustrated in Figure 3-2. Greeley's finished water storage tanks are located at four sites (2003 *Water Master Plan*):

- 23rd Avenue: Four reservoirs with a total capacity of 37 MG;
- Mosier: A two-celled reservoir with a total capacity of 15 MG;
- Gold Hill: A single reservoir with a capacity of 15 MG; and
- Zone 4: A single 2-MG elevated storage tank.

In general, water from the Bellvue WTP is primarily delivered to Zone 1, but it may also be delivered to Zones 2 and 3 via the Mosier Pump Station. Water from the Boyd Lake WTP is primarily delivered to the Gold Hill Reservoir, which serves Zone 3, but it can also serve Zones 1 and 2 via PRVs. Zone 4 is supplied by pumping water from Zone 3.

Greeley's distribution system also includes 489 miles of pipes. A summary of distribution system pipe materials is presented in **Error! Reference source not found.**, and a summary of customer service line (i.e., the pipe segments from the water meter to the buildings) materials is shown in Table 3-3. **Error! Reference source not found.** indicates that the dominant pipe material is CIP followed by DIP and C900 PVC. Most service lines are made of copper. Although there are still a few service lines for which the material has not been identified, there are no known lead service lines in Greeley's service area.

Table 3-1. Materials of the Transmission Pipelines from the WTPs to Greeley

Material	Diameter (inches)	Length (feet)	Proportion of System (%) (1)
Cast iron pipe (CIP)	20 to 36	134,593	16.7%
Concrete	27	35,985	4.5%
Ductile iron pipe (DIP)	16 to 60	108,276	13.4%
Polyvinyl chloride (PVC)	24	340	<0.1%
Steel	14 to 60	527,256	65.4%

(1) *The proportion is based on a total pipe length of 806,450 feet.*

Table 3-2. Pipe Materials Present in Greeley's Distribution System

Material	Diameter (inches)	Length (feet)	Proportion of System (%) (1)
Asbestos cement pipe (ACP)	6	1,868	0.1%
C900 polyvinyl chloride (PVC)	4 to 16	613,027	23.8%
Cast iron pipe (CIP)	2 to 48	1,115,566	43.3%
Copper	1 to 3	1,180	<0.1%
Ductile iron pipe (DIP)	3 to 36	802,607	31.1%
Galvanized iron pipe (GIP)	2 to 3	999	<0.1%
Polyvinyl chloride (PVC)	2 to 3	3,261	0.1%
Steel	12 to 36	40,948	1.6%

(1) *The proportion is based on a total pipe length of 2,579,456 feet.*

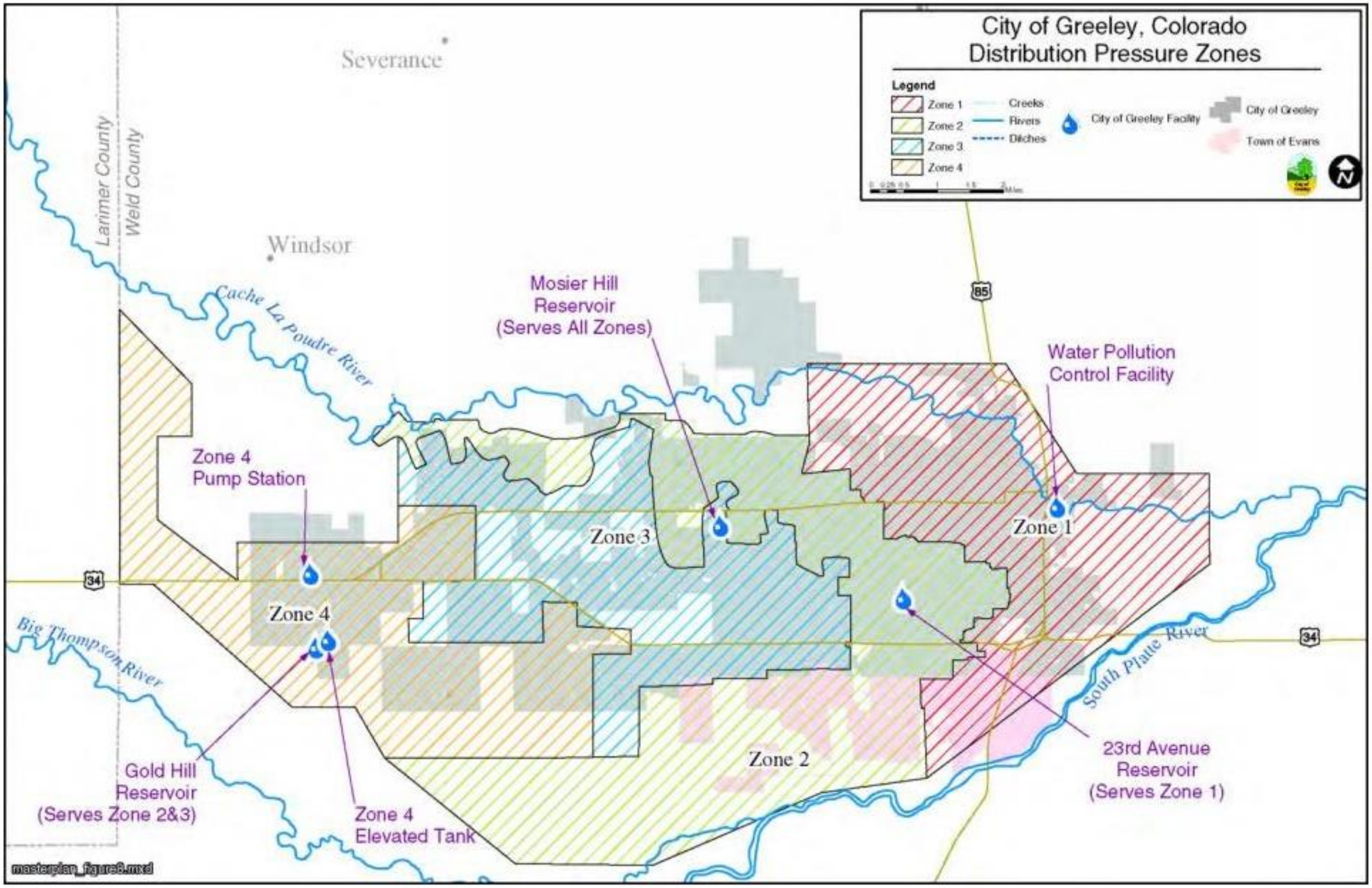


Figure 3-2. Greeley's Distribution System Pressure Zones

Source: 2003 Water Master Plan

Table 3-3. Customer Service Line Materials Present in Greeley's Distribution System

Material	Number of Service Lines	Length (feet)	Proportion (%) (1)
Unknown	27	873	0.1%
Cast iron pipe (CIP)	24	3,600	0.3%
Copper	28,343	1,025,184	97.1%
Ductile iron pipe (DIP)	253	21,428	2.0%
Polyvinyl chloride (PVC)	72	2,584	0.2%
Cross-linked polyethylene (PEX)	68	2,359	0.2%

(1) *The proportion is based on a total pipe length of 1,056,028 feet.*

3.4 Terry Ranch Wells

As mentioned in Section 1, the new water supply will consist of groundwater from an ASR system underlying the TR land parcels. The well locations are illustrated in

Figure 3-3. Before introducing water from the TR wells into the existing distribution system, it will be treated for radionuclides (mainly radon, uranium, and gross alpha particles) using a highly-selective uranium absorptive media, also called single-use ion exchange (IX). The media provider confirmed that treated water has no measurable changes in total dissolved solids (TDS), ion constituency, pH, dissolved gases or physical characteristics. In other words, the water produced from this passive absorption process is essentially the raw groundwater without radionuclides. Detailed information is presented in the Draft Technical Memorandum titled *Terry Ranch Water Supply Project - Treatment Concept Design* (2020).

At the time this TM was prepared, the treatment process proposed was involving pumping water from the TR wells into detention ponds with a 2-hour storage capacity. After stabilization, the water will be redirected to an equalization tank (EQ) to equalize the flow from the various wells pumping at different rates, ensure a consistent feed rate and quality to the absorptive IX media, and provide the contact time needed to remove radon. Following equalization, water will be pumped through the absorptive IX media for radionuclide removal. Each treatment train will consist of two vessels operated in a lead/lag configuration to improve efficiency of usage of the absorptive IX media with the vessels. Post-contactor chlorine gas or sodium hypochlorite will be fed at a dose ranging from 1 to 3 mg/L Cl_2 to provide 4-log inactivation of viruses as required by the Groundwater Rule and to control biological growth in the pipeline to Greeley. The simplified process flow diagram is presented in Figure 3-4.

From the TR WTP, water will be conveyed through a 32-mile pipeline. Two options were considered when this TM was prepared: a single 36-inch steel, epoxy-lined pipe, or dual 24-inch steel, epoxy-lined pipes. The pipeline(s) will connect to Greeley's distribution system at the Gold Hill Tank in the western part of Greeley, where the TR WTP water will be blended with water from the Bellvue and Boyd Lake WTPs.

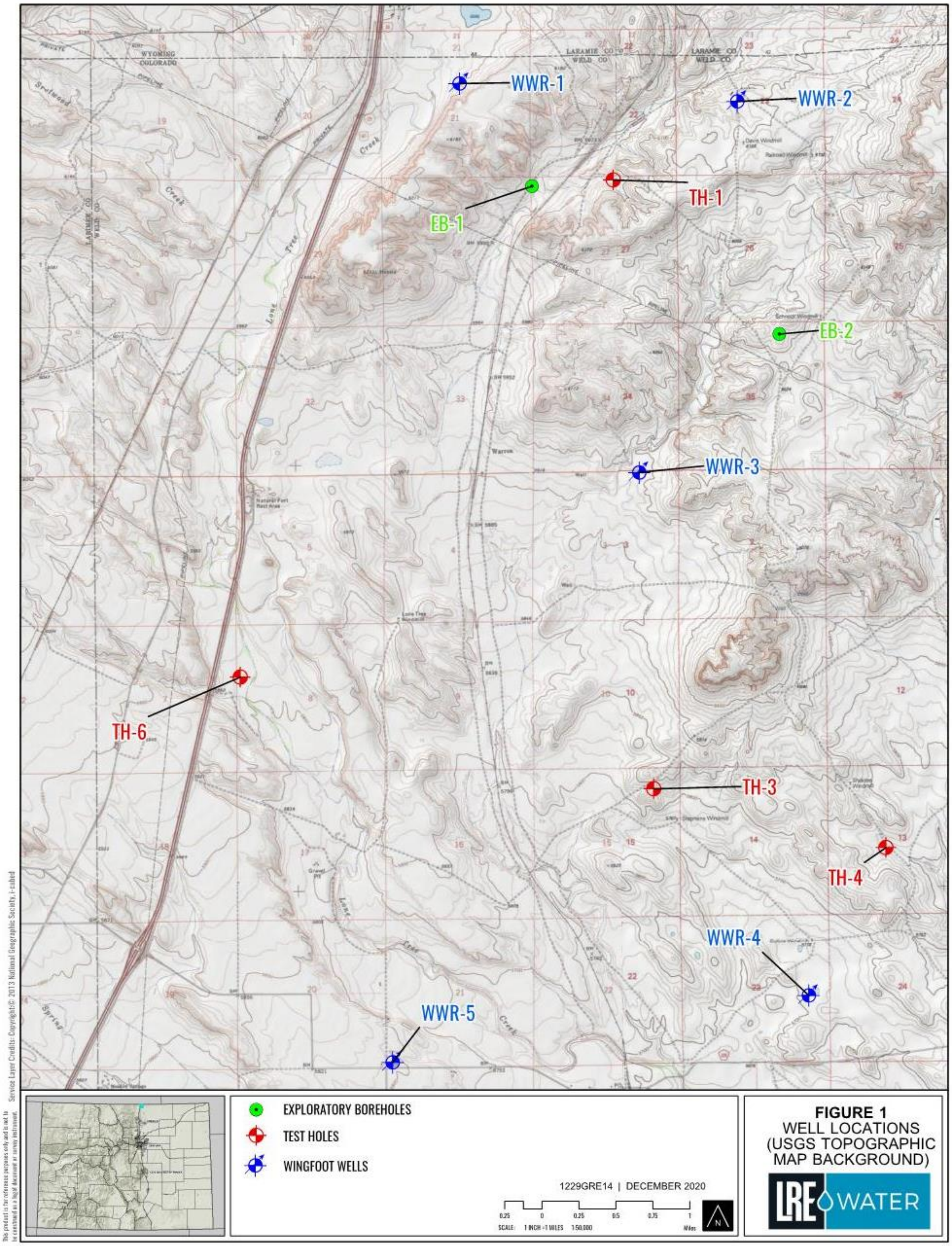


Figure 3-3. Terry Ranch Aquifer Storage and Recovery Well Locations

Source: Draft Technical Memorandum titled Terry Ranch Groundwater Quality Characterization – Sampling and Analysis Methods and Results (January 5, 2021)

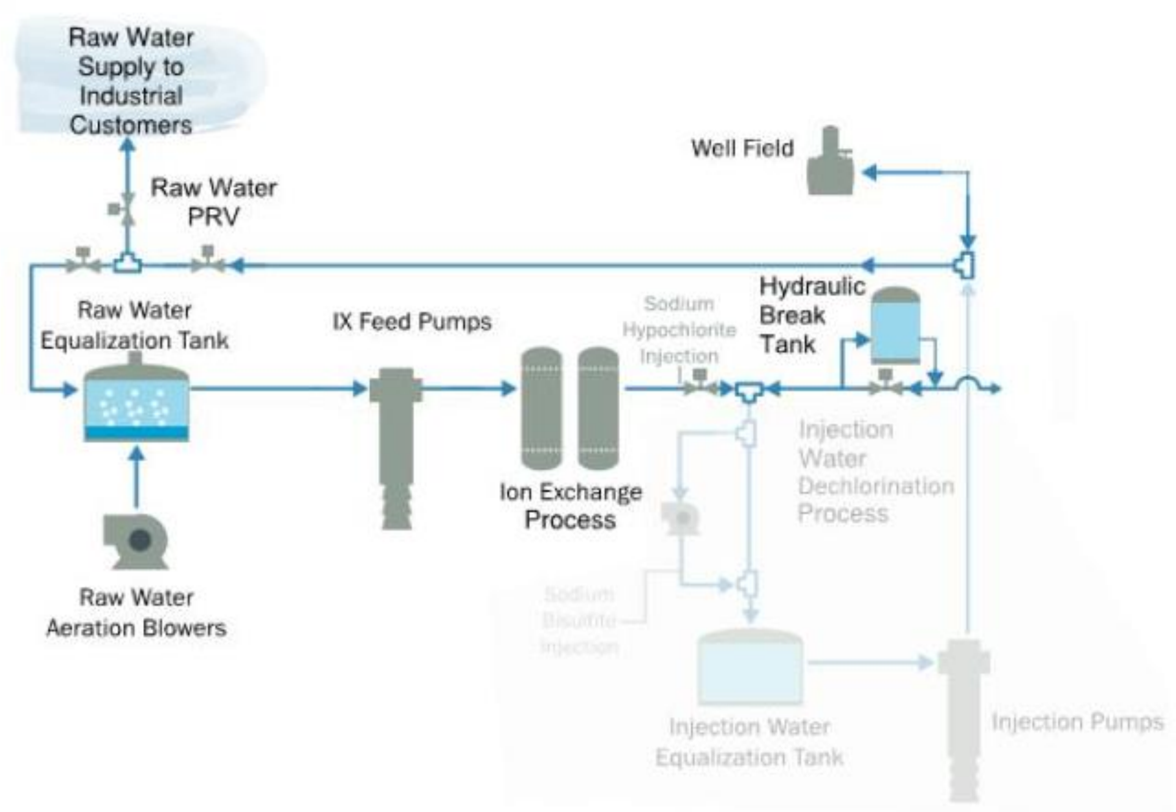


Figure 3-4. Flow Diagram for the Proposed Treatment Process for the Terry Ranch Wells

Shaded treatment processes refer to the future aquifer storage and injection process.

Source: Draft Technical Memorandum titled Terry Ranch Water Supply Project - Treatment Concept Design (2020)

Section 4

Corrosion Control Evaluation

This section summarizes the data analysis conducted to evaluate the potential effects of introducing treated groundwater from the TR wells on Greeley's distribution system. This evaluation includes analysis of lead and copper data, water quality in relation to corrosion and metal release, corrosion indices, and suitable CCT.

4.1 Lead and Copper Data

Greeley served fewer than 100,000 people until 2016 and was on Reduced Monitoring for LCR compliance. Thus, it was eligible to measure lead and copper at 30 customer taps once every three years. As explained in Section 2.1, CDPHE required Greeley to sample for lead and copper annually at the Reduced Monitoring number of customer taps starting in 2017. At the same time, Greeley's population increased to over 100,000 people, and thus, 50 customer tap samples were required.

Detailed lead and copper results were provided for the most recent samplings, and data summarized in Consumer Confidence Reports were used to complement this evaluation. Greeley sampled for lead and copper at customer taps according to Reduced Monitoring requirements in 2014 and 2017 (30 and 50 taps, respectively). Greeley also sampled in July 2018, August 2019 and August 2020, as required by CDPHE in response to the Flint, MI, lead crisis. For these sampling events, lead and copper concentrations were measured at 50 customer taps.

4.1.1 Lead Sampling Results

Lead concentrations measured in Greeley's distribution system during the most recent samplings are summarized in Table 4-1. These results show that the 90th percentiles of lead concentrations were well below the AL of 0.015 mg/L during all samplings.

Table 4-1. Lead Concentrations Measured During Recent LCR Samplings

Sampling Period	90th Percentile (mg/L)	Maximum Concentration (mg/L)	Number of Samples Collected
2014	0.0019 (1)	N/A	30 (1)
2017	0.0043 (1)	N/A	50 (1)
2018	0.0047	0.0138	50
2019	0.0047	0.0179	50
2020	0.0029	0.0064	50

N/A: Not available
(1) Source: Consumer Confidence Reports

The Final LCRR published in January 2021 adds a lead Trigger Level of 0.010 mg/L based on the 90th percentile to compel water systems to take proactive actions. If the 90th percentile lead level exceeds this Trigger Level, systems are required to take various actions based on whether they practice CCT and whether they have lead service lines (LSLs) or service lines made of unknown materials. Water systems on Reduced Monitoring are also required to sample annually at the standard number of distribution system sites. Table 4-1 indicates that all samplings conducted by Greeley since 2014 have shown 90th percentiles for lead less than the Trigger Level of 0.010 mg/L.

The LCRR proposes a “find-and-fix” process focusing on CCT and WQPs that requires water systems to conduct additional samplings if individual customer tap(s) exceed 0.015 mg/L for lead. Within five days of this finding, systems need to collect WQP sample(s) at or near the site(s) where lead concentrations exceeded 0.015 mg/L and collect follow-up lead sample(s) within 30 days at each site where lead concentrations exceeded 0.015 mg/L. Systems also need to notify the affected customer(s) within three days if follow-up sample(s) exceed 0.015 mg/L for lead. In addition, systems need to recommend solutions to its Primacy Agency within six months of the end of the monitoring period when the high lead concentrations were measured. Table 4-1 indicates that the maximum lead concentrations were high during certain samplings. In Summer 2019, two of the samples collected had lead concentrations greater than 0.015 mg/L, suggesting that lead solubility, or plumbosolvency, may not be well-controlled throughout the entire distribution system. When examining individual lead results more closely, three customer addresses repeatedly showed higher lead concentrations during the 2018, 2019 and 2020 samplings (2530 55th Avenue, 4207 West 22nd Street Road, and 2589 53rd Avenue), suggesting that lead material may be localized to this zone of Greeley’s service area. In this area, the distribution system mainly consists of cast iron and ductile iron pipes. According to the LCRR requirements described at the beginning of this paragraph, Greeley would have had to undertake a “find-and-fix” process following its 2019 sampling if the LCRR were effective during that sampling.

4.1.2 Copper Sampling Results

Copper concentrations measured at Greeley’s customer taps during the most recent samplings are summarized in Table 4-2. Results indicate that the 90th percentiles of copper concentrations were below the AL of 1.3 mg/L during all samplings. Based on the 90th percentiles and maximum concentrations provided, copper solubility, or cuprosolvency, appears to be well-controlled in Greeley’s system.

Table 4-2. Copper Concentrations Measured During LCR Samplings Since 2015

Sampling Period	90th Percentile (mg/L)	Maximum Concentration (mg/L)
2014	0.26 (1)	N/A
2017	0.29 (1)	N/A
2018	0.27	0.37
2019	0.41	0.75
2020	<0.2	0.25

N/A: Not available
(1) Source: Consumer Confidence Reports

4.2 Water Quality

This section compares water quality from Greeley’s existing water sources with water quality anticipated from the TR wells. Water quality data for a wide range of parameters responsible for corrosion and metal release are presented here. These parameters include water temperature, pH, total alkalinity, TDS, chloride, sulfate, total hardness, calcium, magnesium (free chlorine is another important parameter and discussed in detail in Section 5). Iron and manganese are also discussed in this section; not because they are responsible for corrosion or metal release, but because their presence informs the selection of CCT.

Unless otherwise noted, three years of data collected between January 2017 and December 2019 in finished water from the Bellvue and Boyd Lake WTPs and distribution system sites where WQPs are measured were used. Because Greeley began serving more than 100,000 people in 2017, WQP results obtained from 10 distribution system sampling sites were used.

For the TR wells, water quality data obtained from five Wingfoot Water Resources production wells (WWR; numbered WWR-1 to WWR-5) and two temporary monitoring wells or exploratory boreholes (EB-1 and EB-2) were examined. Three types of tests were conducted from these wells and boreholes: composite, depth-specific, and packer tests. For this analysis, only the composite samples collected from the discharge line after 48 hours of pumping were used because they are most representative of water that will be used once the TR WTP is online and treated groundwater is introduced in Greeley's distribution system. Depth-specific and packer test samples were eliminated because they are collected from specific screened intervals or aquifer zones only, and thus, do not represent an entire well or borehole. A pilot treatment plant was operated for 30 days from November to December 2020 at EB-2 to evaluate the proposed treatment strategy for the TR wells, which is described in Section 3.4. To evaluate the water quality at EB-2, samples collected from the composite tests and at the pilot plant influent, before any treatment, were used. These limitations led to a handful of data points, at the most, for the target parameters.

Consistent with information received from the provider of the absorptive IX media that will be used at the TR WTP, it was assumed that water quality would not change after treatment. Additional information can be found in the Draft Technical Memorandum titled *Terry Ranch Water Supply Project - Treatment Concept Design* (2020). Thus. water quality observed in untreated TR well water was used to evaluate the impact of this new water source on Greeley's existing distribution system.

Water quality data from the Bellvue WTP, Boyd Lake WTPs and TR wells are summarized in Table 4-3. Figure 4-1 to Figure 4-22 illustrate data provided for the most critical parameters responsible for corrosion and metal release, as made available, in the current and future water sources, as well as in the distribution system. Additional figures were included in this suite to illustrate seasonal variability, whenever observed with the data provided. In the Box-and-Whiskers plots, the vertical lines represent the minimum and maximum concentrations, the bottom and top of the boxes represent the 10th and 90th percentiles, respectively, and the dash illustrates the average concentration. Each parameter is discussed in the sections below.

As mentioned in Section 1, the following three scenarios were examined:

1. Each individual water sources independently, including water from the TR wells;
2. Blend of water treated by the Bellvue WTP and Terry Ranch well water; and
3. Blend of water treated by the Bellvue and Boyd Lake WTPs and Terry Ranch well water.

Because the Boyd Lake WTP is only used in summertime, Scenario 2 is applicable to wintertime only, and thus, water quality data obtained only in wintertime were used for the Bellvue WTP for this scenario. Likewise, Scenario 3 is expected to occur only in summertime, and thus, summer water quality data were used for the Bellvue WTP for this scenario. For Scenarios 2 and 3, equal proportions of water from each source were examined recognizing that the individual water sources would represent extreme water quality conditions, and any water blends would represent intermediate conditions. Also, the limited water quality data available for the TR wells when this TM was prepared did not justify a more extensive analysis.

Table 4-3. Summary of Water Quality from Greeley's Current and Future Water Supply Sources

Parameter	Unit	Bellvue WTP (1)			Boyd Lake WTP			TR Wells						
		Minimum	Average	Maximum	Minimum	Average	Maximum	EB-1	EB-2	WWR-1	WWR-2	WWR-3	WWR-4	WWR-5
Temperature	°C	2.0	11.4	21.0	8.9	19.4	23.2	NA	16.2	13.6	17.4	15.5	12.6	13.6
pH		7.04	7.83	8.86	7.00	7.23	8.28	NA	7.15	8.01	7.67	7.93	7.91	7.77
Alkalinity	mg/L as $CaCO_3$	20	36	70	45	79	111	164	197	184	182	188	202	172
TDS	mg/L	52	73	121	241	356	494	298	254	272	250	242	277	254
Chloride	mg/L	1.6	8.7	11.6	9.1	17.4	24.4	3.5	4.5	3.8	4.2	3.9	4.1	4.7
Sulfate	mg/L	6.0	14.4	18.0	75.0	137.4	230.0	31.9	17.7	19.6	17.2	16.5	14.3	14.9
Hardness	mg/L as $CaCO_3$	17	28	58	90	124	185	113	161	128	125	169	172	157
Calcium	mg/L	7.2	11.1	20.8	36.0	49.6	74.0	38.9	48.7	41.7	31.8	42.9	48.8	41.9
Magnesium	mg/L	1.0	8.4	20.0	7.3	16.9	29.8	5.8	9.6	5.9	6.0	9.0	10.5	10.7
Iron	mg/L	0.001	0.004	0.014	ND	0.002	0.042	0.365	0.015	0.014	0.036	0.030	0.063	0.077
Manganese	mg/L	0.001	0.006	0.023	0.003	0.017	0.033	0.005	0.016	0.0017	0.009	0.025	0.024	0.016
Free chlorine	mg/L Cl_2	0.54	1.04	2.74	0.74	1.37	1.90	--	--	--	--	--	--	--

NA: Not available

ND: Non-detect

(1) *For the Bellvue WTP, water quality data collected between January 2017 and December 2019 were used, except for chloride and sulfate which include data collected in 2020.*

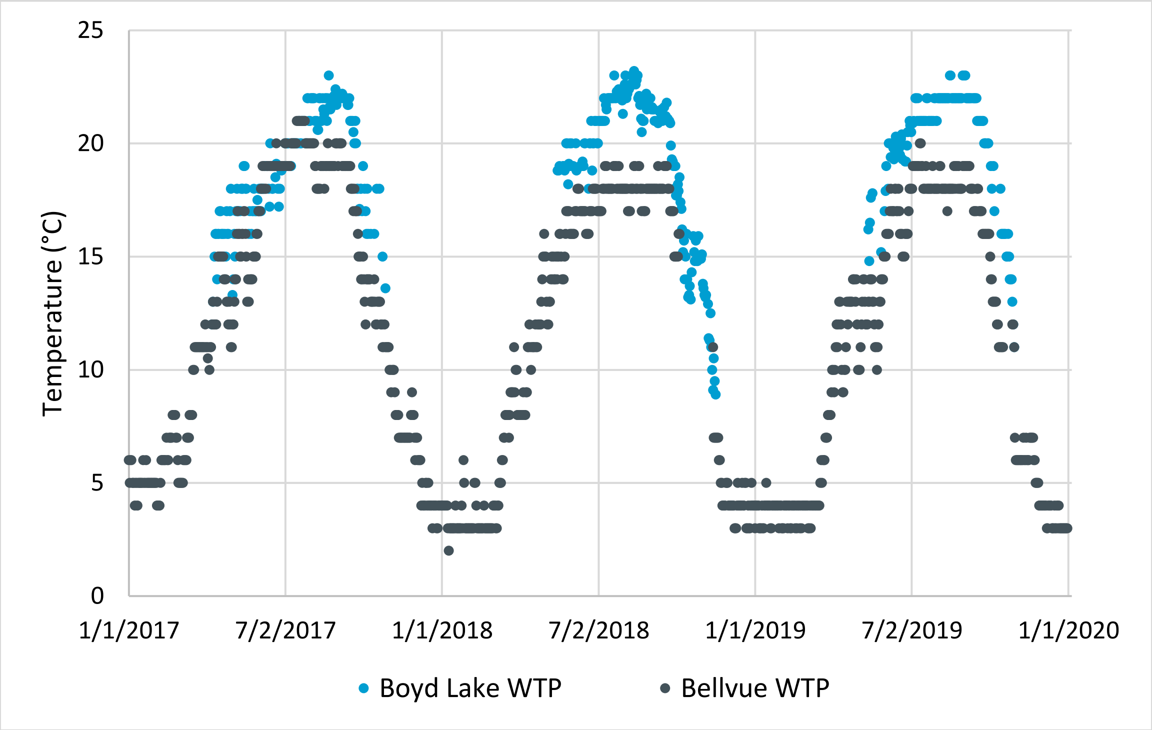


Figure 4-1. Water Temperature Measured at the WTP Effluents

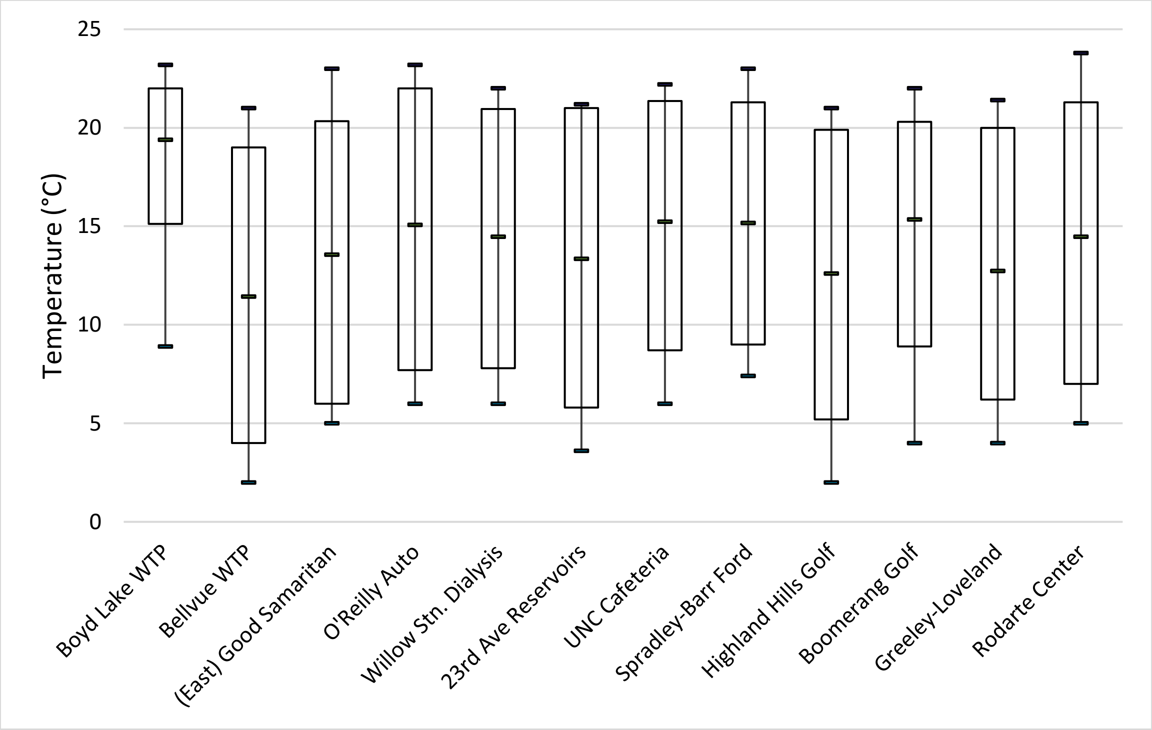


Figure 4-2. Water Temperature Measured at the WTP Effluents and Distribution System WQP Sampling Sites

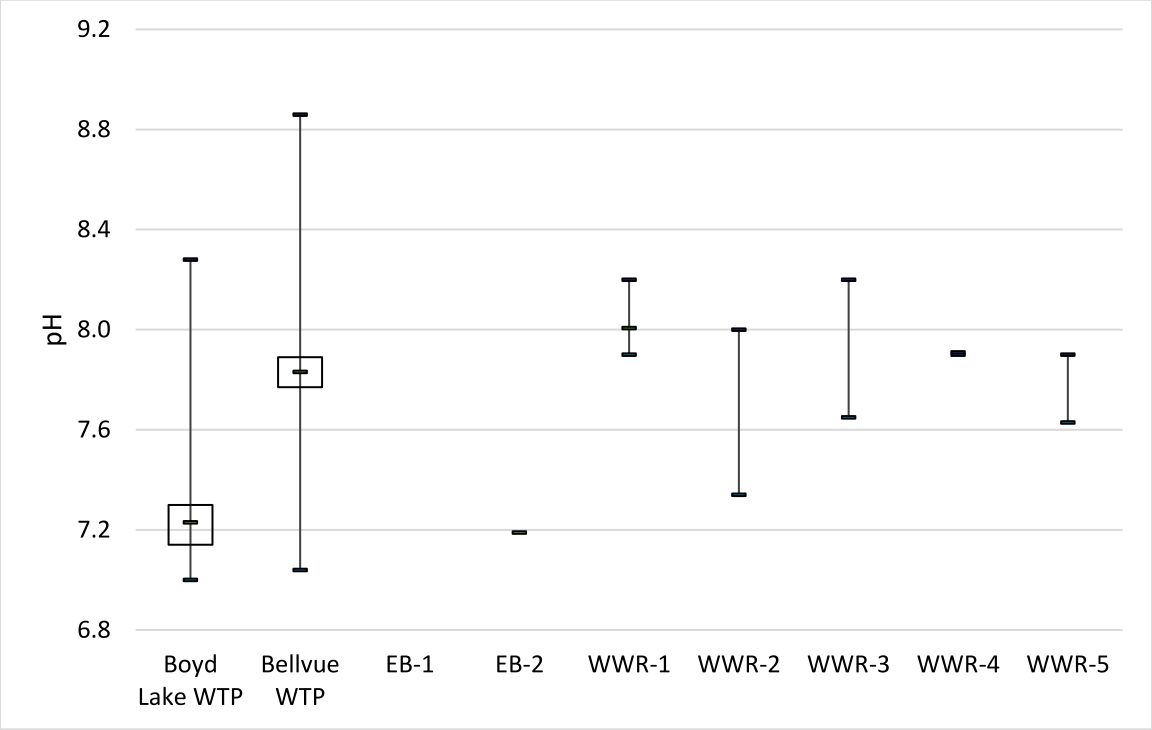


Figure 4-3. pH Measured at the WTP Effluents and TR Groundwater Wells

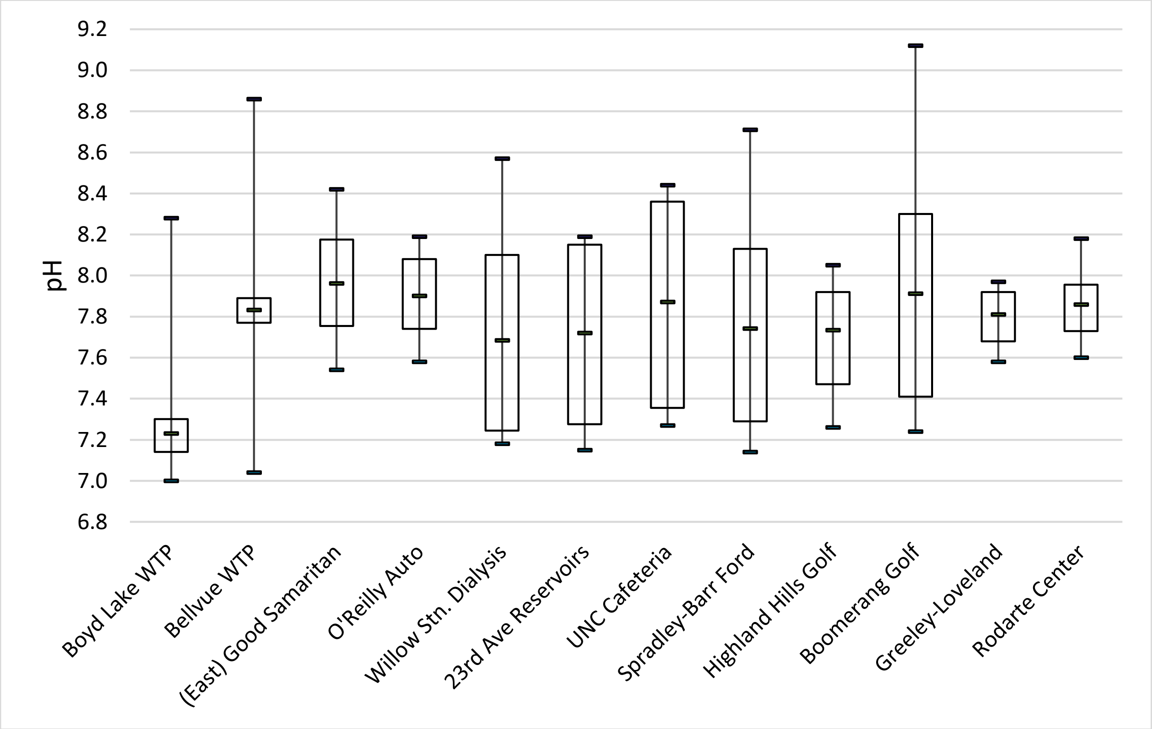


Figure 4-4. pH Measured at the WTP Effluents and in Distribution System WQP Sampling Sites

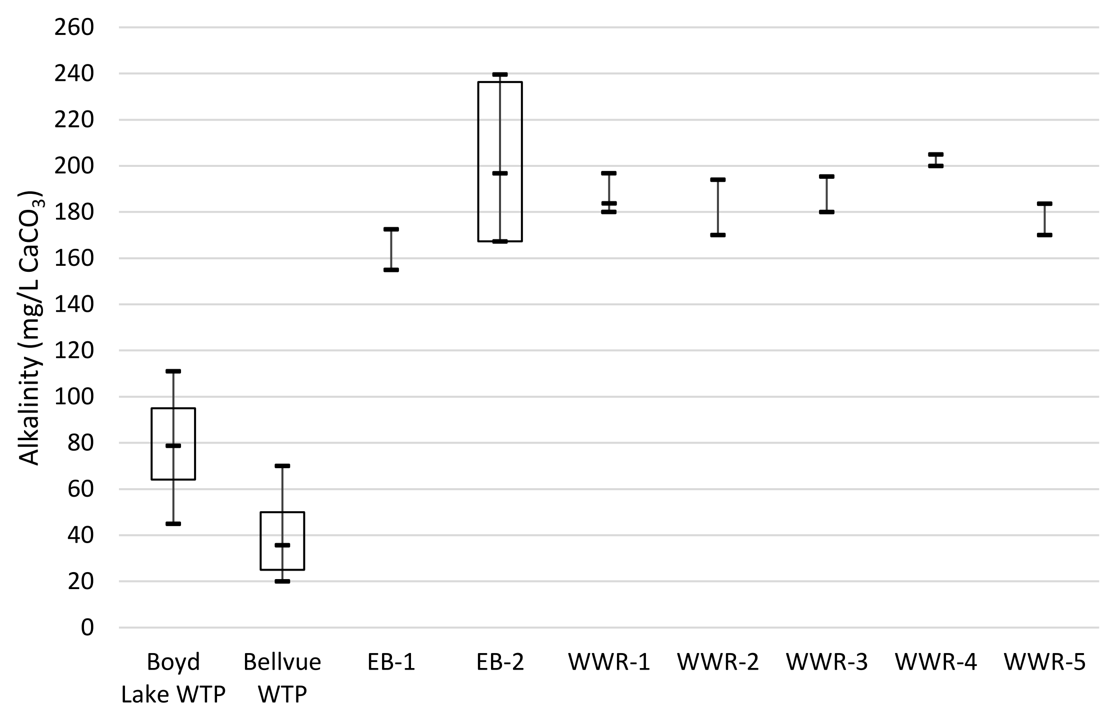


Figure 4-5. Total Alkalinity Measured at the WTP Effluents and TR Groundwater Wells

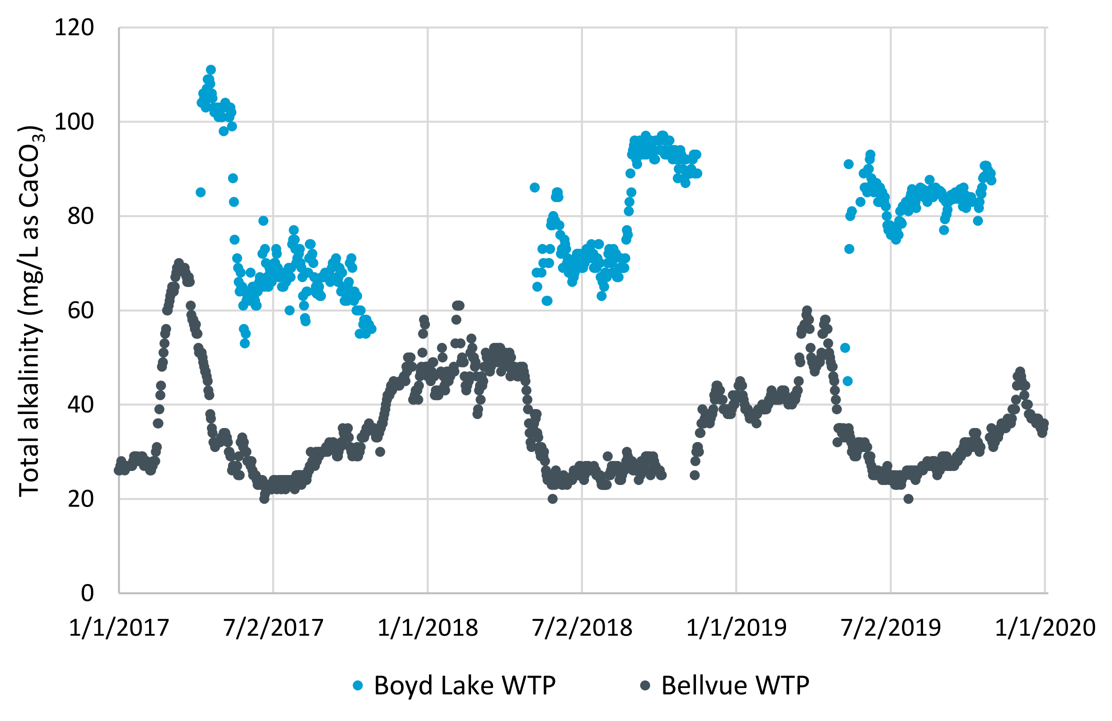


Figure 4-6. Total Alkalinity Measured at the WTP Effluents

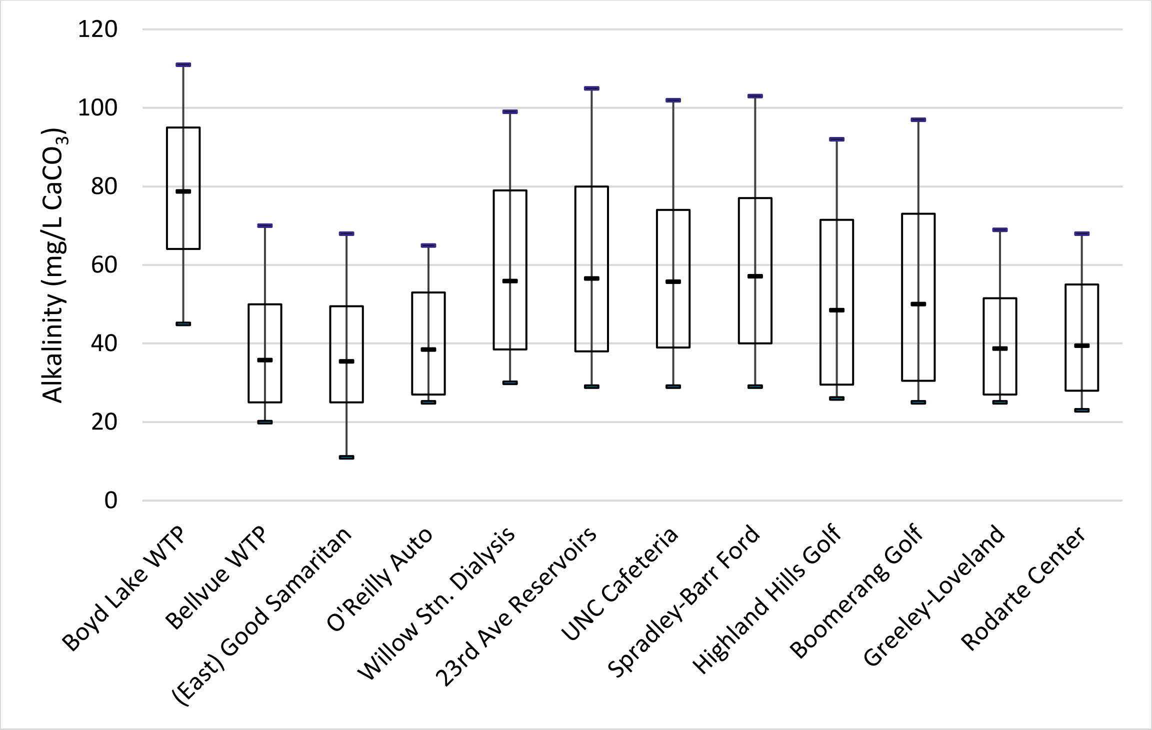


Figure 4-7. Total Alkalinity Measured at the WTP Effluents and Distribution System WQP Sampling Sites

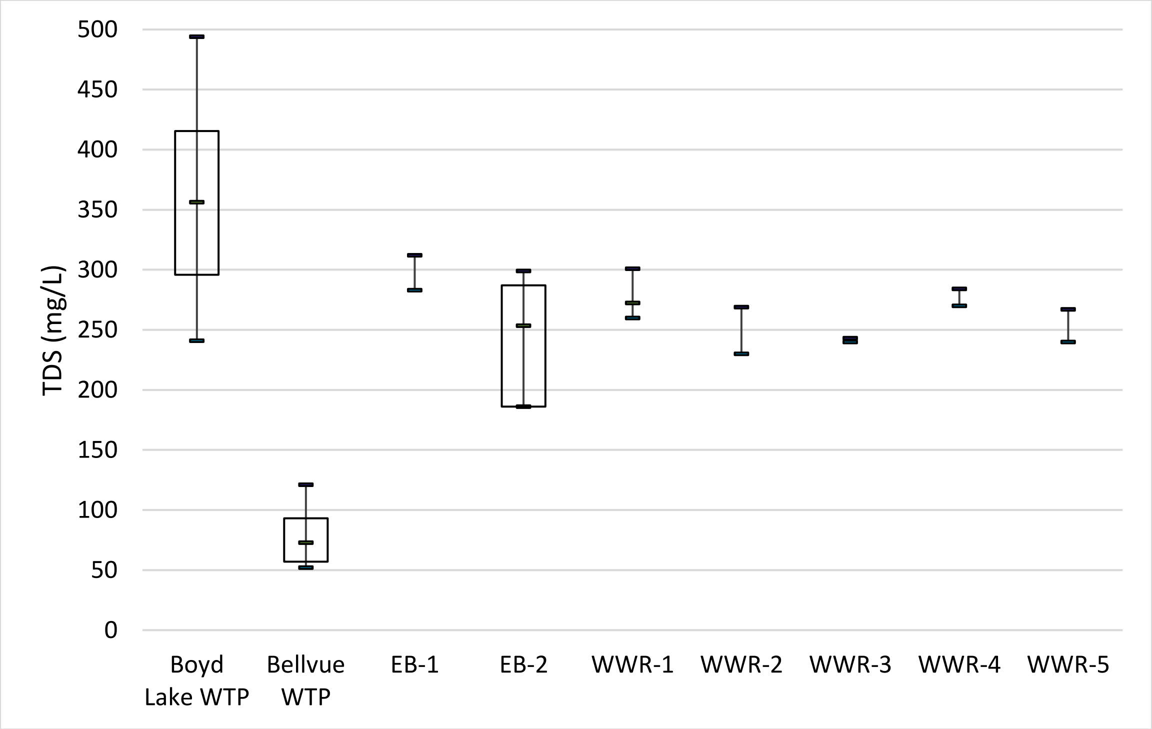


Figure 4-8. TDS Concentrations Measured at the WTP Effluents and TR Groundwater Wells

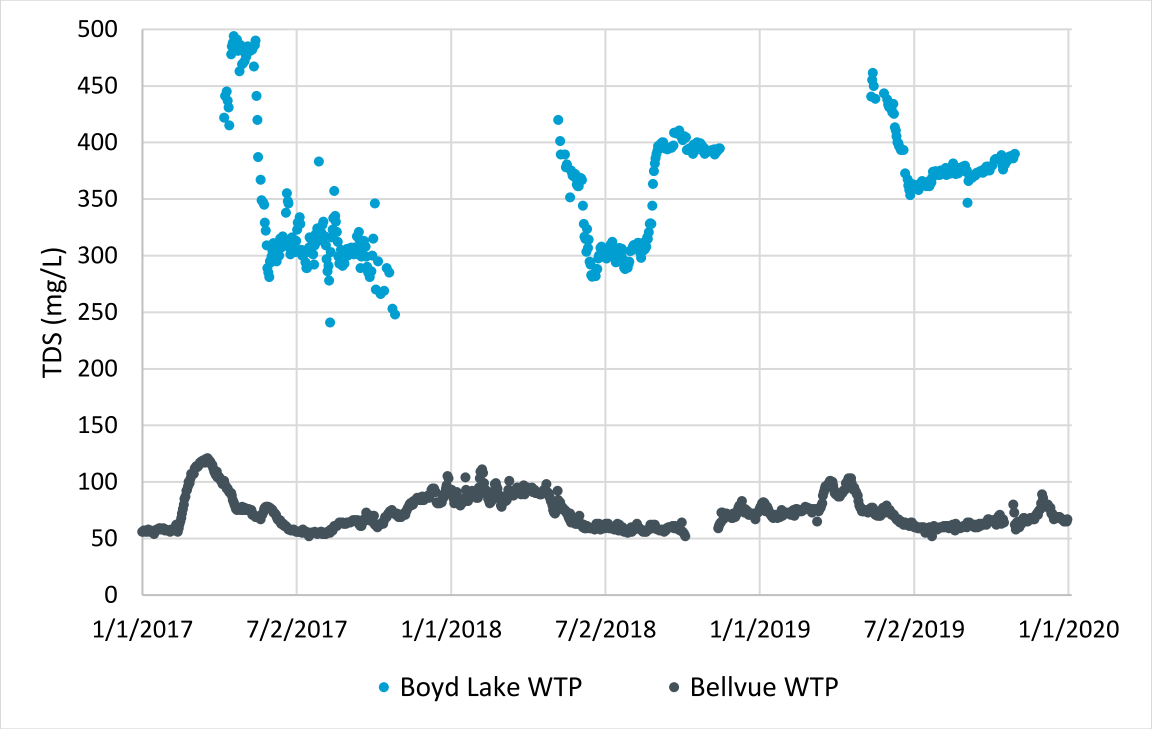


Figure 4-9. TDS Measured at the WTP Effluents

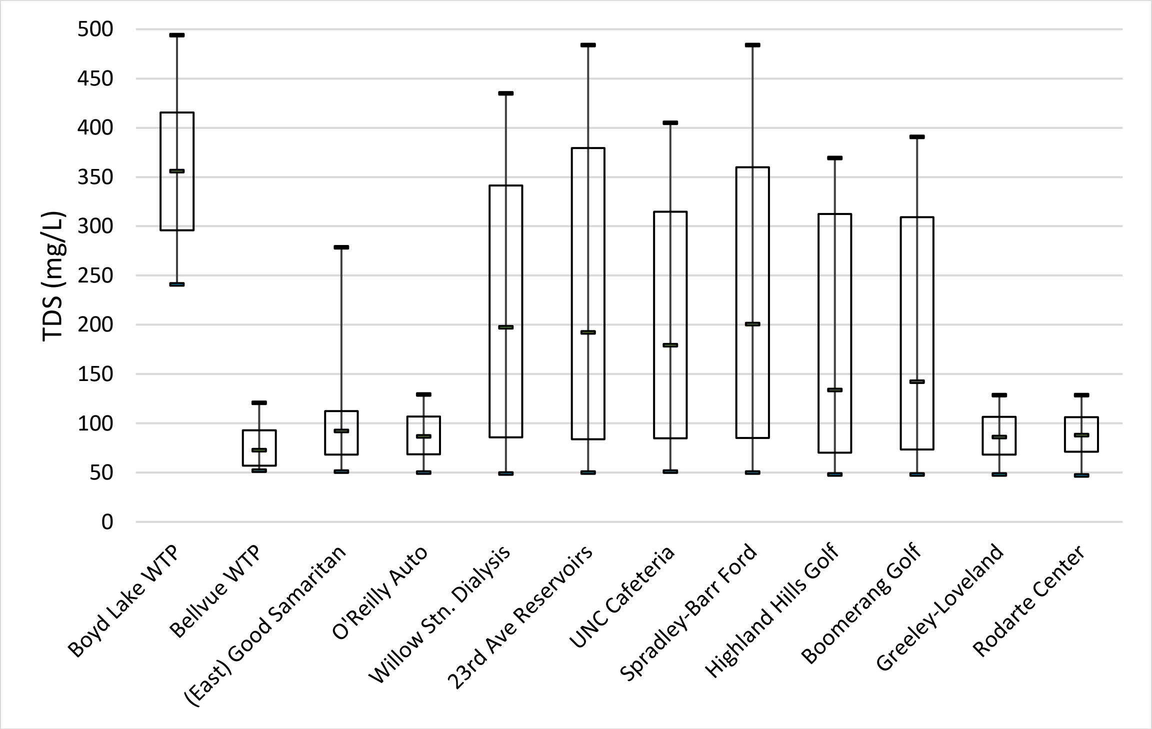


Figure 4-10. TDS Concentrations Measured at the WTP Effluents and Distribution System WQP Sampling Sites

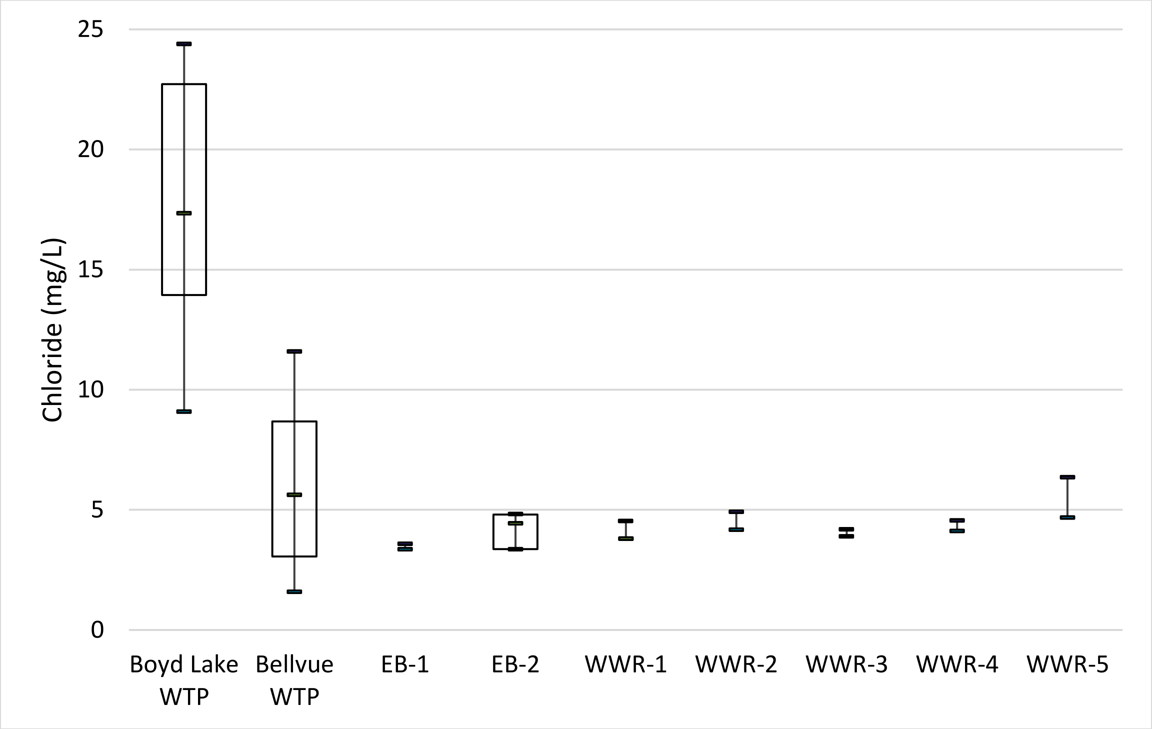


Figure 4-11. Chloride Concentrations Measured at the WTP Effluents and TR Groundwater Wells

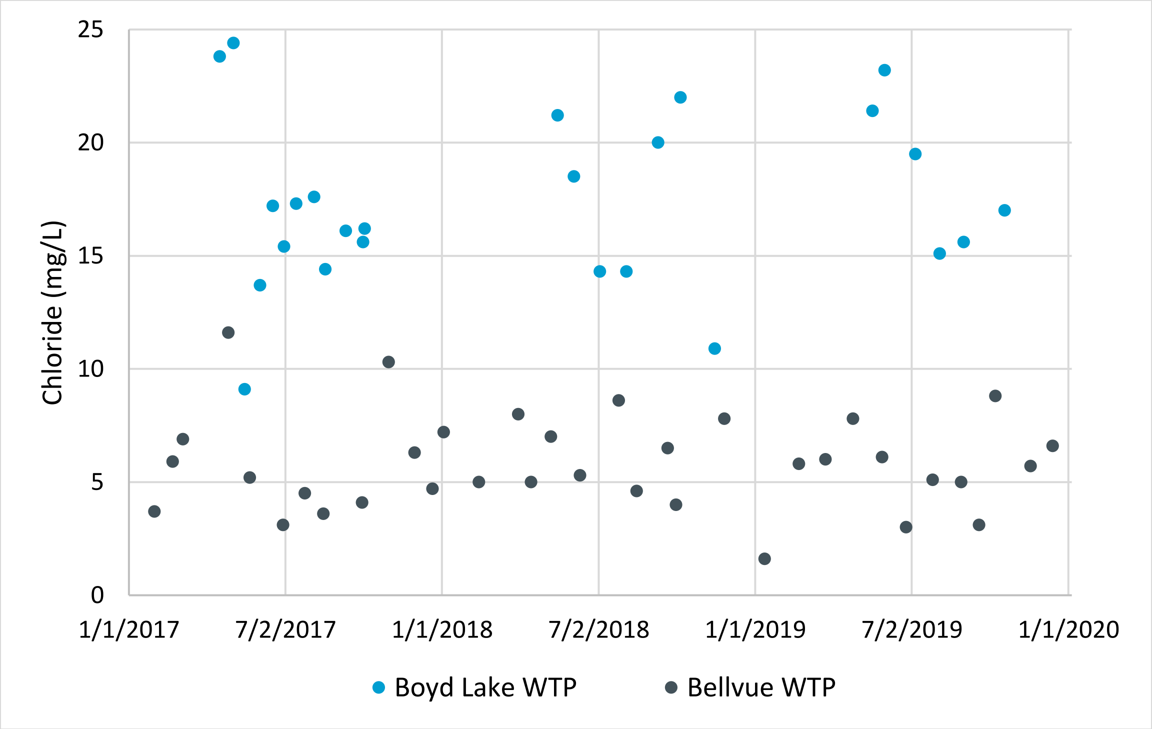


Figure 4-12. Chloride Concentrations Measured at the WTP Effluents

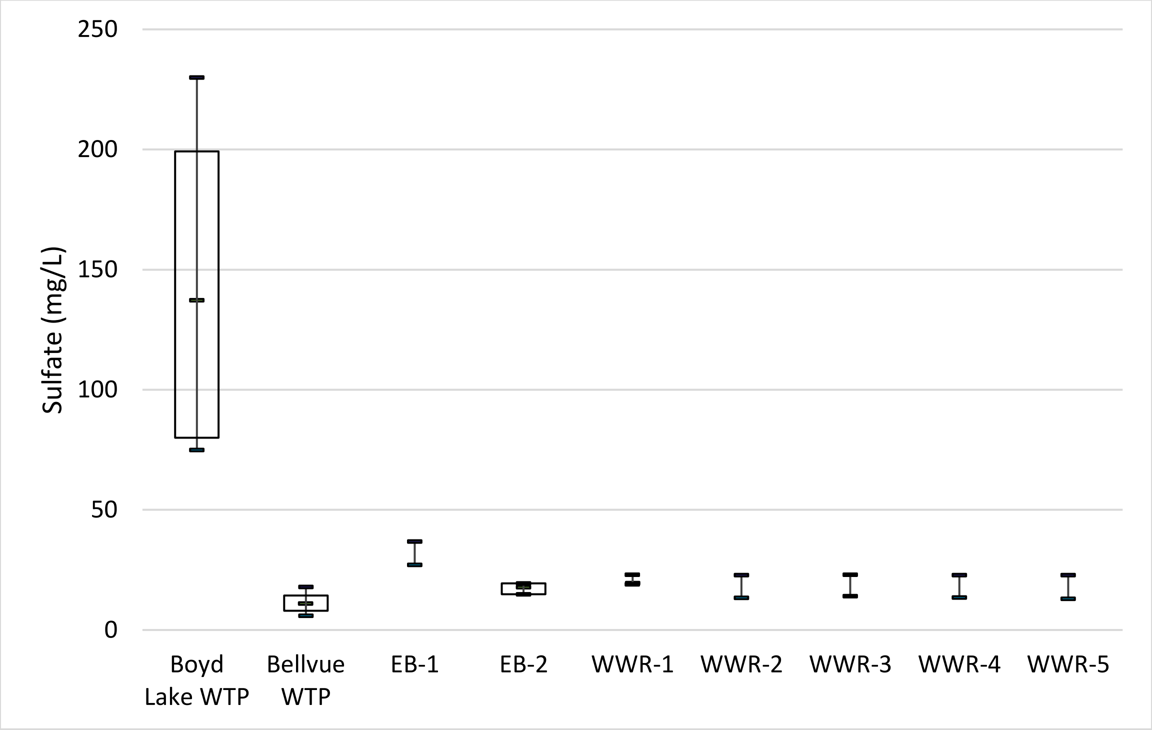


Figure 4-13. Sulfate Concentrations Measured at the WTP Effluents and TR Groundwater Wells

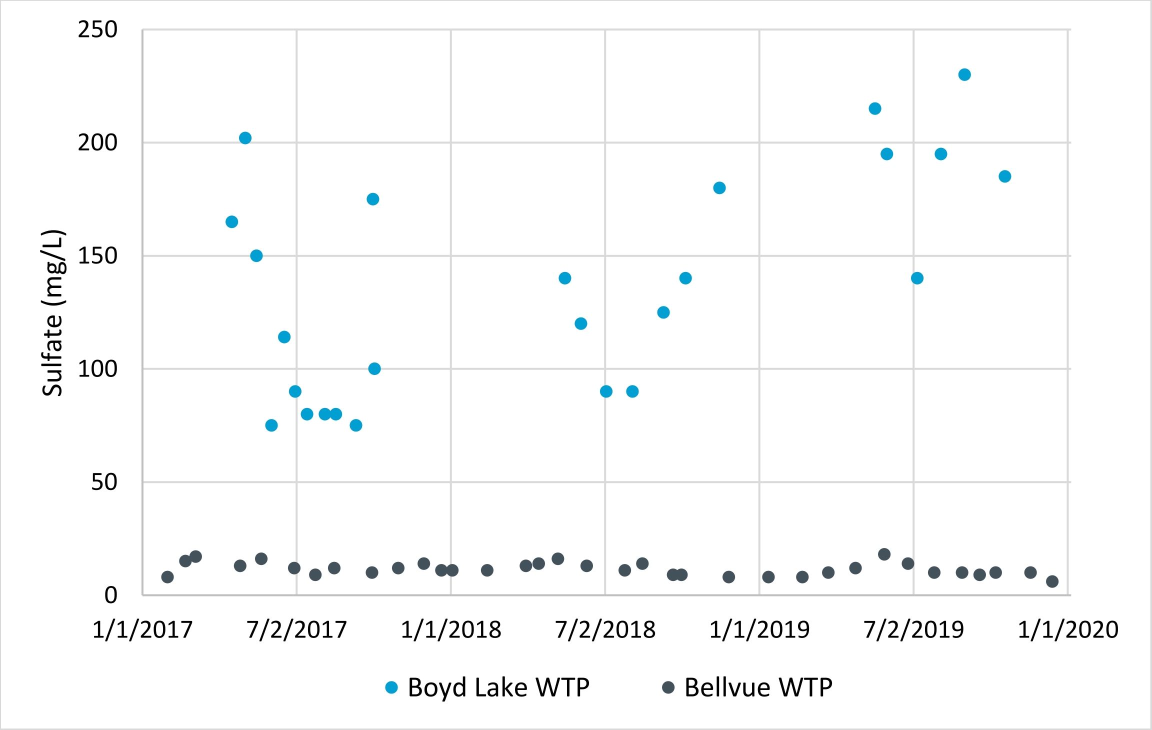


Figure 4-14. Sulfate Concentrations Measured at the WTP Effluents

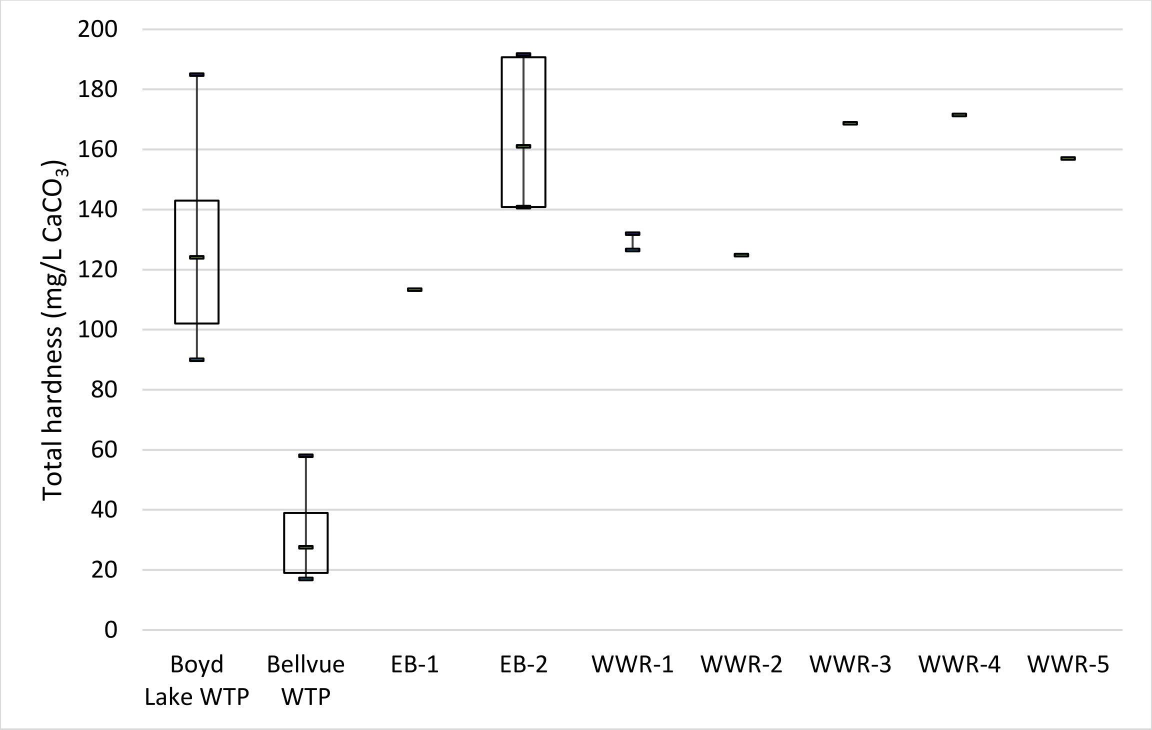


Figure 4-15. Total Harness Measured at the WTP Effluents and TR Groundwater Wells

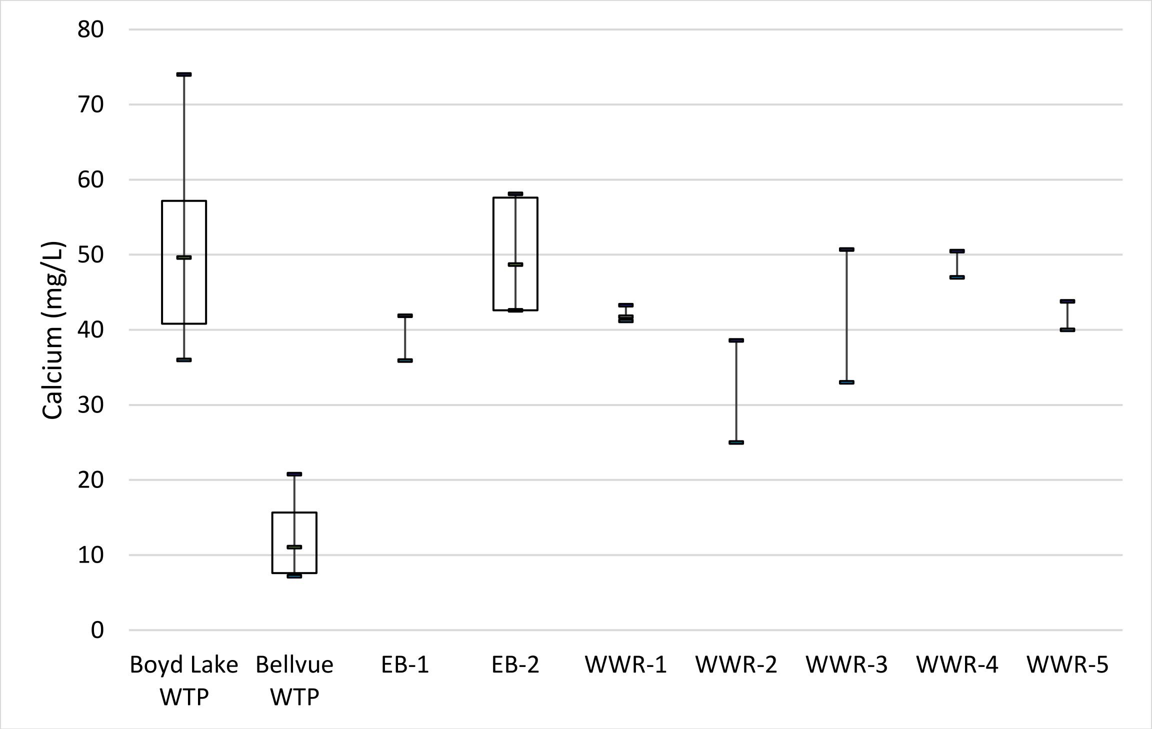


Figure 4-16. Calcium Concentrations Measured at the WTP Effluents and TR Groundwater Wells

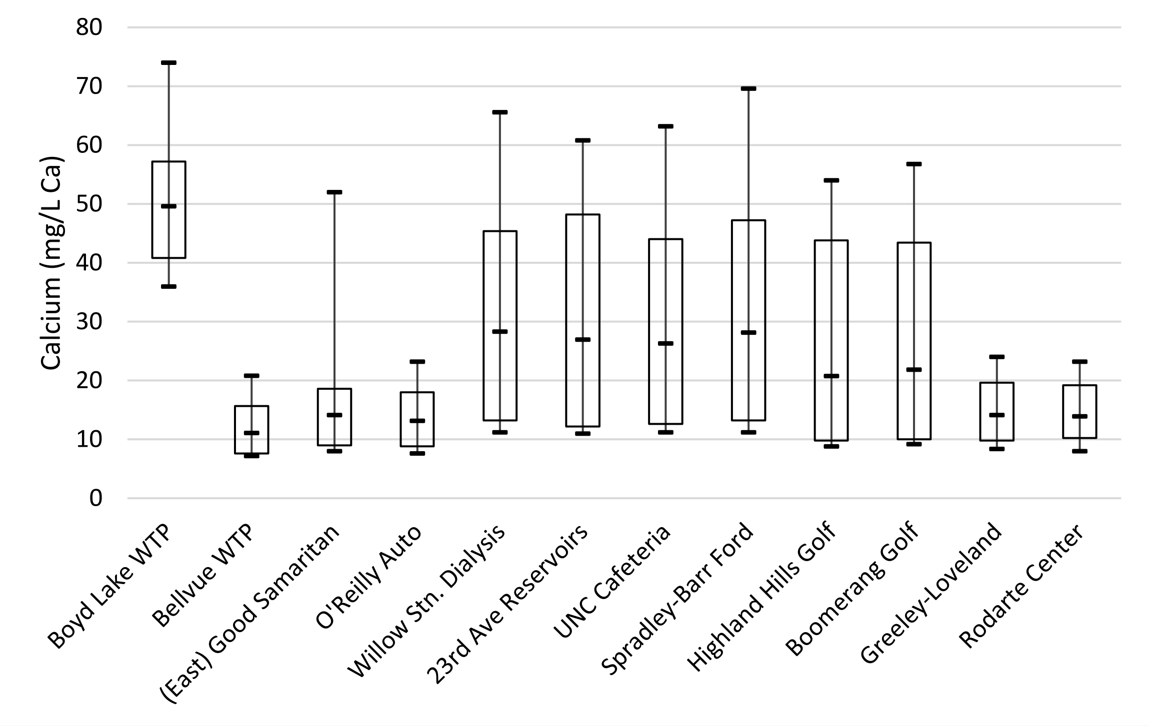


Figure 4-17. Calcium Concentrations Measured at the WTP Effluents and in the Distribution System

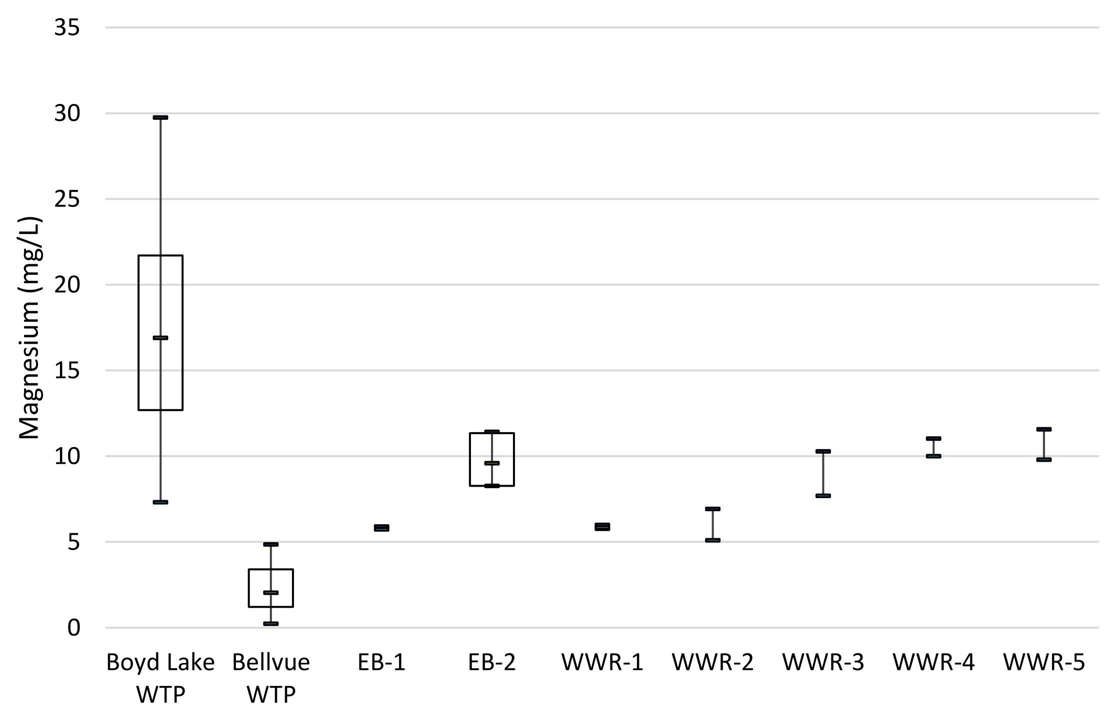


Figure 4-18. Magnesium Concentrations Measured at the WTP Effluents and TR Groundwater Wells

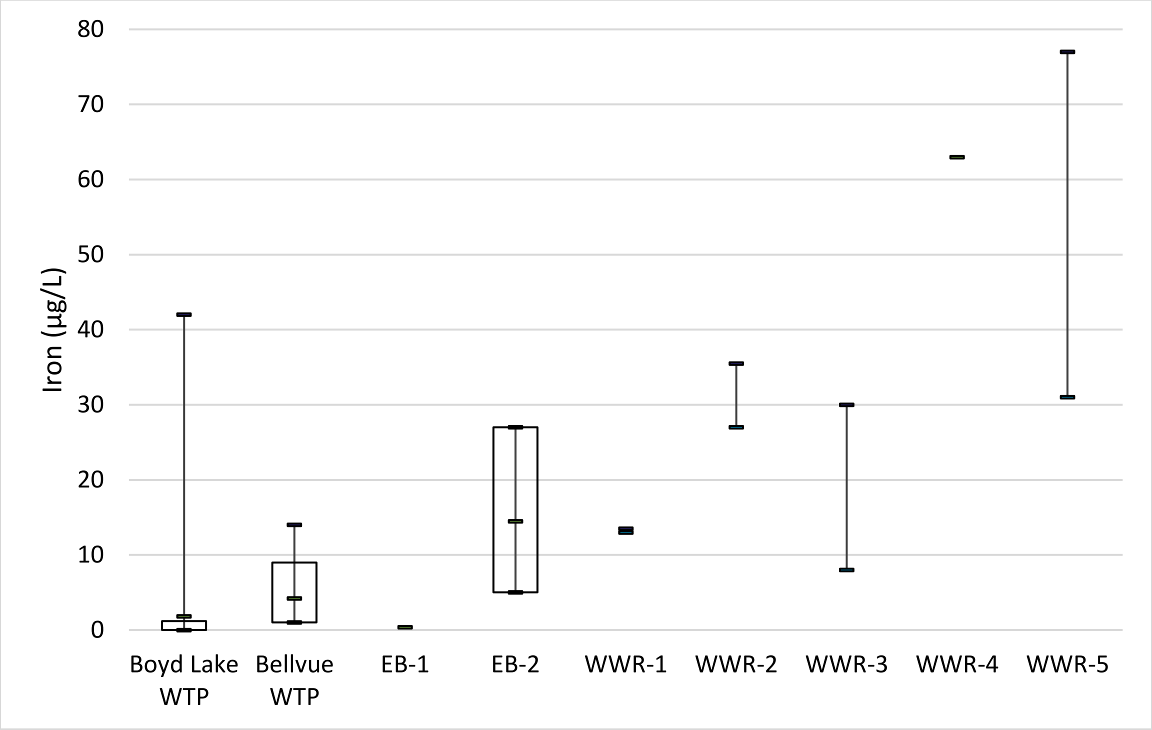


Figure 4-19. Iron Concentrations Measured at the WTP Effluents and TR Groundwater Wells

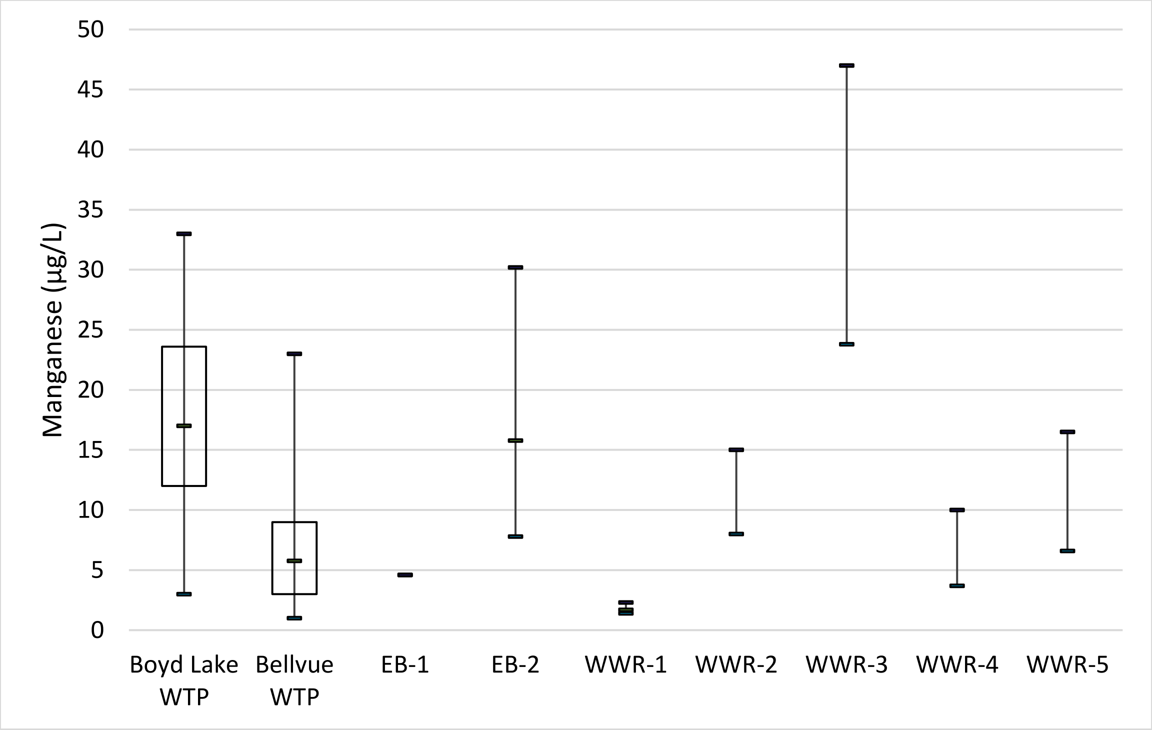


Figure 4-20. Manganese Concentrations Measured at the WTP Effluents and TR Groundwater Wells

4.2.1 Water Temperature

Figure 4-1**Error! Reference source not found.** illustrates water temperature measured at the effluent of the Bellvue and Boyd Lake WTPs. The Boyd Lake WTP is only operated in the warmer seasons and as a result, the minimum and average temperatures recorded at the plant effluent were 8.9 and 19.4°C, respectively (as shown in Table 4-3), whereas the minimum and average temperatures recorded in water treated by the Bellvue WTP were lower (2.0 and 11.4°C, respectively) to account for lower temperatures measured in wintertime. Water temperatures measured at the distribution system sampling sites capture typical seasonal variability (Figure 4-2).

For the TR wells, only one temperature data point was available for each well and borehole. Temperatures varied from 12.6 to 17.4°C.

4.2.2 pH

As shown in Figure 4-3, pH measured in water treated by the Bellvue and Boyd Lake WTPs were quite different, with averages of 7.8 and 7.2, respectively. This difference leads to significant variations in the distribution system at certain sampling sites where water from both WTPs blends, as shown in Figure 4-4. Distribution systems are not well suited to withstand changes in water quality, particularly with respect to pH, because it tends to disturb corrosion products and scales that have deposited on pipe surfaces and may release metals. The differences in pH at the distribution system sampling sites also highlights sites that receive water from only one of the WTPs: the East Good Samaritan, O'Reilly Auto, Greeley-Loveland, and Rodarte Center WQP sampling sites appear to be supplied by water treated by the Bellvue WTP only. Figure 4-4 also indicates that pH is slightly higher in the distribution system than in water treated by the WTPs.

Daily pH data measured at the WTP effluents did not show significant seasonal variability, and thus, changes in pH over time is not presented.

Only two to three data points were available for each of the TR production wells and only one data point was available for the EB-2. pH data were not available for EB-1; to continue this evaluation, the pH value measured at EB-2 was used for EB-1, i.e., 7.15. Results indicate important pH differences in pH in water from the TR wells, ranging from 7.15 to 7.9 as shown in Figure 4-3; however, these differences do fall within the same pH range as observed in water treated by the WTPs.

4.2.3 Total Alkalinity

Total alkalinity measured in water treated by the Boyd Lake WTP is significantly higher than in water treated by the Bellvue WTP (Figure 4-5 and Figure 4-6). The lowest alkalinity measured at the Bellvue WTP effluent indicates that this water supply has a tendency to be corrosive. However, Figure 4-5 suggests that the lowest alkalinity values are measured in summertime, when the Boyd Lake WTP is online and blended with Bellvue WTP water in the distribution system. As a result, sections of the distribution system that are only supplied by the Bellvue WTP (such as Zone 1) may experience seasonal changes in alkalinity and potentially corrosive conditions in summertime, whereas sections of the distribution system that are supplied by the Bellvue WTP in wintertime and a blend of both Bellvue and Boyd Lake WTPs in summertime may experience more consistent alkalinity and less corrosive conditions. Additional information is presented in Section 4.3.1.

The few samples that had been collected from the TR wells when this TM was prepared (2 to 5 samples) show much higher alkalinity (Figure 4-5), typical of groundwater sources. Blending water treated by the Bellvue WTP with water from the TR wells would therefore increase the overall alkalinity in the distribution system and decrease water corrosiveness.

4.2.4 Total Dissolved Solids

TDS concentrations measured in water treated by the Boyd Lake WTP are surprisingly high for a surface water source (Figure 4-8). They are much higher than those measured at the effluent of the Bellvue WTP, and slightly higher than those expected from the TR wells based on the limited data available.

Figure 4-9 shows seasonal variability in TDS concentrations measured in water treated by the Boyd Lake WTP, similar to those observed for alkalinity (Section 4.2.3). Changes in TDS concentrations are not as pronounced in water treated by the Bellvue WTP.

Like alkalinity, distribution system TDS concentrations can be used to differentiate between sites that are only supplied by the Bellvue WTP and sites that receive a blend of water from both WTPs (Figure 4-10).

4.2.5 Chloride and Sulfate

Consistent with the alkalinity and TDS data, chloride, and particularly sulfate, concentrations are surprisingly high in water treated by the Boyd Lake WTP, and significantly higher than concentrations measured in water treated by the Bellvue WTP (Figure 4-12 and Figure 4-14). Chloride and sulfate concentrations measured from the Bellvue WTP are similar to those measured from the TR wells (Figure 4-11 and Figure 4-13).

As mentioned at the beginning of Section 4.2, data used in this evaluation were collected between January 2017 and December 2019. However, for chloride and sulfate measured in water treated by the Bellvue WTP, concentrations measured in 2020 were added to the dataset. Overall, the impact of including the 2020 data is small: for example, the average chloride concentration is 5.8 mg/L without the 2020 data or 6.0 mg/L with the 2020 data. For sulfate, the average concentration is 11.5 mg/L without the 2020 data compared to 11.0 mg/L with the 2020 data.

4.2.6 Calcium and Magnesium

Calcium concentrations show trends similar to those observed for TDS concentrations. The Bellvue WTP produces water with very low calcium concentrations (Figure 4-16). The Boyd Lake WTP and TR wells show similar calcium concentrations. As observed with other parameters, calcium concentrations measured in the distribution system can be used as a tracer of water sources (Figure 4-17).

In water treated by the Boyd Lake WTP, magnesium concentrations were significantly higher that at the Bellvue WTP effluent, and also higher than in water from the TR wells (Figure 4-18).

4.2.7 Iron and Manganese

As mentioned at the beginning of Section 4.2, iron and manganese are not responsible for corrosion or metal release, but their presence in treated water informs the selection of CCT.

Iron concentrations were very low and often not detected in water treated by the Boyd Lake WTP. Concentrations were higher in water treated by the Bellvue WTP. In groundwater from the TR production wells and exploratory boreholes, only one or two data points were provided for iron concentrations (except for EB-2 for which four data points were available), and results varied widely (Figure 4-19).

As opposed to the iron concentrations, manganese concentrations were higher in water treated by the Boyd Lake WTP than in water from the Bellvue WTP (Figure 4-20). For EB-2 of the TR wells, manganese concentrations reported from EB-2 were eliminated from this evaluation because they were very high, much higher than those reported at the pilot treatment plant influent and effluent and other wells. Only the manganese concentrations measured during the pilot study were used. Manganese concentrations vary widely in the TR wells, although the wells and boreholes that showed higher manganese concentrations are not necessarily the ones that show higher iron concentrations. Because these trends were developed with few data points (two to three concentrations, except for EB-2 for which 11 data points were available), additional data are required to confirm trends reported here.

4.3 Corrosion and Metal Release

There is no known lead material in the Greeley distribution system, but because this evaluation is conducted for compliance with the LCR, the potential for the current and future water supply sources to corrode and release lead and copper is discussed in this section.

Two approaches were used to assess corrosion potential using water quality data presented in Section 4.2: 1) assessment of lead release (or plumbosolvency) and copper release (or cuprosolvency), and 2) calculation of corrosion indices. These two approaches are discussed in this section.

4.3.1 Stability of Corrosion Scale

This section relies on the background information on lead and copper corrosion control theory that was presented in Sections 2.2.1 and 2.2.2, respectively.

4.3.1.1 Lead Corrosion and Release

As mentioned in Section 2.2.1, there are three primary mechanisms for lead corrosion control (Brown et al., 2013):

1. pH and alkalinity adjustment to form passivating lead carbonate scales (Pb(II) mineral scales)
2. Maintenance of a high ORP to form passivating lead oxide scales (Pb(IV) mineral scales)
3. Addition of a chemical corrosion inhibitor such as orthophosphate- or silicate-based compounds.

Greeley relies on pH adjustment to control corrosion in its distribution system because a higher pH helps control lead corrosion through the formation of lead carbonate mineral scales (first mechanism listed above). Greeley also uses free chlorine as distribution system residual disinfectant, and thus, ORP levels are likely sufficient to form and maintain lead oxide scales (second mechanism). Greeley does not currently use chemical corrosion inhibitors, and therefore, the third mechanism does not apply. Mechanisms 1 and 2 listed above are examined in this section.

4.3.1.1.1 pH and Alkalinity

When adding a new water source, changes in pH and DIC can modify the solubility of lead carbonate (Pb(II)) mineral scales and, in some instances, the new water supply may favor formation of a different lead carbonate scale. If this occurs, the system may experience periods of increased plumbosolvency even if the new water quality conditions favor, at equilibrium, low lead solubilities.

Contour Diagram of Theoretical Lead Carbonate Solubility: Evaluation of dominant lead carbonate mineral forms can be conducted using pH-DIC lead solubility contour plots as shown in Figure 4-21.

Water quality data presented in Section 4.2 were used to determine the potential for transitioning lead carbonate minerals when water from the TR wells will be blended with surface water treated by the Bellvue and Boyd Lake WTPs and introduced in the distribution system. These data are presented on the contour diagram for theoretical lead carbonate solubility shown in Figure 4-21. The red square represents water quality from the Bellvue WTP, the blue square represents the Boyd Lake WTP, and the green square represents the TR wells. For the Bellvue and Boyd Lake WTPs, DIC concentrations were calculated using the minimum and maximum water temperatures, and 10th and 90th percentiles for pH and alkalinity presented in Section 4.2 (the minimum and maximum values were omitted to eliminate potential outliers). For the TR wells, the minimum and maximum water quality conditions of individual wells were used to calculate the resulting water quality, which is represented by the perimeter of the green square in Figure 4-21. A blend of all production wells and boreholes in equal proportions was assumed considering the uncertainty about the proportion of each TR wells that will be used at any given time. The law of mixtures was used to calculate the resulting water quality upon blending considering that most water quality parameters responsible for corrosion and metal release are conserved, i.e., they do not change over time or upon mixing water sources. The only exception to this law is perhaps pH, which may not entirely follow the law of mixtures. However, in absence of alternative data, pH after blending was calculated using the approach used for all other water quality parameters. Considering the limitations of this analysis, the areas corresponding to Greeley's water sources and their blends represent worst-case conditions as the minimum pH would not necessarily occur when DIC concentration is minimum, and similarly for the maximum values represented by the squares.

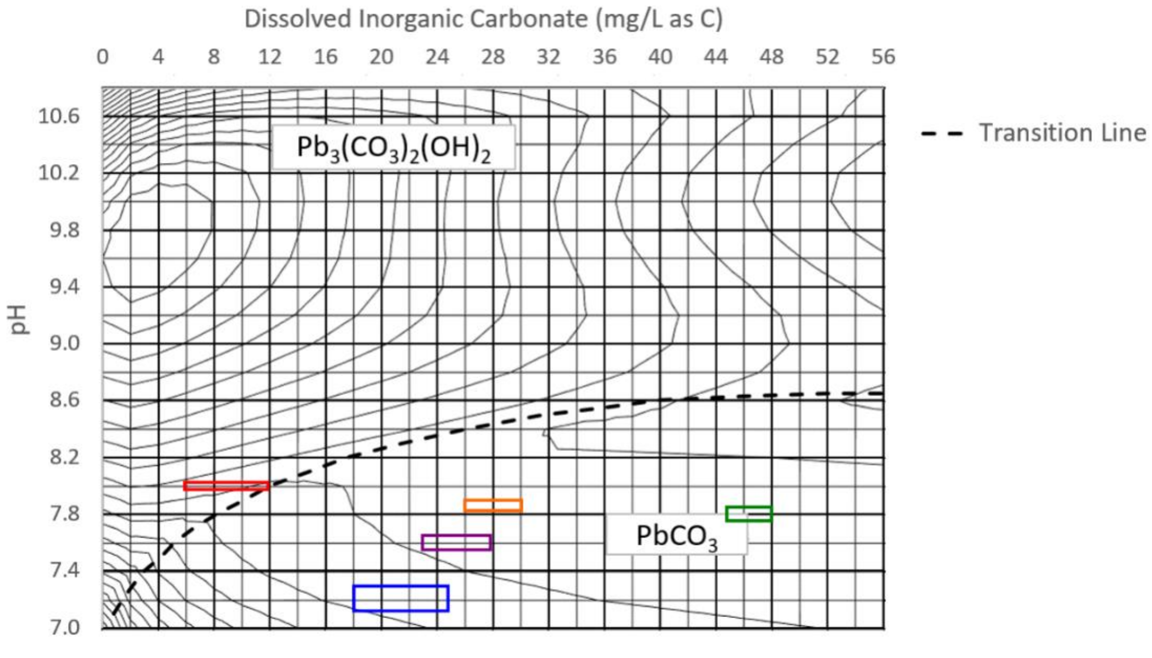


Figure 4-21. Contour Diagram of Theoretical Lead Carbonate Solubility at 25°C

Water quality conditions from the Bellvue WTP are illustrated by the red square, the Boyd Lake WTP is shown by the blue square, and the TR wells are illustrated by the green square. The orange square illustrates a blend of water treated by the Bellvue WTP and TR wells, and the purple square represents a blend of Bellvue WTP, Boyd Lake WTP, and TR wells.

As explained in Section 2.2.1, cerussite is less stable than hydrocerussite and is more prone to sloughing, which can release lead. However, one of the key elements to limit lead release in drinking water distribution systems is to maintain stable water quality and distribution conditions to preserve the passivating lead carbonate minerals that are present. If water quality conditions change such that the dominant mineral form is no longer thermodynamically favorable (in Figure 4-21 this would mean changing from cerussite to hydrocerussite by crossing the dotted line), the water system may experience increases in lead as one mineral scale dissolves and the other forms.

Figure 4-21 shows that water treated by the Bellvue WTP is the only one in the hydrocerussite zone, whereas water from the Boyd Lake WTP and TR wells are well within the cerussite zone. This indicates that lead carbonate mineral scales may be disturbed when water in the distribution system transitions between low-alkalinity water from Bellvue WTP only to a higher-alkalinity blend from both the Bellvue WTP and Boyd Lake WTP. This is similar to the situation that will occur when water from the TR wells will be introduced in the distribution system.

However, the transition zone is not a clear cut between the different lead mineral scales and can vary according to water quality, hydraulic conditions, and many other factors. Looking at Figure 4-21, water quality conditions obtained from the Bellvue WTP are not very far from the cerussite zone. There is also a temporal factor to consider. As explained in Section 4.2.3, when the system is supplied by the Bellvue WTP only (generally November through March), the Bellvue WTP water tends to be higher in alkalinity. During the summers, when the Bellvue WTP water has the lowest-alkalinity, the lower alkalinity is offset by blending with higher-alkalinity water from the Boyd Lake WTP. Therefore, the highest risk will be those areas that are served predominately by Bellvue WTP water only (e.g., Zone 1), even when other water sources are operational. Note, this same situation is likely to be occurring every summer when Greeley uses water treated by the Boyd Lake WTP. Historical lead data collected for LCR compliance, also during the summer months, have not shown extensive lead release except at isolated customer taps.

An equal blend of water treated by the Bellvue WTP and TR wells was estimated and resulting water quality conditions are illustrated by the orange square in Figure 4-21. For this scenario, only the wintertime water quality data were used for the Bellvue WTP considering that the Boyd Lake WTP is offline in winter. An equal blend of water treated by the Bellvue WTP, Boyd Lake WTP, and TR wells was also estimated and is illustrated by the purple square. For this scenario, only the summertime water quality data were used for the Bellvue WTP because this is the period when the Boyd Lake WTP is online. Results indicate that all blends of water sources would be well within the cerussite zone. Thus, plumbosolvency is not expected once water from the TR wells will be blended with surface water treated by the Bellvue and Boyd Lake WTPs and introduced in the distribution system.

<u>Lead Solubility Diagram:</u> The effect of DIC concentrations on lead release was also examined using the diagram illustrated in Figure 4-22. At the range of pH and DIC concentrations currently observed in water treated by the Bellvue and Boyd Lake WTPs (i.e., pH of 7.1 to 8.0, and DIC concentrations of 6.3 to 25 mg/L as C, based on water quality data from each WTP independently), lead release is relatively low, recognizing that both WTPs are online when alkalinity is lowest at the Bellvue WTP effluent, and therefore, low DIC concentrations are not likely to occur, except in sections of the distribution system that are only supplied by the Bellvue WTP, e.g., Zone 1.

Blending of water treated by the Bellvue WTP and TR wells would lead to a pH ranging from 7.6 to 7.7 and DIC concentrations of 26 to 30 mg/L as C, whereas blending of all three water sources would result in a pH ranging from 7.4 to 7.6 and DIC concentrations of 23 to 28 mg/L C. These two blending scenarios would result in equal or lower lead release potential when compared to the non-blended water sources.

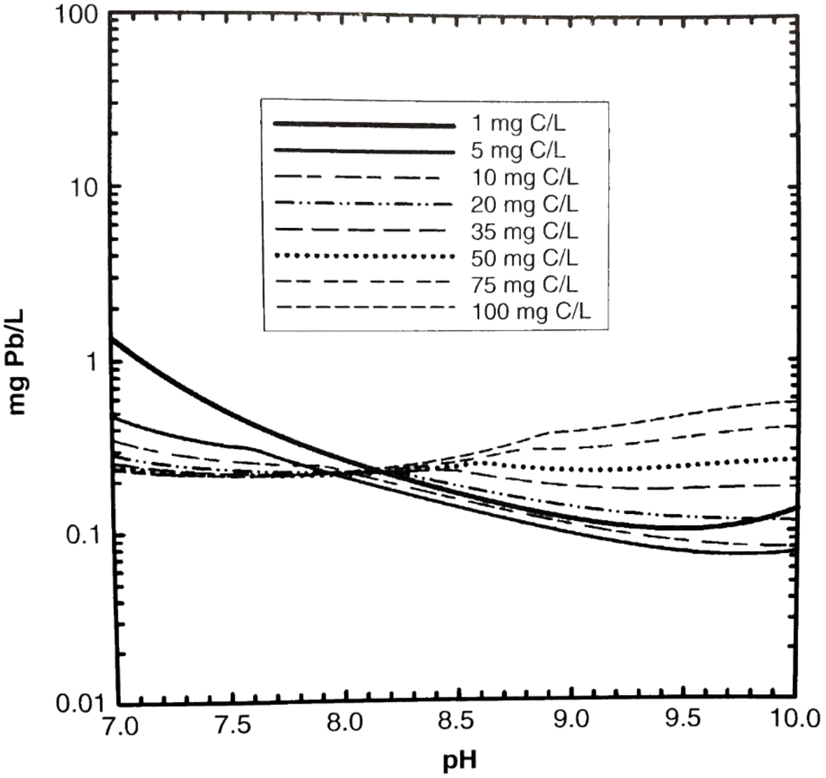


Figure 4-22. Lead Solubility as a Function of pH and DIC Concentration at 25°C and I = 0.01 mole/L

Source: Schock and Lytle (2011)

4.3.1.1.2 ORP

Greeley uses free chlorine as distribution system residual disinfectant, which can result in ORP levels that are high enough to form and maintain stable lead oxide (Pb(IV)) scales. The Pourbaix diagram for lead, illustrated in Figure 4-23, can be used for this evaluation. This diagram represents the form of lead scales as a function of pH and ORP. In Figure 4-23, the red square represents current water quality conditions from the distribution system using data described in Section 4.2, and the green square represents the TR wells. To illustrate the distribution system data, the 10th and 90th percentiles of pH were used, with the minimum and maximum free chlorine residuals measured at the distribution system sampling sites to capture worst-case conditions. For the TR wells, the minimum and maximum pH values measured from each individual well were used with a chlorine residual of 2.5 mg/L Cl_2 to represent the higher end of the range of water quality conditions after chlorination. Free chlorine residuals were converted into ORP using Figure 4-24. The colored areas of the Pourbaix diagram represent worst-case conditions as the low pH would not necessarily occur when ORP is minimum, and similarly for the maximum values represented by the squares.

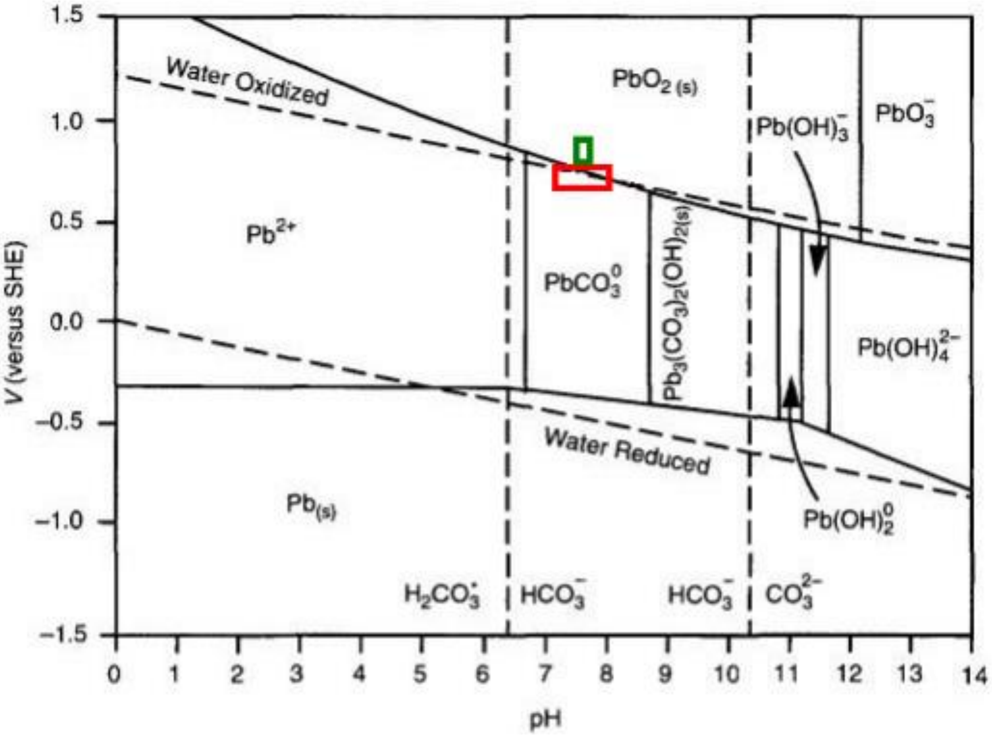


Figure 4-23. Pourbaix Diagram for Lead at a DIC of 40 mg/L as $CaCO_3$

Current water quality conditions in the distribution system are illustrated by the red square, and the TR wells are illustrated by the green square.

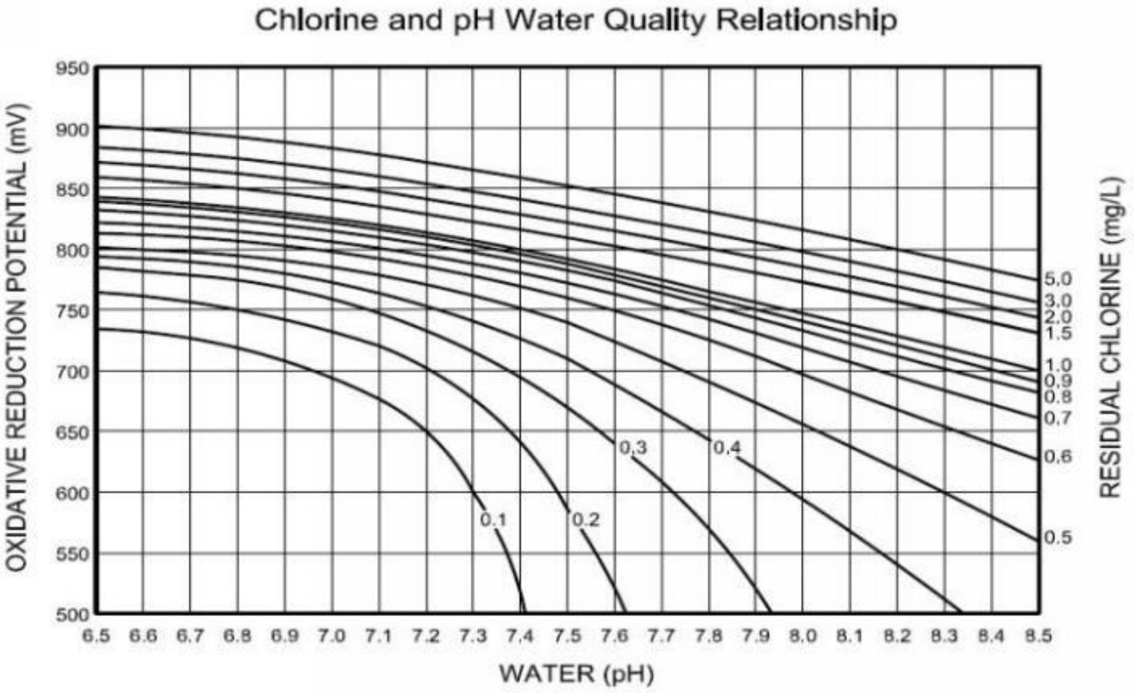


Figure 4-24. Free Chlorine, pH and ORP Diagram

The Pourbaix diagram indicates that the current water quality conditions in Greeley's distribution system (illustrated by the red square) tend to form lead scales that are at the limit between cerussite and lead oxide Pb(IV), should any lead material be present in Greeley's system, which suggests that lead release is possible. According to Figure 4-23 and under the conditions described above, the TR wells would move water quality conditions further from the cerussite zone. However, as the chlorine residual will be consumed, the ORP will decrease, bringing the water quality conditions within the cerussite zone.

Considering the level of precision of these graphs and the limited water quality data provided for the TR wells, it is fair to state that the Pourbaix diagram suggests that introducing TR well water in the existing distribution system is not likely to disturb the existing corrosion scales any more than it is currently occurring.

4.3.1.2 Copper Corrosion and Release

The diagram in Figure 4-25 was used to assess copper corrosion and release. The red square represents water quality from the Bellvue WTP, the blue square represents the Boyd Lake WTP, and the green square represents the TR wells. For the Bellvue and Boyd Lake WTPs, the 10th and 90th percentiles for pH and alkalinity were used (the minimum and maximum values were omitted to eliminate potential outliers). For the TR wells, the minimum and maximum water quality conditions of individual wells were used to draw the perimeter of the green square. These areas represent worst-case conditions as the minimum pH would not necessarily occur when alkalinity is minimum, and similarly for the maximum values represented by the squares.

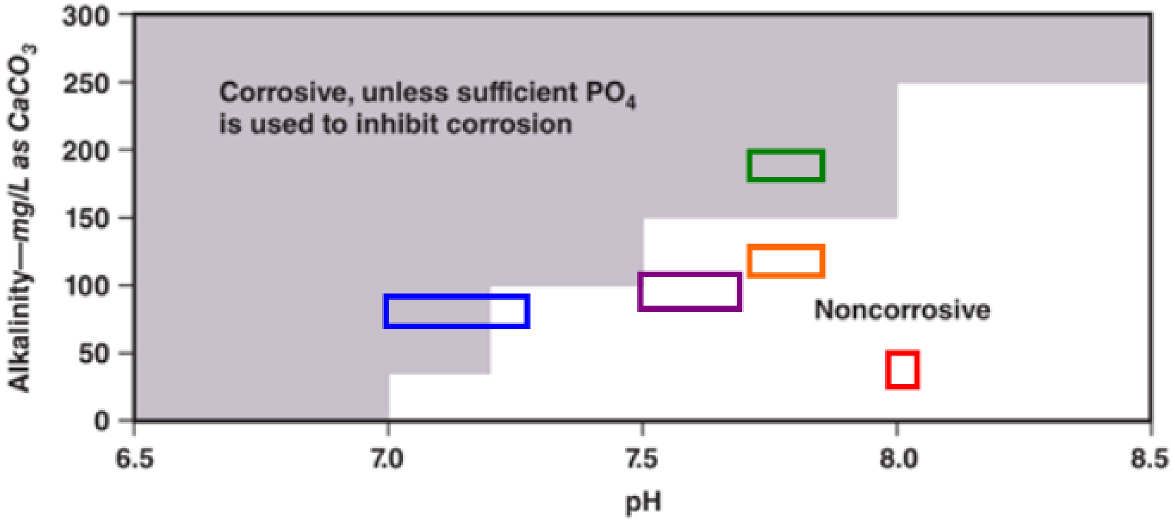


Figure 4-25. Copper Release as a Function of pH and Alkalinity

Water quality conditions from the Bellvue WTP are illustrated by the red square, the Boyd Lake WTP is shown by the blue square, and the TR wells are illustrated by the green square. The orange square illustrates a blend of water treated by the Bellvue WTP and TR wells, and the purple square represents a blend of Bellvue WTP, Boyd Lake WTP, and TR wells.

Results indicate that water treated by the Bellvue WTP is not corrosive towards copper, but water treated by the Boyd Lake WTP can be corrosive at its lower pH levels. Water from the TR wells, if used alone without blending, would also be corrosive towards copper unless a corrosion inhibitor is used. Upon blending, however, the resulting waters (either a blend of Bellvue WTP and TR well water, or a blend of Bellvue, Boyd Lake WTP and TR well water) are not likely to be corrosive towards copper. Considering the precision of this graph and the limited data available for the TR wells, it is fair to assess that cuprosolvency should not be extensive in Greeley's distribution system when water from the TR wells will blend with the existing water sources.

4.3.2 Corrosion Indices

In addition to the corrosion scale analysis presented above, indices of corrosion and aggressiveness were calculated to assess the potential for Greeley's current and future water sources and their blends to corrode distribution system materials and release metals. The water quality data presented in Section 4.2 and the Water!Pro™ software were used. Results are summarized in Table 4-4. Background information about these indices is presented in Appendix A.

As explained in Appendix A, some of the corrosion indices (i.e., LSI, AI, RI and CCPP) are poor indicators of plumbosolvency or cuprosolvency because they focus primarily on the tendency to deposit or form $CaCO_3$. In addition, it is now understood that $CaCO_3$ does not effectively control plumbosolvency or cuprosolvency because the $CaCO_3$ does not deposit in a uniform layer on the inside of system piping. In fact, the LCRR no longer accepts calcium adjustment as corrosion control treatment for this reason. These parameters can only be useful to assess the impact of corrosion on non-lead or copper piping materials, such as cement-mortar lined pipes and asbestos-cement pipes.

One important corrosion index with regards to metal corrosion and release is the CSMR. Literature suggests that CSMR values in excess of 0.6 can lead to increased galvanic corrosion in premise plumbing. The Larson Ratio (LR) is another important index used to characterize metal corrosion. It determines the effect of chloride, sulfate and bicarbonate alkalinity on corrosion of metallic pipes including pitting of copper pipes, and potential disruptions of existing iron scales, which may lead to red- or brown-water occurrences. LR values below 5.0 are considered not corrosive.

As explained in Appendix A, the indices of aggressiveness and corrosion must be used carefully as there are many waters with non-corrosive or non-aggressive indices that are corrosive/aggressive, and vice versa. The purpose of calculating these indices is to evaluate the natural aggressiveness and corrosiveness of a water without inhibitor and narrow down suitable corrosion control strategies. It is one tools out of the many that are discussed in this TM.

Table 4-4. Corrosion Indices of Greeley's Water Sources

Parameters	TR Wells								Bellvue WTP	Bellvue / TR Blend (1)	Boyd Lake WTP	Bellvue / Boyd / TR Blend (2)
	EB-1	EB-2	WWR-1	WWR-2	WWR-3	WWR-4	WWR-5	TR Well Blend				
Final pH	7.17	7.13 – 7.21	7.97 – 8.26	7.38 – 8.26	7.70 – 8.26	7.96	7.68 – 7.96	7.44 – 7.66	8.00 – 8.02	7.54 – 7.741	7.18 – 7.34	7.40 – 7.55
DIC (mg/L C)	43.4 – 48.4	47.6 – 66.3	44.4 – 45.0	45.1 – 47.3	45.4 – 47.2	49.3 – 50.5	43.1	44.9 – 48.9	6.33 – 12.3	25.7 – 31.4	18.4 – 25.2	22.9 – 28.2
AI	11.3 – 11.4	11.4 – 11.7	12.2 – 12.5	11.4 – 12.3	11.9 – 12.6	12.3 – 12.6	11.9 – 12.2	11.6 – 12.0	10.6 – 11.3	11.3 – 11.7	11.0 – 11.4	11.2 – 11.5
RI	8.1 – 8.3	7.4 – 8.2	7.04 – 7.37	7.14 – 8.29	6.77 – 7.73	7.11 – 7.20	7.32 – 7.70	7.43 – 7.95	8.83 – 10.7	8.02 – 8.65	8.09 – 9.1	8.02 – 8.98
LSI	-0.58 – -0.46	-0.51 – -0.11	0.30 – 0.61	-0.46 – +0.46	-0.02 – +0.74	0.38 – 0.43	-0.01 – +0.32	-0.25 – +0.11	-1.34 – -0.41	-0.55 – -0.16	-1.04 – -0.37	-0.79 – -0.24
CCPP (mg/L $CaCO_3$)	-26.3 – -24.5	-27.9 – -8.1	7.6 – 13.3	-16.2 – +11.5	-0.36 – +18.3	11.4 – 13.7	-0.17 – +8.31	-9.56 – +4.45	-4.38 – -2.03	-9.24 – -3.03	-19.6 – -8.74	-14.4 – -4.76
LR	0.21 – 0.25	0.11 – 0.13	0.14	0.12 – 0.14	0.11 – 0.13	0.10	0.13 – 0.14	0.15 – 0.16	0.38 – 0.80	0.21 – 0.24	1.78 – 2.37	0.64 – 0.84
CSMR	0.13 – 0.17	0.27 – 0.41	0.25 – 0.27	0.26 – 0.45	0.27 – 0.38	0.35 – 0.42	0.35 – 0.58	0.30 – 0.44	0.26 – 1.17	0.30 – 0.63	0.07 – 0.29	0.11 – 0.39

AI: Aggressiveness Index

CCPP: Calcium carbonate precipitation potential

CSMR: Chloride-to-sulfate mass ratio

DIC: Dissolved inorganic carbon

LR: Larson Ratio

LSI: Langelier Saturation Index

RI: Ryznar Saturation Index

TDS: Total dissolved solids

(1) For the Bellvue WTP, wintertime water quality conditions were used considering that the Boyd Lake WTP is online in summertime and this condition is only likely to occur in wintertime.

(2) For the Bellvue WTP, summertime water quality conditions were used considering that the Boyd Lake WTP is online in summertime only.

4.3.2.1 Terry Ranch Wells

Consistent with the analyses discussed above, an equal proportion of the production wells and boreholes was used to calculate the “TR Well Blend” indices shown in Table 4-4. The law of mixtures was used to calculate the resulting water quality upon blending considering that most water quality parameters involved in corrosion, metal release, and the calculation of the corrosion indices are conserved. A sodium hypochlorite concentration of 2.5 mg/L Cl_2 was assumed, as this would represent worst-case conditions when the maximum dose of 3.0 mg/L of free chlorine is applied in water treated by the TR WTP.

Corrosion indices were calculated to represent worst-case conditions (i.e., low water temperature, high TDS, low alkalinity, low calcium, low magnesium, high chloride, and low sulfate concentrations), as well as best conditions (i.e., high temperature, low TDS, high alkalinity, high calcium, high magnesium, low chloride, and high sulfate concentrations), which led to the ranges of indices shown in Table 4-4. However, these best- and worst-case conditions should be considered extreme occurrences because low alkalinity, calcium, magnesium, and sulfate concentrations would not necessarily occur when TDS and chloride concentrations are both high, and similarly for the best-case conditions.

The indices of aggressiveness presented in Table 4-4 indicate that the production wells tend to be passive or deposit $CaCO_3$, a preferred condition, but the exploratory boreholes appear to be quite aggressive towards cement-mortar lined pipes and asbestos-cement pipes. The blend of TR well water shows a wide range of LSI, CCPP, AI and RI, indicating that under certain conditions, the TR wells may be aggressive towards cement-based pipes. These indices, however, are similar or better than those calculated with water treated by the Bellvue and Boyd Lake WTPs, suggesting that the introduction of TR well water into the existing distribution system is not likely change the aggressiveness of the water distributed by Greeley, and may even decrease it. Moreover, Greeley’s distribution system contains very little cement-base materials, as described in Section 3.3.

The LR and CSMR suggest that none of the wells appear to be corrosive towards metals, including lead and copper, and thus, would not compromise Greeley’s existing distribution system pipes. These copper corrosion trends differ from those presented in Section 4.3.1.2, where it was found that water from the TR wells tends to be corrosive towards copper. Considering the limited water quality data used for this evaluation, additional data will help clarify these conflicting trends.

4.3.2.2 Blends of Bellvue WTP and Terry Ranch Wells

For the Bellvue WTP (without blending), the corrosion indices shown in Table 4-4 were obtained using worst-case conditions (i.e., low water temperature, low pH, high TDS, low alkalinity, low calcium, low magnesium, high chloride, and low sulfate concentrations), and best conditions (i.e., high temperature, high pH, low TDS, high alkalinity, high calcium, high magnesium, low chloride, and high sulfate concentrations). The 10th and 90th percentiles of each parameter were used (the minimum and maximum values were omitted to eliminate potential outliers), except for water temperature, for which the minimum and maximum temperatures were used. As mentioned above, these best- and worst-case conditions should be considered extreme occurrences, and intermediate values are likely to better represent water quality. A dose of sodium hypochlorite of 1.5 mg/L Cl_2 was assumed to represent booster chlorination at the site where water from the TR wells will enter Greeley’s distribution system (additional information about disinfectant residual is presented in Section 5).

The indices of aggressiveness presented in Table 4-4 indicate that water treated by the Bellvue WTP (without blending with other water supplies) tends to be aggressive towards cement-mortar lined pipes and asbestos-cement pipes, and the higher CSMR values (i.e., above 0.6 in certain conditions) suggest that premise plumbing may be susceptible to galvanic corrosion.

To evaluate blending of water treated by the Bellvue WTP and TR wells, only the wintertime water quality data measured at the Bellvue WTP effluent were used considering that the Boyd Lake WTP is online in summer. Blending equal amounts of water treated by the Bellvue WTP and TR wells does not improve the aggressiveness of the water towards cement-mortar lined pipes and asbestos-cement pipes, and may actually exacerbate it slightly. After blending, however, the resulting water is no longer likely to be corrosive towards metals, including lead and copper.

Additional simulations were conducted using year-round water quality data from the Bellvue WTP blended with TR well water. Results were fairly similar to those obtained when blending wintertime water quality data from the Bellvue WTP and TR well water. The LSI ranged from -0.11 to -0.77, and the CCPP ranged from -14 to -2.0 mg/L as $CaCO_3$, whereas the LR was around 0.23 and the CSMR ranged from 0.28 to 0.67.

4.3.2.3 Blends of Bellvue WTP, Boyd Lake WTP and Terry Ranch Wells

As explained above, the corrosion indices for the Boyd Lake WTP (without blending) shown in Table 4-4 were obtained using the best-case conditions and worst-case conditions. As mentioned above, these conditions should be considered extreme occurrences and intermediate values are likely to better represent water quality. A dose of sodium hypochlorite of 1.5 mg/L as Cl_2 was assumed to represent booster chlorination at the site where water from the TR wells will enter the distribution system.

When assessing the corrosiveness and aggressiveness of water treated by the Boyd Lake WTP (without blending), results indicate that this water is quite aggressive towards cement-mortar lined pipes and asbestos-cement pipes. However, it does not appear to be corrosive towards metals, including lead and copper, although water treated by the Boyd Lake WTP shows the highest LR values of all of Greeley's water supplies (1.78 to 2.37).

The low pH of the Boyd Lake WTP has been noted above in Section 4.3.1.2, and simulations were performed to assess the effects of a higher finished water pH of 7.8, which is closer to the pH measured in water treated by the Bellvue WTP and TR wells. Increasing pH at the effluent of the Boyd Lake WTP would significantly improve water quality and decreases the water's aggressiveness (LSI and CCPP increase to -0.07 and -0.81, respectively), without impairing metal corrosion (the LR and CSMR remain at 1.94 and 0.13, respectively). Only a small amount of caustic soda would be required to increase pH to 7.8: a dose of 5.3 mg/L was estimated using the average water quality conditions provided. Alkalinity is sufficient at the Boyd Lake WTP and additional alkalinity would not be required. As mentioned in Section 4.3.1.2, increase pH in water treated by the Boyd Lake WTP would also reduce the corrosiveness of the water towards copper pipes. Before increasing water pH at the effluent of the Boyd Lake WTP, the consequences of this change would need to be evaluated more comprehensively, including effect on disinfectant stability, trihalomethane (THM) formation potential, and others.

To calculate water quality parameters that would result from blending equal amounts of all three water sources, only the summertime results obtained from the Bellvue WTP were used, recognizing that the Boyd Lake WTP is offline in winter. As for the previous simulations presented above, the best- and worst-case conditions were examined, although these should be considered extreme occurrences only. With regards to aggressiveness, the indices indicate that the resulting water blend would remain aggressive. It would be more aggressive than the TR well water, but not as aggressive as water treated by the Boyd Lake WTP alone. An equal blend of all three water sources would not be corrosive towards metals, including lead and copper.

Additional simulations were conducted using an equal blend of Boyd Lake WTP water after pH adjustment to 7.8 (using the small dose of caustic soda of 5.3 mg/L discussed above), with water treated by the Bellvue WTP and TR wells. Although not perfectly passive, the resulting water blend would be less aggressive towards cement-mortar lined pipes and asbestos-cement pipes, with LSI and CCPP of --0.34 and -5.55, without exacerbating the corrosiveness of the water towards metal. Increasing treated water pH at the Boyd Lake WTP would also limit pH differences between Greeley's water supplies.

4.4 Corrosion Control Treatment

Results presented in the above sections were used to assess whether the existing CCT practiced by Greeley at the Bellvue and Boyd Lake WTPs (i.e., pH adjustment with caustic soda) or alternative CCT should be considered when water from the TR wells will enter Greeley's distribution system, and if so, which treatment would be best. Although the above sections suggest increasing pH at the Boyd Lake WTP to limit the aggressiveness of this water source, this evaluation assumes that the existing CCT of pH adjustment to 7.2 at the Boyd Lake WTP and 7.8 at the Bellvue WTP are deemed optimized and meet the regulatory requirements of the LCR.

4.4.1 Lead Corrosion

Based on the lead sampling results discussed in Section 4.1, the 90th percentiles have remained low and do not indicate that an alternative CCT is needed. There have been isolated occurrences of high lead concentrations at certain customer taps; these can be handled separately, directly with the customers of these properties, although water systems will be required to take actions under the LCRR, as explained in Section 4.1.1.

Results presented in Section 4.3.1 indicate that the water sources and their blends tend to form cerussite lead mineral scales, should any lead material be present in Greeley's service area, except for water treated by the Bellvue WTP which tends to form hydrocerussite. This indicates that changing water source may disturb lead corrosion scales in the distribution system. Results of the corrosion index analysis presented in Section 4.3.2 also indicate that water treated by the Bellvue WTP has the highest CSMR values under certain conditions, which suggests an increased galvanic corrosion potential in premise plumbing. However, water quality conditions of the Bellvue WTP are not very far from the cerussite zone, and the CSMR are not consistently high. Also, Greeley has been distributing water treated by the Bellvue WTP in wintertime and blended with water treated by the Boyd Lake WTP in summertime without experiencing widespread lead release (isolated homes have shown higher lead concentrations, but these can be addressed on a case-by-case basis). In addition, distribution system water is blended with water treated by the Boyd Lake WTP when Bellvue WTP water quality conditions are most different from the other water sources (i.e., summertime low alkalinity), except in certain sections of Greeley's distribution system (e.g., Zone 1).

Blending with groundwater from the TR wells would eliminate the change in lead mineral scales from cerussite to hydrocerussite thereby limiting potential lead release, should any lead material be present in Greeley's distribution system. Results of the corrosion index analysis presented in Section 4.3.2 confirm this assessment: upon blending, the LR and CSMR values decrease below the threshold that indicates corrosive water quality conditions.

This suggests that the only scenario during which a change in CCT could be considered would be when water treated by the Bellvue WTP is distributed alone without blending with other water supplies. However, considering that Greeley has been operating under this scenario without widespread lead release, a change in CCT may not be necessary. Blending of the existing surface water sources with groundwater from the TR wells will be beneficial and will decrease the potential for plumbosolvency and galvanic corrosion.

4.4.2 Copper Corrosion

Based on the copper sampling results discussed in Section 4.1, the 90th percentiles have remained low and do not indicate that an alternative CCT is needed.

Section 4.3.1 indicates that water treated by the Bellvue WTP is not corrosive towards copper, but water treated by the Boyd Lake WTP can be corrosive when pH is low. Water from the TR wells, if used alone without blending, would also be corrosive towards copper unless a corrosion inhibitor is used. However, results from the corrosion indices presented in Section 4.3.2 do not fully support this argument: the LR values are well below the threshold of 5 (although the LR values calculated at the Boyd Lake WTP effluent are the highest of all of Greeley's water supplies), and the CSMR values are below the threshold of 0.6 in all production wells and boreholes. Upon blending, the resulting water would not be as corrosive towards copper. Before proposing an alternative CCT, additional water quality data should be collected from the TR wells to resolve the conflicting trends observed.

4.4.3 Impact on Cement-Based Materials

When examining each water source independently without blending, results indicate a wide range of conditions varying from non-aggressive to very aggressive for the TR wells, with the boreholes showing quite aggressive tendencies towards cement-mortar lined pipes and asbestos-cement pipes.

Water treated by the Boyd Lake WTP (without blending) is quite aggressive towards cement-mortar lined pipes and asbestos-cement pipes. As mentioned above, increasing the pH of the Boyd Lake WTP treated water to 7.8 would require only small amounts of caustic soda (a dose of 5.3 mg/L was estimated using the average water quality conditions provided) to decrease the water's aggressiveness. Water treated by the Bellvue WTP may also be aggressive towards cement-mortar lined pipes and asbestos-cement pipes, but not to the same extent as water from the Boyd Lake WTP.

Blending equal amounts of water treated by the Bellvue WTP and TR wells would lead to water that remains slightly aggressive. When all three water sources are blended in equal amounts, the resulting water blend would not be as aggressive as water treated by the Boyd Lake WTP, but would remains somewhat aggressive. Additional simulations were conducted using an equal blend of Boyd Lake WTP water after pH adjustment to 7.8, with water treated by the Bellvue WTP and TR wells. Although not perfect, the resulting water blend would be less aggressive towards cement-mortar lined pipes and asbestos-cement pipes, without exacerbating the corrosiveness of the water. Increasing treated water pH at the Boyd Lake WTP would also limit pH differences between Greeley's water supplies.

Because water aggressiveness does not indicate lead or copper corrosion or release, these conditions should not be used to inform whether a CCT is appropriate. Moreover, Greeley's distribution system contains very little cement-base materials, as detailed in Section 3.3.

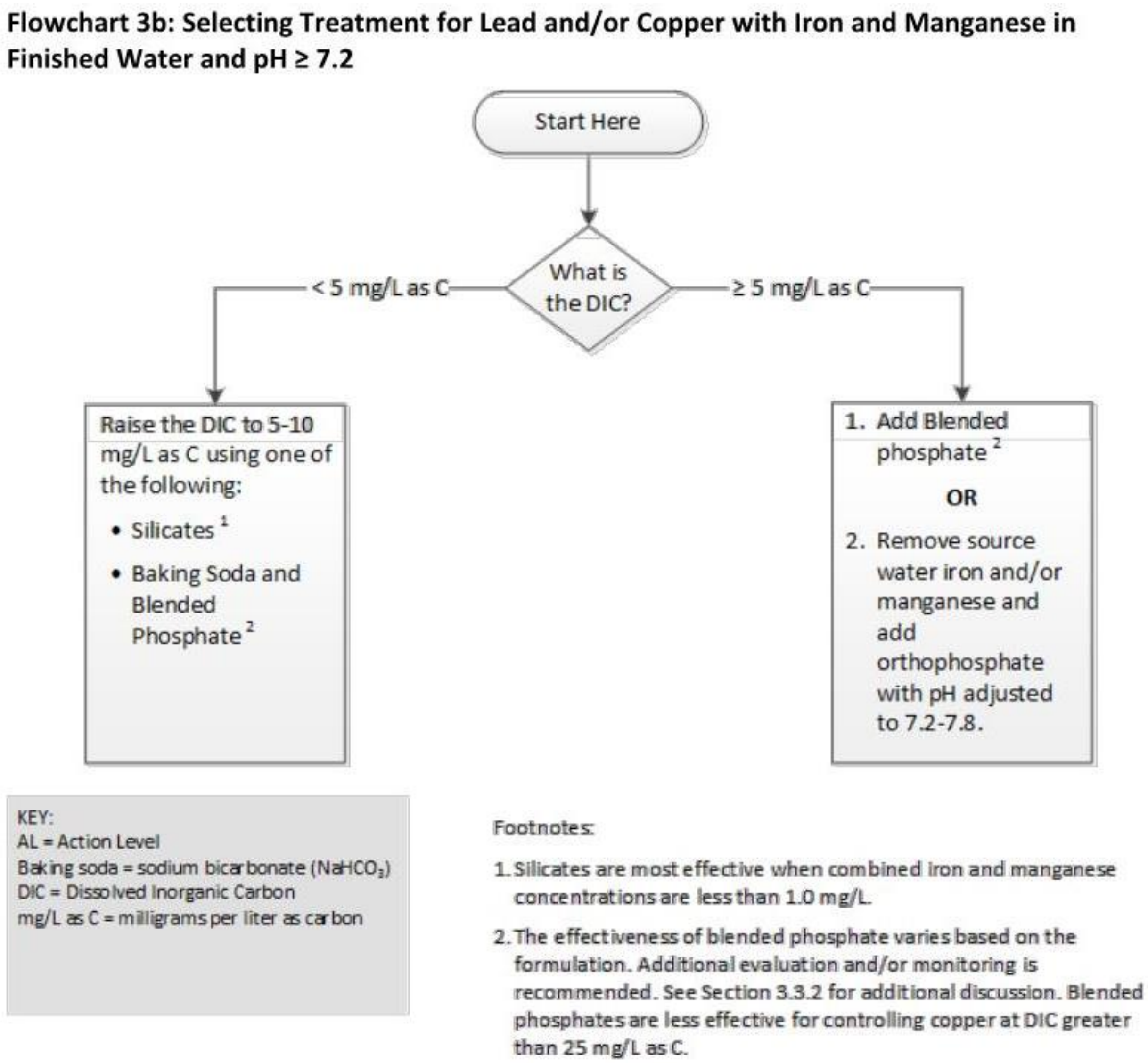
4.4.4 LCR Guidance Manual

The corrosion control treatment options presented in the LCR include: 1) alkalinity and pH adjustments; and 2) addition of a phosphate- or silicate-based corrosion inhibitor (calcium hardness adjustment was also included in the LCR but it is now recognized that $CaCO_3$ scales do not effectively passivate lead or copper piping and this option has been removed in the LCRR). Greeley has been relying on pH adjustment to control corrosion in its distribution system and lead and copper concentrations measured at customer taps (presented in Section 4.1) have shown this method to be successful to meet the LCR requirements. Water quality data presented in Section 4.2 indicate that alkalinity is sufficient in water treated by the Boyd Lake WTP, but slightly low in water treated by the Bellvue WTP, particularly in summer (the 10th and 90th percentiles are 25 and 50 mg/L as $CaCO_3$, respectively). However, water from the Bellvue WTP is blended with water from the Boyd Lake WTP during low-alkalinity periods in most areas of Greeley's distribution system, which increases the overall alkalinity.

The guidance manual to identify optimum corrosion control treatment provided by the USEPA (2016) was used to assess alternative corrosion treatment that could be applicable to Greeley's system. Water pH and DIC concentrations shown in Table 4-4 dictates that the flowchart shown in Figure 4- is the most suitable for the TR wells because pH is generally above 7.2 and the wells contain some iron and manganese (see Section 4.2.7). With DIC concentrations ranging from 43 to 66 mg/L as C, a blend a poly- and ortho-phosphates would be the most suitable CCT if it were found to be needed and if iron and manganese are not removed (orthophosphate would be the recommended corrosion inhibitor if iron and manganese are removed). However, analyses presented in the above sections indicate that the TR wells are not likely to require additional CCT to comply with the LCR. The impact of adding a phosphate corrosion inhibitor on wastewater treatment facilities would also need to be examined.

For the Bellvue WTP, Figure 4-27 illustrates the most suitable recommendations considering that water treated by this WTP has very low concentrations of iron and manganese, a pH generally greater than 7.8, and a DIC ranging from 6.0 and 14 mg/L as C. Should a change in CCT be required, available options include increasing pH or adding an orthophosphate corrosion inhibitor. Increasing pH is not recommended because pH of water treated by the Bellvue WTP is already greater than any other water supplies of Greeley. Increasing pH further would exacerbate the differences observed between Greeley's water supplies. The only option would be to add orthophosphate, which may help limit lead scale disruption in areas of the distribution systems that experience changes in water sources, as discussed in Section 4.3.1.1. Despite the high CSMR of Bellvue treated water, however, Greeley has not experienced widespread lead or copper release and thus, a change in CCT was not found necessary.

To illustrate water quality measured at the Boyd Lake WTP effluent, which includes some iron and manganese as described in Section 4.2.7, a relatively low pH oscillating around 7.2 (see Figure 4-3), and DIC concentrations ranging from 18 to 25 mg/L as C, either Figure 4-26 or Figure 4-28 can apply, i.e., increase pH (Figure 4-28) or use a blend of poly- and ortho-phosphates (Figure 4-26). Because pH of water treated by the Boyd Lake WTP is significantly lower than pH of Greeley's other water supplies, increasing pH would be the preferred option and should be considered to limit the water aggressiveness. Should lead or copper become a challenge at Greeley's customer taps, adding a phosphate-based corrosion inhibitor could be another alternative if iron and manganese are not removed (an orthophosphate inhibitor would be recommended if iron and manganese are removed), but this evaluation did not this to be necessary.



Flowchart 3b: Selecting Treatment for Lead and/or Copper with Iron and Manganese in Finished Water and pH ≥ 7.2

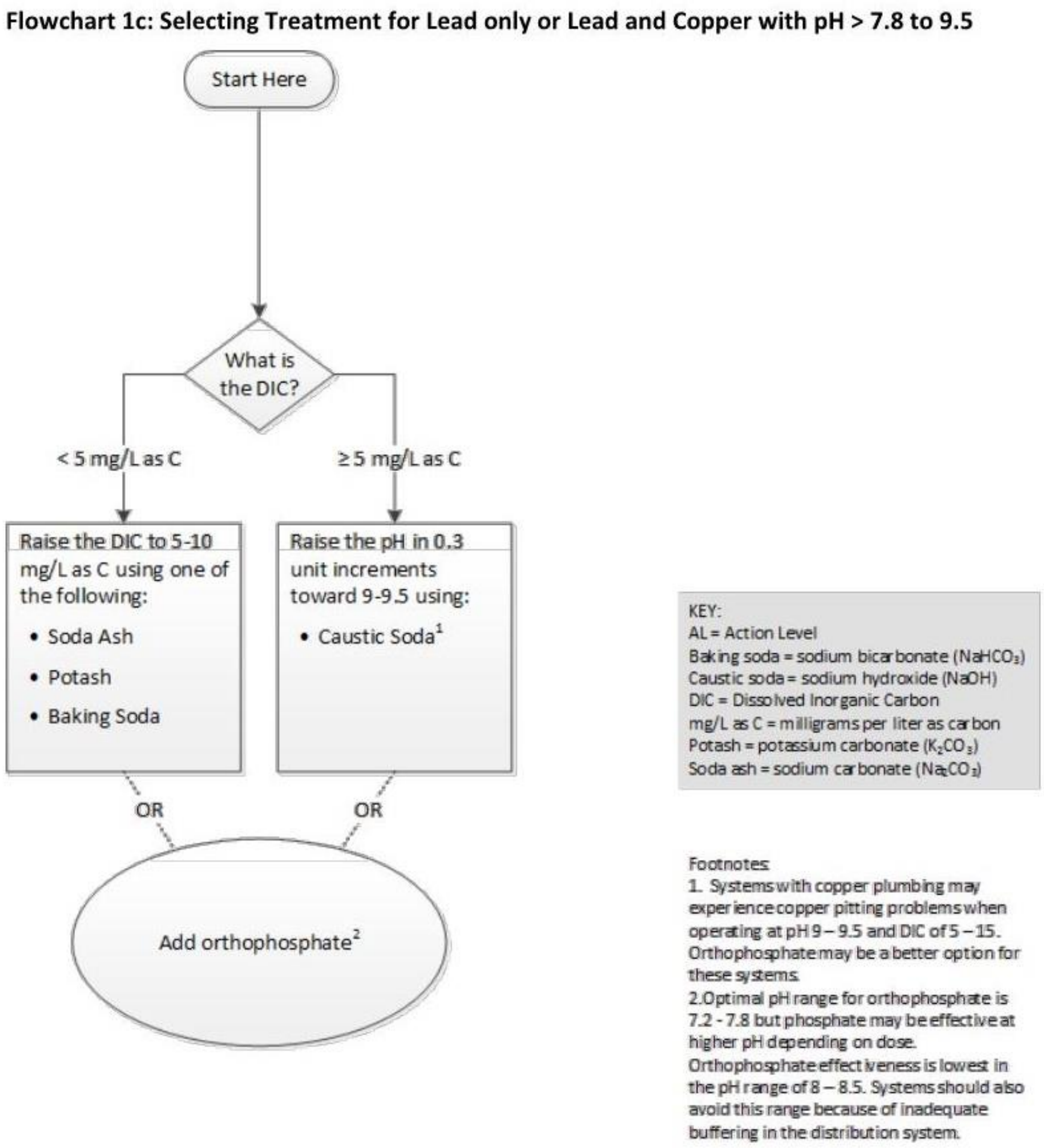
KEY:
AL = Action Level
Baking soda = sodium bicarbonate ($NaHCO_3$)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon

Footnotes:

1. Silicates are most effective when combined iron and manganese concentrations are less than 1.0 mg/L.
2. The effectiveness of blended phosphate varies based on the formulation. Additional evaluation and/or monitoring is recommended. See Section 3.3.2 for additional discussion. Blended phosphates are less effective for controlling copper at DIC greater than 25 mg/L as C.

Figure 4-26. U.S. EPA Recommended Corrosion Control Treatment for the TR Wells

Source: USEPA (2016)



Flowchart 1c: Selecting Treatment for Lead only or Lead and Copper with pH > 7.8 to 9.5

KEY:
AL = Action Level
Baking soda = sodium bicarbonate ($NaHCO_3$)
Caustic soda = sodium hydroxide (NaOH)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Potash = potassium carbonate (K_2CO_3)
Soda ash = sodium carbonate (Na_2CO_3)

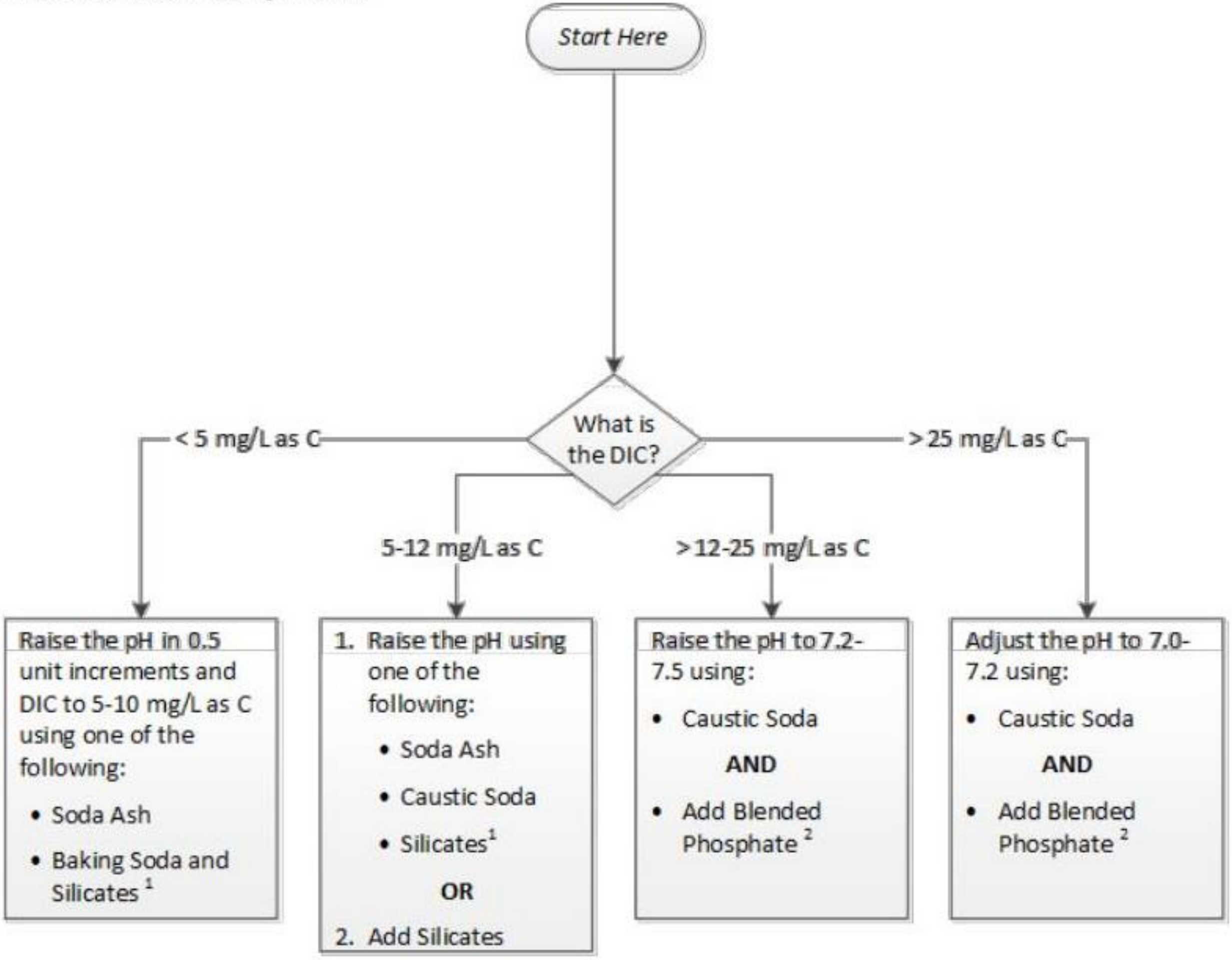
Footnotes

1. Systems with copper plumbing may experience copper pitting problems when operating at pH 9 – 9.5 and DIC of 5 – 15. Orthophosphate may be a better option for these systems.
2. Optimal pH range for orthophosphate is 7.2 - 7.8 but phosphate may be effective at higher pH depending on dose. Orthophosphate effectiveness is lowest in the pH range of 8 – 8.5. Systems should also avoid this range because of inadequate buffering in the distribution system.

Figure 4-27. U.S. EPA Recommended Corrosion Control Treatment for the Bellvue WTP

Source: USEPA (2016)

Flowchart 3a: Selecting Treatment for Lead and/or Copper with Iron and Manganese in Finished Water and pH < 7.2



KEY:
AL = Action Level
Caustic soda = sodium hydroxide (NaOH)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Soda ash = sodium carbonate (Na_2CO_3)

Footnotes:

1. Silicates are most effective when combined iron and manganese concentrations are less than 1.0 mg/L.
2. The effectiveness of blended phosphate varies based on the formulation. Additional evaluation and/or monitoring is recommended. See Section 3.3.2 for additional discussion.

Figure 4-28. U.S. EPA Corrosion Control Treatment for the Boyd Lake WTP

Source: USEPA (2016)

Section 5

Disinfectant Residual

This section summarizes the data analysis conducted to evaluate the effect of introducing treated groundwater from the TR wells on the free chlorine used as distribution system disinfectant residual. A cursory evaluation of the need for booster chlorination stations was also conducted using the information provided.

5.1 Existing Conditions

Free chlorine residuals measured in water treated by the Bellvue and Boyd Lake WTPs between January 2017 and December 2019 are illustrated in Figure 5-1. Over the study period, the average chlorine residual measured in water treated by the Bellvue WTP was low, i.e., 1.0 mg/L as Cl_2, compared to the average residual measured in water treated by the Boyd Lake WTP, i.e., 1.4 mg/L, although most of the low residuals measured at the Bellvue WTP effluent were observed before May 2018.

Free chlorine residuals measured in water treated by the WTPs and at the WQP sampling sites of Greeley's distribution system are summarized in Figure 5-2. These results highlight the distribution system sites where residuals tend to be lower. Alkalinity, TDS and hardness presented in Section 4.2 suggest that four distribution system sites are receiving water treated by the Bellvue WTP only (as opposed to seasonally receiving a blend of Bellvue WTP and Boyd Lake WTP water): Good Samaritan, O'Reilly Auto, Greeley-Loveland, and Rodarte Center. Figure 5-2 suggests that these sites were able to maintain slightly higher free chlorine residuals than the other distribution system sites that receive a blend of water from the Bellvue and Boyd Lake WTPs, despite lower residuals in water leaving the Bellvue WTP. This is because TOC concentrations were much lower in water treated by the Bellvue WTP than in water treated by the Boyd Lake WTP (Figure 5-3); the average TOC concentration was 2.0 mg/L as C in Bellvue WTP water and 3.8 mg/L in Boyd Lake WTP water. The high TOC concentrations in Boyd Lake WTP treated water is likely responsible for the lower chlorine residuals observed at the distribution system sites that receive this water source, particularly since the Boyd Lake WTP is only used in summertime when water temperature is higher and chlorine residual decays faster.

This evaluation suggests that adding booster chlorination station(s) at strategic location(s) in the distribution system would help Greeley maintain a sufficient chlorine residual throughout is service area. A map of Greeley's distribution system with WQP sampling sites indicates that the lower chlorine residuals appear to occur mainly in the southeastern portion of the service area near the 23rd Street Booster Station and Reservoir. An evaluation of hydraulic conditions in Greeley's distribution system was not part of this assessment but assuming that the 23rd Street Booster Station and Reservoir supplies the low chlorine residual area, then optimizing the use of this chlorine booster station could help re-establish chlorine residual. Alternatively, chlorine could be added at an upstream booster station to benefit a larger service area. Identifying the exact location of booster chlorination stations would require a more comprehensive evaluation of chlorine residuals throughout Greeley's distribution system (i.e., at more sampling sites, for example, at the sampling sites used for compliance with the Total Coliform Rule, TCR) in conjunction with hydraulic modeling to understand water flow direction. Because booster chlorination also increases DBP concentrations, the overall impact would need to be examined in bench-scale tests.

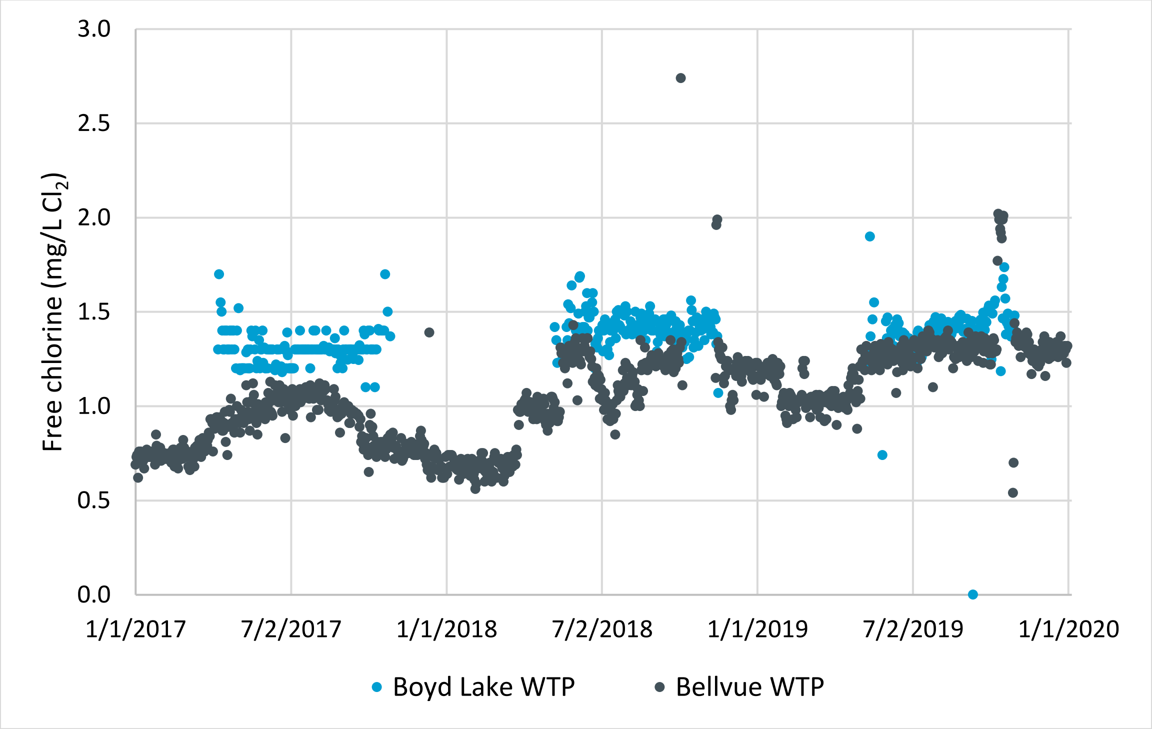


Figure 5-1. Free Chlorine Residuals Measured at the WTP Effluents

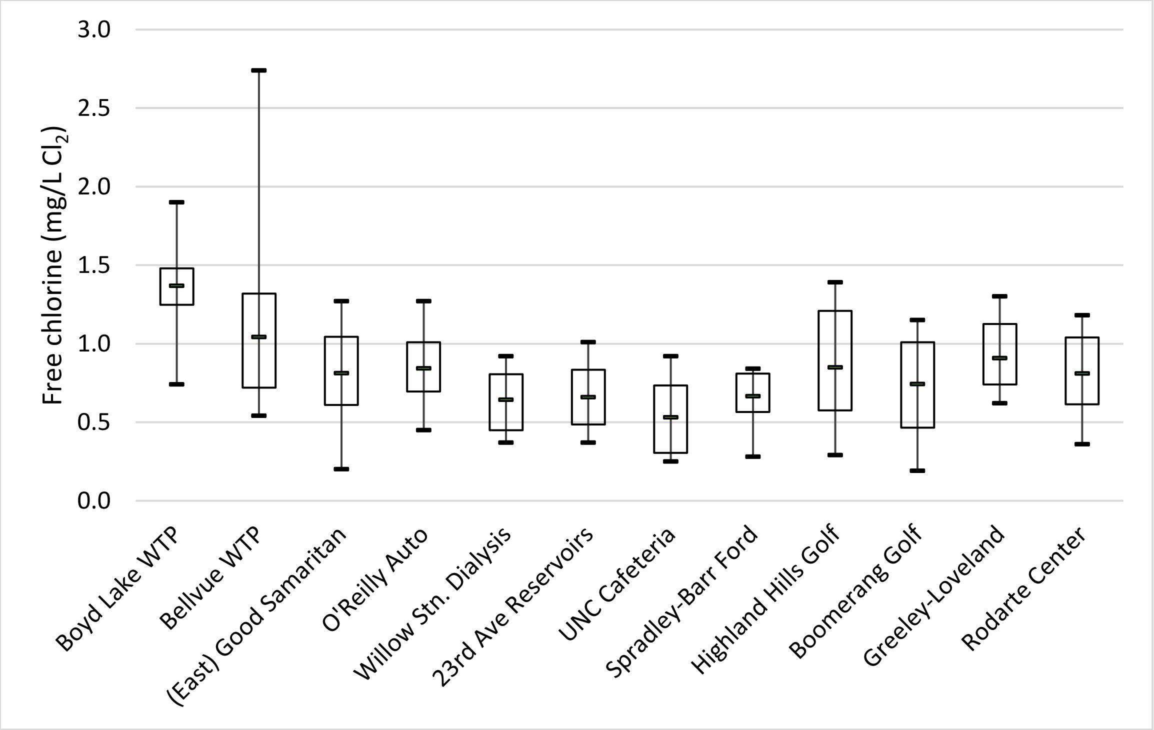


Figure 5-2. Free Chlorine Residuals Measured at the WTP Effluents and WQP Distribution System Sites

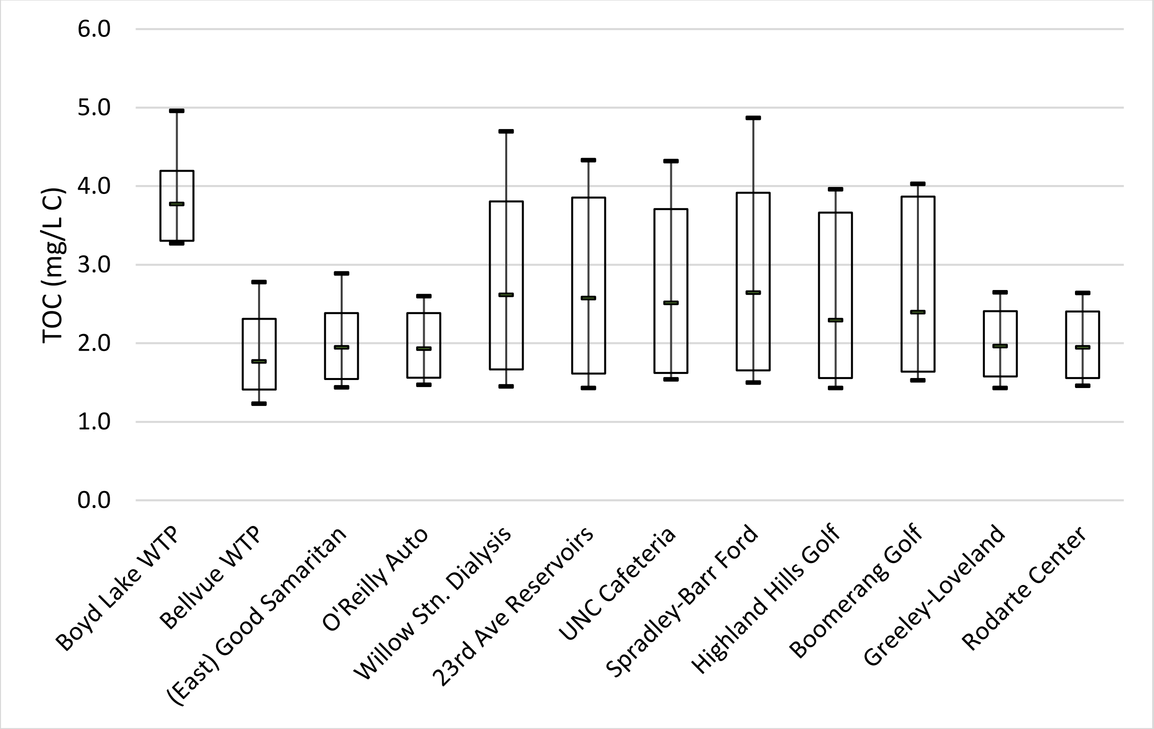


Figure 5-3. TOC Concentrations Measured at the WTP Effluents and in the Distribution System

5.2 Future Conditions

Only one TOC concentration was provided for the TR wells: 1.7 mg/L as C collected from WWR-4 in July 2020. This concentration is low compared to others measured in Greeley's distribution system, and similar to the average TOC concentration measured in water treated by the Bellvue WTP. Thus, it appears that water from the TR wells is not likely to decompose chlorine residual rapidly, although bench-scale tests should be conducted to verify this assumption.

The TR Project will be developed in milestones, as mentioned in Section 1, and thus, water will move slowly in the 32-mile pipeline between the TR wells and Greeley's existing distribution system at the beginning of the Project. At an estimated flow velocity of 1 to 2 feet per second (fps), water will reside in the pipeline for 23 to 47 hours, which may allow sufficient time for chlorine residual to decompose before water enters Greeley's distribution system. A booster chlorination station at the Gold Hill Tank, where water from the TR wells is expected to connect with the existing distribution system, may help Greeley maintain a sufficient chlorine residual throughout its service area.

Only one sampling was conducted near the site where water from the TR wells will connect with the existing distribution system. This site was labeled "Bellvue at Dugens" and it was sampled in September 2020. Free chlorine residual was near the method detection limit (0.04 mg/L Cl_2), and TOC concentration was substantial at 2.1 mg/L C. This confirms that, at a minimum, a booster chlorination station where water from the TR wells will connect to the existing distribution system may be helpful.

Section 6

Conclusions and Recommendations

This TM presents the tasks that were conducted to evaluate the effect of the TR wells on Greeley's existing distribution system when TR's groundwater will blend with surface water treated by the Bellvue and Boyd WTPs. Potential options to mitigate the challenges identified were proposed. The following three scenarios were examined:

1. Each individual water source independently, including water from the TR wells;
2. Blend of water treated by the Bellvue WTP and Terry Ranch wells; and
3. Blend of water treated by the Bellvue and Boyd Lake WTPs and Terry Ranch wells.

Because the Boyd Lake WTP is only used in summertime, water quality data obtained in winter were used for the Bellvue WTP for Scenario 2. Likewise, Scenario 3 is expected to occur only in summertime, and thus, summer water quality data were used for the Bellvue WTP for this scenario. For Scenarios 2 and 3, equal proportions of water from each source were examined recognizing that the individual water sources would represent extreme water quality conditions, and any water blends would represent intermediate conditions. Also, the limited water quality data available for the TR wells when this TM was prepared did not justify a more extensive analysis.

Results and findings obtained during this evaluation are summarized here:

- The lead and copper concentrations measured at customer taps during the most recent samplings indicate that cuprosolvency and plumbosolvency are currently well-controlled in Greeley's service area. Isolated occurrences of high lead concentrations have been observed at certain customer taps. Although these do not warrant changing Greeley's CCT and can be handled directly with the customers of these properties, water systems in this position will need to initiate actions under the LCRR.
- Most of Greeley's current and future water sources tend to form lead carbonate mineral scales of the cerussite type, whereas water treated by the Bellvue WTP leans towards the formation of hydrocerussite. Any blends of these water sources are likely to be of the cerussite type. Thus, the existing lead mineral scales could be disturbed when water from the TR wells will be introduced the distribution system. However, Greeley's system is already experiencing seasonal changes in water source when the Boyd Lake WTP is online in summertime, without widespread lead or copper releases. Thus, a change in CCT is not found necessary based on the data provided.
- With regards to copper corrosion, water treated by the Bellvue WTP is not corrosive towards copper, but water treated by the Boyd Lake WTP can be corrosive at its lower pH range. Increasing the finished water pH at the Boyd Lake WTP would reduce the corrosiveness of the water towards copper pipes. Although the indices of corrosion do not fully concur with the assessment that water treated by the Boyd Lake WTP can be corrosive towards copper pipes, the LR values were the highest of all of Greeley's water supplies.
- Some of the analyses conducted indicated that water from the TR wells, if used alone without blending, would also be corrosive towards copper unless a corrosion inhibitor is used. However, the corrosion indices calculated do not support this observation. Before proposing an alternative

CCT, additional water quality data should be collected from the TR wells to resolve the conflicting trends observed. Water from the TR wells will not be as corrosive towards copper upon blending with water treated by the Bellvue WTP or Boyd Lake WTP,

- The indices of aggressiveness indicate that the TR wells tend to be passive or deposit $CaCO_3$, a preferred condition, with the exception of the boreholes that are aggressive towards cement-mortar lined pipes and asbestos-cement pipes. The blend of TR well water shows that under certain conditions, the TR wells may be aggressive towards cement-based pipes. The TR well indices of aggressiveness, however, are similar or better than those calculated with water treated by the Bellvue and Boyd Lake WTPs (the surface water sources are both quite aggressive), suggesting that the introduction of TR well water into the existing distribution system is not likely change the aggressiveness of the water distributed by Greeley, and may even decrease it. Moreover, Greeley's distribution system contains very little cement-base materials, as detailed in Section 3.3.
- The corrosion indices suggest that none of the TR wells appear to be corrosive towards metals, including lead and copper. Thus, the limited water quality data provided suggest that water from the TR wells would not compromise Greeley's existing distribution system pipes.

Analyses conducted suggest that a change in CCT is not warranted; however, the low pH of the water treated by the Boyd Lake WTP compared to the Bellvue WTP and future TR wells was noted and leads to significant pH variations in the distribution system. Distribution systems are not well suited to withstand changes in water quality, including high pH variations, because such variations tend to disturb corrosion scales that have deposited on pipe surfaces and may release metals. Increasing pH at the effluent of the Boyd Lake WTP would significantly improve water quality, decreases the water's aggressiveness, and reduce the corrosiveness of the water towards copper pipes. A target pH of 7.8 is proposed because it is similar to Greeley's other water supplies and would only require a small amount of caustic soda (a dose of 5.3 mg/L was estimated). Before increasing pH at the effluent of the Boyd Lake WTP, the consequences of this change would need to be evaluated more comprehensively, including effect on disinfectant stability, trihalomethane (THM) formation potential, and others.

This TM also includes a cursory assessment of chlorine residuals throughout the existing distribution system and whether booster chlorination stations may be needed once the TR groundwater is introduced into the existing distribution system. Analysis of chlorine residual data suggests that optimizing the use of the 23rd Street Booster Station and Reservoir could help re-establish chlorine residual in the southeastern part of the distribution system where chlorine residual is lower. Alternatively, chlorine could be added at an upstream booster station to benefit a larger service area. A booster chlorination station at the Gold Hill Tank, where water from the TR wells is expected to connect with the existing distribution system, may also help Greeley maintain a sufficient chlorine residual throughout its service area. Identifying the exact location of booster chlorination stations would require a more comprehensive evaluation of chlorine residuals throughout Greeley's distribution system with chlorine residual at more sampling sites in conjunction with hydraulic modeling to understand water flow direction. Because booster chlorination stations also increase DBP concentrations, the overall impact would need to be examined in bench-scale tests.

Section 7

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Section 8

Limitations

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Appendix A: Background on Corrosion

Appendix A

Appendix A: Background on Corrosion

Corrosion, as it applies to drinking water quality, is a complex process involving several parameters. This appendix provides background both on general corrosion processes, and the relevant water quality parameters and indices, as well as background on corrosion control treatment strategies. The material in this appendix is more detailed than was considered necessary for the main report but provides important context that may be beneficial to readers.

Corrosion

In water systems, corrosion is an electrochemical interaction between a metal surface (e.g., a pipe wall) and water. During this process, metal is oxidized and transferred to the water or to another location on the metal surface. There are many forms of corrosion depending on the material, but the most important forms for drinking water are the following:

- Uniform corrosion, where the electrochemical interaction occurs along the inner pipe wall, resulting in a relatively uniform loss of metal across the surface.
- Non-uniform corrosion, where metal is lost from a localized point, causing pitting and mounding in some cases.
- Galvanic corrosion which comes from a coupling of dissimilar metals or internally in metallic alloys.

While it is important to understand and control corrosion, metal release into the water is the process that drives drinking water regulations, and that may present the greatest risks to public health. Metal release is a function of the reactions that occur between the metal ions that are released, and the physical, chemical and biological characteristics of the water and of the metal surface.

Pipe scales that build up on the metal surface are also important. They can include two types of compounds: 1) passivating films that form when pipe material and water react directly with each other; and 2) deposited scale material that forms when substances in the water (e.g., iron, manganese, aluminum, calcium, phosphate-base compounds) precipitate or sorb to, and then build up on the pipe surface. Scales can have several layers; they are influenced by treatment history, and they, too, can influence the effectiveness of subsequent corrosion control treatment process.

The characteristics of the scales and their structure dictate the amount of metal that can be released into the water during normal conditions and following physical disturbances (e.g., flushing, infrastructure work). If conditions favor the formation of insoluble, adherent scales to the inner pipe wall, then the rate of metal release will be low. However, if scales do not adhere well to the pipe wall or if they are very soluble, then metal release may be greater. Other compounds in the water (i.e.. aluminum, iron, manganese, and calcium) can significantly influence scale formation and properties.

Erosion of pipe internal surfaces and linings is a phenomenon that differs from metal corrosion. It derives from aggressive waters and mainly affects cement-mortar lined pipes and asbestos-cement pipes, which are composed of various calcium silicates and calcium aluminates that can dissolve in aggressive waters. This process can be responsible for the presence of sediments in the distribution system. It can be prevented or limited by the formation of a thin layer of $CaCO_3$ on the inner pipe surface.

Distribution System Materials

Corrosion outcomes may vary from one material to another under similar water quality characteristics, i.e., water that may be passivating for one material may be corrosive for another. The general trends that can be observed in metallic and non-metallic pipes are described in this section.

Non-metallic pipes: Cement-mortar lined pipes and asbestos-cement pipes are composed of various calcium silicates and calcium aluminates that can dissolve into aggressive water. Note that aggressive waters do not affect the asbestos present in the pipes; only the calcium-based compounds are dissolved. Dissolution of the cement mortar's calcium hydroxides can be prevented or limited by the formation of a thin layer of $CaCO_3$ on the pipe surface.

- *Only a small proportion of Greeley's transmission mains are made of concrete, i.e., 4.5 percent. The majority of the transmission mains are made of iron-base materials, as detailed hereunder.*
- *Likewise, less than 1 percent of the distribution system pipes are made of asbestos cement.*

Iron-base pipes: Two independent phenomena occur in iron pipes: iron corrosion, and iron release. These phenomena are complex, and measures that limit one may not be effective at controlling the other. Iron release may be responsible for red water occurrences, which arise through oxidation of ferrous ions (Fe^{2+}) in the bulk solution and the subsequent precipitation of ferric hydroxide (Fe^{3+}) based compounds. Iron corrosion and release are affected by many water quality parameters including pH, alkalinity, oxidants (i.e., chlorine, DO), carbon dioxide and inorganic ions. Their effects are inter-related and difficult to isolate. Nonetheless, it is recognized that increasing the alkalinity generally decreases corrosion rates, metal solubility and red-water occurrences. When increasing pH from 7 to 9, iron is generally less soluble, leading to less iron release. Increasing the concentrations of inorganic ions such as chloride and sulfate has also been linked to red water occurrences.

- *The majority of Greeley's transmission pipes are made steel (over 65 percent), cast iron pipes (CIP; nearly 17 percent) or ductile-iron pipes (DIP; approximately 13 percent).*
- *Greeley's distribution system also contains significant amounts of iron-base materials, including CIP (43 percent) and DIP (31 percent), with less than 2 percent steel pipes.*
- *A small number of service lines are also made of DIP (2 percent) or CIP (0.3 percent).*

Galvanized pipes: The zinc oxide layer present on the surface of galvanized pipes is responsible for their resistance to corrosion because the corrosion rate of zinc is less than the corrosion rate of iron. The resistance of galvanized pipes to corrosion depends on alkalinity and pH, with the highest resistance between pH 7 and 8.5.

- *Only a very small proportion of Greeley's distribution system is made of galvanized pipes, i.e., less than 0.1 percent.*

Lead: Passivation of lead-tin solder (often used to join copper pipes in pre-1986 plumbing) occurs when lead carbonate and its hydroxide precipitates are formed. Lead leaching from lead-tin solder is strongly influenced by pH and CSMR. Based on equilibrium calculations, pH adjustment in the range of 8.0 to 8.5 can reduce lead solubility in water, whereas DO and possibly ammonia can enhance lead release. Galvanic corrosion at the interface between lead solder and copper is influenced by the CSMR; literature suggests that CSMRs above 0.6 will increase galvanic corrosion. As for lead contained in brass, high CSMR appears to similarly enhance its release.

Copper: Copper corrosion is influenced by several parameters: copper release increases as alkalinity, sulfate and DO concentrations increase, and pH decreases. Other parameters also influence copper corrosion, including bicarbonate, ORP, chloride, organic material, and to some extent ammonia. For new copper pipes, DIC is also important.

- *Only a very small proportion of Greeley's distribution system is made of copper pipes, i.e., less than 0.1 percent.*
- *Most service lines are made of copper, i.e., more than 97 percent.*

Zinc: Chloride, hardness, alkalinity and pH can affect dezincification of copper-zinc brass alloys. Dezincification also appears to be more prevalent in waters with a high chloride-to-hardness ratio.

Water Quality

Many water quality parameters may affect corrosion in a conflicting manner. The main water quality factors responsible for corrosion of distribution system materials are discussed here.

Temperature: Temperature influences all chemical and biological reactions. Higher water temperature increases corrosion rates, but also increases the tendency of $CaCO_3$ to precipitate and lead carbonate scales to form, thereby helping the formation of a protective layer on distribution system materials.

pH: Low pH may increase corrosion rates of metals, whereas high pH tends to protect pipes and decrease corrosion rates. High pH can also be responsible for dezincification of brasses and increased copper release. pH also influences the effectiveness of corrosion control treatment.

Alkalinity and dissolved inorganic carbon (DIC): While higher alkalinity tends to decrease corrosion rates, helps form a protective film of $CaCO_3$ or lead carbonates, and controls pH changes, it may increase corrosion of copper, lead and zinc. Although alkalinity is often the preferred analysis, DIC concentration is the parameter more closely related to corrosion because it directly measures the available carbonate (CO_3^{2-}) species in the water that can react with metals to form passivating scales. When examined altogether, pH, alkalinity and DIC form a better indicator of corrosion control effectiveness than pH and alkalinity alone. Generally, at a given pH, lead solubility increases with increasing DIC concentration above approximately 20 mg/L as C; lead solubility is minimum at DIC concentrations between 5 and 10 mg/L as C. DIC concentrations also influence orthophosphate effectiveness.

Oxidants, including chlorine and chloramines: Oxidants can serve as electron acceptors or cathodes. High chlorine residuals increase corrosion of metals, particularly copper, iron and steel. Chlorine can also decrease alkalinity. On the other hand, higher chlorine residuals reduce microbiologically-induced corrosion (MIC). Because monochloramine is a less reactive oxidant than chlorine (i.e., it has a lower ORP), it does not affect materials and does not decrease alkalinity as much as free chlorine when used at similar concentrations.

Oxidation-reduction potential (ORP): Under certain conditions, ORP can have a significant impact on lead release. In the absence of a corrosion inhibitor or other interfering surface deposits, high-ORP waters could promote the formation of lead dioxide scales on pipe surfaces. These lead dioxide scales are very insoluble, thereby preventing lead from being released into the water. However, they require the presence of the oxidized form of lead, Pb(IV), which is only possible with a high ORP. Conversely, a decrease in ORP (which may result from the conversion from free chlorine to monochloramine for example) may contribute to lead release through dissolution of Pb(IV) minerals.

Dissolved oxygen (DO): DO often serves as electron acceptor (cathode) in corrosion reactions, thereby allowing the corrosion reactions to continue. High DO concentrations can also increase copper corrosion. In certain circumstances however, high DO concentrations may be beneficial by facilitating the production of protective mineral oxide layers; this is the case for lead for example.

Total dissolved solids (TDS) and conductivity: These parameters tend to increase corrosion rates by completing the electrochemical circuit responsible for corrosion reactions. The nature of the ions that compose TDS can also affect corrosion: for example, if bicarbonate and calcium ions are major TDS contributors, as opposed to chloride and sulfide ions.

Hardness and calcium: Hardness and calcium concentration may favor the precipitation of calcium as $CaCO_3$, thereby providing protection inside distribution system structures. Higher calcium concentrations stabilize the calcium present in cement-mortar lined pipes and asbestos-cement pipes, thereby preventing its release, and can reduce corrosion rates of unlined iron pipes. However, the link between calcium hardness and metal corrosion is not straightforward. For example, films of $CaCO_3$ only rarely form on lead, copper and galvanized pipes. Thus, enhancing $CaCO_3$ precipitation is not considered an effective form of corrosion control for these pipe materials. One of the drawbacks of high calcium hardness is that it may cause excessive scaling or even turbidity.

Chloride and sulfate: High concentrations of chloride and sulfate may promote corrosion in metallic pipes by reacting with the metals in solution and causing them to stay in solution or by interfering with the formation of normal protective oxides and films. In this regard, chloride is typically three times more active than sulfate. Sulfate is known to inhibit lead corrosion, although its role in iron corrosion should not be underestimated. Pitting corrosion in copper piping has been associated with chloride and bicarbonate concentrations.

Iron and manganese: When present in the water, these metals can react with dissolved lead and form deposits in premise plumbing. This can present health risks if these deposits are later released into the drinking water. Manganese can also interfere with the formation of lead scales and other passivating films.

Fluoride: Fluoridation with hydrofluosilicic acid can decrease alkalinity and pH in low-alkalinity waters. Very little information is available regarding the effect of fluoride on pipe corrosion, but it is likely that fluoride enhances corrosion, like chloride and sulfate.

Hydrogen sulfide (H_2S): High H_2S concentrations may increase corrosion rates by reacting with metal ions to form non-protective insoluble sulfides.

Ammonia: Ammonia may form soluble complexes with many metals, including copper and lead, thereby interfering with the formation of passivating films and increasing corrosion rates.

Organic material: High concentrations of organic materials may decrease corrosion by coating pipe surfaces, but some organics can bond with metals and accelerate corrosion or metal release, which may include lead. Organic compounds can also complex calcium ions, keeping them from forming a protective film of $CaCO_3$. Lastly, organic materials can serve as food source for microorganisms, thereby potentially increasing biofilm density and microbial attacks of pipe surfaces.

Corrosion Indices

Several indices have been developed to quantify a water's tendency to be aggressive or corrosive towards distribution system materials. Each index is calculated from a number of water quality parameters (described above in this appendix), thereby providing a more thorough assessment than evaluations that are based on individual water quality parameters alone.

Many indices are based on corrosion control through $CaCO_3$ saturation, recognizing that a slight over-saturation of $CaCO_3$ may promote its precipitation resulting in the deposition of a thin protective layer inside distribution system pipes. A number of indices have been developed based on this principle, including the Langelier Saturation Index (LSI), the Ryznar Saturation Index (RI), the Aggressiveness Index (AI), and the Calcium Carbonate Precipitation Potential (CCPP).

Because $CaCO_3$ saturation is not directly linked to corrosion of metallic pipes and metal release, other indices were developed, such as the Buffer Intensity, the Larson Ratio (LR, or Larson Index) and the Chloride-to-Sulfate Mass Ratio (CSMR). These indices are better suited to provide indication of lead and copper release than the aggressiveness indices. Table A-1 presents the definition, purpose and significance of the indices of corrosion and aggressiveness that were examined during this study.

Results obtained from indices of corrosion and aggressiveness should be used carefully and these indices should not be included as WQPs for several reasons:

- An index’ applicability is limited by the conditions in which it was developed. Certain indices were developed under specific conditions (e.g., soft waters, specific water temperature or pH, pipe material) and may not provide representative results under different conditions. Thus, the indices must be used properly, i.e., they must be paired with the pipe materials and conditions for which they were developed to avoid erroneous predictions. For example, the relationship between LSI or CCPP and iron corrosion is not direct, and other indicators should be considered. The aggressiveness indicators (i.e., LSI, CCPP, RSI ad AI) should also not be used to evaluate lead or copper control. The CSMR has been proposed fairly recently; thus, this index should be used cautiously considering the limited information that is available at this point. This explains the need to examine a combination of indices rather than focusing on only one index and use results cautiously.
- In poorly buffered waters (low alkalinity and low DIC concentrations), the presence of localized pH changes may lead to significantly different corrosion and aggressiveness indices, thereby creating inconsistent corrosion reactions that can exacerbate the problem.
- Various models and calculators are available to estimate the aggressiveness indices. They may provide slightly different results depending on their level of accuracy. For example, whether TDS concentration is used as an estimate of the mineral content of the water, or whether individual ion species are considered can affect the indices of aggressiveness. The calculation method for the saturation pH (pH_s) may also affect the indices of aggressiveness.
- The significance of the indices in the presence of a corrosion inhibitor is questionable. In the presence of polyphosphates for example, the pH_s equations are invalid, leading to LSI values that are overestimated.
- The indices do not consider MIC, which may occur if the disinfectant residual is unstable and microbial regrowth occurs.

Thus, corrosion and aggressiveness indices must be used carefully as there are many waters with non-corrosive or non-aggressive indices that are corrosive/aggressive, and vice versa. The purpose of calculating these indices is to evaluate the natural aggressiveness and corrosiveness of a water without inhibitor and determine suitable corrosion control strategies. Testing the proposed strategies at bench and/or pilot scale is necessary to confirm the trends suggested by the indices.

Table A-1. Definitions of Corrosion Indices

Index	Definition and Purpose	Significance
Langelier Saturation Index (LSI)	pH of the water relative to its pH of equilibrium or saturation with $CaCO_3$ (i.e., pH_s). Indicator of the “directional tendency” of a water and driving forces involved, without representing the capacity of a water to precipitate or dissolved $CaCO_3$. LSI = (Measured pH) – pH_s	LSI > 0.2: Water may tend to precipitate $CaCO_3$, which can be associated with non-aggressive conditions LSI between -0.5 and +0.5: Water is passive LSI < -0.5: Water may tend to dissolve $CaCO_3$, which can be associated with aggressive conditions
Ryznar Saturation Index (RI)	Directional tendency of a water with respect to its pH of saturation (similar to the LSI). RSI = 2 pH_s – (Measured pH)	RSI < 6: Water is considered saturated, which can be associated with non-aggressive conditions RSI between 6 and 7: Water is passive RSI > 7: Water is under-saturated, which can be associated with aggressive conditions RSI > 8.5: Water is very aggressive
Aggressiveness Index (AI)	Measure of the attack of water on cement matrix and asbestos-cement pipes; simplification of the LSI. AI = (Measured pH) + $\log_{10}$(calcium hardness) + $\log_{10}$(total alkalinity)	AI > 12: Water is considered non-aggressive AI between 10 and 12: Water is moderately aggressive AI < 10: Water is considered aggressive
Calcium carbonate precipitation potential (CCPP)	Mass of $CaCO_3$ that will precipitate as the water comes to equilibrium with $CaCO_3$; the value obtained is equal to the amount of $CaCO_3$ (in mg/L $CaCO_3$) that will precipitate or dissolve as the water approaches equilibrium. CCPP = 44.6 ($TALK_i$) ($TALK_{eq}$) $TALK_i$: Total alkalinity at initial state $TALK_{eq}$: Total alkalinity at equilibrium state	CCPP > 0: Water tends to precipitate $CaCO_3$, which can be associated with non-aggressive conditions (CCPP between 4 and 10 has often been recommended to provide adequate precipitation of $CaCO_3$) CCPP between 0 and -5: Water is passive CCPP between -5 and -10: Water is moderately aggressive CCPP < -10: Water tends to dissolve $CaCO_3$, which can be associated with aggressive conditions
Buffer intensity	Resistance of a solution to pH changes, by considering alkalinity, DIC concentration, and pH.	Waters with high buffer intensities have less pH increases at the cathodes and anodes, than waters with low buffer intensities Corrosion rates and pitting corrosion tend to decrease as buffer intensity increases
Larson Ratio (LR, or Larson Index)	Determines the effect of chloride, sulfate and bicarbonate alkalinity on corrosion of metallic pipes including pitting of copper pipes, and potential disruptions of existing iron scales, which may lead to red- or brown-water occurrences. (Concentrations in mole/L.) LR = $[SO_4^{2-}] + [Cl^-]$ / [Total Alkalinity]	LR < 5.0: Water is considered non-corrosive; chlorides and sulfate should not interfere with natural film formation LR > 5.0: Water is likely corrosive
Chloride-to-sulfate mass ratio (CSMR)	Assesses zinc and lead releases from brass, lead and copper joints. CSMR = $[Cl^-]$ / $[SO_4^{2-}]$	CSMR < 0.6: Water is considered non-corrosive towards brass, lead and copper CSMR > 0.6: Water is considered corrosive towards brass, lead and copper

Hydraulic Conditions

Corrosion and aggressiveness are highly dependent on hydraulic conditions, such as water velocity and water usage. High water velocity can reduce lead and copper release by transporting the corrosion inhibitor to the pipe surfaces at a higher rate. However, lead and copper corrosion can accelerate in some cases by increasing the rate at which the oxidants in water come into contact with the metal surface. High water velocity can mobilize loosely adherent scales and cause sporadic metal release. Conversely, low water velocity can decrease the effectiveness of the corrosion control inhibitor in forming a passivating scale. Increased water age can cause water quality changes that can increase corrosion and microbial growth.

These phenomena can be exacerbated by flow reversals and hydraulic pressure transients, as well as physical disturbances such as infrastructure work (e.g., line repair or replacement, meter installation or replacement, valve shutoff, and pipe flushing). Lastly, the conservation efforts that are mandated throughout the State of California significantly influence hydraulic conditions in distribution systems, thereby affecting the trends in corrosion and aggressiveness.

Corrosion Control Strategies

The selection of a corrosion control strategy needs to consider water quality, as well as distribution system materials and hydraulic conditions. If corrosion control is deemed necessary, the approaches that can be used are (1) alkalinity and pH adjustment (which affects DIC concentration), and (2) the use of corrosion inhibitors to form less soluble metal compounds (e.g., carbonates, silicates, or phosphates) that adhere to the inner pipe walls. The Final LCRR eliminates the calcium hardness adjustment option, recognizing that $CaCO_3$ scales do not effectively passivate lead or copper piping. These methods are described below. If a corrosion inhibitor is deemed necessary, its dosage needs to be carefully determined using laboratory, bench and/or pilot tests, pipe racks, pipe-loop or metal coupon tests, with appropriate measurement methods.

Alkalinity and pH Adjustment

Corrosion inhibition by adjustment of alkalinity, pH and DIC concentration can induce the formation of less solution compounds on the inner surface of metal pipes, a process called passivation. This can be performed by adding chemical compounds, as detailed in Table A-2. Limestone contactors have also been used in small systems. When carbon dioxide (CO_2) concentrations are sufficient (i.e., 4 to 10 mg/L CO_2) and pH is low (i.e., less than 7.2), aeration has also shown sufficient reduction in DIC concentration by removing CO_2, which results in an increase in pH. Aeration can also remove other constituents such as iron, manganese, radon, volatile organic compounds (VOCs) and H_2S.

Each of the compounds listed in Table A-2 has advantages and disadvantages; for example, lime seems attractive because it also increase calcium hardness, but its dosage is more complex, which puts an additional burden on operation staff, and undissolved lime may increase turbidity at the plant effluent. Other compounds may modify pH, but do not buffer it (e.g., caustic soda, carbon dioxide).

Specifically, with regards to lead materials, the goal of alkalinity and pH adjustment is to form stable passivating scales on lead-containing plumbing materials. Unless ORP is high, these scales are primarily comprised of lead carbonates: either cerussite ($PbCO_3$) or hydrocerussite ($Pb_3(CO_3)_2(OH)_2$). In generally, formation of hydrocerussite is favored at low DIC and at pH conditions above 8.5; at lower pH conditions and higher DIC, cerussite is favored. Hydrocerussite is typically more stable than cerussite and is the preferred form of lead carbonate for lead passivation, although it tends to dissolve at pH below approximately 8.5, unless DIC concentrations are low. Cerussite is less stable and more prone to sloughing, leading to lead release, when water quality is not favorable to its production. However, in systems with relatively low amounts of lead-bearing plumbing materials, either form of lead carbonate can effectively control plumbosolvency if water quality conditions are stable.

When water quality conditions change in a distribution system, the scales can shift between hydrocerussite and cerussite. The kinetics of dissolution and formation are not the same between the two minerals. Therefore, there is a period of heightened vulnerability when conditions shift between minerals; if the less-favored mineral dissolves more quickly than the favored mineral forms, elemental lead may be exposed to the bulk water leading to an increase in lead dissolution. Such behavior was documented by Roth et al. (2018) during bench-scale testing from a system blending surface water and groundwater. In that system, the surface water favored the formation of hydrocerussite, while cerussite was the dominant mineral when the system switched to groundwater. Lead, brass, and copper with lead solder coupons that were passivated under groundwater conditions saw lead levels more than double when exposed to a blend of predominately surface water. Such results suggest that the kinetics of cerussite dissolution exceeded those of hydrocerussite formation, leaving the leaded materials exposed without a passivating layer during the transition of scale minerals.

Table A-2: Chemical Processes Used to Adjust Alkalinity and pH

Chemical	Effect on pH	Effect on Alkalinity	Effect on DIC
Baking soda (sodium bicarbonate, $NaHCO_3$)	Moderate increase in pH	0.60 mg/L $CaCO_3$ alkalinity per mg/L as $NaHCO_3$	0.14 mg/L as C
Carbon dioxide (CO_2)	Lowers pH	None	per mg/L as $NaHCO_3$
Caustic soda (sodium hydroxide, NaOH)	Raises pH	1.55 mg/L $CaCO_3$ alkalinity per mg/L as NaOH	0.27 mg/L as C
Hydrated lime (calcium hydroxide or slaked lime, $Ca(OH)_2$)	Raises pH	1.21 mg/L $CaCO_3$ alkalinity per mg/L as $Ca(OH)_2$	per mg/L as CO_2
Soda ash (sodium carbonate, Na_2CO_3), or potash (potassium carbonate, KCO_3)	Moderate increase in pH	0.90 mg/L $CaCO_3$ alkalinity per mg/L as Na_2HCO_3	None
Sodium silicates (Na_2SiO_3)	Moderate increase in pH	Moderate increase (depends on formulation)	None

Phosphate- and Silicate-Based Agents

Corrosion inhibitors “passify” metals by preventing reactions at the anode (when anodic inhibitors are used) or the cathode (with cathodic inhibitors). The best corrosion inhibitors are those that provide both types of inhibition. Orthophosphates, zinc salts, and sodium silicates are the main chemicals used for corrosion inhibition by passivation and are described in this section.

For most of the corrosion inhibitors discussed below, certain water quality characteristics (e.g. pH, hardness, and alkalinity levels) must be present to ensure their effectiveness. Also, a corrosion inhibitor needs to be present at or above a certain concentration throughout the distribution system to be effective, and for some inhibitors, a pre-conditioning period at a higher dose may be necessary. Lastly, and as discussed above, the effects of passivating agents are influenced by distribution system hydraulic conditions.

Orthophosphates: These compounds include phosphoric acid (H_3PO_4), and mono-, di- and tri-basic sodium phosphate (NaH_2PO_4, Na_2HPO_4 and Na_3PO_4, respectively). They are anodic inhibitors that adsorb to surfaces and form protective films. Orthophosphate reacts with divalent metals (e.g., Pb^{2+} and Cu^{2+}) to form compounds that have a strong tendency to stay in solid form and not dissolve into water. Thus, they are recognized as effective agents to reduce lead and copper and have also been used to decrease iron release.

One of the drawbacks of orthophosphates is that they are essential nutrient of microorganisms and have been shown to increase bacterial growth in unlined cast-iron pipes and solder in certain conditions.

Polyphosphates: These compounds are commonly used in various forms, including sodium tripolyphosphate, sodium hexametaphosphate, and other sodium and potassium polyphosphates. The primary utilization of polyphosphates is to reduce tuberculation of iron and steel and sequester iron and manganese by binding the metals into their structures so they cannot precipitate. They can also sequester lead and copper, keeping them in the water, and thereby increasing concentrations measured at customer taps and the risk of exposure. Thus, polyphosphates are dissolved in the water rather than creating a film on pipe surfaces like orthophosphates. But because polyphosphates eventually degrade into orthophosphates through hydrolysis, the regulatory agencies do not recognize them as treatment processes to eliminate iron or manganese from water sources. Also, they are not effective corrosion inhibitors.

Polyphosphates can react according to different mechanisms: they can revert to orthophosphate and form protective films that reduce lead release, but they can also increase the release of lead (both particulate and soluble) and copper via alternative reactions. Studies suggest that the later mechanism (increase lead and copper release) may predominate in most cases. Also, polyphosphates may increase iron corrosion and release at low dosages. They can also attack and soften cement linings, asbestos-cement pipes and existing scale deposits, as well as increase the solubility of lead and copper, and prevent $CaCO_3$ formation and deposition.

Phosphate blends: Phosphate blends can offer multiple protections, e.g., corrosion protection, hardness stabilization, red-water suppression, and sequestration of iron and manganese. In moderately hard waters, they have shown to be effective for lead and copper suppression. However, the lead corrosion scales created by phosphate blends may not be as robust as the scales created by orthophosphates, and thus, may be more susceptible to hydraulic conditions and physical disturbances. In addition, the polyphosphate portion of the blend may counteract the benefit of the orthophosphate portion in forming solid lead and copper compounds if the polyphosphate has a high affinity for sequestering lead or copper. It is unclear if blended phosphates work well to control copper corrosion and studies have shown conflicting results, especially at high alkalinity. The composition and dosage of phosphate blends are specific to the water to be treated and depend on several parameters including pH and calcium concentration. The USEPA (2016) recommends demonstration-scale studies with adequate monitoring to determine the exact compound and dose required.

Zinc: Zinc phosphates are bimetallic phosphates that typically combine 10 to 30 percent zinc with ortho- or poly-phosphates. Zinc is a cathodic inhibitor that prevents the contact between oxidizing agents (such as oxygen or chlorine) and the metal by precipitating at the cathode, thereby forming a non-conductive barrier. Zinc-based inhibitors are typically used to prevent leaching of calcium from cement mortar lined and asbestos-cement pipes and protect metal pipes by forming protective films. When zinc is combined with orthophosphates, it offers both anodic inhibition (by the orthophosphates) and cathodic inhibition (by the zinc). Evidence suggest that blends of zinc and orthophosphate are better suited to decrease iron release from cast iron pipes than agents that contain orthophosphate alone. They are also considered among the most effective corrosion inhibitors for mild steel and ductile iron because they provide both cathodic and anodic protection. With regards to controlling lead and copper corrosion, the presence of zinc in an inhibitor does not improve the effect of orthophosphate, and orthophosphate alone is sufficient.

Zinc-based inhibitors present the following drawbacks: (1) they may be problematic for wastewater treatment plants that are limited in zinc discharge; and (2) their efficiency may be limited at high pH, high alkalinity and high calcium concentrations.

Silicates: Silicate-based corrosion inhibitors are mixtures of soda ash and silicon dioxide. Although these compounds are not commonly used, they are efficient anodic inhibitors that can sequester iron and manganese if their combined concentration does not exceed 1 mg/L, and limit red-water occurrences by forming protective films. They have also been shown to successfully reduce lead and copper release in customer taps, in the first liter of sample (i.e., first draw). Their usage is limited to soft waters with low pH and high DO concentration. Their effectiveness depends on silicate level, pH and DIC concentration. Higher doses are generally required to control lead release compared to other corrosion inhibitors, i.e., greater than 20 mg/L.

Calcium Hardness Adjustment

Calcium hardness adjustment to increase $CaCO_3$ precipitation is often practiced to protect cement-based pipes, but it does not directly affect corrosion of lead, copper and galvanized pipes. If sufficient calcium is present in the water, increasing pH, alkalinity and/or DIC may be sufficient to favor $CaCO_3$ precipitation. Alternatively, a number of compounds can be used to increase calcium concentration, including lime and calcium carbonate. Excessive calcium concentrations is not desirable because it may limit a water system’s ability to raise pH (which limits metal corrosion) due to potential scaling problems.