Evaluation of Corrosion Indices for Predicting Lead Leaching in Water Distribution Systems

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Evaluation of Corrosion Indices for Predicting Lead Leaching in Water Distribution Systems

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by
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Abstract

Ingestion of lead in drinking water has potentially dangerous health effects. Corrosion indices are routinely used in the water industry to predict corrosion potential. We evaluated twelve corrosion indices to see how accurately they predict lead leaching, using water quality data from seven water utilities. We determined the two best indices: the Calcium Saturation Index and Stiff & Davis Stability Index. We designed a corrosion monitoring program for drinking water utilities to aid in dealing with corrosion concerns.

Acknowledgements

We would like to thank the following individuals who assisted us and guided throughout our project:

- Our advisors, Professor Jeanine Dudle and Professor John Bergendahl, for their contributions and thoughtful critiques towards the development of our project.
- Robert F. Ferrari from Northeast Water Solutions, Inc. for sponsoring this project and sharing with us the knowledge he has gained from his experience as an engineer and providing us with engineering evaluation reports.
- The water municipalities for providing us with valuable water quality data and for answering questions related to our project.

Executive Summary

Introduction

In recent years, high lead concentrations in municipal drinking waters have raised concern over the United States' deteriorating water infrastructure and prior use of lead in water distribution system pipes. Scientific studies have identified water systems in which corrosion of lead pipes has led to unacceptable lead concentrations at the tap of many homeowners; while news outlets have informed the public of the negative health consequences of ingesting lead. Based on the negative health impacts of lead, the U.S. Environmental Protection Agency (EPA) regulates lead concentrations in drinking waters through the Lead and Copper Rule (LCR), which sets a lead limit above which utilities must take action to reduce corrosion. However, in 2004, over 4,000 homes in Washington, D.C. had water with lead levels greater than the EPA Action Limit. In 2014, news broke about dangerously high lead levels in Flint, Michigan's drinking water. Just one year ago in February 2019, the Pittsburgh Water and Sewer Authority was criminally charged for violating Pennsylvania's safe drinking water law by changing corrosion treatment without notifying the State Department of Environmental Protection. Due to this change, lead concentrations surpassed the LCR Action Limit. The Natural Resources Defense Council (NRDC) estimated that in 2015 alone, there were over 8,000 LCR violations in the U.S.

To accomplish our project goals, we established four main objectives:

1. Research corrosion indices, including those used in water treatment practice as well as lesser known indices.
2. Obtain data on water quality and lead concentrations for Cambridge, Massachusetts; Milwaukee, Wisconsin; Newark, New Jersey; New York City, New York; Providence, Rhode Island; Tempe, Arizona; and Washington, D.C. water treatment systems.
3. Calculate corrosion index values using water quality data.
4. Compare corrosion index values to lead levels measured in the water systems.

Background

Corrosion reactions result in the degradation of a material through chemical and electrochemical processes. Figure 1 below depicts the mechanisms involved to induce corrosion on metal surfaces. Two reactions are occurring at the same time; at the anode, oxidation and at the cathode, reduction reactions. As a result of these interconnected reactions and the influence of an electrolyte (such as water), a corrosion cell is formed whereby the metal surface dissolves.

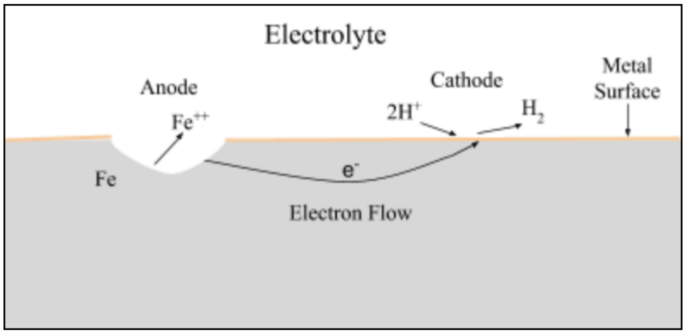


Figure A. Mechanisms for Corrosion for Iron (McNaught & Wilkinson, 1997).

There are several types of corrosion that can occur: uniform corrosion, non-uniform corrosion, galvanic corrosion, concentration cell corrosion, erosion corrosion, and localized corrosion. In addition to the various forms of corrosion, there are a number of factors in the water that contribute to corrosion. These include: alkalinity, ammonia, buffer capacity, chloride and sulfate, chlorine residual, copper, dissolved inorganic carbon, dissolved oxygen, electrical current and grounding, hardness, microorganisms, pH, temperature, total dissolved solids, velocity, and water treatment practices. In order to prevent corrosion many of these factors can be adjusted. However, the use of corrosion inhibitors is also a common practice in the water industry. The implementation of a phosphate- or silicate-based inhibitor is the most widely used.

Lead contamination can result in major health impacts. Lead accumulates over time in the body and as a result can cause significant issues for young children, infants, and fetuses. With the EPA's Lead and Copper Rule (LCR), 90th percentile lead concentrations must remain below the action limit of 15 µg/L. In addition to health concerns, corrosion is a leading cause of failing water infrastructure in the United States. In past years, there have been public health crises regarding high lead concentrations in drinking water across the country in cities such as Flint, Michigan; Washington, D.C.; and Pittsburgh, Pennsylvania.

There are many indices that have been developed to aid water utilities in predicting corrosion. The majority of indices predict $CaCO_3$ precipitation rather than corrosion. Theoretically, if $CaCO_3$ precipitates, it will form a protective scale on the inside of pipes and prevent lead from leaching into the water. Some indices predict galvanic corrosion or corrosion in pipes made of mild steel. Still other indices measure the aggressiveness of the water, which may or may not lead to corrosion.

Methodology

To accomplish our objectives, we researched the mechanisms of corrosion, including the interactions between water and the interior surface of pipes in distribution systems. These reactions may result in precipitation of protective scales or in metal leaching, which leads to erosion of the interior surface of pipes in water distribution systems. We then researched corrosion indices by reading scholarly journals, academic textbooks on water quality, and government manuals. Our project primarily focused on cities on the East coast (Cambridge, Massachusetts; Providence, Rhode Island; Newark, New Jersey; New York City, New York; and Washington, D.C.) and also included Milwaukee, Wisconsin and Tempe, Arizona. The cities assessed had various lead contamination levels in the water ranging from low to high. Water quality information was obtained through Robert F. Ferrari at Northeast Water Solutions, Inc. in the form of engineering evaluation reports and Professor Jeanine Dudle at Worcester Polytechnic Institute in the form of monthly water quality data. We also utilized Water Quality Reports (also known as Consumer Confidence Reports or CCRs) for each municipality and directly contacted water utilities by email or phone for more information. With the water quality data we collected, we calculated the index values for the utilities for the years 2007 to 2018. Not all of the utilities had enough information, so not all of the indices were calculated for the entire time period. After the corrosion index values were calculated, we compared the predicted corrosion potential to the concentration of lead found in water samples. Using the LCR data provided by each municipality's water quality report, we determined over a 12-year span (2007 – 2018) if there were changes in lead concentrations. We classified water systems with 90th percentile lead levels that exceeded 15 ug/L as very corrosive, between 10 and 15 ug/L as moderately corrosive, and less than 10 ug/L as not corrosive. We then determined if the calculated index values accurately predicted the corrosion potential by comparing them with actual lead concentrations at each water facility. If the water facility analyzed had lead concentrations that changed over time, we compared values of corrosion indices for years where the LCR was met with years that exceeded the rule to see if the corrosion indices accurately predict changes in lead leaching over time.

Results

We calculated various corrosion indices and assessed their ability to predict potential corrosivity of treated drinking waters from different municipalities based on lead concentrations. From our results, we identified two indices—the Calcium Saturation Index (CSI) and Stiff & Davis Index (S&DSI)—that had the most accurate corrosion predictions.

The Calcium Saturation Index (CSI) was calculated for 5 out of the 7 sites analyzed. Cambridge, Milwaukee, and Tempe all had CSI values that predicted scaling and also had low lead concentrations in the water. Both Cambridge and Milwaukee had low 90th percentile lead concentrations for the time periods they were assessed. For the years that Tempe was analyzed, most of the 90th percentile lead levels were low, but in 2018, Tempe had moderate corrosion with a 90th percentile lead concentration of 12.0 µg/L even though the CSI still predicted scaling. It is interesting to note that Tempe's lead levels increased over time, but CSI values have remained relatively constant. For Providence, CSI values indicated scaling. However, Providence's 90th percentile lead levels almost always violated the LCR for the time period studied. New York City was the only water system with CSI values that predicted corrosion. This is somewhat accurate, as New York City's 90th percentile lead concentrations mostly indicate moderate corrosion. The CSI was accurate for two of the cities analyzed, moderately accurate for one, and not accurate for two. It is unclear whether orthophosphate or pH adjustment treatments affect the reliability of the CSI. The CSI was accurate for Tempe, which does not appear to have corrosion treatment. The index was also accurate for Cambridge and somewhat accurate for New York City, which both adjust the pH of their water. However, Providence also adjusts the pH of their water (along with alkalinity), and the CSI erroneously predicted scaling. It seems that orthophosphate addition does not affect the validity of the CSI. Milwaukee and New York City both add orthophosphate and the CSI was still accurate for Milwaukee.

The Stiff and Davis Stability Index is intended for waters with more than 10,000 mg/L of total dissolved solids, while drinking waters have significantly lower TDS levels. All of the water systems reviewed resulted in scaling predictions even though all of the cities had detectable lead concentrations. New York City had the values closest to predicting corrosion. Providence had the highest index values suggesting that Providence's water would be most likely to produce $CaCO_3$ scale. Overall, Cambridge had 90th percentile lead concentrations below the action limit and also had S&DSI values that indicate scaling. Likewise, for Tempe, there was a correlation between S&DSI and 90th percentile lead concentrations. As lead level increased the S&DSI value dropped, which means the water is less likely to scale with the pipe material. New York City and Providence both had S&DSI values that suggest scale formation despite having 90th percentile lead concentrations above the action limit. The S&DSI does not show any trend with respect to 90th percentile lead concentrations for both municipalities. Similar to other indices evaluated, the use of orthophosphates as a corrosion inhibitor could confound the results of the S&DSI. Both Newark and D.C. did not have enough data available to calculate this index.

Conclusions & Recommendations

Table A summarizes our conclusions about the applicability of the corrosion indices that we analyzed. From our results, we determined that the CSI and S&DSI were the best indices. We recommend that utilities use these indices to predict lead corrosion and we also designed a corrosion monitoring program for utilities to incorporate into their corrosion treatment.

Table A: Ranking of Index Predictions

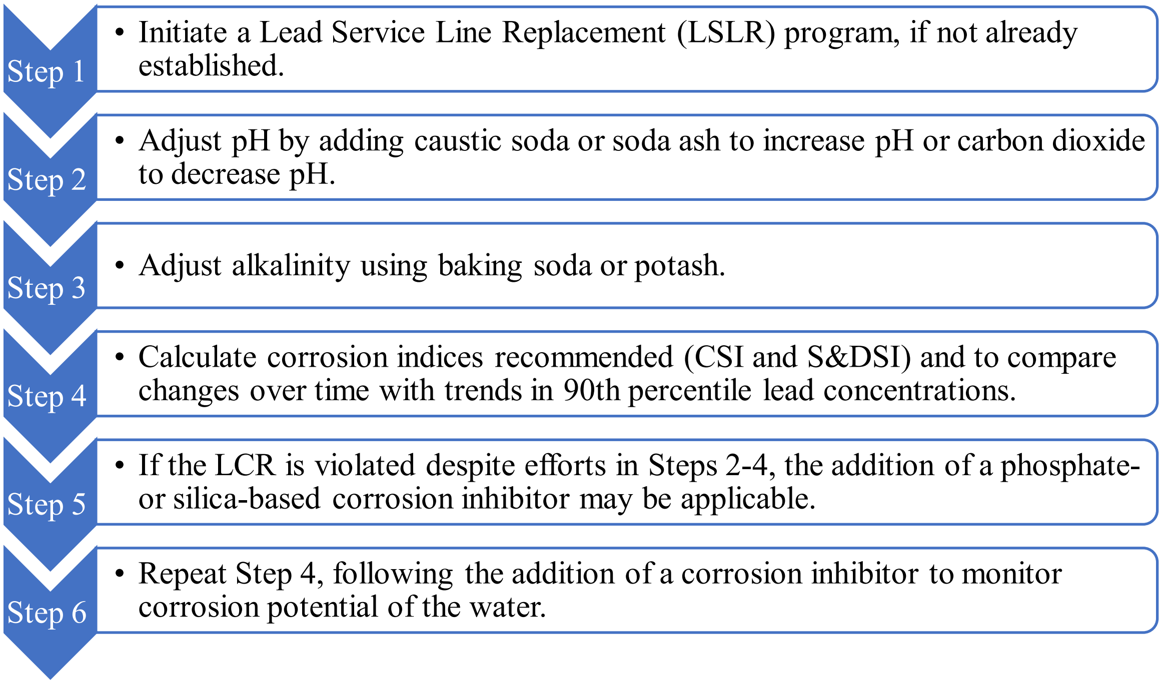
Utility		Milwaukee	Newark	D.C.	NYC	Cambridge	Providence	Tempe	Ranking (sum of points / maximum possible points)
		Treatment							
Type of Index	Index	Ortho	Ortho	Ortho	Ortho, pH adj.	pH adj.	pH & alk adj.	None	
$CaCO_3$ precipitation	LSI	0	N/A	0	0	3	0	1	0.17
	RSI	0	N/A	0	0	0	2	1	0.13
	S&DSI	4	N/A	N/A	0	4	0	3	0.55
	PSI	0	N/A	0	0	0	3	0	0.13
	CCPP	3	N/A	0	3	3	0	2	0.46
	DFI	0	N/A	0	0	3	0	1	0.17
	ME	0	N/A	0	0	3	0	1	0.17
	CSI	4	N/A	N/A	0	4	0	3	0.55
Corrosion of mild steel	L&SkI	4	1	0	0	0	3	1	0.32
	LR	0	1	0	0	0	3	1	0.18
Galvanic corrosion	CSMR	4	2	0	0	0	4	1	0.39
Aggressiveness of water	AI	3	1	0	2	3	0	4	0.46

Note on Rankings: 0 = index was inaccurate, 1 = index was moderately inaccurate, 2 = index was neutral, 3 = index was moderately accurate, 4 = index was accurate

The CSI provided accurate results for Milwaukee, Cambridge, and Tempe. The CSI predicted no corrosion for Milwaukee and the city had low 90th percentile lead levels. Likewise, Cambridge had CSI values predicting no corrosion and relatively low 90th percentile lead levels. For Tempe, the CSI received a ranking of 3, indicating moderate accuracy because as 90th percentile concentrations increased to moderate levels, the CSI showed no change. It is interesting to note that the two water utilities that had inaccurate rankings (NYC and Providence) have higher 90th percentile lead concentrations. This could suggest that the CSI is limited in its applicability.

The Stiff & Davis Stability Index (S&DSI) was the other most accurate index. Like the CSI, the S&DSI had an accurate prediction for Milwaukee and Cambridge, predicting $CaCO_3$ scaling and the cities had low 90th percentile lead concentrations. Tempe had a moderately accurate corrosion prediction. The S&DSI predicted scaling for Tempe and there were low lead levels. However, Tempe's 90th percentile lead levels increased over time and the index did not reflect this trend. It is interesting to note that the S&DSI was designed for waters with total dissolved solids over 10,000 mg/L. In all of the water utilities analyzed, the TDS never reached this concentration. Therefore, the results of the S&DSI could in fact be confounding or inapplicable to this project.

We designed a corrosion monitoring and prevention program that water utilities can use. It should be noted that if a water municipality already uses a corrosion index that is not one of our recommended indices specified below and the index successfully predicts lead concentrations, they can continue to apply such practices as they see fit. If a utility is struggling to find the optimal corrosion index for their corrosion monitoring program, we have developed a step by step process below to aid in this matter.



Step 1
- Initiate a Lead Service Line Replacement (LSLR) program, if not already established.

Step 2
- Adjust pH by adding caustic soda or soda ash to increase pH or carbon dioxide to decrease pH.

Step 3
- Adjust alkalinity using baking soda or potash.

Step 4
- Calculate corrosion indices recommended (CSI and S&DSI) and to compare changes over time with trends in 90th percentile lead concentrations.

Step 5
- If the LCR is violated despite efforts in Steps 2-4, the addition of a phosphate- or silica-based corrosion inhibitor may be applicable.

Step 6
- Repeat Step 4, following the addition of a corrosion inhibitor to monitor corrosion potential of the water.

Figure B. Steps for Corrosion Monitoring and Prevention

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1.0 Introduction

In recent years, high lead concentrations in municipal drinking waters have raised concern over the United States' deteriorating water infrastructure and prior use of lead in water distribution system pipes. Scientific studies have identified water systems in which corrosion of lead pipes has led to unacceptable lead concentrations at the tap of many homeowners; while news outlets have informed the public of the negative health consequences of ingesting lead. Based on the negative health impacts of lead, the U.S. Environmental Protection Agency (EPA) regulates lead concentrations in drinking waters through the Lead and Copper Rule (LCR), which sets a lead limit above which utilities must take action to reduce corrosion. However, in 2004, over 4,000 homes in Washington, D.C. had water with lead levels greater than the EPA Action Limit (Nakamura, 2004a). In 2014, news broke about dangerously high lead levels in Flint, Michigan's drinking water (LaFrance, 2017). Just one year ago in February 2019, the Pittsburgh Water and Sewer Authority was criminally charged for violating Pennsylvania's safe drinking water law by changing corrosion treatment without notifying the State Department of Environmental Protection. Due to this change, lead concentrations surpassed the LCR Action Limit (Rubinkam, 2019). The Natural Resources Defense Council (NRDC) estimated that in 2015 alone, there were over 8,000 LCR violations in the U.S. (Olson & Fedinick, 2016).

Corrosion in water distribution systems results from chemical and electrochemical processes that lead to the deterioration of the pipe material. In systems where pipe materials are made of or contain lead or scales with lead, corrosion can lead to dissolution of lead into the water. In general, corrosion degrades water systems and can result in leaks and water main breaks. Each day, nearly 6 billion gallons of drinking water are lost due to leaks in pipes, and over 24,000 water main breaks occur annually (ASCE, 2017). The outcome is elevated costs for municipalities and the federal government.

It can be difficult to evaluate the extent of corrosion in a system, as pipes cannot be easily examined in situ for corrosion impacts. Therefore, indirect methods have been developed to predict corrosion potential. One of these methods is calculation of a corrosion index, which is based on water quality parameters. The purpose of this research project was to determine which corrosion indices most accurately predict corrosion in drinking waters based on leaching of lead, and which indices are most widely applicable to different situations. To accomplish our project goals, we established four main objectives:

1. Research corrosion indices, including those used in water treatment practice as well as lesser known indices.
2. Obtain data on water quality and lead concentrations for Cambridge, Massachusetts; Milwaukee, Wisconsin; Newark, New Jersey; New York City, New York; Providence, Rhode Island; Tempe, Arizona; and Washington, D.C. water treatment systems.
3. Calculate corrosion index values using water quality data.
4. Compare corrosion index values to lead levels measured in the water systems.

We researched corrosion indices using a variety of resources including academic textbooks, peer-reviewed journal articles, and government publications. Research involved understanding what the corrosion indices were, how they were developed, what they predict, and how the indices are calculated. We obtained water quality data primarily through Water Quality Reports, also known as Consumer Confidence Reports (CCRs), that we found online through water utility websites. Additional data were collected by contacting individual water utilities, Robert F. Ferrari at Northeast Water Solutions, Inc., and Professor Jeanine Dudle at Worcester Polytechnic Institute. With the data we collected, we calculated corrosion index values over a 12-year time span from 2007 to 2018. After comparing the corrosion index predictions to the water systems' lead levels, we determined which indices were most accurate in predicting the corrosion potential of the waters. With our conclusions about the most accurate indices, we recommended that water utilities use the two most accurate indices and we designed a corrosion control monitoring program.

2.0 Background

In this chapter, we discuss what corrosion is and what factors can influence corrosion levels in distributed water (DW). As well, we evaluate the policies and regulations set by the United States Environmental Protection Agency (US EPA) that guide water municipalities on how to control corrosion in DW systems. We also examine case studies of lead leaching in drinking water and how different cities acted to resolve the issue. Lastly, we describe corrosion indices that can be used to predict corrosion and the different parameters used to calculate the indices.

2.1 Corrosion

The International Union of Pure and Applied Chemistry defines corrosion as "an irreversible interfacial reaction of a material (metal, ceramic, polymer) with its environment which results in consumption of the material" or erosion of the material such that it dissolves into the surrounding environment (McNaught & Wilkinson, 1997). In other words, corrosion reactions result in the degradation of a material through chemical and electrochemical processes. Figure 1 below depicts the mechanisms involved to induce corrosion on metal surfaces. Two reactions are occurring at the same time; at the anode, oxidation and at the cathode, reduction reactions. As a result of these interconnected reactions and the influence of an electrolyte (such as water), a corrosion cell is formed whereby the metal surface dissolves.

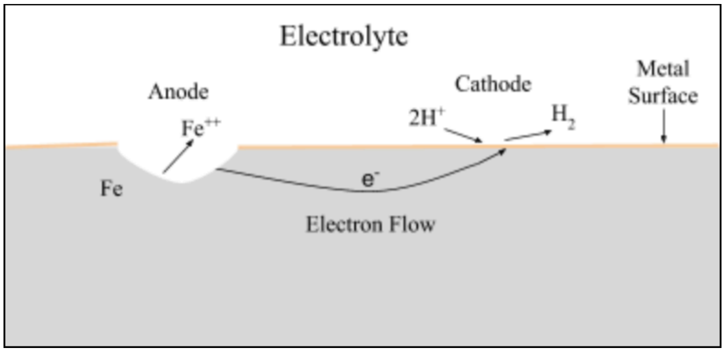


Figure 1. Mechanisms for Corrosion for Iron (McNaught & Wilkinson, 1997).

Understanding the mechanisms behind corrosion is necessary to understanding why pipes in water distribution systems corrode. As a result, the subsequent sections examine the types of corrosion common in water pipes, the factors that contribute to corrosion, and the practices implemented to prevent corrosion in water distribution systems.

2.1.1 Types of Corrosion

Corrosion can occur in several different ways based on the materials used, mechanisms for protective film development, pipe installation errors, and the water conditions.

Uniform Corrosion

As described earlier, corrosion results from an electrochemical reaction, where an anode site transfers electrons to a cathode region. One can further classify corrosion by evaluating the reactions that erode the metal surface. For instance, in uniform corrosion the anode and cathode sites can interchange, resulting in a more even decay of the pipe surface. This is referred to as a polyelectrode (Benjamin et al., 1996).

Non-Uniform Corrosion

Figure 2. Pitting of a copper pipe (Balkan, n.d.).

In non-uniform corrosion, the anode and cathode remain in one place and the anode site observes a localized loss of the metal surface, which can induce what is called pitting. Pitting, otherwise known as localized corrosion, is represented in Figure 2 (Balkan, n.d.). Pitting corrosion is usually more serious than uniform corrosion due to its ability to spread and seem like uniform corrosion. Thus, pitting corrosion is easily overlooked even with corrosion detection systems (Eckert, 2016). Eventually this site of pitting can spread to the outer surface and result in a leak. What makes non-uniform corrosion more dangerous is the fact that pitting is not necessarily going to occur even when the pipe observes a nonuniform corrosion (Cantor & Hill, 2011). A number of non-uniform corrosion mechanism are identified in the following sections.

Galvanic Corrosion

Galvanic corrosion describes a pipe system that is made up of various metal types with anode and cathode regions that do not change. Galvanic corrosion occurs from the interaction between two differing metals and the existence of a corrosion cell (Benjamin et al., 1996). Furthermore, one of the metals will serve as the anode and the other as a cathode. Other factors contributing to galvanic corrosion are the positioning of two dissimilar metals next to each other in terms of their relation in the galvanic series of metals, which is discussed below.

Galvanic Series of Metals

Figure 3 depicts the relationship between metal types (cathodic vs. anodic) and the potential for galvanic corrosion. As the list goes up metals become more anodic and therefore more corrosive. Likewise, as two metals become more dissimilar, meaning if two metals chosen in the chart had a large distant from one another, the more anodic metal species would have a stronger corroding potential (Penn Engineering, 2019). Based on the chart, steel and cast iron are both together in terms of their corrosion potential, which means there is a lesser chance for corrosion to take place. However, when compared to lead, lead is more cathodic and farther away from iron and steel indicating an increased potential for galvanic corrosion if they were installed together in a DW system. As mentioned in section 2.1, water acts as an electrolyte during the corrosion process. For this reason, when choosing the proper pipe materials for water distribution systems it is essential to evaluate the corrosion potential of metals to ensure minimal galvanic corrosion.

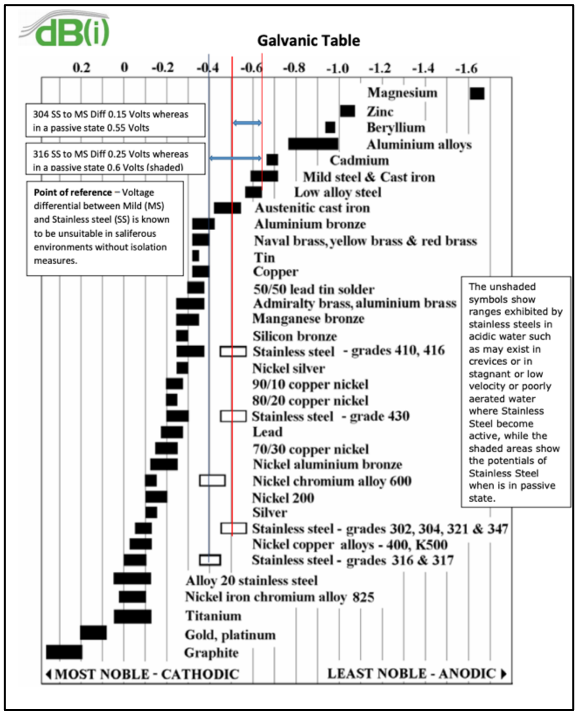


Figure 3. Galvanic Series of Metals (Penn Engineering, 2019).

Concentration Cell Corrosion

Concentration cell corrosion occurs where oxygen is concentrated in one location rather than evenly distributed in the pipe system or tank. For instance, a low dissolved oxygen (DO) region could develop around a bolt and a metal surface which is still in contact with a higher DO concentration in the main water pipe or storage tank (Cantor & Hill, 2011). In addition, a low DO area could form under pipeline debris and therefore get in contact with the higher DO and result in corrosion (Cantor & Hill, 2011). This last example would be less common in a DW system because treated water is less likely to have debris left over from the water treatment plant.

Erosion Corrosion

Erosion corrosion is a result of high velocity water scouring the metal surface of the pipe walls. This is a common feature where pipe systems have a bend (Cantor & Hill, 2011). At the bend the scouring flows in the direction at which the water had been going and forms a horseshoe like shape pit into the pipe where corrosion can occur.

Localized Corrosion

Localized corrosion results in pitting of the material, where the anode site is relatively small compared to the cathode. The rate of failure is significantly elevated compared to uniform corrosion. This type of corrosion can occur at the same time as a galvanic or uniform corrosion system, where a high stress area is present. In addition, this reaction occurs in areas where a protective film opens up and leaves itself vulnerable to the chemicals in the water that cause corrosion (Benjamin et al., 1996). Protective barriers are discussed in section 2.1.5.

2.1.2 Factors Contributing to Corrosion

Though the water itself is treated to specific drinking water standards regulated by the EPA, many factors play a role in causing corrosion that are difficult to treat and prevent. In water distribution pipes, the major reasons for corrosion are the chemistry of the water, the type of metal used, and the issues associated with protective coatings and scaling. Corrosion can be accelerated by pipe deformities, impurities, or nonuniformities, and improper welding techniques at pipe joints in homes (Droste & Gehr, 2019).

Factors associated with water that affect corrosion in metal pipes include: pH, dissolved inorganic carbon (DIC), temperature, chloride, sulfate, dissolved oxygen (DO), hydrogen sulfide, total dissolved solids (TDS), chlorine residue, and copper. The three most important parameters mentioned are pH, alkalinity, and DIC (Cantor & Hill, 2011). Table 1 provides a breakdown of each factor and its impact on corrosion in pipe systems.

Table 1. Constituents Impacting Corrosion (Benjamin et al., 1996; Droste, 2019; Cantor & Hill, 2011; Office of Water, 2016; Singley, 1984; Tchobanoglous & Schroeder, 1985)

Factor	**Impact**
Alkalinity	Researchers have identified the importance of alkalinity in producing protective films as well as in regulating pH in terms of balancing acidic species in water. Alkalinity, as shown below, is the sum of bicarbonate, carbonate, and hydroxide anions. High alkalinity in water is known to aid in forming high buffering capacities and resisting pH fluctuation. Waters with low alkalinity have a more difficult time in neutralizing acids as well as in maintaining pH. $\text{Alkalinity} = 2[CO_3^{2-}] + [HCO_3^-] + [OH^-] - [H^+]$, all variables in units of molar concentrations except for alkalinity, which is in units of eq/L.
Ammonia	Ammonia can increase the solubility of metals such as copper and lead by developing chemical complexes that interrupt corrosion control treatment (CCT). For instance, excess amounts of ammonia can lead to nitrification, where bacteria in the water break down ammonia into nitrite and nitrate, which are known to lower pH and alkalinity. Brass fixtures containing lead can corrode from such reactions.
Buffer Capacity	Buffer intensity/capacity describes the ability of water to resist a deviation in pH. Carbonate and bicarbonate are best suited as buffering species in water. The highest buffer capacities have been measured at a pH of 6.3 and above 9.0 and are the lowest at a pH range of 8.0 – 8.5.
Chloride and sulfate	High concentrations of each substance increase corrosion of iron, copper, and lead in piping systems. This is discussed further in the water treatment section of this table.
Chlorine residue	Promotes metallic corrosion for iron, copper, and steel.

Copper	Causes pitting in galvanized pipe.
Dissolved Inorganic Carbon (DIC)	Dissolved inorganic carbon is more specifically related to measuring the carbonate species in solution that can react with copper and lead to form protective scales. Usually expressed in mg/L of carbon, C or calcium carbonate, $CaCO_3$. The formula to calculate DIC is below: $DIC = [CO_2] + [H_2CO_3] + [CO_3^{2-}] + [HCO_3^-]$, all in units of molar concentrations. While DIC is similar to alkalinity, DIC varies by water temperature, pH, ionic strength, and alkalinity levels. Also, it is known that as DIC concentrations rises so does the buffer capacity of the water. For this reason, DIC should remain high enough to maintain pH in the water distribution system.
Dissolved oxygen	Increases the rate of corrosion reactions with regards to copper if levels are increased. In terms of lead, high DO provides a mechanism for lead oxides to form a scale.
Electrical Currents & Grounding	Could play a role in metal solubility by pitting, however, metal loss is usually found on the exterior surface where electrical currents exit the pipe to the soil.
Hardness	Hardness is the sum of all multivalent cations, however, calcium and magnesium are the most abundant in terms of a water system. Hardness is reported as mg/L of $CaCO_3$. Many common corrosion indices use hardness to predict scaling or precipitation of $CaCO_3$. If there is a high hardness, pH may need to be adjusted to control lead concentrations due to corrosion, however, this also may lead to the scaling of calcium carbonate, which on certain cold metal (lead, galvanized, or copper) pipes is not effective in producing a scale and therefore hinders corrosion control.
Microorganisms	Microbially Influenced Corrosion (MIC) causes pitting in pipes when microorganisms feed on the nutrients in the water while secreting an enzyme that lowers the pH surrounding itself. As a result, the area with a lower pH allows corrosion to occur on the pipe.
pH	Low pH promotes corrosion since ions in the water are able to disassociate with the metal surface while high pH can aid in preventing corrosion by limiting the conductivity of ions and metals. In waters with low pH, water ions can cause zinc to excrete from brass fittings, where traces of lead are known to exist.
Temperature	Like most chemical reactions, high temperatures increase the rate of corrosion.

Total dissolved solids (TDS)	High TDS elevates conductivity and corrosion rates. Elevated levels of TDS indicate high concentrations of ions (e.g., Ca^{2+}, Na^{+}, Mg^{2+}, Cl^{-}, CO_3^{2-}) , which increases the reactiveness of the water and the potential for corrosion to occur. This being said, low TDS can also lead to corrosive water since the water has the ability to accept many anions and cations in the pipe system. For instance, scales that have formed can be dissolved and result in the metal surface being exposed to conductive ions in the water.
Velocity	Water chemistry that promotes scale-forming can benefit from high flow rates by aiding in the distribution of protective coatings on the surface of the pipe. However, in copper pipe systems, high velocities are associated with removing this protective coating, greatly increasing pipe deterioration. High flow rates with DO can also trigger corrosion, by helping oxygen react with the surface of metal. Low flows, such as stagnant flows, cause tuberculation and pitting both of which are common in iron distribution systems.
Water Treatment	Water treatment processes tend to reduce natural organic matter (NOM), and alkalinity, while adding chloride and sulfate for disinfection and coagulation, respectively. Both are known to increase the corrosive potential of the water. Fluoridation and hydrofluosilicic acid decrease pH and alkalinity as well. Softening and membrane filtration also play a role in corrosion processes.

2.1.3 Effects of Corrosion

The United States water distribution infrastructure in most areas has exceeded it service life and much of this infrastructure is up for replacement. Currents estimates by the American Society of Civil Engineers (ASCE) suggest that nearly 6 billion gallons of treated water are lost due to leaking pipes each day and over 240,000 water main breaks occur each year. Due to leaks, roughly 14 to 18% of the treated water in the U.S. is wasted, which could support the water demands of nearly 15 million homes (ASCE, 2017). Corrosion is a major factor in causing these leaks and water main breaks. For example, Jim Lary indicates that in the mid-20th century, cast iron and ductile iron (DI) were the main pipe materials distributing drinking water. However, iron pipes are vulnerable to corrosion (caused by soil acidity, water quality, and temperature changes) which ultimately leads to leaks and breaks (Lary, 2000). Consequently, the ASCE notes that in order to improve and upgrade the piping infrastructure in America, at least $1 trillion will need to be invested (ASCE, 2017).

In addition to pipe degradation of water distribution systems, there are considerable health issues to those individuals who consume water contaminated with lead and copper. Lead accumulates over time in the body and as a result can cause significant issues for young children, infants, and fetuses (USEPA, 2019a). The reason why this age group is more impacted by lead exposure is due to the immaturity of the blood-brain barrier, which protects the brain from pathogens and toxins that are present in the bloodstream, and elevated absorption of the gastrointestinal system (Götz & Woodruff, 2017). Therefore, a lower exposure dose is more dangerous for children than adults since the development process is still ongoing (Brown & Margolis, 2012). These small doses of lead and copper cause harm to the nervous system, learning impairment, hearing loss, slowed growth, and issues with synthesis and function of red blood cells (USEPA, 2019). Studies show that adults exposed at work from lead materials have a greater chance of colds and influenza, kidney failure, gout, and high blood pressure (Brown & Margolis, 2012). Research conducted over the course of 12 years studied 13,000 adults who were exposed to lead conditions. Those who had elevated exposure (blood levels >3.6 μg/dL) had increased risk of death and cardiovascular mortality, but not for cancer mortality (Brown & Margolis, 2012).

2.1.4 Lead Regulations

In order to protect human health, the EPA published the Lead and Copper Rule (LCR) in 1991. According to the rule, if "lead concentrations exceed an action level of 15 ug/L or copper concentrations exceed an action level of 1.3 mg/L in more than 10% of customer taps sampled, the system must undertake a number of additional actions to control corrosion" (USEPA, 2019b). Drinking water systems must monitor lead levels and if the water exceeds the action level, the public must be informed. Before the LCR was published, the previous lead standard was 50 ug/L and was measured at the entry point of the distribution system. The LCR also created a maximum contaminant level goal (MCLG) of 0 for lead (USEPA, 2019b). The LCR has been criticized as poorly enforced and not stringent enough to protect people from lead (Dennis, 2019).

The EPA recently announced proposed revisions to the LCR on October 10, 2019, after working on them since 2010 (Dennis, 2019). This is the first major revision of the rule since it was first published. There are no proposed changes to the action level of 15 ug/L and MCLG of 0, but there is a new proposed trigger level of 10 ug/L. If a water system exceeds the 10 ug/L trigger level but not the 15 ug/L action level, then the system would have to adjust their corrosion treatment to reduce lead levels. If the drinking system does not currently treat for corrosion, they would conduct a corrosion control study. The water systems would also have to initiate outreach and lead service line (LSL) replacements, and work with the state to set an annual goal for LSL replacement. The EPA also proposed requiring systems that exceed the action level to replace at least 3% of LSLs annually, a reduction from the current 7% requirement (Gannon & Reddy, 2019). If a resident decides to voluntarily replace the portion of lead pipe on their side of the property, the water utility would be required to replace the public portion of the LSL (Dennis, 2019). Another proposed edit to the LCR is a new requirement for systems to test drinking water in 20% of schools and childcare centers every year (Gannon & Reddy, 2019). Water utilities would be required to create a LSL inventory and make it public to the community. The EPA would also add changes to close loopholes that allow water systems to hide lead problems. All test samples must be from homes with LSLs, whereas the current rule only requires half of the samples to be from such homes if LSLs are present. Testing protocols would no longer permit methods that can temporarily reduce lead levels; aerators can no longer be removed from faucets and water cannot be pre-flushed. However, environmental advocates say that the changes still ignore the most important part of reducing lead contamination: requiring the removal of the 6 million LSLs in the United States. Erik Olson, a senior director for the Natural Resources Defense Council (NRDC) says "There are going to be problems with lead contamination as long as you leave lead pipes in the ground" (Dennis, 2019).

2.1.5 Treatment and Preventive Options

In order to prevent corrosion in pipe systems, a number of practices have been developed. The type of metal installed for distributing water plays an important role in corrosion prevention. The 1950s marked a transition period from cast iron to ductile iron for piping systems. It was believed that ductile iron (DI) was of higher quality, however, the DI pipe matrix and thinner wall actually made the pipe material more vulnerable to pitting and corrosion (Lary, 2000). In 2010 the EPA initiated the Clean Water and Safe Drinking Water Infrastructure Sustainability Policy for the purpose of ensuring sustainability within water infrastructure (Sustainable Solutions Corporation, 2017). In addition, the EPA created the National Water Program on Climate Change in 2015 to review the environmental and health impacts of polyvinyl chloride (PVC) as an alternate choice for water distribution. The Sustainable Solutions Corporation reports that "PVC pipe and fittings are resistant to chemicals generally found in water…[and that] no known toxicity effects occur in the use of the product" (Sustainable Solutions Corporation, 2017). Other benefits of PVC use include corrosion resistance, a high strength to weight ratio, high flow coefficients, which aid in lowering costs for operations and maintenance. According to the Sustainable Solutions Corporation, the AWWA study called, *Buried No Longer*, was inaccurate about the longevity and performance of PVC pipes installed in the 1960-1970s by noting that PVC can in fact last over 100 years when installed properly (Sustainable Solutions Corporation, 2017).

In the exploration of solutions for limiting corrosion in pipe systems it was determined that surfaces should be coated to prevent completion of an electron circuit. Therefore, a protective coating provides a barrier over corrosion prone surfaces to inhibit this electron transfer from the anode to cathode site. Corrosion-resistant alloys, otherwise called hybrid metals, were created by metallurgists and chemists with the purpose of preventing changes in the crystalline structure of the metal. These noble metals are very stable and resistant to oxidation, but are quite costly and not necessarily feasible for pipe replacements in distribution systems (Droste & Gehr, 2019). Inhibitors are substances that react in water to produce a compound that spreads a protective layer (insulation) to electron transfer. An example of this process would be a chromate ion:

$$2CrO_4^{2-} - 6e^- \rightarrow Cr_2O_3$$

Pure noble metals are high in the Electromagnetic field (EMF) and usually are cathodic (meaning it converts all anodic areas on a metal to cathodes such that corrosion stops). However, they too are expensive and are not strong enough structurally for use as pipes (Droste & Gehr, 2019).

In terms of water chemistry there exists a number of measures to prevent corrosion in water pipes. These methods are discussed below.

Corrosion Inhibitors

The use of chemicals to inhibit corrosion is normal in the water industry. With this said, not all of the chemicals developed for the industry are well suited for controlling corrosion and some just control the aesthetic problems, for example, red water that results from the transport of loose corrosion deposits of iron ions in piping systems (Cantor & Hill, 2011). Popular inhibitors used in the industry are orthophosphates, polyphosphates, blended phosphates, and silicates. These are discussed in detail below.

Orthophosphates

Orthophosphates are chemicals developed to produce protective or passivating films on the walls of lead pipes. Like the naturally occurring barrier made by carbonate (CO_3^{-2}), oxide (O^{-2}), and hydroxide (OH^{-1}) ions, orthophosphate ions bind with the metal ions that secrete from anodic sites to form corrosion by-products that ultimately lead to saturation of the products to produce a solid in the water (Cantor & Hill, 2011). This solid is the protective film. A number of compounds have been developed, but the phosphate compound that controls the solubility of lead is hydroxypyromorphite ($Pb_5(PO_4)_3OH$). Despite positive results of orthophosphates, in some cases with newer pipe lines, lead release increased due to a smaller increase in pH. For orthophosphates, the typical dosage to passivate lead and copper is 0.5 to 3 mg/L (Cantor & Hill, 2011).

Polyphosphates and Blends

Similar to orthophosphates, polyphosphates and polyphosphate-orthophosphate mixtures control corrosion in pipe systems. In fact, in addition to inhibiting corrosion, mixtures of ortho and polyphosphates were developed to control hardness and red-water (Benjamin et al., 1996). Polyphosphates, however, are polymer based with linked units of orthophosphate ions to compose many different chains and structures. They attach metal ions to their molecular structure. For this reason, polyphosphates became popular in treating iron and manganese issues in water pipes. Eventually, over time the polyphosphate structure is expected to breakdown into orthophosphate ions, where it takes on the same role as discussed in the section above. This being said, the timing of this breakdown is complex and difficult to predict. As a result, studies show that despite predictions, there is certainty that some individuals are being exposed to higher concentrations of the metal ions that have bound to the polyphosphate chains (Cantor & Hill, 2011). Polyphosphates effectiveness in controlling lead and copper depends greatly on pH and alkalinity levels. For instance, at water alkalinities less than 30 mg/L and pH values between 7.4 and 7.8, polyphosphates outperformed orthophosphates. However at times where these water parameters do not exist, a study conducted by Cantor et al. (2000) showed that polyphosphate blends quadrupled lead concentrations in the pipe system. These specific water parameters limit the performance of polyphosphates to water treatment facilities that require small doses to treat for iron and manganese levels. Like orthophosphates, the general dosage for lead and copper control is 0.5 to 3 mg/L.

Zinc Polyphosphates

Bimetallic (zinc-containing) phosphates were introduced around 1950 and are a combination of ten to thirty percent zinc and the rest ortho/poly-phosphates. The zinc polyphosphates are less soluble and more difficult to dissolve compared to sodium ortho/poly-phosphates. This being said they perform well in harder more mineralized waters than just straight phosphates. In regards to zinc orthophosphates, studies suggest that the zinc causes the formation of carbonate compounds and obstructs the cathode while the phosphate compounds form over the anode to prevent corrosion (Benjamin et al., 1996). In the past, claims were made that zinc polyphosphates were the best for expediting the formation of a barrier on the pipe surface. Similar to orthophosphates and polyphosphates, the dosage for corrosion control is 0.5 to 3 mg/L.

Silicates

Silicates have been used since the 1930s to form protective layers on metal surfaces. These indirect inhibitors, for instance, sodium silicate or sodium phosphate, use the dissolved oxygen (from aeration) in the water to produce the barrier on the surface of the metal pipe. (Reed, 2016). Other texts argue that pure silicate corrosion protection results from the increase of pH to ultimately induce passivation. In contrast to phosphates, silicates form a thin layer over corroded metal, and require a higher dosage to control corrosion, 4 to 30 mg/L compared to 0.5 to 3 P/L for phosphate inhibitors (Benjamin et al., 1996; Cantor & Hill, 2011). This being said, phosphate-silica blends have been introduced and these two products work together. The silica blocks the anodic sites on the metal surface while the phosphate binds to metal ions in the water to precipitate and form protective layers (Benjamin et al., 1996).

2.2 Cases of Lead Leaching in Drinking Water Systems

In order to gain a sense of the problem associated with lead contamination, the history of lead pipe systems was investigated. The emergence of lead pipes for water distribution started in the late 19th century, especially in cities with populations greater than 30,000 people. Despite costing more than iron, lead had two significant advantages: (1) it lasted roughly 20 years longer than iron and (2) it could be easily bent and adjusted around fixed structures without breaking (Troesken, 2006).

As lead grew in popularity, the Lead Industries Association (LIA) was formed to promote the use of lead. Physicians at the same time started linking negative health conditions to lead exposure. In fact, prior to the development of lead as a standard for water distribution systems, articles from 1859 refer to engineers, physicians, and sanitarians that were concerned with the use of LSLs because of lead secreting into drinking water (Rabin, 2008). This being said, lead continued as a main piping material for drinking water because the federal government had little involvement or regulation in how industries dealt with environmental hazards such as lead secretion. Some city governments even mandated the use of lead for water distribution systems due to its pliability and longevity (35 years) compared to other pipe materials such as plain iron and steel (16 years), galvanized iron (20 years), and cement (28 years) (Troesken, 2006). Eventually policymakers and engineers acknowledged the health impacts of lead consumption as technology advanced. By the 1930s, the federal government as well as state governments mandated regulation of lead used in water distribution systems (Troesken, 2006). Though there existed a gradual decline in lead use, a study conducted by the EPA in 1984 suggests some cities continued to use lead as standard procedure (Rabin, 2008). Out of the 153 municipal systems observed, 112 of them confirmed that lead pipes had been installed in the past while 5 of the public water systems noted that LSLs were authorized well past the 1930s. Another 7 systems stated that they followed the current code, which in 1984 did not fully restrict lead pipe installation. Even the city of Chicago recognized that LSLs were still permitted through the 1980s. Then the Safe Drinking Water Act Amendments of 1986 passed banning the installation of lead pipes for water distribution systems (Durenberger, 1986).

More recent studies conducted by Cornwell et al. (2016) estimate that 6.12 million LSLs exist in the U.S. as of 2016 (Cornwell et al., 2016). These LSLs make up 11,200 community water systems (CWS) serving populations ranging from less than 10,000 to over 50,000 people. Figure 5 from Cornwell et al. (2016) provides a visual representation of the relationship between population size and number of CWSs that contain LSLs. As displayed in Figure 5, 2.8 million or 46% of the LSLs were identified in CWSs providing a population greater than 50,000. The total population of people within the 11,200 CWSs is estimated between 15 and 22 million, roughly 5 to 7.5% of the U.S. population (Cornwell et al., 2016). Cornwell et al. (2016) calculated the cost of full LSL replacement to be around $30 billion. Other estimates range from $16 to $87 billion (Masten et al., 2019).

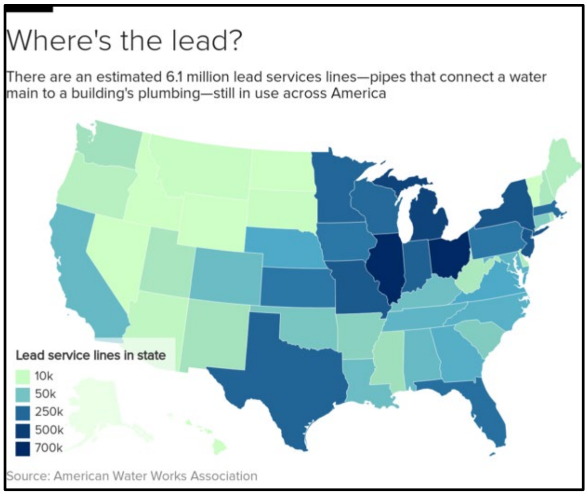


Figure 4. Number of LSLs by state (Layne, 2018).

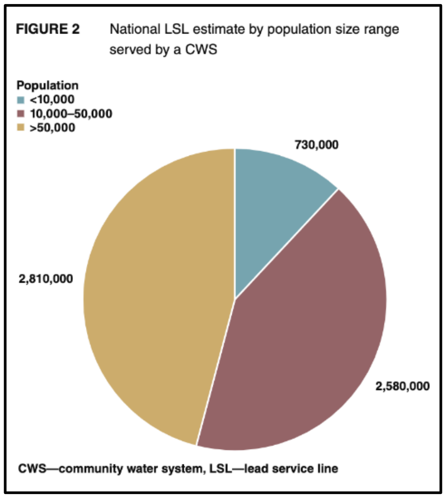


Figure 5. Lead service lines in the U.S. by population size (Cornwell et al., 2016).

Similarly, in Figure 4, a map depicts the United States with approximations of the number of LSLs in each state. On the basis of this map, the Great Lakes region and Northeast are particular areas with greater LSLs still in use. The reasoning as discussed earlier is due to the federal governments little involvement in regulating lead pipe installation during the early 20th century. As the 1984 EPA report noted, cities like Chicago continued to install lead pipes up to the date of the study (Rabin, 2008), and the map clearly shows Illinois as one of the states with the highest number of LSLs, over 700,000.

An additional report from the Natural Defense Resource Council (NRDC) suggests that nearly 5,400 CWSs in the U.S. had over 8,000 reports of violations to the LCR in 2015 alone. The violations included lack of monitoring for lead, reporting breaches in compliance, and failure to treat water with elevated lead levels. These 5,400 CWSs provide drinking water to a population exceeding 18 million (Olson & Fedinick, 2016). Out of the 8,000 known violations, only 900 were enforced by the EPA. Furthermore, in the same year, there were 1,000 CWSs serving 3.9 million people that violated the LCR's action level of 15 µg/L (Olson & Fedinick, 2016). All of these figures come from the EPA's database and were analyzed by the NRDC.

Following the SDWA Amendment of 1986, stricter laws were enacted by the U.S. federal government to restrict the use of lead pipes, flux, or solder in public and residential water pipe systems (Durenberger, 1986). In 1991 the Lead and Copper Rule (LCR) greatly restricted the amount of lead and copper concentrations allowed in water distribution systems. Despite the development of extensive means for limiting human exposure to elevated levels of lead and copper, there are numerous locations across the United States where these metals impact human health.

2.2.1 Flint, Michigan

In the spring of 2014, the city of Flint, Michigan changed their drinking water source from Detroit Water and Sewage Department (DWSD) to the Flint River. Previously, Flint's water had been treated for corrosion issues; however, those in charge of treating the Flint River water at the Flint Water Service Center (FWSC) treatment plant overlooked the importance of corrosion mitigation practices (LaFrance, 2017). The purpose of the source water change was to minimize the cost of treated water; approximations stand at $5 million over a 2-year period (Masten, Davies, Haider, & McPherson, 2019b); (McQuaid, 2016). Within weeks of the water change, residents of Flint observed alterations in water quality, for instance, color, odor, and taste. Even General Motors Corporation (GM), made complaints regarding the water corrosivity and therefore sourced their water from elsewhere (Masten et al., 2019).

In December 2014, LeeAnne Walters, a stay at home mother of four children, noticed the tap water turn brown and yellow (McQuaid, 2016). Her three-year-old son stopped growing due to the health impacts of the water quality. Once testing began at the tap of homes for lead and copper, concentrations exceeded the LCR action level of 15 μg/L by nearly seven times (~100 μg/L) (McQuaid, 2016). Marc Edwards, a Civil and Environmental Engineering Professor at Virginia Polytechnic Institute and State University, received a call from Walters regarding concerns of the health impacts of Flint's water. Edwards, well known for his work in Washington D.C. when he identified a change from chlorine to chloramines for secondary disinfection as the main cause of corrosion in the city's pipe service lines, took the initiative to investigate Flint's problem. In Walter's home, testing from February 2015 reported concentrations of 104 μg/L. Edwards and his research group also took 120 samples from homes in Flint and discovered that 24 (20%) of the samples exceeded the action level of 15 μg/L under the LCR. In addition, the 90th percentile of these samples was 30 μg/L (Masten et al., 2016).

Mona Hanna-Attisha, a pediatrician near Flint, conducted a study on the blood lead levels (BLLs) of children. She concluded that Flint had the highest BLLs following the outbreak of elevated lead concentrations in the water of the FSWC system. Based on her findings, children's BLLs had increased 2.5 times the normal level (Masten et al., 2016; Masten et al., 2019). As a result of these findings the Michigan Department of Environmental Quality (MDEQ) set out to conduct a city-wide sampling of lead in residential homes. Over 33,000 samples were taken from December 2014 to September 2019 with the help of LeeAnne Walters, who is considered one of the few individuals who spearheaded the Flint water crisis, along with Edwards (Masten et al., 2019; McQuaid, 2016).

The characteristics of the water in the Flint River played a significant role in corrosion of the LSLs in the city (Masten et al., 2019). For instance, the treated water had extremely high chloride-to-sulfate mass ratio (CSMR) and Larson-Skold Index (L&SkI) values, low alkalinity, and high TOCs (Masten et al., 2019). The CSMR value based on studies conducted by Edwards (1999) should be below 0.58 to meet the action limit of lead concentrations set by the USEPA. Another report completed by Nguyen et al. (2010) suggested that CSMR values should be less than 0.2 to satisfy the action limit (Masten et al., 2016). In the example of Flint, the six samples collected by Masten et al. (2016) had CSMR values above 0.58, the lowest being 2.8. Likewise, with the L&SkI, values below 0.8 are less likely to promulgate corrosion. The samples from Flint resulted in values above 1.2, an indication of severe corrosion potential. As mentioned in this report, these two indices alone should have concerned professionals in the FWSC of the potential outbreak of lead and copper (Masten et al., 2016). An additional parameter that impacted the use of the Flint River water was the fluctuation of pH over the course of a three month period. Daily pH ranged from 7.00 to 8.46 in treated water, which greatly disrupts equilibrium and the potential for protective layers to form on the surface of pipes. Further, the treatment system also dealt with high bacteria concentrations, specifically total coliform violations in the summer of 2014, which are known to absorb organic matter and therefore reduce the presence of compounds needed to passivate metal surfaces (Masten et al., 2016).

In order to reduce lead levels in the city of Flint, the state of Michigan passed laws to ensure stricter regulation of lead exposure by reducing the action level from 15 μg/L to 12 μg/L as well as to replace all 8,000 LSLs within 20 years. Once the replacement of all lines takes place, there is still no guarantee lead concentrations will diminish to zero right away (Masten et al., 2016; Masten et al., 2019). Years may pass before lead concentrations in all service lines in Flint decrease below the action level. Even then, issues of brass fixtures have been studied and found to secrete lead above the action level in newer buildings with 'lead-free' plumbing (Masten et al., 2019). Other alternatives (for example, filtration systems) have shown promise for controlling lead and copper in tap water.

2.2.2 Washington, D.C.

Most people think of Flint, Michigan when they hear about lead contaminated water. However, the 2004 drinking water crisis in Washington, D.C. exposed even more people to lead. Marc Edwards, who is well known for his research on lead corrosion, says that the "extent of the problem in D.C. was about 20 to 30 times larger than Flint" (Augenstein, 2016). In January 2004, the public became aware of high lead levels in residential water in Washington, D.C. It was discovered that over 4,000 homes had water with lead levels over the 15 ug/L limit set by the Environmental Protection Agency (EPA). Over 2,000 residences had lead levels over 50 ug/L, with 157 homes with lead levels over 300 ug/L. People were shocked to learn that lead levels suddenly became so high when D.C. had not experienced lead issues in the past (Nakamura, 2004a).

The increased lead in the water was found to be caused by a change in the water treatment process at the Washington Aqueduct. Chlorine treatment was originally used to kill bacteria in the water, but it was producing dangerous disinfection by-products in the water. Water treatment operators changed secondary disinfection treatment from chlorine to chloramine instead. However, the chloramine corroded the protective scaling on the lead service lines and caused lead to leach into the water (Augenstein, 2016). The change in water chemistry impacted a vast number of people: the D.C. Water and Sewer Authority (WASA), now called D.C. Water, supplies about 500,000 residents with drinking water and about 23,000 service lines were made with lead (Nakamura, 2004d; Guidotti et al., 2007).

There were several issues with how the D.C. water crisis was handled. WASA had known about the lead issue since 2002 and did not inform residents until November 2003 (Augenstein, 2016). WASA did hold a public meeting about water issues in December 2003, but the lead contamination was not advertised to the public. D.C. council members and the mayor stated that they were unaware of the lead problem (Nakamura, 2004a). WASA also fired Seema S. Bhat, a high-ranking water quality manager in 2003 for repeatedly reporting lead issues to the EPA. Bhat directly informed the EPA about the lead contamination because D.C. clearly exceeded the federal guidelines on lead levels. She wanted WASA to replace LSLs and inform the public of the lead levels. However, her superiors told her to respect the chain of command and eventually fired her (Nakamura, 2004b). The U.S. Centers for Disease Control (CDC) published a report in 2004 that stated that no children in D.C. were found to have elevated blood lead levels, even those in the homes with the highest lead water levels (Augenstein, 2016). However, experts claimed that the CDC study used inaccurate data and did not truly reflect the BLLs of D.C. residents (McGrath, 2010). Edwards conducted his own research in 2008 and found that the BLLs of children were 4 times higher than before the water treatment change. Edwards also found an abnormally high number of late-term miscarriages and spontaneous abortions between 2000 and 2004. In 2010, an investigation by the U.S. House of Representatives' Science and Technology Subcommittee concluded that the CDC made "scientifically indefensible" claims and omitted many test results for children with lead poisoning (Leonnig, 2010).

Another problem with D.C.'s lead crisis was how to resolve it. EPA guidelines required WASA to replace 7% of the city's lead pipes every year, which was about 1,600 service lines with costs between $10 and $20 million. WASA dedicated $17 million to replace about 1,300 lines and the EPA gave an additional $3.7 million in federal funds to contribute to pipe replacements (Nakamura, 2004c). However, WASA only replaced 385 lead lines in the first year of the pipe replacement program (Nakamura, 2004d). WASA can only replace pipes in public space. Homeowners are responsible for replacing pipes on private property, which can cost several thousand dollars that residents may not have (Nakamura, 2004a). Unfortunately, if a lead pipe is only partially replaced by the city, it may make lead corrosion worse. Digging up the line disrupts the entire system and can cause even more lead to break off of the pipe and end up in the water (Augenstein, 2016).

After the lead contaminated water became publicized, water treatment operators added orthophosphate to the treatment process. Orthophosphate reacts with the lead in pipes to form lead oxide which is resistant to leaching. It takes several years for orthophosphate to effectively solve the problem, but improvements were seen within a year of the new treatment. A high dose of orthophosphate was initially used to make sure that a protective layer formed inside the pipes and the dose was eventually lowered as the leaching issue became less severe. The water treatment facility also runs lead pipe loops to mimic the water's behavior in residential homes and monitor lead levels; water is run through pipes that have the same conditions as the pipes in the distribution system, allowing scientists to analyze the effects that the water treatment has on the water (Augenstein, 2016).

2.2.3 Pittsburgh, Pennsylvania

Pittsburgh, Pennsylvania has also experienced lead contaminated water in recent years and the Pittsburgh Water and Sewer Authority (PWSA) was criminally charged in February 2019 for violating the state's safe drinking water law. The Pennsylvania attorney general's office claimed that PWSA mishandled a lead pipe replacement program and put over 150 homes at a higher risk of lead poisoning (Rubinkam, 2019).

Pittsburgh's water issues date back to 2013, when PWSA almost violated the federal action level for lead in water. In September 2013, PWSA monitored lead levels at 50 sites and detected lead levels of 14.8 ug/L at the 90th percentile, just under the federal limit of 15 ug/L. PWSA then changed its anti-corrosion treatment from soda ash to caustic soda in April 2014. The water authority broke state law by not informing the Pennsylvania Department of Environmental Protection (DEP) beforehand or receiving approval for the change. Changing the chemical used for treatment could lead to increased corrosion, opposite of the desired effect, which is why all changes must be approved by the DEP. Inadvertently increasing corrosion in the drinking water system could be a great issue for the city's 16,000 to 20,000 lead water pipes. The

DEP learned about the treatment change in February 2016 and issued a Notice of Violation, requiring PWSA to test for lead in the water system. A few months later, PWSA released the first results from the DEP-required lead testing. The report showed that over 10% of 100 homes tested had lead levels over 22 ug/L and that lead levels in Pittsburgh had been rising since 2001. Like Washington, D.C., Pittsburgh was required to replace 7% of lead pipes every year and had to start a public awareness campaign. In January 2017, PWSA released the lead test results from December where they found that the 90th percentile of lead levels in homes tested was 18 ug/L, still over the 15 ug/L limit (Vicens & Caruso, 2017).

In March 2017, Pittsburgh Mayor Bill Peduto announced a Safe Water Plan to distribute water filters to residents. The city and PWSA devoted $500,000 towards the plan, and People's Gas utility matched the funds to help Pittsburgh residents. The city planned to distribute filters to all residents, regardless of income level, who their water provider is, and if they rent or own their home (Krauss, 2017). The Urban Redevelopment Authority of Pittsburgh also approved the $500,000 Replace Old Lead Lines Program (ROLL) for low-income residents to take out low interest loans to replace their water lines (Hope & Smeltz, 2017; Vicens & Caruso, 2017). 90th percentile lead levels continued to fluctuate, ranging from 10 to 22 ug/L between June 2016 and December 2018. To lower lead levels, PWSA began adding orthophosphate to the water treatment process to produce a protective scale inside pipes to prevent corrosion in spring 2019. PWSA has also continued to replace water pipes: 2,047 public lines and 1,315 private lines were replaced in 2018 (Shoemaker, 2019).

In February 2019, the PWSA was met with criminal charges by the Pennsylvania Attorney General for safe drinking water violations. Within a week, the water authority reached a $50 million settlement to replace water lines and provide filters to low-income residents. PWSA also stated that it planned to replace 3,800 public lines and 2,800 private water lines in the next 2 years (Jones, 2019).

2.2.4 Madison, Wisconsin

In 2001, Madison, Wisconsin began to replace all of the city's lead pipes (Corley, 2016). It was a huge effort, taking 11 years and $15.5 million to replace all of the system's 8,000 lead pipes. The city was the first to do so and demonstrated that it was possible to replace the public and private service lines (Verburg, 2016). Abigail Cantor, a chemical engineer and president of Process Research Solutions, a Madison consulting firm that focuses on drinking water, conducted tests on old pipes and helped jump start the city's lead pipe removal efforts (Powers, 2019; Verburg, 2016). In 1992, Madison found that the 90th percentile of lead levels in water was 16 ug/L. This exceeded the EPA guideline of 15 ug/L, and the city began adding anti-corrosion chemicals to the water (Verburg, 2016). Unfortunately, the chemicals did not resolve the issue. Chemists tried adding polyphosphate to reduce lead levels, but they actually increased by four times (Madison Water Utility, 2016). Orthophosphate was also considered to prevent corrosion because it did reduce the lead in the water. However, there was concern about excessive algae growth (Schmidt, 2016; Verburg, 2016). Phosphate is a plant nutrient and adding it to drinking water could increase nutrient discharges in sewer water. Madison's sewage treatment plant already experienced issues with algae and weed growth in water and had just spent millions of dollars upgrading the plant to reduce nutrient discharges. The city did not want to revert back to old issues, so orthophosphate was ultimately ruled out as a solution (Verburg, 2016).

Because chemical solutions were not applicable, Cantor told the water utility that the only way to reduce lead levels was to remove the lead pipes. Removing all of the lead service lines in

Madison would be a costly process and there was a lot of pushback from residents and regulators. The water utility is only responsible for replacing public service lines and not all homeowners could afford to replace their service lines, but partial replacements can increase lead levels (Corley, 2016). Wisconsin's Department of Natural Resources (DNR) wanted a guarantee that all of the lead service lines would be replaced. It took years for Madison and the DNR to reach an agreement, but on December 21, 2000, an agreement was signed that required residents to replace their lead service lines, with the city partially reimbursing homeowners (Corley, 2016; Verburg, 2016). About 5,600 property owners participated and the city reimbursed half of the cost, up to $1,000 (Schmidt, 2016).

In 2003, homes with replaced pipes were monitored for lead. Even though the lead pipes were removed, lead was still found in the water. EPA drinking water officials were confused as to where the lead was coming from. After studying the pipe system, it was found that the water in the pipes was coming from wells that had high manganese and iron concentrations. The EPA determined that the manganese and iron formed scales inside the pipes and adsorbed lead. The lead in the water was not coming from lead pipes, but from the pieces of scale that had crumbled off into the water (EPA, 2018). When the water utility found the cause of the lead, a flushing program was started and the pipes were flushed with water to remove the scale (Verburg, 2016).

2.2.5 Milwaukee, Wisconsin

Beginning in 1996, Milwaukee Water Works initiated corrosion mitigation practices in their water treatment facility by adding orthophosphates to the system. Prior to the addition of corrosion inhibitors, Milwaukee's 90th percentile lead concentrations were measured around 28 μg/L, well above the LCR action level of 15 μg/L (Lewis et al., 2017). Urban Milwaukee noted that lead levels at one point reached as high as 130 ug/L. Despite stopping lead pipe installation in 1951 for city and in 1961 for private contractors, the number of LSLs known to exist in Milwaukee is estimated between 68,000 and 77,600 (40-46% of the total service lines), indicating the sheer magnitude of lead exposure and therefore the need to deal with this issue (Jannene, 2018). As a result of treatment, the 90th percentile lead levels were reduced to as low as 4.6 μg/L when measured in 2002 and from there 90th percentile levels remained relatively constant around 8.2 μg/L. In 2016 the city passed its 2017 budget which included a program to replace 600 LSLs that had leaks or failures (Health Impact Project, 2017). More specifically, the city is providing $3.6 million out of $3.9 million of its own budget to replace pipe at 600 city-owned residences. As well, $2.6 million in state grants will fund LSL replacement of 300 day care centers and 300 residential homes. The remaining $300,000 will be allocated to aiding in line replacement of privately owned homes and for distributing water filters and bottled water to residences/owners during the construction phase (Health Impact Project, 2017). In addition, home owners are only subject to pay one-third of the total costs up to $1,600, which can be paid over a 10 year period. It is expected that full LSL replacement will take upwards of several decades with an overall cost of $750 million (Health Impact Project, 2017; Jannene, 2018).

In 2016 the Milwaukee Water Works (MWW) conducted a study to see how LSL replacement impacted lead concentration before and after road construction in order to best advise and prepare residents and homeowners of what procedures to follow during such events. This test observed no construction as a control, partial LSL replacement, sewer main replacement, water meter inlet valve replacement, and road reconstruction. The test indicated that road construction of any form had the tendency to increase lead concentration at the tap for the course of a few weeks and then a steady decline from there (Lewis et al., 2017). As a result, the MWW halted water pipe replacements to limit the impact on LSLs in 2015. Following this study, the MWW and Milwaukee Health Department (MHD) developed criterion communicating the risk of construction when repairing LSLs that are leaking or damaged. The document was set out to highlight the following:

a. The importance of providing residents/homeowners with a notification of the leak and the presence of an LSL and what is needed to fix it.
b. Pinpoints the vulnerable populations for the MHD to notify.
c. Offer the residents/homeowners filters and other materials during the construction phase.
d. Additional precautionary steps for places with higher populations of children (i.e. day-care centers and schools).
e. Informing the contractors and residences of the need to flush the system after construction to reduce lead concentrations.
f. Asking for volunteers who be willing to take samples of the water quality after construction to ensure procedures are met and if not what can be changed to mitigate the problem.

2.2.6 Providence, Rhode Island

The city of Providence and surrounding towns of Cranston, Johnstone, and North Providence is an example of a city in New England with lead issues. Providence Water (PW) provides drinking water to 600,000 people, making it one of the largest water distribution systems in the nation that exceeds the LCR. An estimated 13,800 homes (19% of all retail customers) receive water through LSLs (O'Brien, 2016). Data that is public to all on the Providence Water website illustrates the issue of lead concentrations in the city. Since 1997, 90th percentile lead concentrations have exceeded the LCR action level of 15 μg/L in 13 out of the 22 years worth of sampling. On two occasions (2009 and 2013), the 90th percentile lead levels at the time of measurement were 30 μg/L. In 2013, PW started to manage the release of lead by increasing pH and alkalinity. PW also implemented a flushing program to combat the issue (O'Brien, 2016; Providence Water, 2019). Since introducing these practices, lead levels have declined, however, numbers are just below or above the LCR limit. Furthermore, in 2018 the 2nd period sampling was 22 μg/L, thus showing the city's continued problem with lead.

A report by the Providence Journal expressed that homes constructed prior to 1947 had a greater chance of pipes, joints, and soldered points to have lead components (Borg, 2017). In addition, PW indicates that standing water has higher traces of lead due to the water remaining stagnant over a longer period of time. As a result, more lead is able to leach into the system at the joints, fixtures, or other lead containing materials (Borg, 2017). Dyana Koelsch, a spokesperson for the Providence Water Supply Board acknowledged that "Everything coming through the Scituate Reservoir and coming through our thousands of miles of mains is clean ...Our vulnerability is the lead service pipes from the public main to the curb and, even if we fix that, from the curb to private homes" (O'Brien, 2017). As noted by Koelsch, even with the lead service line replacement (LSLR) program the issue is not necessarily resolved. Residences and homeowners must make a choice of whether or not to replace their in-home plumping. This of course is not cheap and it may not fix the problem as discussed in the Flint, Michigan case study. Lead concentrations can linger for extended periods of time after lead pipe removal at levels well above the LCR. For instance in the past few years, Providence, RI campaigned $45 million to replace LSLs, yet due to reports that the replacement could lead to worsening conditions in private homes, this initiative never occurred (O'Brien, 2016).

In order to best adapt to the corrosion of pipes in Providence, PW provides brochures to residences to educate them on the importance of flushing as well as a link to the PW website's interactive map that identifies LSLs throughout the city. Moreover, the literature summarizes the health impacts of lead consumption, where it originates from, and what PW is currently working on to provide safe water to the community.

2.3 Corrosion Indices

Various water quality indices have been used to predict a water's corrosion potential. Many of these indices measure calcium carbonate ($CaCO_3$) saturation to determine if a scale will form or be dissolved inside a pipe. While these indices are widely used for corrosion control, it is important to note that they measure $CaCO_3$ saturation, and not corrosion (Ozair, 2011). The most popular indices used in water treatment are the Langelier Saturation Index (LSI), the Ryznar Stability Index (RSI), Stiff and Davis Stability Index (S&DSI), and the Larson-Skold Index (Leitz & Guerra, 2013).

2.3.1 Langelier Saturation Index

The Langelier Saturation Index (LSI) is the most widely used index (Ozair, 2011). It was developed in 1936 to assess the relationships between $CaCO_3$ saturation and the corrosion of iron or galvanized pipe (National Research Council, 1982). It is used for water with a total dissolved solid (TDS) concentration less than 10,000 mg/L.

The variables needed to calculate a water's LSI are pH, conductivity, TDS, alkalinity, and total hardness (Oram, n.d.). The pH of the water is compared to the pH where the water is saturated with $CaCO_3$, known as pH_s. The following equations are used to calculate LSI:

$$LSI = pH_{actual} - pH_s$$

$$pH_s = pK_2 - pK_s - log[Ca^{+2}] - \log[Alk]$$

pK_2 is the negative log of the second solubility constant of carbonic acid and pK_s is the negative log of the solubility constant for $CaCO_3$. Ca^{2+} is in units of mol/L and alkalinity is in units of mol/L as $CaCO_3$. An LSI value of 0 indicates that the water is in equilibrium with $CaCO_3$; the water will neither precipitate nor dissolve a scale layer of $CaCO_3$. LSI values greater than 0 show that the water is supersaturated with $CaCO_3$ and a scale layer will form. If a water has an LSI value less than 0, the water is undersaturated and will dissolve $CaCO_3$. Waters with LSI values less than -0.5 are categorized as "aggressive". The more negative the LSI value, the more aggressive the water is. Aggressive water is usually correlated with corrosion, with highly aggressive water resulting in corrosion (Ozair, 2011).

2.3.2 Ryznar Stability Index

In 1944, John Ryznar developed another index from empirical observations of corrosion rates and film formation in pipes. He developed Figure 5 from these observations. He modified the LSI to create the Ryznar Saturation Index (RSI), which is defined as:

$$RSI = 2\ pH_s - pH$$

pH_s is the same saturation pH used in LSI, and pH is the measured pH of the water. If a water has an RSI value between 6.5 and 7.0, $CaCO_3$ is considered to be in saturation equilibrium. RSI values less than 6.5 are saturated and a $CaCO_3$ scale will form. RSI values greater than 7.0 are said to be undersaturated and the water will dissolve solid $CaCO_3$, corroding the pipe.

Because RSI is a modification of LSI, all of the limitations of LSI also apply to RSI. An important inconsistency of RSI is that the value for saturation equilibrium changes with pH_s. If the water has a pH_s of 7, then the RSI for saturation equilibrium is 7. However, a water with pH_s of 9 will have an RSI value of 9 for saturation equilibrium (Ozair, 2011). Advantages of the RSI include that it provides better estimates of the severity of scaling and it always yields positive numbers (Cavano, 2005).

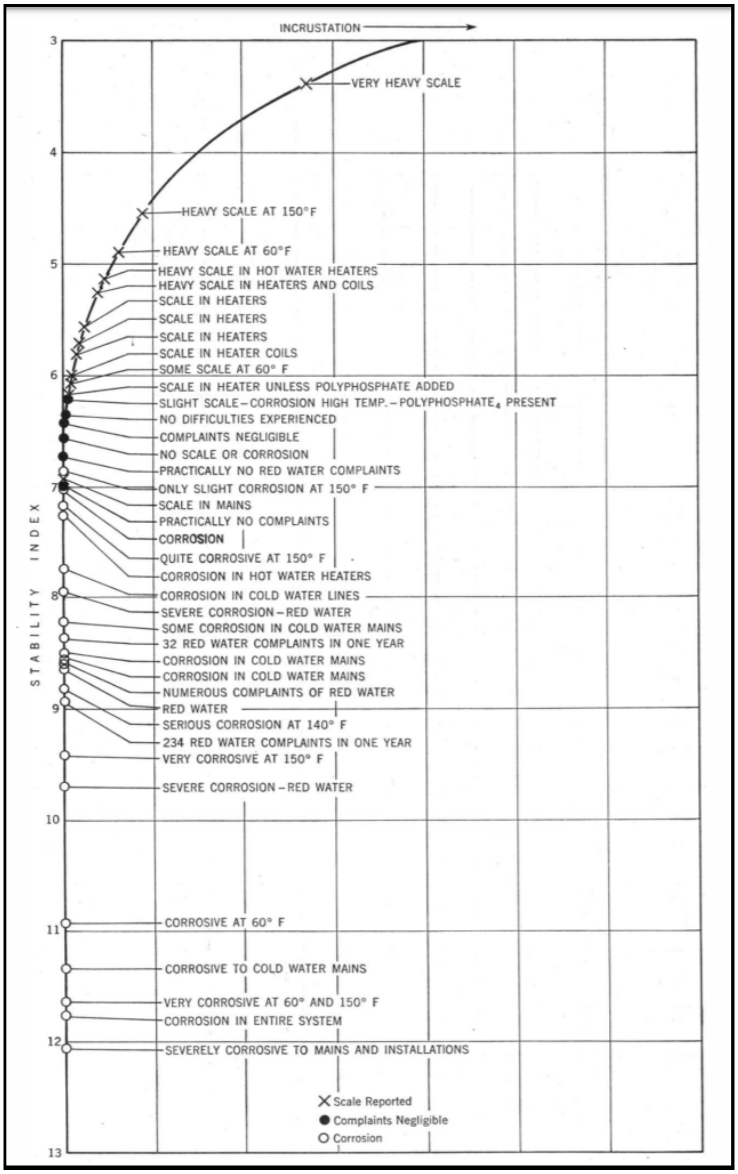


Figure 6. Degrees of Corrosion and Scale from Ryznar's Observations (Singley, 1981).

2.3.3 Stiff and Davis Stability Index

The Stiff and Davis Stability Index (S&DSI) can be used to estimate if calcium carbonate will form a scale. It is used for waters with more than 10,000 mg/L of TDS. This index is specifically designed for scale control for reverse osmosis installation designs (ASTM, 2019). To calculate S&DSI, K and pH_{sat} must be determined. The K value is based on ionic strength of the water (I) and temperature (T in °C). The equations for K are:

$$\text{If I} < 1.2: \quad K = 2.022e^{\frac{(ln(I)+7.544)^2}{102.60}} - 0.0002T^2 + 0.00097T + 0.262$$

$$\text{If I} > 1.2: \quad K = -0.1I - 0.0002T^2 - 0.00097T + 3.887$$

Using K, pCa, and pAlk, pH_{sat} can be calculated. Ca is in units of mg/L as $CaCO_3$, and alkalinity is in units of mg/L as $CaCO_3$.

$$pH_{sat} = pCa + pAlk + K$$

S&DSI can then be calculated using the following equation:

$$S\&DSI = pH - pH_{sat}$$

If S&DSI is positive, it indicates that a calcium carbonate is predicted to form a scale. If S&DSI is negative, then calcium carbonate will not scale and the water may be corrosive (Leitz & Guerra, 2013).

2.3.4 Larson-Skold Index

The Lason-Skold Index (L&SkI) was developed from corrosion measurements in steel lines carrying Great Lakes water. It is very similar to the Larson Ratio and compares the same ions, in addition to carbonate (CO_3^{2-}). It is defined as:

$$\text{L\&SkI} = \frac{[Cl^-] + [SO_4^{2-}]}{[HCO_3^-] + [CO_3^{2-}]}$$

$$\text{Percent of alkalinity as } [HCO_3^-] = 100\% * \left[\frac{1}{1+\frac{K_2}{[H^+]}}\right]$$

$$\text{Percent of Alkalinity as } [CO_3^{-2}] = 100\% - \left(100\% * \left[\frac{1}{1+\frac{K_2}{[H^+]}}\right]\right)$$

Where the ion concentrations are in units of meq/L, and K_2 refers to an equilibrium constant for $CaCO_3$. L&SkI values less than 0.8 signify that scaling will occur. If a water has an L&SkI value between 0.8 and 1.2, then corrosion may occur, and L&SkI values greater than 1.2 indicate high levels of corrosion. L&SkI was derived from empirical measurements using water from the Great Lakes. It is questionable if the index can be used to characterize corrosion in other types of water (Leitz & Guerra, 2013).

2.3.5 Larson Ratio

The Larson Ratio (LR) is used to predict corrosion in iron and steel pipes. It compares the ratio of chloride (Cl^-) and sulfate (SO_4^{2-}) to bicarbonate (HCO_3^-). These ions were chosen because Cl^- and SO_4^{2-} have been shown to significantly affect how ferrous materials behave. As sodium chloride or sodium sulfate concentration increases, corrosion rates and iron uptake in the water dramatically increases. Cl^- is known to be a prominent cause of pitting in stainless steels and can break down protective films on ferrous metals and alloys. Research also shows that the amount of iron and mild steel corrosion caused by Cl^- and SO_4^{2-} is related to their concentrations relative to HCO_3^-. HCO_3^- in water can act with calcium to buffer pH increases from corrosion or form a carbonate scale on pipes, making it a significant factor in iron and steel corrosion. The ratio is defined as:

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

Units for the LR are molar concentrations. The greater LR value that water has, the greater the probability of corrosion is. It is recommended that a water should have an LR value less than 0.5 (Ozair, 2011).

2.3.6 Chloride-to-Sulfate Mass Ratio

Chloride-to-sulfate mass ratio (CSMR) is the ratio of chloride to sulfate (both in mg/L) for a water source:

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

Research had shown that chloride and sulfate levels in water affected galvanic corrosion in pipes. Chloride encouraged more lead leaching when the lead was galvanically connected to copper, but not when the lead materials were not connected to copper. Sulfate was found to prevent corrosion when lead was both isolated or galvanically connected to copper. In 2007, Marc Edwards conducted research to determine a research between CSMR and lead corrosion. Edwards' research found that water with a high CSMR value can corrode lead solder and leach lead from brass. The research suggested that water with low chloride or sulfate concentrations can be more susceptible to lead leaching if the coagulant used for water treatment changes, causing a large shift in CSMR (Edwards & Triantafyllidou, 2007).

2.3.7 Aggressive Index

The Aggressive Index (AI) is used to evaluate if a water will corrode asbestos-cement pipes. It can also be used to evaluate the leaching of cement lining in steel pipes. It is defined as:

$$\mathrm{AI} = \mathrm{pH} + \log \mathrm{AH}$$

Where A represents the alkalinity of the water in units of mg/L as $CaCO_3$ and H is the calcium hardness of mg/L as $CaCO_3$. AI values lower than 10 are considered aggressive. Waters with AI values between 10 and 12 are predicted to have moderate corrosion. If the AI value is greater than 12, scaling will occur (Ozair, 2011).

As a simplified version of LSI, AI has a great number of shortcomings that must be remembered when using the index. AI does not account for temperature, ionic strength, or TDS.

AI assesses $CaCO_3$ saturation, so it should identify nonaggressive waters fairly accurately, as a $CaCO_3$ coating from oversaturation should protect a pipe from corrosion. However, if the water is undersaturated with $CaCO_3$, then AI cannot accurately predict the corrosion of A/C pipes since $CaCO_3$ is just a small component of cement (National Research Council, 1982).

2.3.8 Calcium Saturation Index

The Calcium Saturation Index (CSI) measures calcium carbonate saturation of a water. Calcium carbonate solubility directly affects scale formation on many different appliances, from water heaters to well screens to water taps. CSI can be measured using the following equation:

$$CSI = pH + log[Ca^{++}] + log[Alk] - log\frac{K_s}{K_2} - 9.30 - \frac{2.5\sqrt{\mu}}{1 + 5.3\sqrt{\mu} + 5.5\mu}$$

$[Ca^{++}]$ represents Ca concentration and [Alk] is $CaCO_3$ concentration, both in ppm. μ is ionic strength, K_S is the solubility product for calcium carbonate, and K_2 is the ionization constant for carbonic acid (Larson & Buswell, 1942).

2.3.9 Puckorius Scaling Index

The Puckorius Scaling Index (PSI), sometimes called the Practical Scaling Index, was developed around 1980 by Paul Puckorius and Maxey Brooke. They had experienced issues when using LSI and RSI, and found that the two indices sometimes gave contradicting results or they both predicted scale formation when nothing actually occurred. They developed PSI for predicting scale formation in cooling tower systems by replacing the pH used in RSI with the equilibrium pH (pH_{eq}) (Ozair, 2011). PSI can be calculated as:

$$PSI = 2*pH_s - pH_{eq},$$
$$\text{where } pH_{eq} = 1.485*log[Alk] + 4.54$$

PSI always has positive values and has a similar interpretation as RSI. PSI values below 6 indicate $CaCO_3$ scaling, and values above 6 predict that the water will dissolve $CaCO_3$ and prevent scaling or protective film development. By using pH_{eq} in its equation, PSI attempts to minimize the effects that buffering agents can have on the water (Puckorius & Cartwright, 2012).

2.3.10 Calcium Carbonate Precipitation Potential

The CCPP is regarded as a more accurate calculation due to its "quantitative" analysis of $CaCO_3$ in water, thereby providing an improved measurement of the extent at which $CaCO_3$ precipitates (Gebbie, 2000). The CCPP can be calculated in two ways. The first method is through a hand calculation and the second utilizes a computer-generated model created in 1996 by the American Water Works Association (AWWA), adapted from the Rothberg, Tamburini, and Windsor Model. With regard to hand calculation, the Caldwell and Lawrence Diagram (C-L Diagram) provides a graphical procedure. Figure 6 is the Caldwell and Lawrence Diagram. C2 is

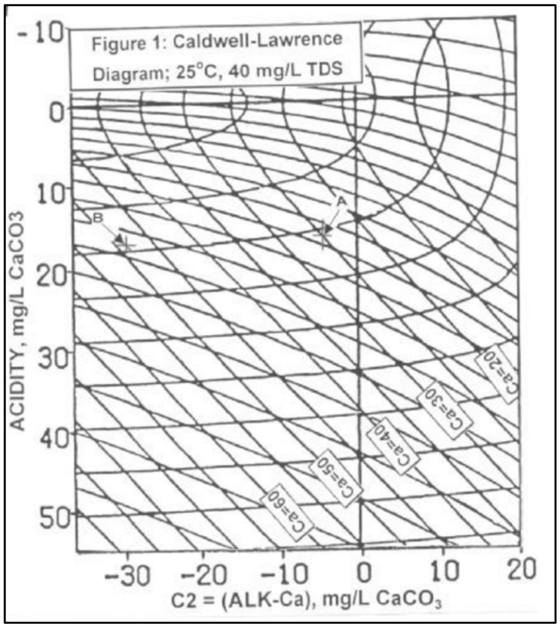


Figure 7. Caldwell-Lawrence Diagram (Caldwell & Lawrence, 1953).

represented on the x-axis and the y-axis is acidity measured in mg/L as $CaCO_3$. The relevant equations are as follows:

$$C2 = [Alk]-[Ca^{+2}]$$

$$\text{Acidity} = [Alk](1 + 4.245 \times 10^{6} \cdot 10^{-pH})$$

$$\text{CCPP} = ([Ca] - [Ca_{Sat}])$$

Like the equations for C2 and acidity, CCPP is in concentrations of mg/L as $CaCO_3$. The C-L Diagram was developed primarily for a standard temperature of 40°C and for TDS equal to 40 mg/L. This being said, the calculation of CCPP can be computed over a diverse set of conditions (up to TDS = 200 mg/L) without leading to significant errors (Gebbie, September 6, 2000). Table 2 defines what CCPP values mean.

Table 2. CCPP Values and their Meaning

Water quality relative to corrosivity	**Value of CCPP in mg/L as $CaCO_3$**
Scaling (water saturated with CCPP)	< 0
Passive	0 to -5
Moderate	-5 to -10
Aggressive (corrosive)	< -10

2.3.11 Riddick Corrosion Index

The Riddick Corrosion Index (RCI) was developed in 1944 by Thomas M. Riddick with the intention of incorporating other water quality parameters other than calcium carbonate solubility to provide a more inclusive equation that depicts what water chemistry causes corrosion in pipe systems (Ozair, 2012). Additional factors involved with the RI include dissolved oxygen, chloride ions, noncarbonate hardness, and silica. The following formula was derived empirically through field work:

$$\mathrm{RI} = \frac{75}{Alk}\left[CO_2 + \frac{1}{2}[Hardness\ - Alk] + Cl^- + 2N\right] \cdot \left[\frac{10}{SiO_2}\right] \cdot \left[\frac{DO + 2}{Sat.\ DO}\right]$$

Hardness and alkalinity are in mg/L expressed as $CaCO_3$. Nitrate (NO_3^-) takes the place of nitrogen in mg/L and the rest are in concentrations of mg/L. Riddick acknowledges that silica and DO are usually not measured during water quality testing, and states that the terms including silica and DO may be omitted if there is no information available on these two parameters. The RI index was developed for the softer waters of the northeastern United States and therefore does not represent the harder waters of the central plains (Ozair, 2012; Singley, Beaudet, & Markey, 1984). Larger RI values predict more corrosive water. RI values from 0 and 5 indicate that scale will form and values from 6 and 25 indicate noncorrosive water. RI values between 51 and 75 predict that a water will be corrosive, values from 76 to 100 indicate very corrosive water, and waters with RI values over 101 are predicted to be extremely corrosive (Singley, Beaudet, & Markey, 1984).

2.3.12 McCauley's Driving Force Index

The McCauley's Driving Force Index (DFI) was developed in 1960 by Robert F. McCauley and similar to previously discussed indices, integrates $CaCO_3$ precipitation. The DFI is helpful in predicting the weight of precipitate that forms (DeZuane, 1997); (Singley et al., 1984)). The equation for the DFI is as follows:

$$\mathrm{DFI} = \frac{Ca^{++} \cdot CO_3^-}{K_{SO} \times 10^{10}}$$

Calcium concentration is measured in the form of mg/L as $CaCO_3$ likewise with CO_3^-. K_{SO} is the solubility product of $CaCO_3$. A DFI < 1 indicates water is supersaturated and will likely precipitate $CaCO_3$. A DFI = 1 means no precipitation or depositing will occur. Lastly, a DFI > 1 suggests water is undersaturated and $CaCO_3$ will likely dissolve in the pipe system. A study conducted by Rossum and Merrill in 1983 observed indices that involved $CaCO_3$ and found that the LI and DFI are in fact suitable indicators for the saturation of $CaCO_3$, but not for any other measurement. Furthermore, their report concluded that the Calcium Carbonate Precipitation Potential (CCPP) was most satisfactory in calculating saturation of $CaCO_3$ (Imran et al., 2005).

2.3.13 Momentary Excess

In 1952, J.F. Dye developed an equation for Momentary Excess (ME). This index is based on the solubility of $CaCO_3$ and can be expressed as:

$$\mathrm{ME} = \frac{Ca^{2+} + CO_3^{2-}}{2} - [(\frac{Ca^{2+} + CO_3^{2-}}{2})^2 - (Ca^{2+} * CO_3^{2-}) + (K_s * 10^{10})]^{0.5}$$

Ca^{2+} and CO_3^{2-} are both in units of mg/L $CaCO_3$ (Singley, 1981). ME values greater than 0 indicate that the water is oversaturated in $CaCO_3$, and ME values less than 0 indicate undersaturation. A water with an ME value equal to 0 means that the water is at saturation equilibrium (Rossum & Merrill, 1983).

3.0 Methodology

Our goals were to determine which corrosion indices most accurately predict corrosion in drinking water based on leaching of lead, and which indices are most widely applicable to different situations. To accomplish these goals, our objectives were:

1. Research corrosion indices including those used in water treatment practice as well as lesser known indices.
2. Obtain data on water quality and lead concentrations for Cambridge, Massachusetts; Milwaukee, Wisconsin; Newark, New Jersey; New York City, New York; Providence, Rhode Island; Tempe, Arizona; and Washington, D.C water treatment systems.
3. Calculate corrosion index values using water quality data.
4. Compare corrosion index values to lead levels measured in the water systems.

The results of the data collection and analysis were then used to evaluate the overall usefulness of the various indices for predicting corrosion.

3.1 Research Corrosion & Corrosion Indices

We first researched the mechanisms of corrosion, including the interactions between water and the interior surface of pipes in distribution systems. These reactions may result in precipitation of protective scales or in metal leaching, which leads to erosion of the interior surface of pipes in water distribution systems. We then researched corrosion indices by reading scholarly journals, academic textbooks on water quality, and government manuals. Some indices are used to predict the potential for calcium carbonate precipitation, while others predict galvanic corrosion potential in pipes or use a ratio to compare concentrations of ions in the system such as the Chloride-to-Sulfate Mass Ratio (CSMR), which indicates whether or not lead chlorides will form in a water distribution system. For each index, we determined the purpose of the index, what water quality parameters the index is based on, and how the index is calculated. Specifically, we found an equation for each index, including what units were required for each parameter in the equation, and found resources in which to look up constants if necessary for a particular equation. In addition, we investigated which indices are most commonly used in the drinking water industry and under what conditions (e.g. water quality, pipe material, and geographical location) the indices were developed. A detailed discussion of the findings is provided in Chapter 2.

3.2 Obtain Data

Our project primarily focused on cities on the East coast, such as Cambridge, Massachusetts; Providence, Rhode Island; Newark, New Jersey; New York City, New York; and Washington, D.C. We assessed cities with various lead contamination in the water: Cambridge had very low lead levels, while Providence, Newark, and Washington, D.C. all experienced either present or past lead issues. We also tried to obtain data on Pittsburgh, Pennsylvania, a city with a current lead crisis, but the water utility did not return our calls or emails. Tempe, Arizona was analyzed because Robert F. Ferrari at Northeast Water Solutions, Inc. in Exeter, RI had data available for that city. Milwaukee, Wisconsin was reviewed in this report because they had adequate data available in their Water Quality Reports, and the city implemented an intensive Lead Service Line Replacement program.

We obtained water quality data through a variety of resources. First, we obtained data from Robert Ferrari at Northeast Water Solutions, Inc., Exeter, RI, in electronic format for the cities of Providence, Rhode Island and Tempe, Arizona. In addition to the data provided by Mr. Ferrari, Professor Jeanine Dudle at Worcester Polytechnic Institute provided us with water quality data from Cambridge, Massachusetts. We also utilized Water Quality Reports (also known as Consumer Confidence Reports or CCRs) from both Cambridge and Tempe, as well as Milwaukee, Wisconsin; Newark, New Jersey; New York City, New York; Providence, Rhode Island; and Washington, D.C. for additional water quality data. The Water Quality Reports were found through the online U.S. EPA Find Your Local CCR Database at https://ofmpub.epa.gov/apex/safewater/f?p=ccr_wyl:102. CCRs can be located by inputting a state and city, town, or county and the database provides links to individual water utility websites that match your search criteria. The CCRs can then be found on the water utility websites. Not all of the CCRs provided enough information to calculate the various corrosion indices, so Milwaukee, Newark, and Providence were contacted by email or phone to request additional water data. The water quality variables needed to calculate the indices are listed in Table 3.

Cambridge, Newark, New York City, and Washington, D.C. were analyzed for the years 2007 to 2018. For years prior to 2007, the water quality reports tended to provide less data pertinent to calculating the indices. Water quality data for Milwaukee was only available online for the years 2014 to 2018. Data for Providence varied over the years, so indices were calculated from 2009 to 2018, 2013 to 2018, or 2015 to 2018, depending on how much information was available. Most of the indices were calculated from 2007 to 2018 for Tempe, but two indices were analyzed from 2011 to 2018, due to limited data.

3.3 Calculate Corrosion Indices

From the research discussed in section 3.1, we identified the necessary parameters to calculate the corrosion indices. Water quality variables and constants required for each index are shown in Table 3. We calculated each index using the equations shown in Chapter 2. While some of the indices can be easily calculated by hand, others are more complex and are more efficiently calculated using a spreadsheet program. All indices were calculated in MS Excel for ease of analysis and comparison to lead concentrations (as discussed in Section 3.4).

3.4 Compare Corrosion Indices to Lead Concentrations

After calculating corrosion index values for various water supplies, we compared the predicted corrosion potential to the concentration of lead found in water samples. There are methods to directly measure corrosion, including physical inspection of pipes, x-ray diffraction, and Raman spectroscopy, that were not practicable for our research project. Therefore, we used lead concentrations as reported in annual Water Quality Reports (available online at each municipal website) as indirect measurement of corrosion within each water system.

Using the LCR data provided by each municipality's water quality report, we determined over a 12-year span (2007 – 2018) if there were changes in lead concentrations. We classified water systems with 90th percentile lead levels that exceeded 15 ug/L as very corrosive, between 10 and 15 ug/L as moderately corrosive, and less than 10 ug/L as not corrosive. We then determined if the calculated index values accurately predicted the corrosion potential by comparing them with actual lead concentrations at each water facility. If the water facility analyzed had lead concentrations that changed over time, we compared values of corrosion indices for years where the LCR was met with years that exceeded the rule to see if the corrosion indices accurately predict changes in lead leaching over time. Typically, facilities monitor for lead once every year, but some are allowed to reduce monitoring to up to once every three years while others must test for lead twice a year. With the 12-year timeframe that we used for most of the water systems, we were able to still see trends in lead concentrations even if the water system conducted lead testing every three years.

Table 3. Variables Needed to Calculate Corrosion Indices

Indices	**Variables Needed**																			
	Alkalinity (mg/L as $CaCO_3$)	**Ca^{2+} (mg/L as $CaCO_3$)**	**Ca_{sat}^{+2} (mg/L)**	**Cl^- (mg/L or meq/L)**	**CO_3^{-2} (mg/L or meq/L)**	**CO_2 (mg/L)**	**Conductivity (µS/cm)**	**DO (mg/L)**	**DO_{sat} (mg/L)**	**HCO_3^- (mg/L or meq/L)**	**Hardness (mg/L as $CaCO_3$)**	**K_{sp} (mol/L)**	**K_2 (mol/L)**	**NO_3^- (mg/L as Nitrogen)**	**pH**	**pH_{sat}**	**SO_4^{-2} (mg/L or meq/L)**	**SiO_2 (mg/L)**	**Temp (°C)**	**Ionic Strength (µS/cm)**
AI	✓										✓				✓					
CCPP	✓	✓	✓												✓					
CSI	✓	✓					✓					✓	✓		✓				✓	✓
CSMR				✓													✓			
LSI	✓	✓										✓	✓		✓				✓	
LR				✓						✓							✓			
L&SkI				✓	✓					✓							✓			
DFI		✓			✓							✓							✓	
ME		✓			✓							✓							✓	
PSI	✓															✓				
RI	✓			✓		✓		✓	✓		✓			✓				✓		
RSI															✓	✓			✓	
S&DSI	✓	✓					✓								✓	✓			✓	✓

*The solubility product constant (K_{sp}) is for $CaCO_3$ and K_2 is carbonate equilibrium constant. These values were found using Table 2.10 in the textbook by Tchobanoglous & Schroeder (1985). Ionic strength (µ), was estimated using the equation: **$1.6 \cdot 10^{-5} \cdot$Conductivity**, provided by Tchobanoglous & Schroeder (1985). The saturated dissolved oxygen (DO_{sat}) concentration was found using an online resource, Rice et al. (2017). The saturated calcium (Ca_{sat}^{+2}) was found for the CCPP using the Caldwell-Lawrence Diagram as shown in Chapter 2, section 2.3.10. Saturated pH (pH_{sat}) is found using the equation provided in Chapter 2, section 2.3.1. The rest of the variables in the table came from Water Quality Reports available on each city's municipal website.

4.0 Results from Calculating Corrosion Indices

In this chapter, we discuss our findings from calculating various corrosion indices and assessing their ability to predict potential corrosivity of treated drinking waters from different municipalities based on comparison to lead concentrations. We calculated the Langelier Saturation Index, Ryznar Stability Index, Stiff and Davis Stability Index, Larson-Skold Index, Larson Ratio, Chloride-to-Sulfate Mass Ratio, Aggressive Index, Calcium Saturation Index, Puckorius Scaling Index, Calcium Carbonate Precipitation Potential, Riddick Corrosion Index, McCauley's Driving Force Index, and Momentary Excess values for the cities of Cambridge, Massachusetts; Milwaukee, Wisconsin; Newark, New Jersey; New York City, New York; Providence, Rhode Island; Tempe, Arizona; and Washington, D.C. Most of the index values were calculated using annual data obtained from consumer confidence reports (CCRs) from the years 2007 to 2018. Some cities did not provide enough water quality data for this entire time span, so they were assessed for a shorter time frame. Not all of the CCRs provided information about the temperature of the water, so it was assumed to be 20°C for Cambridge and Newark. Tempe did not provide temperature data for the years 2007 to 2011, so temperature was also assumed to be 20°C for those years.

Treated drinking water is mostly measured as it leaves the plant. Lead samples are taken at the tap of homeowners. Between the time the water leaves the treatment plant and the time that it arrives in people's homes, there are many chemical reactions that can take place that alter the characteristics in the water. Because of these differences, there are confounding variables that may not have been accounted for in this assessment.

4.1 Municipality Characteristics

Each municipality analyzed in this research project has different characteristics. The water utilities serve different numbers of people, contain a different number of lead service lines (LSLs), practice different corrosion treatment methods, and test for lead at different time intervals. Table 4 outlines the features of each water utility, and further sections provide more detailed descriptions to provide context for the corrosion index evaluation.

Table 4. Water Utility Characteristics

Municipality	Cambridge	Milwaukee	Newark	NYC	Providence	Tempe	D.C.
Population Served	105,162	647,290	294,272	8,271,000	310,060	150,000	632,323
Total Service Lines	15,082	168,973	Unknown	919,884	Unknown	Unknown	126,852
Lead Service Lines	2,426	75,403	18,000	150,190	37,300	None	21,953
Corrosion Control Program	pH adjustment	Ortho-phosphate, LSLR	Ortho-phosphate, LSLR	Ortho-phosphate, pH adjustment, LSLR	pH & alk. adjustment, LSLR	None	Ortho-phosphate, LSLR
Monitoring Frequency	1x / 3 year	1x / 3 year	2x / year*	1x / year	2x / yr	1x / 3 year	2x / year

*As of 2017, Note: LSLR = Lead Service Line Replacement program

Orthophosphate is a common chemical used to reduce corrosion in drinking water pipes. It is added to finished drinking water and is a food-grade chemical that the U.S. Food and Drug Administration and the EPA recognize as safe (D.C. Water, 2004). Milwaukee, Newark, New York City, and Washington, D.C. use orthophosphate to inhibit lead corrosion. Ideally, the orthophosphate forms a precipitate (lead phosphate), which is meant to stay in solid form such that lead does not dissolve in the distributed water. Table 5 displays residual orthophosphate concentrations measured in the distributed water of these systems. In theory, residual phosphate in the water indicates that the reaction between lead and orthophosphate went to completion, assuming no other metal concentrations such as iron or aluminum impacted scale potential.

Table 5. Orthophosphate Concentrations in Distributed Water

Municipality	Milwaukee	NYC	D.C.
Year	PO_4^{2-} (mg/L)		
2018	1.64	2.10	2.40
2017	1.66	2.10	2.47
2016	1.60	2.10	2.43
2015	1.58	2.12	2.50
2014	1.64	2.11	2.36
2013	N/A	2.13	2.34
2012	N/A	2.07	2.17
2011	N/A	2.09	2.20
2010	N/A	2.09	2.45
2009	N/A	1.98	2.11
2008	N/A	2.02	2.30
2007	N/A	2.00	2.29

N/A: Data on phosphate residuals was not available

The EPA Lead and Copper Rule (LCR) requires water systems to monitor lead and copper concentrations at customer drinking water taps. The number of samples and frequency of sampling depends on the how many people the utility serves and results from past sampling periods. Table 6 shows the number of samples taken by the water systems studied in this project.

Table 6. Number of Lead Samples Taken at Each Municipality

Municipality	Cambridge	Milwaukee	Newark	NYC	Providence	Tempe	D.C.
Year	Number of Samples Taken						
2018	N/A	N/A	129/246*	481	303	50	118/104*
2017	61	50	108/104*	487	348	N/A	121/108*
2016	N/A	N/A	140	498	300	N/A	125/115*
2015	N/A	N/A	N/A	350	276	50	108/110*
2014	N/A	51	25	191	204	N/A	111/104*
2013	N/A	N/A	25	220	111	N/A	110/113*
2012	N/A	N/A	25	238	109	52	108/105*
2011	61	N/A	N/A	114/238*	119	N/A	103/100*
2010	N/A	N/A	N/A	222	109	N/A	100/105*
2009	N/A	N/A	26	70	N/A	50	102/103*
2008	60	N/A	N/A	185	N/A	N/A	103/112*
2007	60 (2005)	N/A	N/A	191	N/A	N/A	104/101*

*Number of lead samples taken in a 6-month period (# first half of year/ # second half of year)

Under the LCR, every municipality serving over 50,000 people is required to test for lead every year. However, if a water utility is able to provide documentation of two consecutive 6-months where lead levels are below the EPA Action Limit, the number of lead samplings can be reduced to every 3 years (Electronic Code of Federal Regulations, 1991). As Table 5 shows, Cambridge, Milwaukee, and Tempe only require sampling every 3 years while Newark, NYC, Providence, and D.C. provide 90th percentile lead concentrations every year or every 6 months.

4.1.1 Cambridge, MA

The Cambridge Water Department (CWD) in Cambridge, Massachusetts serves 105,162 residents. As of January 21, 2020, CWD recorded about 2,400 LSLs out of approximately 15,000 total service lines (CWD, n.d.b.). To reduce corrosion, the water utility adds sodium hydroxide to adjust the pH (CWD, n.d.a.). With 90th percentile lead levels consistently below the 15 µg/L Action Level, Cambridge has reduced lead testing to every 3 years. The most recent lead testing was done in 2017 (CWD, 2018).

4.1.2 Milwaukee, WI

Milwaukee Waterworks is a large water utility that serves 647,290 people in Milwaukee (EPA, 2017). As of July 2019, Milwaukee had approximately 75,000 LSLs out of 169,000 total service lines. Milwaukee has been replacing LSLs in the city since 2017. From 2017 to 2020, the city replaced 2,650 LSLs (Milwaukee Water Works, n.d.). Table 7 shows the number of LSL replacements from 2017 to July 2019 and the reason why they were replaced. For corrosion control, Milwaukee Water Works has added orthophosphate to drinking water since 1996 under the direction of the EPA and Wisconsin Department of Natural Resources (DNR) (Milwaukee Water Works, 2018). Table 4 in Section 4.1 displays orthophosphate concentrations as phosphate in Milwaukee's distributed water. Milwaukee is required to sample 50 sites for lead every three years (Milwaukee Water Works, n.d.). Most large water utilities are required to test for lead at least annually, but the LCR allows for State approval of less frequent monitoring if the utility meets LCR action levels for a certain period of time (Code of Federal Regulations). Milwaukee sources its drinking water from Lake Michigan, which has a moderate hardness level (Milwaukee Water Works, n.d.).

Table 7. Number of LSL Replacements in Milwaukee (Dettmer & Beversdorf, 2019)

Reason for LSL Replacement	**2017**	**2018**	**2019**	**Total (%)**
Leak or failure	438	542	268	1248 (66)
Child cares and schools	149	204	55	408 (22)
Water main relay project	18	124	25	167 (9)
Owner initiated	10	40	13	63 (3)
Other utility work	6	0	1	7 (<1)

4.1.3 Newark, NJ

The Newark Water and Sewer Department serves over 290,000 customers (EPA, 2017). In May 2019, Newark started a new corrosion control treatment strategy of adding zinc orthophosphate to the water to reduce lead in drinking water (City of Newark, 2018). Exact dosage numbers are not provided in water quality reports and therefore concentrations were not included in Table 5. In March 2019, Newark invested $115 million into a lead service line replacement (LSLR) program with a goal to replace 18,000 LSLs over 30 months. The lead pipes will be replaced with copper pipes at no cost to the homeowner. As of February 2020, the city has replaced over 6,500 LSLs (City of Newark, n.d.). Since 2017, Newark has conducted lead sampling every 6 months due to LCR violations, and per regulations, this sampling sequence will continue until lead levels are below action limit for a consecutive 3 years.

4.1.4 New York City, NY

New York City is a large water utility that serves 8,271,000 customers (EPA, 2017). It is estimated that about 150,000 out of the city's 919,884 service lines are made from lead (NYC DEP, 2020). In 2017, New York state passed its Clean Water Infrastructure Act to require the State Department of Health to create a Lead Service Line Replacement program (NY Department of Health, 2020). Under this program, New York City uses state funds to replace privately-owned LSLs at no cost to low-income homeowners (NYC DEP, n.d.). To control corrosion, the city adds orthophosphates to the water and maintains optimal water quality parameters (NYC DEP, 2018). Orthophosphate concentrations as phosphate in New York City's water can be found in Table 4. The water utility also adds sodium hydroxide to increase pH and reduce corrosion (NYC DEP, 2018). Since 2007, New York City has tested lead concentrations at the tap at least once every year. The lead levels in these samples did not violate the LCR, except in 2010 when the 90th percentile lead concentration was 19 µg/L. More detailed information about how many samples were tested for lead can be found in Table 5.

4.1.5 Providence, RI

Providence Water serves 74,000 households (about 310,000 people), and about 12,300 of them have a LSL (EPA, 2017; Providence Water, n.d.c.). Providence Water offers residents a 3-year, 0% interest loan to help pay for the replacement of private LSLs (Providence Water, 2018). To control lead corrosion, Providence Water adjusts the pH and alkalinity of the water. The utility has also been evaluating the use of orthophosphate to reduce lead leaching, and current studies demonstrate that it may be an effective corrosion treatment option (Providence Water, n.d.a.). Since 2007, Providence Water has been monitoring lead levels at the tap every six months (Providence Water, n.d.b.).

4.1.6 Tempe, AZ

Tempe, Arizona serves about 160,000 people. The water treatment plants in Tempe receive water from several sources: the Salt River, Verde River, and Colorado River watersheds. The Salt River has higher total dissolved solids (TDS) chlorides concentrations, and the Verde River has a higher hardness. In 1992, Tempe's lead levels complied with the LCR action levels, allowing the city to reduce lead testing to every three years (City of Tempe, n.d.). It should be noted that Tempe's water department claims that there are no LSLs in use (City of Tempe, 2015).

4.1.7 Washington, D.C.

D.C. Water in Washington, D.C. provides water to over 672,000 residents (D.C. Water, n.d.c.). According to a map published by D.C. Water, the city has 21,953 LSLs out of 126,852 total service lines (D.C. Water, 2019). In 2001, Washington, D.C. had a lead crisis which prompted them to address corrosion control (D.C. Water, n.d.a.). In 2004, the water utility began adding orthophosphate to the water to reduce lead corrosion. Washington, D.C. also uses lime and caustic soda to adjust the pH of the water for optimum corrosion control (D.C. Water, 2019). Washington, D.C. has a lead pipe replacement assistance program that provides all property owners with a 50% discount, up to $2,500, for pipe replacements. Depending on household size and income, some homeowners are eligible for 80% or 100% of cost coverage (D.C. Water, n.d.b.). Since 2004, Washington, D.C. has been monitoring for lead every 6 months.

4.2 Langelier Saturation Index

The Langelier Saturation Index (LSI) was calculated using annual water quality data for the following municipalities: Cambridge, MA; Milwaukee, WI; New York City, NY; Providence, RI; Tempe, AZ; and Washington, D.C. Sufficient data to calculate the LSI was not available for Newark, New Jersey. LSI values were calculated for the years 2007 to 2018, except for Milwaukee and Providence. Milwaukee CCRs provided sufficient data for calculating LSI for the years 2014 to 2018, but not 2007 to 2013. Data provided by Providence Water only provided enough information to calculate the LSI from 2013 to 2018, and not 2007 to 2012.

When interpreting LSI values, values greater than 0 indicate $CaCO_3$ is oversaturated, values equal to 0 indicate that the water is neutral, and values less than 0 indicate $CaCO_3$ is undersaturated. $CaCO_3$ oversaturation will result in scale formation and $CaCO_3$ undersaturation will result in aggressive water that can corrode the pipe. The further away from 0 a value is, the more severe the effects are. For example, LSI values between -1 and 0 predict mild corrosion, while LSI values less than -4 predict severe corrosion.

Table 8 details LSI values and 90th percentile lead concentrations for the municipalities assessed for the 12-year time period. Of the six cities analyzed, two yielded positive LSI values: Cambridge and Providence. Over the 12-year time period, Cambridge's LSI values ranged from 0.05 to 0.38. Cambridge's 90th percentile lead levels ranged from 5.0 to 9.0 µg/L, which are below the EPA Action Level. Providence's positive LSI values suggest that the water is not corrosive, but the city's 90th percentile lead levels surpass the Action Level for every year except one. Providence's 90th percentile lead concentrations was the lowest in 2015, where the 90th percentile levels were 9 µg/L in the first half of the year and 15 µg/L in the second half of the year (right at the Action Level). Tempe had mostly negative values with overall yearly values ranging from -0.86 to 0.01. The city's lead ranged from 4.5 to 12.0 µg/L. Milwaukee and Washington, D.C. had similar LSI values. Milwaukee had LSI values ranging from -0.66 to -0.74; Washington, D.C.'s LSI values ranged from -0.64 to -0.82. Both cities produced LSI values that predict mild corrosion. Washington, D.C.'s 90th percentile lead levels ranged from 2 to 11 µg/L, while Milwaukee's 90th percentile lead levels ranged from 7.2 to 8.2 µg/L. New York City had the most negative LSI values, ranging from -2.14 to -2.84. The more negative numbers indicate more severe corrosion, and this is reflected in the city's 90th percentile lead levels. From 2007 to 2018, New York City's 90th percentile lead concentrations ranged from 6 to 19 µg/L, exceeding the EPA Action Limit in 2010.

Table 8. LSI Values For Each Municipality

Municipality	Cambridge		Milwaukee		NYC**		Providence		Tempe		D.C.**	
Year	LSI	90th*	LSI	90th*	LSI	90th*	LSI	90th*	LSI	90th*	LSI	90th*
2018	0.27	N/A	-0.66	N/A	-2.30	11.0	0.88	11/22	-0.86	12.0	-0.76	3/2
2017	0.29	7.0	-0.69	7.2	-2.34	11.0	0.90	14/17	-0.54	N/A	-0.78	3/3
2016	0.38	N/A	-0.73	N/A	-2.14	11.0	0.79	13/16	-0.81	N/A	-0.64	2/3
2015	0.18	N/A	-0.68	N/A	-2.36	12.0	0.91	9/15	-0.30	8.4	-0.69	2/4
2014	0.26	5.0	-0.74	8.2	-2.64	11.0	0.90	10/16	-0.36	N/A	-0.74	2/4
2013	0.13	N/A	N/A	N/A	-2.63	11.0	0.85	13/30	-0.21	N/A	-0.82	4/6
2012	0.14	N/A	N/A	N/A	-2.75	10.0	N/A	14/25	-0.22	6.5	-0.75	3/4
2011	0.17	5.0	N/A	N/A	-2.71	6/13	N/A	15/21	-0.32	N/A	-0.74	5/5
2010	0.05	N/A	N/A	N/A	-2.82	19.0	N/A	21/20	-0.26	N/A	-0.78	7/9
2009	0.13	N/A	N/A	N/A	-2.84	10/6	N/A	16/30	0.01	4.5	-0.77	6/7
2008	0.24	9.0	N/A	N/A	-2.83	11/8	N/A	14/21	-0.20	N/A	-0.76	7/8
2007	0.28	7.0	N/A	N/A	-2.74	15/9	N/A	20/21	-0.02	N/A	-0.66	10/11

*90th percentile lead concentrations in µg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

<u>LSI Value Note:</u> green = >0, yellow = 0, red = <0

<u>90th Percentile Note</u>: green = 0-10 µg/L, yellow = 10-15 µg/L, and red = 15+ µg/L exceeding AL

Figure 8 shows the relationship between the LSI values and 90th percentile lead concentrations over the 12-year span for New York City. Following the LCR violation in 2010, 90th percentile concentrations stabilized back to 11 and 12 µg/L. The LSI shows this trend with a slight increase in the value: -2.74 in 2007 to -2.30 in 2018. The LSI seems to be more accurate when predicting more severe corrosion with more negative LSI values.

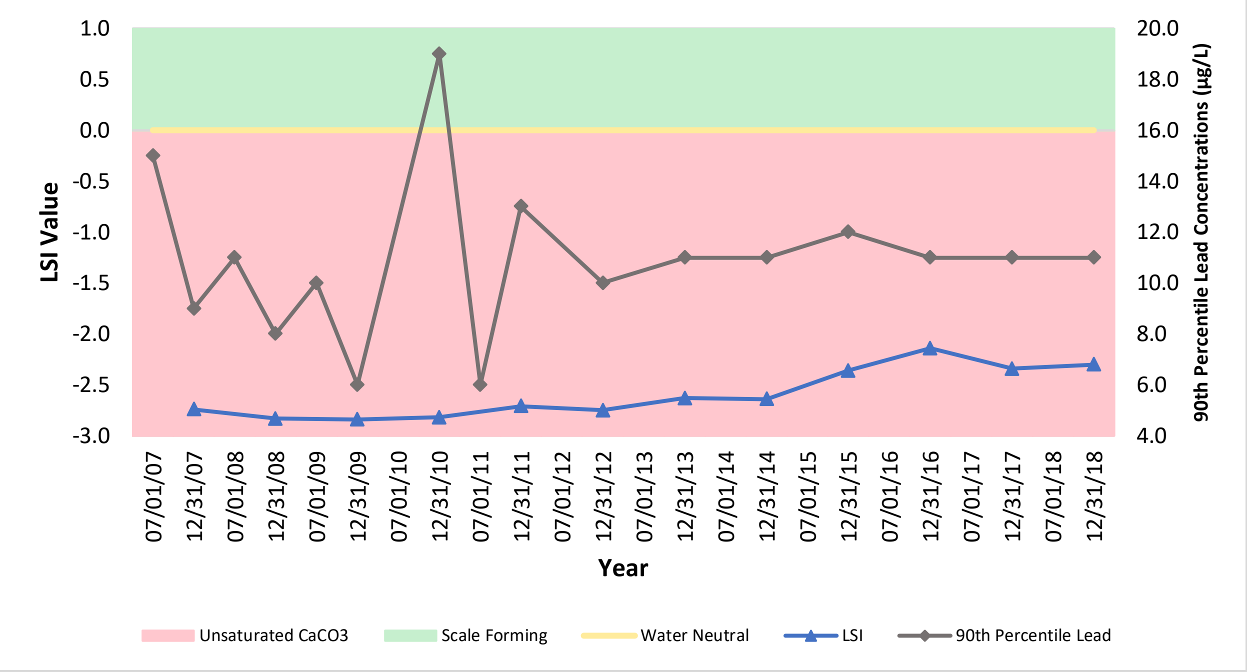


Figure 8. LSI and 90th Percentile Lead Concentrations for New York City

Overall, for cities that do not use a phosphate-based corrosion inhibitor, the LSI values suggest that it is accurate for predicting $CaCO_3$ precipitation potential for Cambridge while for

Providence and Tempe the results indicate otherwise. There are a number of reasons why the LSI varies for each water utility. Temperature, pH, and alkalinity play a large role in water corrosivity. For Providence, pH is relatively high, over 10, which could confound the LSI values because it's mainly ideal for waters with a range between 7.2 and 7.6. For Tempe, the LSI may be accurate in suggesting that the water is not conducive of $CaCO_3$ precipitation, but there is only a small correlation to 90th percentile lead concentrations. Since Tempe has no lead pipes, the only potential source of lead contamination is the homeowners plumbing. Therefore, the source is much smaller than if sourced from a distributed water system. Also, the temperature of the water in Tempe ranges from 23.3 to 25.6ºC, which is higher than the other water utilities investigated. For municipalities that use orthophosphates (Milwaukee, NYC, and D.C.), all three utilities had negative LSI values despite 90th percentile lead levels being below the EPA Action Limit. As indicated in section 4.1, the use of a corrosion inhibitor can confound results. The lead levels for each utility suggests that the phosphate-based treatment is working to reduce concentrations of lead at the tap even though LSI values indicate corrosion. Therefore, the LSI could be a misrepresentation of the water characteristics.

4.3 Ryznar Stability Index (RSI)

Like the LSI, the Ryznar Stability Index (RSI) was evaluated using the same municipalities for the same time span. Cambridge, New York City, Tempe, and Washington, D.C. were evaluated for the years 2007 to 2018, Milwaukee was evaluated for the years 2014 to 2018, Providence was evaluated from 2013 to 2018, and Newark did not provide enough data for any RSI calculations.

To interpret the RSI, values less than 5.5 predict a large potential for $CaCO_3$ scale formation and values between 5.5 and 6.2 predict moderate $CaCO_3$ scaling. RSI values between 6.2 and 6.8 indicate that the water is neutral. RSI values between 6.8 and 8.5 represent aggressive water and corrosion can occur. RSI values greater than 8.5 indicate very aggressive water with extreme corrosion.

Table 9 compares the RSI and 90th percentile lead values for the water systems from 2007 to 2018. For all of the cities evaluated, all of them had high RSI values predicting moderate or extreme corrosion. Tempe had the lowest RSI values, ranging from 7.77 to 8.52. Tempe's RSI values indicate that corrosion would occur, and 90th percentile lead levels demonstrate that there is lead in the water, but not enough to trigger the EPA Action Level. It is interesting to note that Washington, D.C. had higher RSI values ranging from 8.91 to 9.19, indicating extreme corrosion. However, Washington, D.C. had 90th percentile lead concentrations (ranging from 2 to 11 µg/L) that were generally lower than Tempe's lead concentrations. Similar to the LSI, New York City's RSI values predicted the most extreme corrosion compared to the other water systems assessed. New York City had the highest RSI values, ranging from 11.68 to 12.88, and the second highest 90th percentile lead levels ranging from 6 to 19 µg/L. Providence generally has higher 90th percentile lead concentrations than New York City, but the RSI predicts that Providence would have less corrosion than New York City.

Table 9. RSI Values For Each Municipality

Municipality	Cambridge		Milwaukee		NYC**		Providence		Tempe		D.C.**	
Year	RSI	90th*	RSI	90th*	RSI	90th*	RSI	90th*	RSI	90th*	RSI	90th*
2018	8.46	N/A	9.04	N/A	12.00	11.0	8.66	11/22	8.52	12.0	9.16	3/2
2017	8.42	7.0	9.02	7.2	12.09	11.0	8.58	14/17	8.29	N/A	9.19	3/3
2016	8.37	N/A	9.07	N/A	11.68	11.0	8.78	13/16	8.51	N/A	8.97	2/3
2015	8.61	N/A	9.05	N/A	12.02	12.0	8.59	9/15	8.00	8.40	9.05	2/4
2014	8.55	5.0	9.12	8.2	12.57	11.0	8.58	10/16	8.03	N/A	9.12	2/4
2013	8.80	N/A	N/A	N/A	12.55	11.0	8.61	13/30	7.83	N/A	9.18	4/6
2012	8.71	N/A	N/A	N/A	12.71	10.0	N/A	14/25	7.94	6.50	9.08	3/4
2011	8.68	5.0	N/A	N/A	12.73	6/13	N/A	15/21	8.15	N/A	9.06	5/5
2010	8.80	N/A	N/A	N/A	12.85	19.0	N/A	21/20	8.22	N/A	9.10	7/9
2009	8.73	N/A	N/A	N/A	12.88	10/6	N/A	16/30	7.87	4.50	9.13	6/7
2008	8.63	9.0	N/A	N/A	12.86	11/8	N/A	14/21	8.09	N/A	9.10	7/8
2007	8.58	7.0	N/A	N/A	12.78	15/9	N/A	20/21	7.77	N/A	8.91	10/11

*90th percentile lead concentrations in µg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

LSI Value Note: green = > 0, yellow = 0, red = < 0

90th Percentile Note: green = 0-10 µg/L, yellow = 10-15 µg/L, and red = 15+ µg/L exceeding AL

Figure 9 shows a trend between Tempe RSI values and 90th percentile lead concentrations. As lead concentrations increased the RSI also increased slightly from 2007 to 2018. The RSI suggests that the water over time changed from moderately corrosive to extremely corrosive (RSI in 2007 was 7.77 and by 2018, 8.52).

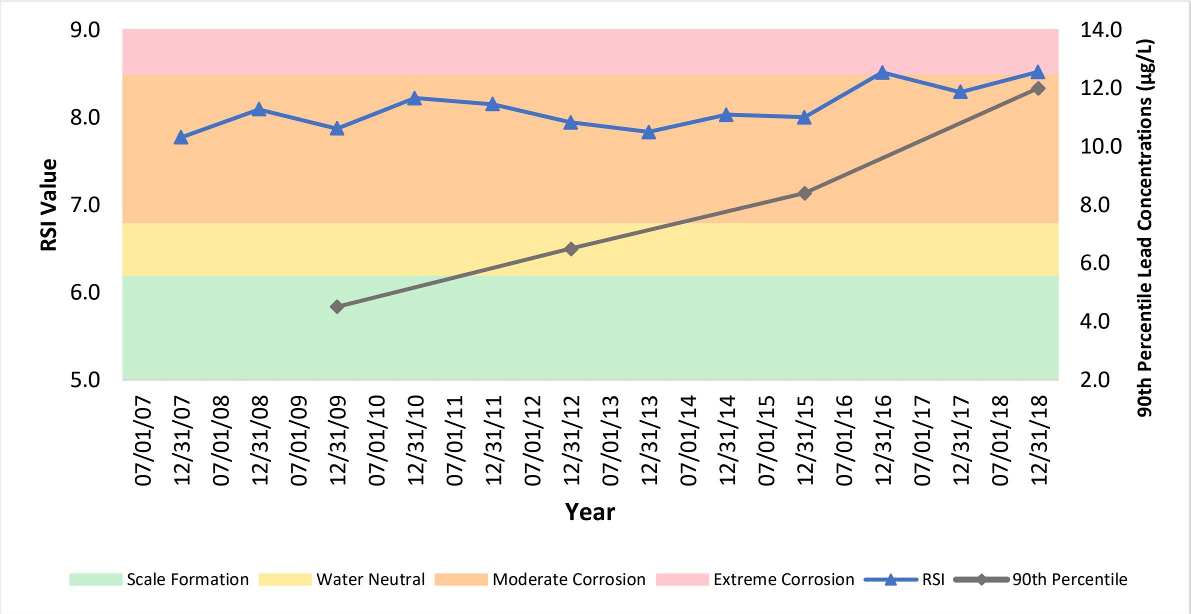


Figure 9. RSI and 90th Percentile Lead Concentrations for Tempe

All the water utilities that use a phosphate-based inhibitor (Milwaukee, NYC, and D.C.) had RSI predictions of extreme corrosion. The other municipalities (Cambridge, Providence, and Tempe) had moderate to extreme corrosion predictions based on their index values. Comparing the RSI to 90th percentile lead concentrations for facilities that treat for corrosion using an inhibitor show no correlations between the two variables. Both Tempe and Providence do not use phosphate for treatment and do suggest a correlation between the RSI value and 90th percentile lead levels. This suggests that using a corrosion control treatment impacts the reliability of the RSI in predicting corrosion. Note that while all of the municipalities assessed had RSI values indicating corrosion, the RSI may predict more extreme corrosion than what is actually occurring in the pipes; only Providence consistently violated the LCR and New York City only violated it in 2010. Other factors that the RSI does not account for include chlorides, sulfates, and the number of LSLs in service. These omissions may limit the accuracy of this index.

4.4 Stiff and Davis Stability Index

The Stiff and Davis Stability Index does not seem likely to be relevant for predicting corrosion in drinking water because the index is intended for waters with more than 10,000 mg/L of total dissolved solids (ASTM, 2019). This index was still calculated for the municipalities that provided sufficient data—Cambridge, Milwaukee, New York City, Providence, and Tempe—to see if it accurately predicted corrosion. All cities were evaluated for the years 2007 to 2018, except for Milwaukee, which was analyzed from 2014 to 2018, and Providence, which was analyzed from 2015 to 2018. To interpret the Stiff and Davis Index, positive values indicate that $CaCO_3$ will scale and negative values indicate that $CaCO_3$ will not scale and the water can be corrosive.

Results comparing the Stiff and Davis Index can be seen in Table 10. All of the water systems reviewed resulted in positive Stiff and Davis values. However, all of the cities had detectable lead concentrations. New York City had the lowest index values ranging from 0.66 to 1.00. Even though the values are still positive, they are closest to predicting corrosion and New York City had the second highest 90th percentile lead concentrations. Providence had the highest index values ranging from 5.26 to 5.35. These index values suggest that Providence's water would be most likely to produce $CaCO_3$ scale, protecting pipes from corrosion. Figure 10 shows the relationship between Providence's Stiff and Davis Index values and 90th percentile lead concentrations. However, Providence's water has exceeded the LCR Action Level in the second half of the year from 2016 to 2018.

Table 10. S&DSI Values for Each Municipality

Municipality	Cambridge		Milwaukee		NYC**		Providence		Tempe	
Year	SDS	90th*	SDS	90th*	SDS	90th*	SDS	90th*	SDS	90th*
2018	3.19	N/A	2.75	N/A	0.76	11.0	5.30	11/22	2.18	12.0
2017	3.19	7.0	4.23	7.2	0.84	11.0	5.26	14/17	3.84	N/A
2016	3.33	N/A	4.36	N/A	0.66	11.0	5.35	13/16	3.86	N/A
2015	3.23	N/A	4.21	N/A	0.67	12.0	5.30	9/15	3.75	8.40
2014	3.37	5.0	4.30	8.2	0.92	11.0	N/A	10/16	3.79	N/A
2013	3.49	N/A	N/A	N/A	0.92	11.0	N/A	13/30	3.79	N/A
2012	3.35	N/A	N/A	N/A	0.88	10.0	N/A	14/25	3.80	6.50
2011	3.37	5.0	N/A	N/A	1.04	6/13	N/A	15/21	3.86	N/A
2010	3.27	N/A	N/A	N/A	1.00	19.0	N/A	21/20	N/A	N/A
2009	3.37	N/A	N/A	N/A	1.00	10/6	N/A	16/30	N/A	4.50
2008	3.47	9.0	N/A	N/A	1.00	11/8	N/A	14/21	N/A	N/A
2007	3.53	7.0	N/A	N/A	1.00	15/9	N/A	20/21	N/A	N/A

90th percentile lead concentrations in µg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

SDS Value Note: green = >0, red = <0

90th Percentile Note: green = 0-10 µg/L, yellow = 10-15 µg/L, and red = 15+ µg/L exceeding AL

Figure 10 illustrates the S&DSI and 90th percentile lead concentrations for Providence. The S&DSI suggests that Providence water is scale-forming which contradicts the measured lead concentrations, many of which are above the LCR Action Limit.

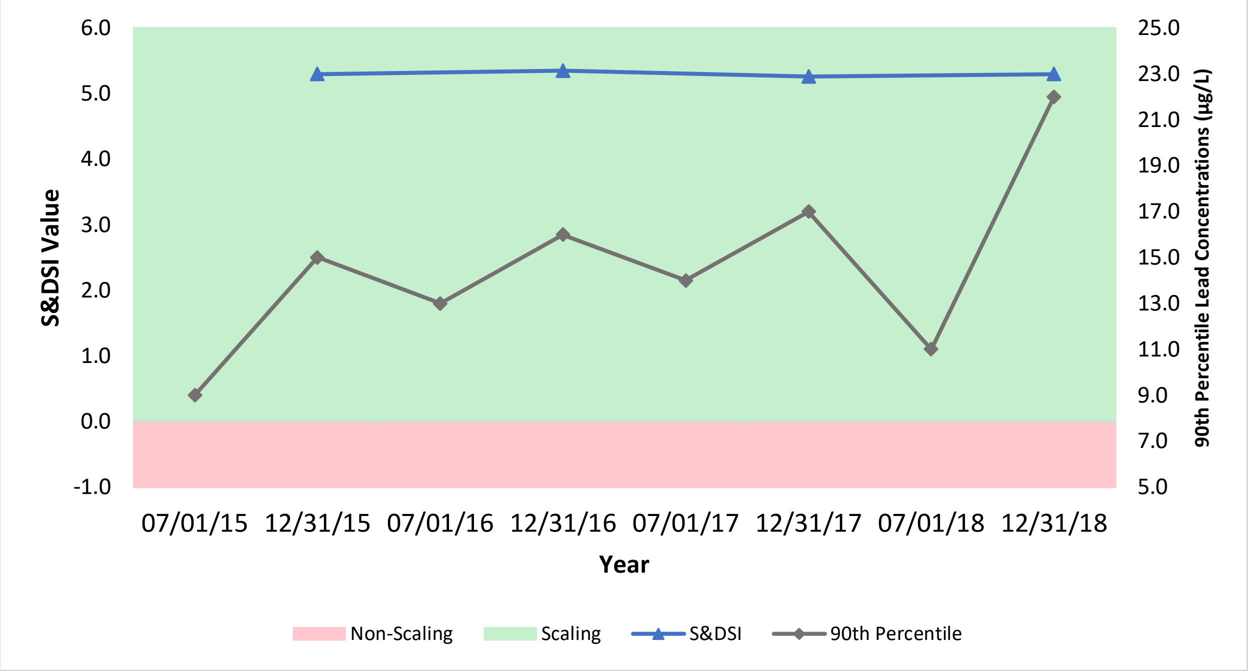


Figure 10. S&DSI and 90th Percentile Lead Concentrations for Providence

Overall, Cambridge had 90th percentile lead concentrations below the action limit and also had S&DSI values that indicate scaling. Likewise, for Tempe, there was a correlation between S&DSI and 90th percentile lead concentrations. As lead levels increased the S&DSI value dropped from 2017 to 2018 by 1.66, which means the water is less likely to scale with the pipe material. New York City and Providence both had S&DSI values that suggest scale formation despite having 90th percentile lead concentrations above the action limit. The S&DSI does not show any trend with respect to 90th percentile lead concentrations for both municipalities. Similar to other indices evaluated, the use of orthophosphates as a corrosion inhibitor could confound the results of the S&DSI. Both Newark and D.C. did not have enough data available to calculate this index.

4.5 Larson-Skold Index

The Larson-Skold Index (L&SkI) was calculated for all seven water departments. Cambridge, Newark, New York City, Tempe, and Washington, D.C. were analyzed from 2007 to 2018. Data for Milwaukee allowed the L&SkI to be calculated for the years 2014 to 2018, and data for Providence allowed for 2009 to 2018.

Larson-Skold Index values less than 0.8 indicate that scaling will occur. L&SkI values between 0.8 and 1.2 indicate that corrosion may occur. L&SkI values greater than 1.2 indicate high levels of corrosion.

Table 11. L&SkI Values for Each Municipality

Municipality	Cambridge		Milwaukee		Newark**		NYC**		Providence		Tempe		D.C.**	
Year	LkI	90th*	LkI	90th*	LkI	90th*	LkI	90th*	LkI	90th*	LkI	90th*	LkI	90th*
2018	9.88	N/A	0.45	N/A	2.60	17.8/47.9	1.60	11.0	3.42	11/22	3.13	12.0	1.34	3/2
2017	10.11	7.0	0.48	7.2	2.87	27/26.7	1.60	11.0	3.41	14/17	2.87	N/A	1.62	3/3
2016	10.16	N/A	0.48	N/A	2.53	10.0	1.73	11.0	3.95	13/16	3.34	N/A	1.56	2/3
2015	8.98	N/A	0.47	N/A	2.74	10.0	1.62	12.0	3.55	9/15	3.67	8.40	1.84	2/4
2014	6.87	5.0	0.51	8.2	2.75	19.3	1.27	11.0	1.56	10/16	2.29	N/A	1.70	2/4
2013	4.46	N/A	N/A	N/A	1.83	9.0	1.09	11.0	1.56	13/30	2.41	N/A	1.53	4/6
2012	5.71	N/A	N/A	N/A	1.98	3.4	1.20	10.0	1.48	14/25	2.48	6.50	1.42	3/4
2011	6.63	5.0	N/A	N/A	2.55	5.0	1.64	6/13	1.54	15/21	1.56	N/A	1.60	5/5
2010	5.94	N/A	N/A	N/A	2.14	5.0	1.46	19.0	1.80	21/20	1.92	N/A	1.74	7/9
2009	6.24	N/A	N/A	N/A	2.52	0.5	1.58	10/6	2.30	16/30	2.36	4.50	1.69	6/7
2008	5.91	9.0	N/A	N/A	2.47	3.8	1.50	11/8	N/A	14/21	1.67	N/A	1.59	7/8
2007	5.68	7.0	N/A	N/A	2.13	3.8	1.37	15/9	N/A	20/21	2.55	N/A	1.37	10/11

*90th percentile lead concentrations in µg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

L&SkI Value Note: green = <0.8, yellow = 0.8-1.2, red = >1.2

90th Percentile Note: green = 0-10 µg/L, yellow = 10-15 µg/L, red = 15+ µg/L

Table 11 shows the L&SkI values for the cities compared to their 90th percentile lead levels. All of the water systems assessed yielded L&SkI values greater than 1.2, except for Milwaukee. Milwaukee's L&SkI values ranged from 0.45 to 0.51. Milwaukee's 90th percentile lead levels were also below the EPA Action Level at 8.2 and 7.2 µg/L. Washington, D.C. had higher L&SkI values, ranging from 1.34 to 1.84, but had generally lower 90th percentile lead concentrations than Milwaukee, ranging from 2 to 11 µg/L. Cambridge had very high L&SkI values. They ranged from 4.46 to 10.16, indicating the potential for extreme levels of corrosion. Yet Cambridge's 90th percentile lead levels ranged from 5.0 to 9.0 µg/L, which does not violate the LCR. Newark's 90th percentile lead concentrations vary a great deal from 2007 to 2018, but the city's L&SkI values experience much less variation. Newark's L&SkI values range from 1.83 to 2.87, all indicating the potential for high corrosion rates. Newark's L&SkI values for the years 2011 and 2018 are 2.55 and 2.60, respectively. Even though the index values are very similar, the corresponding 90th percentile lead levels are very different. Newark's 90th percentile lead level was 5.0 µg/L for 2011 and 17.8 µg/L for the first half of 2018 and 47.9 µg/L for the second half of 2018.

Figure 11 shows L&SkI and 90th percentile concentrations over a 12-year span for Newark. As lead concentrations increase, one can see a steady increase in the L&SkI from 2.13

in 2007 to as high as 2.87 in 2017. While this is not a significant change, it does indicate a trend over time between the two variables.

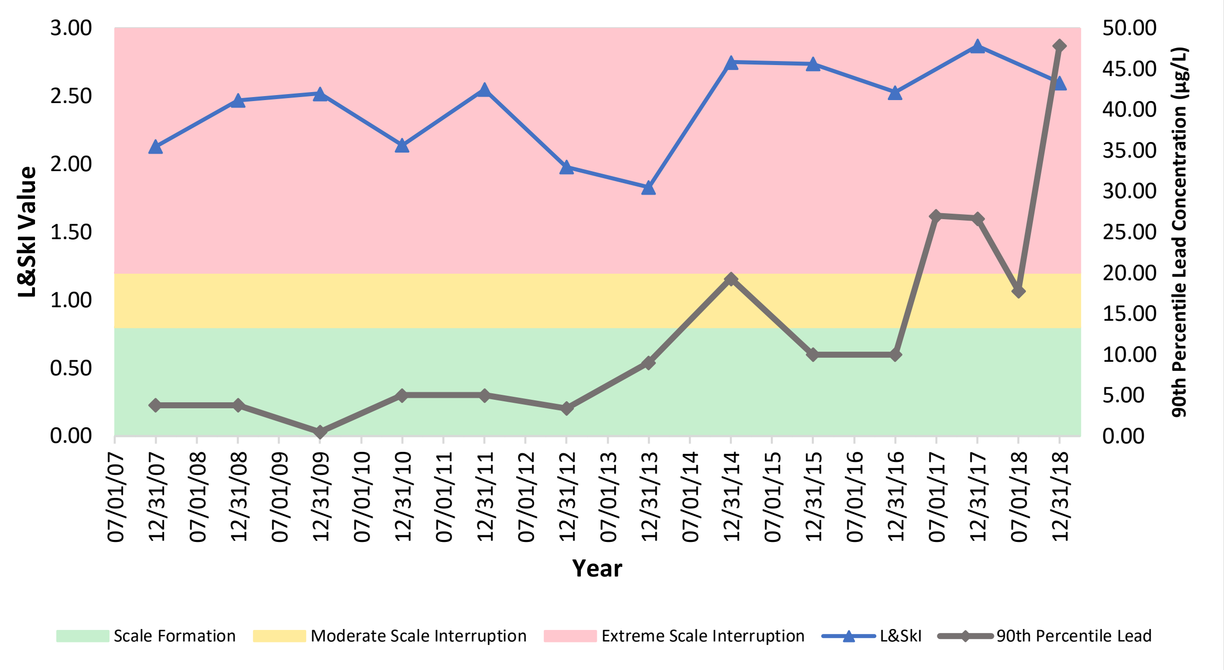


Figure 11. Larson-Skold Index and 90th Percentile Lead Concentrations for Newark

Figure 12 also illustrates this correlation between rising L&SkI values and rising lead concentrations, in this case for Tempe. The change in the L&SkI value over time is more defined than in Newark with a range of 1.56 to as high as 3.67. The L&SkI does increase with time as 90th percentile lead concentrations rise.

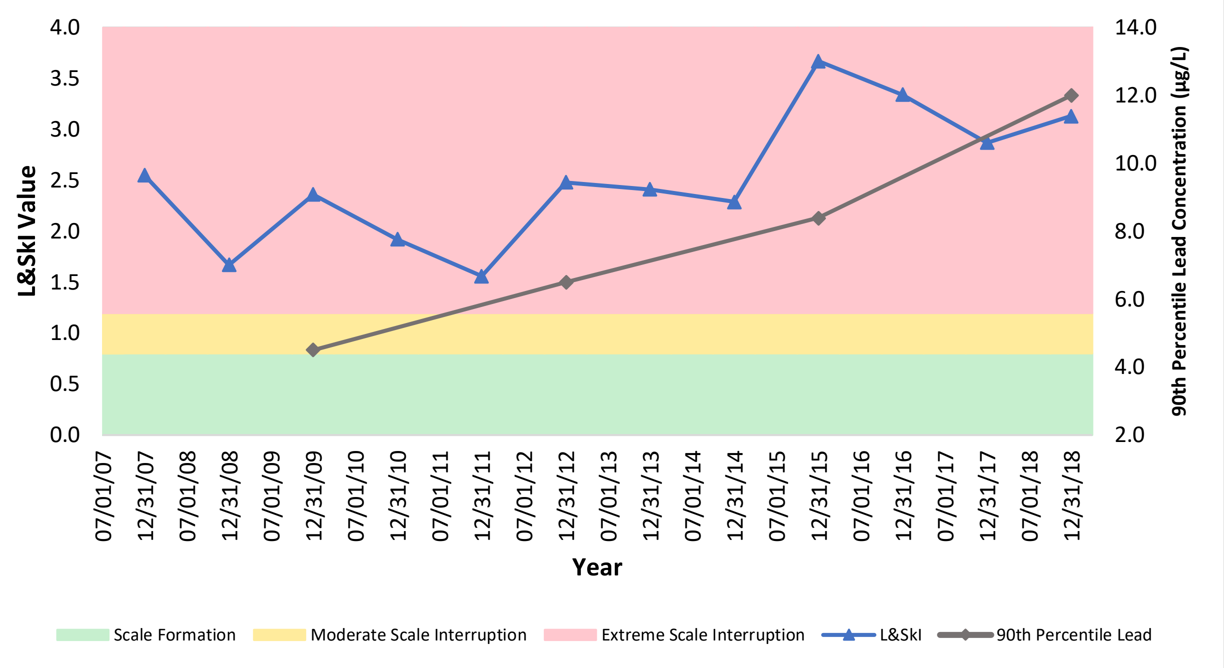


Figure 12. L&SkI and 90th Percentile Lead Concentrations for Tempe

Water utilities that did not show a correlation between L&SkI and 90th percentile lead concentrations include Cambridge, Milwaukee, New York City, Providence, and Washington, D.C.. It should be noted that Milwaukee, New York City, and Washington, D.C. use orthophosphates for optimal corrosion control treatment, which could impact the results of the L&SkI since 90th percentile lead concentrations for these utilities are lower than the action limit, which means the L&SkI values were predicting more corrosion than what actually is occurring in the distributed water systems. This being said, the indices do not account for phosphate concentrations and therefore this may confound results. These results suggest that the L&SkI Index is accurate in simulating the corrosion potential of the water for a select group of utilities, in this instance, Newark and Tempe.

4.6 Larson Ratio

The Larson Ratio (LR) was calculated for all seven water utilities. LR values were calculated for Cambridge, Newark, New York City, Tempe, and Washington, D.C. from 2007 to 2018, Milwaukee from 2014 to 2018, and Providence from 2009 to 2018. Milwaukee and Providence were analyzed for different time periods due to information availability.

LR values greater than 0.5 imply that the surface of the distributed water pipe is more likely to corrode. An LR value less than 0.5 indicates the metal surface of the pipe is less likely to corrode. The Larson Ratio is intended to predict corrosion in iron and steel pipes and has a formula similar to the L&SkI. The L&SkI takes into account carbonate and bicarbonate, while the LR only considers bicarbonate as the major source of carbonate ions in the distributed water. Therefore, the calculated LR values are similar to the L&SkI, therefore, providing similar predictions of corrosion potential.

Table 12. LR Values for Each Municipality

Municipality	Cambridge		Milwaukee		Newark		NYC**		Providence		Tempe		D.C.**	
Year	LR	90th*	LR	90th*	LR	90th*	LR	90th*	LR	90th*	LR	90th*	LR	90th*
2018	12.55	N/A	0.55	N/A	3.17	17.8/47.9	1.96	11.0	7.74	11/22	3.81	12.0	1.63	3/2
2017	12.85	7.0	0.59	7.2	3.50	27/26.7	1.95	11.0	7.65	14/17	3.50	N/A	1.98	3/3
2016	13.07	N/A	0.59	N/A	3.09	10.0	2.11	11.0	8.73	13/16	4.07	N/A	1.90	2/3
2015	11.37	N/A	0.58	N/A	3.36	10.0	1.98	12.0	8.13	9/15	4.48	8.40	2.25	2/4
2014	8.79	5.0	0.62	8.2	3.38	19.3	1.55	11.0	3.50	10/16	2.80	N/A	2.07	2/4
2013	5.69	N/A	N/A	N/A	2.23	9.0	1.33	11.0	3.22	13/30	2.94	N/A	1.86	4/6
2012	7.25	N/A	N/A	N/A	2.43	3.4	1.46	10.0	2.34	14/25	3.03	6.50	1.74	3/4
2011	8.44	5.0	N/A	N/A	3.12	5.0	2.00	6/13	2.45	15/21	1.90	N/A	1.95	5/5
2010	7.48	N/A	N/A	N/A	2.63	5.0	1.78	19.0	3.36	21/20	2.34	N/A	2.13	7/9
2009	7.92	N/A	N/A	N/A	3.08	0.5	1.93	10/6	4.02	16/30	2.89	4.50	2.06	6/7
2008	7.59	9.0	N/A	N/A	3.02	3.8	1.83	11/8	N/A	14/21	2.04	N/A	1.94	7/8
2007	7.33	7.0	N/A	N/A	2.60	3.8	1.67	15/9	N/A	20/21	3.11	N/A	1.67	10/11

*90th percentile lead concentrations in µg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

<u>LR Value Note:</u> green = <0.5, red = >0.5

<u>90th Percentile Note:</u> green = 0-10 µg/L, yellow = 10-15 µg/L, red = 15+ µg/L

Table 12 provides annual LR data for the each of the cities. Every water system analyzed yielded corrosive predictions. Milwaukee had the lowest LR values that were closest to 0.5 with values ranging from 0.55 to 0.62. Milwaukee's 90th percentile lead levels were measured at 7.2

and 8.2 μg/L. Even though Washington, D.C. and Cambridge had higher LR values ranging from 1.63 to 2.25 and 5.69 to 13.07, respectively, both cities generally had lower lead concentrations in the water. Washington, D.C.'s 90th percentile lead levels ranged from 2 to 11 μg/L, while Cambridge's ranged from 5 to 9 μg/L. Cambridge's LR values were very high, compared to the other utilities, but the 90th percentile lead concentrations did not violate the LCR. The LR predicted corrosion for the entire time period analyzed for Newark. But 90th percentile lead concentrations were low from 2007 to 2013 before increasing from 2014 to 2018. LR values for Newark do not vary greatly, but there is an increase in the value from 2.23 to 3.38 from 2013 to 2014, the year that Newark went over the Action Level. Figure 13 displays the LR and 90th percentile lead levels for Providence. The LR was accurate in predicting corrosion for Providence. However, lower LR values should indicate less corrosion, and Providence's lead concentrations decreased while the LR values increased.

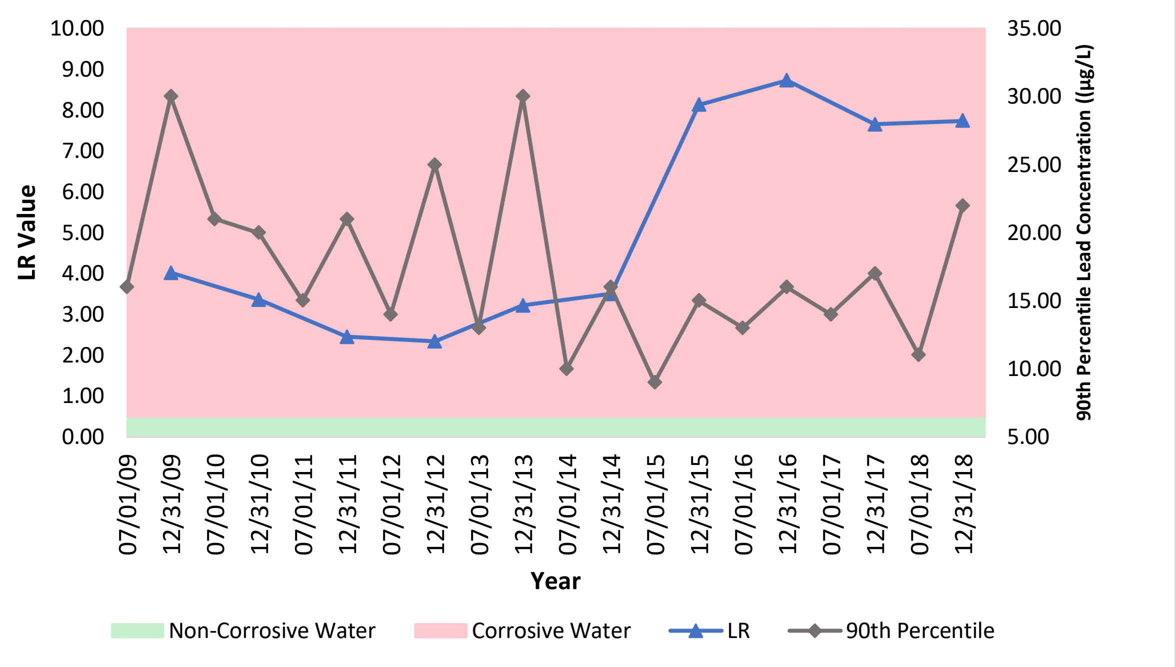


Figure 13. LR and 90th Percentile Lead Concentrations for Providence

The LR predicted corrosion in all of the water utilities, regardless of if they added orthophosphate to the water or not. The only city that the LR correctly predicted corrosion for was Providence. The LR was moderately accurate for New York City, as it had mild corrosion and the LR predicted corrosion. Both of these cities adjust the pH of the water to reduce corrosion, and pH levels can affect the LR, which may be why the LR was accurate for these water utilities. However, Cambridge also adjusts the pH of the water and the LR incorrectly predicted corrosion in Cambridge's water.

4.7 Chloride-to-Sulfate Mass Ratio

The Chloride-to-Sulfate Mass Ratio (CSMR) is a ratio of the concentration of chloride (mg/L) to the concentration of sulfate (mg/L) in the water system of interest. CSMR values were calculated for all seven municipalities. Cambridge, Newark, New York City, Tempe, and Washington, D.C. were assessed for the time period from 2007 to 2018. Milwaukee was assessed for the years 2014 to 2018 and Providence was assessed from 2015 to 2018 due to limited data availability.

CSMR values greater than 0.58 suggest that the water is corrosive. Water with a CSMR value less than 0.58 is predicted to not be corrosive.

Table 13. CSMR Values for Each Municipality

Municipality	Cambridge		Milwaukee		Newark		NYC**		Providence		Tempe		D.C.**	
Year	CSMR	90th*	CSMR	90th*	CSMR	90th*	CSMR	90th*	CSMR	90th*	CSMR	90th*	CSMR	90th*
2018	7.15	N/A	0.56	N/A	3.79	17.8/47.9	3.85	11.0	1.51	11/22	2.63	12.0	0.74	3/2
2017	6.88	7.0	0.54	7.2	4.07	27/26.7	3.53	11.0	1.40	14/17	2.11	N/A	0.69	3/3
2016	7.81	N/A	0.52	N/A	3.46	10.0	3.69	11.0	1.34	13/16	3.33	N/A	0.79	2/3
2015	7.07	N/A	0.55	N/A	5.46	10.0	3.77	12.0	0.90	9/15	2.70	8.40	1.23	2/4
2014	6.89	5.0	0.53	8.2	3.18	19.3	2.62	11.0	N/A	10/16	2.47	N/A	0.95	2/4
2013	4.68	N/A	N/A	N/A	2.43	9.0	2.05	11.0	N/A	13/30	2.17	N/A	0.65	4/6
2012	4.80	N/A	N/A	N/A	1.67	3.4	1.88	10.0	N/A	14/25	2.78	6.50	0.60	3/4
2011	5.06	5.0	N/A	N/A	2.46	5.0	2.26	6/13	N/A	15/21	2.02	N/A	0.65	5/5
2010	4.99	N/A	N/A	N/A	2.53	5.0	2.22	19.0	N/A	21/20	2.62	N/A	0.70	7/9
2009	4.64	N/A	N/A	N/A	3.10	0.5	2.34	10/6	N/A	16/30	2.90	4.50	0.67	6/7
2008	4.50	9.0	N/A	N/A	2.27	3.8	2.00	11/8	N/A	14/21	1.14	N/A	0.62	7/8
2007	4.72	7.0	N/A	N/A	1.90	3.8	1.80	15/9	N/A	20/21	1.97	N/A	0.59	10/11

*90th percentile lead concentrations in µg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

CSMR Value Note: green = <0.58, red = >0.58

90th Percentile Note: green = 0-10 µg/L, yellow = 10-15 µg/L, red = 15+ µg/L

Table 13 displays the CSMR values calculated for each water system. Milwaukee was the only water system with CSMR values below 0.58 with values ranging from 0.52 to 0.56. These values correctly predict low lead concentrations in the water; Milwaukee's 90th percentile lead levels ranged from 7.2 to 8.2 µg/L. All of the other cities had CSMR values that predicted corrosive water. Washington, D.C. had values ranging from 0.59 to 1.23, indicating corrosive water. But the city's 90th percentile lead levels were well below the EPA Action Level, ranging from 2 to 11 µg/L. Cambridge had higher 90th percentile lead levels than D.C., but they were still below the Action Level, ranging from 5 to 9 µg/L. However, Cambridge's CSMR values predict corrosion, with values ranging from 4.50 to 7.15. Providence's CSMR values range from 0.90 to 1.51 and correctly predict corrosion in the water; Providence's 90th percentile lead concentrations from 2015 to 2018 range from 9 to 22 µg/L. It is interesting to note though that Providence's CSMR values are lower than Cambridge's, even though Cambridge did not violate the LCR. The CSMR was moderately accurate for predicting corrosion in New York City's water. New York City's CSMR values range from 1.80 to 3.85, indicating corrosion. New York City's 90th percentile lead levels range from 6 to 19 µg/L, with most of the 90th percentiles in the 10 to 15 µg/L range indicating mild corrosion. Newark's CSMR values are interesting to look at and can be seen in Figure 14, since the city's 90th percentile lead levels increase over time. From 2007 to 2013, Newark's 90th percentile lead concentrations ranged from 0.5 to 9.0 µg/L and had CSMR values from 1.67 to 3.10. From 2014 to 2018, Newark had 90th percentile lead levels ranging from 10 to 47.9 µg/L and CSMR values ranging from 3.18 to 5.46. Even though the CSMR incorrectly predicted corrosion from 2007 to 2013, Newark's lead levels do generally increase as the CSMR values increase.

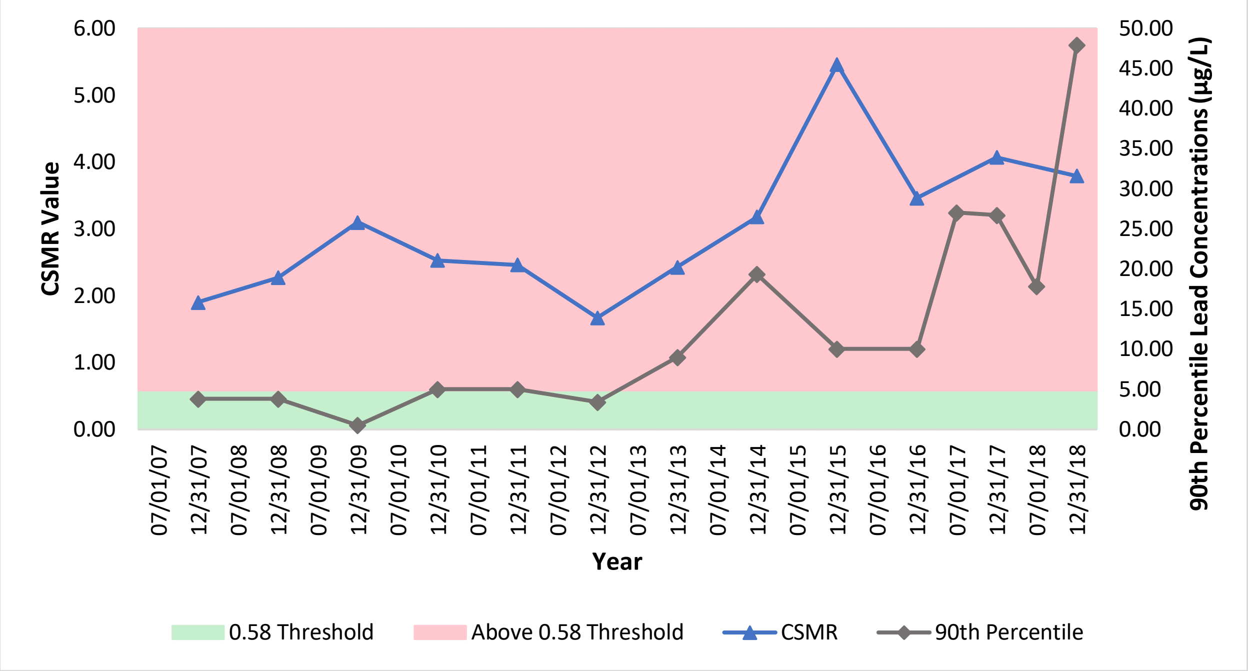


Figure 14. CSMR and 90th Percentile Lead Concentrations for Newark

In conclusion, it seems that the CSMR is relatively accurate for predicting corrosion in drinking water systems. New York City and Washington, D.C. treat their water with orthophosphate to reduce corrosion, so this could be the reason for the incorrect corrosion predictions from the CSMR. However, Milwaukee also adds orthophosphate to their water and Cambridge does not add orthophosphate, and the CSMR was accurate for both of those utilities, indicating that orthophosphate treatment may not be the reason for inaccurate CSMR predictions. Overall, it appears that the CSMR is not the most accurate corrosion index available.

4.8 Aggressive Index

The Aggressive Index (AI), adapted from the LSI, was originally applied for predicting corrosion of asbestos-cement pipe systems. AI values were calculated for the years 2007 to 2018 for Cambridge, Newark, New York City, Tempe, and Washington, D.C. AI values were calculated for 2014 to 2018 for Milwaukee and from 2009 to 2018 for Providence due to limited data availability.

The AI defines values below 10 as very aggressive water or corrosive while values above 12 are non-aggressive or non-corrosive. Between 10 and 12, the AI indicates a moderately aggressive water system.

Table 14. AI Values for Each Municipality

Municipality	Cambridge		Milwaukee		Newark		NYC**		Providence		Tempe		D.C.**	
Year	AI	90th*	AI	90th*	AI	90th*	AI	90th*	AI	90th*	AI	90th*	AI	90th*
2018	12.37	N/A	11.87	N/A	10.13	17.8/47.9	10.15	11.0	13.27	11/22	11.37	12.0	11.47	3/2
2017	12.39	7.0	11.79	7.2	10.43	27/26.7	10.08	11.0	13.22	14/17	11.70	N/A	11.40	3/3
2016	12.48	N/A	11.76	N/A	10.40	10.0	10.29	11.0	13.13	13/16	11.46	N/A	11.45	2/3
2015	12.28	N/A	11.83	N/A	11.57	10.0	10.08	12.0	13.27	9/15	11.92	8.40	11.46	2/4
2014	12.36	5.0	11.78	8.2	10.78	19.3	9.80	11.0	13.27	10/16	11.91	N/A	11.39	2/4
2013	12.26	N/A	N/A	N/A	10.37	9.0	9.80	11.0	13.20	13/30	12.00	N/A	11.28	4/6
2012	12.23	N/A	N/A	N/A	10.96	3.4	9.65	10.0	12.89	14/25	12.02	6.50	11.35	3/4
2011	12.28	5.0	N/A	N/A	10.80	5.0	9.69	6/13	12.89	15/21	12.02	N/A	11.38	5/5
2010	12.15	N/A	N/A	N/A	10.89	5.0	9.59	19.0	12.94	21/20	12.06	N/A	11.37	7/9
2009	12.22	N/A	N/A	N/A	10.95	0.5	9.59	10/6	12.81	16/30	12.31	4.50	11.38	6/7
2008	12.34	9.0	N/A	N/A	10.73	3.8	9.59	11/8	N/A	14/21	12.10	N/A	11.43	7/8
2007	12.38	7.0	N/A	N/A	10.38	3.8	9.70	15/9	N/A	20/21	12.28	N/A	11.53	10/11

*90th percentile lead concentrations in µg/L
**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)
AI Value Note: green = >12, yellow = 10-12, red = <10
90th Percentile Note: green = 0-10 µg/L, yellow = 10-15 µg/L, red = 15+ µg/L

Table 14 depicts the average AI values for each municipality observed. Three water systems had AI values that indicated non-corrosive water. Cambridge was one of these systems, with AI values ranging from 12.15 to 12.48. Cambridge had 90th percentile lead values consistent with a non-corrosive prediction, ranging from 5 to 9 µg/L. Providence also had AI values predicting scaling: results ranged from 12.81 to 13.27. However, Providence had high 90th percentile lead levels, ranging from 9 to 30 µg/L, with all of the years assessed except for 2015 violating the LCR.

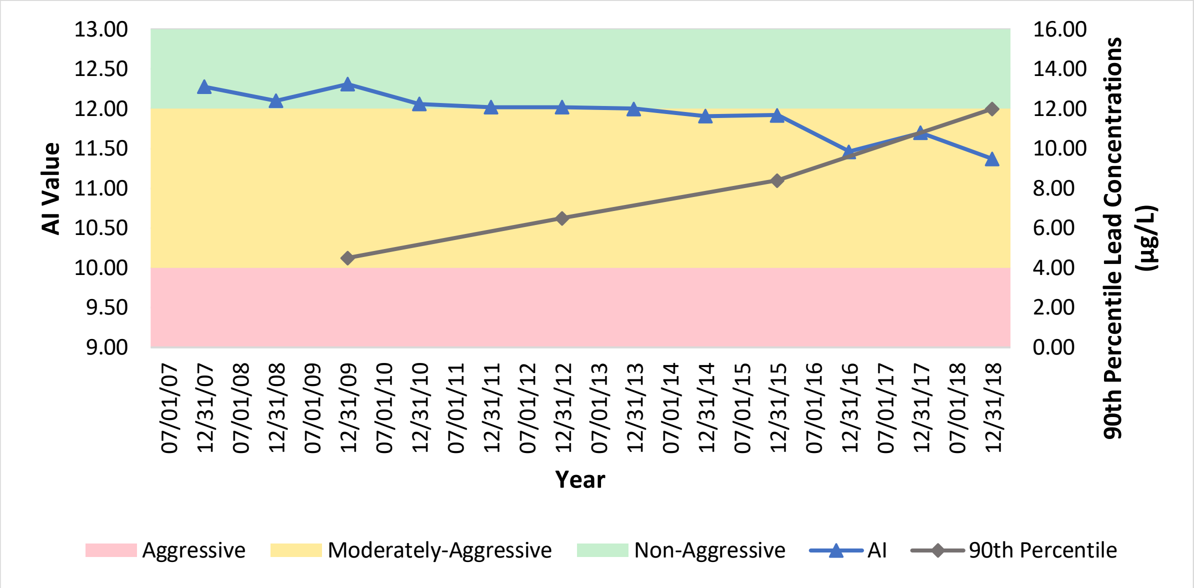


Figure 15. AI and 90th Percentile Lead Concentrations for Tempe

Figure 15 shows the relationship between Tempe's AI values and 90th percentile lead concentrations. Tempe's AI values had varied corrosion predictions. From 2007 to 2013, Tempe's AI values were greater than 12, ranging from 12.00 to 12.31. The 90th percentile lead concentrations (4.50 to 6.50 µg/L) were consistent with an index value showing a non-aggressive water for the time period. From 2014 to 2018, Tempe's AI values decreased and ranged from 11.37 to 11.92, predicting moderate corrosion. Tempe's 90th percentile lead levels increased in this time period, ranging from 8.49 to 12.0 µg/L. Both Milwaukee and Washington, D.C. yielded AI values that indicate moderate corrosion. But the utilities had low 90th percentile lead concentrations ranging from 7.2 to 8.2 µg/L and 2 to 11 µg/L, respectively. Washington, D.C. generally had lower 90th percentile lead levels than Cambridge, but the AI predicted that Washington, D.C. would have more corrosive water than Cambridge. New York City was the only water utility that had AI results predict high corrosion. From 2007 to 2014, New York City's AI values were below 10, ranging from 9.59 to 9.80. For the same time period, the city's 90th percentile values were moderately high for the most part; they varied from 6 to 19 µg/L. From 2015 to 2018, the AI values for New York City ranged from 10.08 to 10.29, predicting moderate corrosion. The 90th percentile lead values correctly reflected these results, ranging from 11.0 to 12.0 µg/L. Newark's AI values predicted moderate corrosion for the entire time frame assessed. However, only 2016 and 2015 had 90th percentile lead levels that reflect moderate corrosion (10 µg/L). From 2007 to 2013, Newark's 90th percentile lead concentrations ranged from 0.5 to 9.0 µg/L. In 2014, 2017, and 2018, Newark violated the LCR.

Only Cambridge and Tempe's AI values correctly represented lead levels. Neither of these two cities add orthophosphate to the water, so orthophosphate addition to water may lead to false corrosion predictions. Providence also does not add orthophosphate as a corrosion control treatment, but the AI values incorrectly suggested noncorrosive water. Thus, orthophosphate addition may not be the only reason for the inaccuracy of the AI.

4.9 Calcium Saturation Index

The Calcium Saturation Index (CSI) was calculated for 5 out of the 7 sites analyzed. Cambridge and New York City were assessed for 2007 to 2018. CSI values were calculated for Milwaukee from 2014 to 2018, Providence from 2015 to 2018, and Tempe from 2011 to 2018. Information for prior years and for Newark and Washington, D.C. were not available.

CSI values less than -0.3 indicate aggressive water that can be corrosive. CSI values between -0.3 and 0.3 indicate that the water is neutral and calcium is balanced. CSI values greater than 0.3 predict $CaCO_3$ scaling.

Table 15. CSI Values for Each Municipality

Municipality	Cambridge		Milwaukee		NYC**		Providence		Tempe	
Year	CSI	90th*	CSI	90th*	CSI	90th*	CSI	90th*	CSI	90th*
2018	0.84	N/A	1.18	N/A	-1.12	11.0	1.50	11/22	1.90	12.0
2017	0.86	7.0	1.18	7.2	-1.13	11.0	1.51	14/17	1.83	N/A
2016	0.95	N/A	1.29	N/A	-1.03	11.0	1.41	13/16	1.97	N/A
2015	0.76	N/A	1.06	N/A	-1.25	12.0	1.52	9/15	1.83	8.40
2014	0.84	5.0	1.07	8.2	-1.45	11.0	N/A	10/16	1.97	N/A
2013	0.71	N/A	N/A	N/A	-1.55	11.0	N/A	13/30	2.00	N/A
2012	0.73	N/A	N/A	N/A	-1.56	10.0	N/A	14/25	1.84	6.50

2011	0.75	5.0	N/A	N/A	-1.48	6/13	N/A	15/21	1.77	N/A
2010	0.63	N/A	N/A	N/A	-1.63	19.0	N/A	21/20	N/A	N/A
2009	0.71	N/A	N/A	N/A	-1.66	10/6	N/A	16/30	N/A	4.50
2008	0.82	9.0	N/A	N/A	-1.67	11/8	N/A	14/21	N/A	N/A
2007	0.87	7.0	N/A	N/A	-1.55	15/9	N/A	20/21	N/A	N/A

*90th percentile lead concentrations in µg/L
**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)
CSI Value Note: green = >0.3, yellow = -0.3-0.3, red = <-0.3
90th Percentile Note: green = 0-10 µg/L, yellow = 10-15 µg/L, red = 15+ µg/L

Table 15 displays CSI values and 90th percentile lead levels for the cities analyzed. Cambridge, Milwaukee, and Tempe all had CSI values that predicted scaling and also had low lead concentrations in the water. Cambridge's CSI values ranged from 0.63 to 0.95. Milwaukee's CSI values ranged from 1.06 to 1.29. Tempe's CSI values ranged from 1.77 to 2.00. Both Cambridge and Milwaukee had low 90th percentile lead concentrations for the time periods they were assessed. Cambridge's 90th percentile lead levels ranged from 5.0 to 9.0 µg/L, and Milwaukee's 90th percentile lead levels ranged from 7.2 to 8.2 µg/L. Figure 16 displays Tempe's CSI values and 90th percentile lead concentrations. For the years that Tempe was analyzed, most of the 90th percentile lead levels were low (ranging from 6.50 to 8.40 µg/L), but in 2018, Tempe had moderate corrosion with a 90th percentile lead concentration of 12.0 µg/L even though the CSI still predicted scaling. It is interesting to note that Tempe's lead levels have increased over time, but CSI values have remained relatively constant. Providence had CSI values ranging from 1.41 to 1.52, which also indicates scaling. However, Providence's 90th percentile lead levels almost always violated the LCR for the time period studied (ranging from 9 to 22 µg/L). New York City was the only water system with CSI values that predicted corrosion, ranging from -1.67 to -1.03. This is somewhat accurate, as New York City's 90th percentile lead concentrations mostly indicate moderate corrosion, ranging from 6 to 19 µg/L.

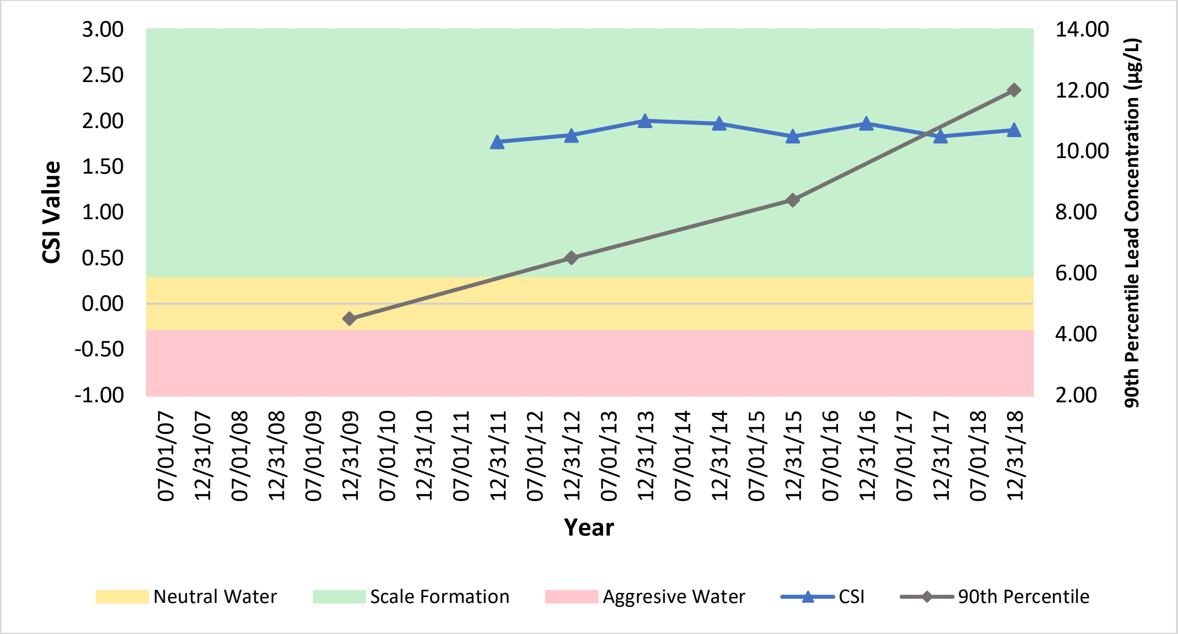


Figure 16. CSI and 90th Percentile Lead Concentrations for Tempe

It is unclear whether orthophosphate or pH adjustment treatments affect the reliability of the CSI. The CSI was accurate for Tempe, which does not appear to have a corrosion treatment in place. The index was also accurate for Cambridge and somewhat accurate for New York City, which both adjust the pH of their water. However, Providence also adjusts the pH of their water (along with alkalinity), and the CSI erroneously predicted scaling. It seems that orthophosphate addition does not affect the validity of the CSI. Milwaukee and New York City both add orthophosphate and the CSI was still accurate for Milwaukee.

4.10 Puckorius Scaling Index

The Puckorius Scaling Index (PSI) as explained in Chapter 2 of this report was adapted from the LSI and RSI to better predict the scale formation in cooling towers. PSI values for calculated for Cambridge, New York City, Tempe, and Washington, D.C. from 2007 to 2018. Milwaukee PSI values were calculated from 2014 to 2018 and Providence PSI values were calculated from 2013 to 2018. Limited time frames were analyzed for these two cities and PSI values for Newark could not be calculated due to insufficient water quality data.

PSI values less than 6 indicate that the water is oversaturated and $CaCO_3$ will form a protective scale. PSI values greater than 6 indicate that the water is undersaturated, dissolving $CaCO_3$ and preventing protective film development.

Table 16. PSI Values for Each Municipality

Municipality	Cambridge		Milwaukee		NYC**		Providence		Tempe		D.C.**	
Year	PSI	90th*	PSI	90th*	PSI	90th*	PSI	90th*	PSI	90th*	PSI	90th*
2018	10.64	N/A	9.23	N/A	12.89	11.0	12.68	11/22	7.53	12.0	9.60	3/2
2017	10.61	7.0	9.12	7.2	13.04	11.0	12.57	14/17	7.76	N/A	9.63	3/3
2016	10.69	N/A	9.16	N/A	12.51	11.0	12.84	13/16	7.60	N/A	9.41	2/3
2015	10.79	N/A	9.21	N/A	12.82	12.0	12.61	9/15	7.67	8.40	9.49	2/4
2014	10.74	5.0	9.24	8.2	13.55	11.0	12.56	10/16	7.47	N/A	9.56	2/4
2013	10.96	N/A	N/A	N/A	13.53	11.0	12.54	13/30	7.42	N/A	9.51	4/6
2012	10.84	N/A	N/A	N/A	13.63	10.0	N/A	14/25	7.66	6.50	9.44	3/4
2011	10.88	5.0	N/A	N/A	13.80	6/13	N/A	15/21	7.83	N/A	9.42	5/5
2010	10.86	N/A	N/A	N/A	13.86	19.0	N/A	21/20	8.21	N/A	9.44	7/9
2009	10.87	N/A	N/A	N/A	13.89	10/6	N/A	16/30	8.07	4.50	9.54	6/7
2008	10.85	9.0	N/A	N/A	13.87	11/8	N/A	14/21	8.09	N/A	9.46	7/8
2007	10.90	7.0	N/A	N/A	13.88	15/9	N/A	20/21	7.71	N/A	9.20	10/11

*90th percentile lead concentrations in μg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

PSI Value Note: green = <6, red = >6

90th Percentile Note: green = 0-10 μg/L, yellow = 10-15 μg/L, red = 15+ μg/L

Table 16 shows the results from the PSI calculations compared to the cities' 90th percentile lead levels. Every water system assessed yielded PSI values greater than 6, predicting corrosive water. Cambridge, Milwaukee, Tempe, and Washington, D.C. all had corrosive water according to the PSI, but they had low 90th percentile lead concentrations. Cambridge's PSI values ranged from 10.61 and 10.96, and had 90th percentile lead concentrations ranging from 5.0 to 9.0 μg/L. PSI values for Milwaukee ranged from 9.12 to 9.24, and the 90th percentile lead levels ranged from 7.2 and 8.2 μg/L. Tempe had the lowest PSI values ranging from 7.42 and 8.21. Tempe's 90th percentile lead concentrations ranged from 4.50 to 12.0 μg/L. Washington, D.C.'s PSI levels ranged from 9.20 and 9.63, and had 90th percentile lead concentrations ranging from 2 to 11 µg/L. New York City had the highest PSI values out of all the municipalities studied: PSI values ranged from 12.51 to 13.89. However, the city's 90th percentile lead values mostly indicated moderate corrosion, ranging from 6 to 19 µg/L. A graph comparing Providence's PSI values and 90th percentile lead levels can be seen in Figure 17. Providence was the only city analyzed that consistently had high 90th percentile lead levels (ranging from 9 to 30 µg/L). PSI values did reflect corrosion (ranging from 12.54 to 12.84), but they indicated less corrosion than New York City's PSI values.

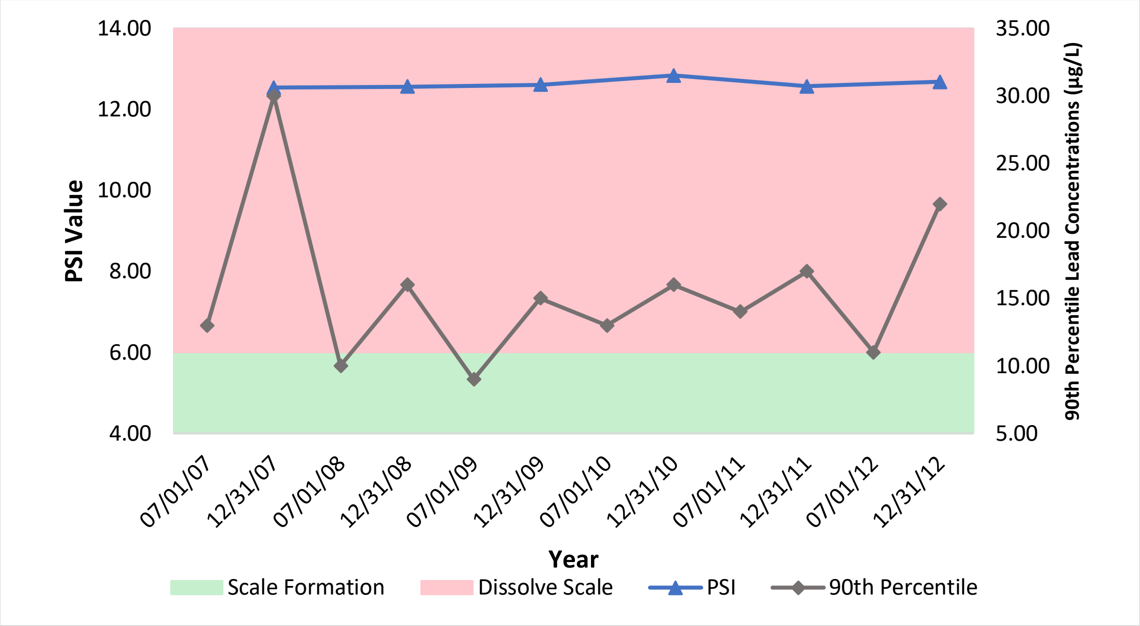


Figure 17. PSI and 90th Percentile Lead Concentrations for Providence

Out of six water systems looked at, the PSI was only accurate for one: Providence. These results indicate that the PSI is not the best index to use to predict corrosion in drinking water systems. This could be because the index was developed to predict corrosion in cooling towers, which have different characteristics than drinking water systems. Corrosion treatments may also impact the accuracy of the PSI. Five of the cities assessed had different corrosion prevention treatments or no treatment at all, and the PSI was incorrect for all of them. Providence (the only city with correct corrosion predictions) is the only city to adjustment alkalinity as a part of their corrosion prevention method. The alkalinity adjustment directly affects PSI values, as alkalinity is used to calculate pH_{eq} which is used to calculate final PSI values.

4.11 Calcium Carbonate Precipitation Potential

The Calcium Carbonate Precipitation Potential (CCPP) was also calculated for the different water systems. The resulting average CCPP values and average 90th percentile lead levels are compared in Table 16. CCPP values were calculated for Cambridge, New York City, Tempe, and Washington, D.C. from 2007 to 2018. Because of limited data availability, CCPP values were calculated from 2014 to 2018 for Milwaukee, 2013 to 2018 for Providence, and not at all for Newark.

To interpret CCPP values, values less than -10 indicate that the water is corrosive. CCPP values between -5 and -10 indicate moderate corrosion and CCPP values between -5 and 0 mean that the water is passive (neither scaling nor corrosion will occur). CCPP values greater than 0 indicate scaling.

Table 17. CCPP Values for Each Municipality

Municipality	Cambridge		Milwaukee		NYC**		Providence		Tempe		D.C.**	
Year	CCPP	90th*	CCPP	90th*	CCPP	90th*	CCPP	90th*	CCPP	90th*	CCPP	90th*
2018	-0.08	N/A	-5.08	N/A	-9.02	11.0	26.95	11/22	-52.66	12.0	-2.60	3/2
2017	-0.08	7.0	-1.35	7.2	-6.77	11.0	25.96	14/17	-18.15	N/A	-2.10	3/3
2016	-1.08	N/A	-0.10	N/A	-7.03	11.0	21.46	13/16	-39.54	N/A	-4.61	2/3
2015	-1.32	N/A	-0.85	N/A	-7.02	12.0	24.46	9/15	-3.60	8.40	-2.60	2/4
2014	-1.31	5.0	-7.60	8.2	-9.27	11.0	26.46	10/16	-7.15	N/A	-5.11	2/4
2013	-2.04	N/A	N/A	N/A	-9.52	11.0	25.96	13/30	-5.16	N/A	-6.11	4/6
2012	-1.81	N/A	N/A	N/A	-9.77	10.0	N/A	14/25	-2.15	6.50	-6.11	3/4
2011	-1.56	5.0	N/A	N/A	-8.76	6/13	N/A	15/21	-2.63	N/A	-2.11	5/5
2010	-1.81	N/A	N/A	N/A	-8.27	19.0	N/A	21/20	-3.11	N/A	-0.61	7/9
2009	-1.55	N/A	N/A	N/A	-8.27	10/6	N/A	16/30	1.36	4.50	-2.11	6/7
2008	-1.05	9.0	N/A	N/A	-8.52	11/8	N/A	14/21	-0.38	N/A	-5.11	7/8
2007	-1.80	7.0	N/A	N/A	-7.52	15/9	N/A	20/21	5.34	N/A	-5.11	10/11

*90th percentile lead concentrations in µg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

<u>CCPP Value Note:</u> green = > 0, yellow = 0 to -5, orange = -5 to -10, red = < -10

<u>90th Percentile Note:</u> green = 0-10 µg/L, yellow = 10-15 µg/L, red = 15+ µg/L

Table 17 shows the results from theCCPP calculations compared to the cities' 90th percentile lead levels. Providence was the only city that had positive CCPP values for the entire time period from 2013 to 2018. Tempe had the largest range of values from -52.66 to 5.34. Tempe's water did not exceed the 90th percentile 15 µg/L lead limit in the time period, but it did reach 15 µg/L in 2007 and 2008. Almost all of Cambridge's CCPP values from 2007 to 2018 ranged between -2.04 to -0.08, which predicts passive water. Passive water means that $CaCO_3$ will not form a protective scale inside the pipe, but the water also will not corrode the pipe. These corrosion predictions correlate with Cambridge's low average 90th percentile lead levels. From 2007 to 2018, Washington, D.C.'s CCPP values ranged from -6.11 to -0.61, with a mix of $CaCO_3$ moderate corrosion and passive water index interpretations. These CCPP values do not show a strong correlation to 90th percentile lead concentrations. CCPP values were also calculated for the years 2004 and 2005 for Washington, D.C. because the city experienced a lead health crisis during that time. The CCPP values for 2004 and 2005 were -27.79 and -30.30, respectively, which indicates that the water is corrosive. The analysis corresponds with 2004's 90th percentile lead levels of 59 µg/L from January to June and 54 µg/L from July to December. In 2005, the 90th percentile level was much lower at 15 µg/L, just at the Federal Action Level.

NYC's CCPP values ranged from -9.77 to -6.77 indicating mildly corrosive water. The CCPP values for NYC do not seem to correlate well with 90th percentile lead concentrations. Even after lead levels stabilize in 2012, the CCPP predicts mildly corrosive water. Milwaukee's CCPP values were only calculated from 2014 to 2018 due to limited data availability and it was found that the CCPP interpretations varied more than other cities. In 2014, the CCPP index was -7.60, indicating corrosive water. From 2015 to 2017, the CCPP ranged from -1.35 to -0.10, indicating passive water. 2018 had a CCPP value of -5.08, which predicts mildly corrosive water. Milwaukee's 90th percentile lead levels were measured at 8.2 and 7.2 µg/L for 2014 and 2017, respectively.

Figure 18 depicts the relationship between CCPP values and 90th percentile lead concentrations for Tempe. As the lead levels increase from 4.5 to 12 µg/L from the CCPP drops drastically from -3.6 in 2015 to -39.54 in 2016. Then it rises back up to -18.15 in 2017 and decreases again to -52.66 in 2018. It should be noted that from 2015 to 2016 acidity increased from 163.66 to 245.51, which seems to be a major factor in measuring the corrosion potential of the water. Likewise with 2017 to 2018, acidity changed from 177.50 to 259.28 resulting in another major decrease in the CCPP value.

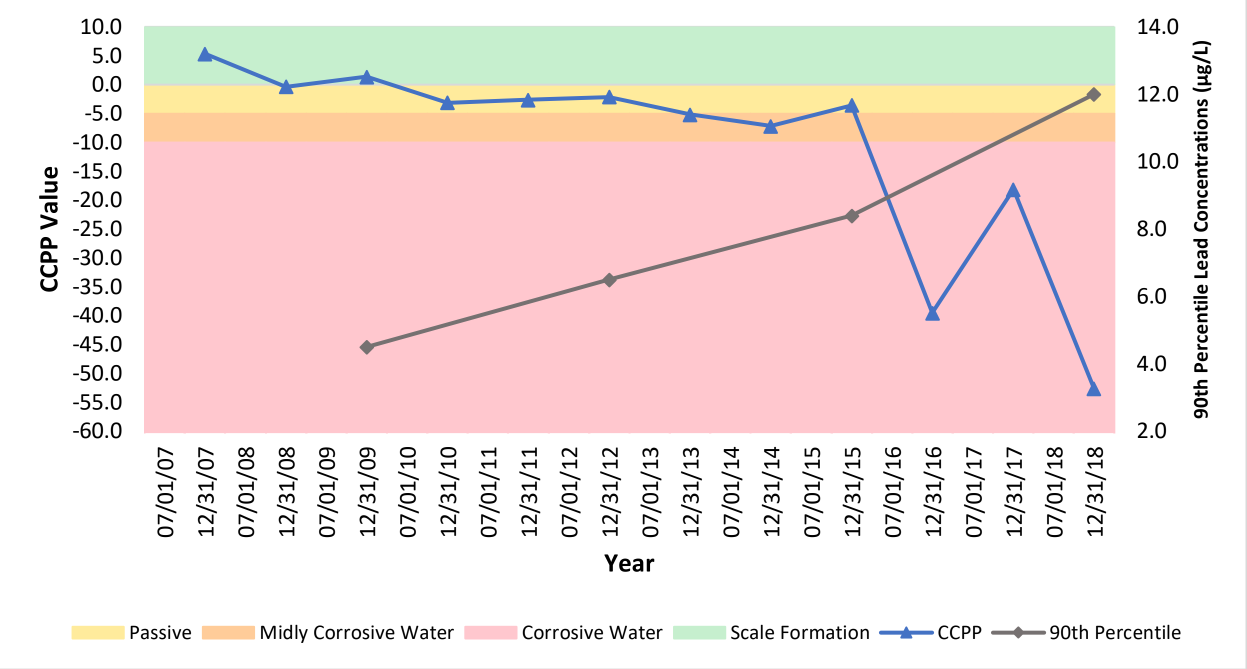


Figure 18. CCPP and 90th Percentile Lead Concentrations for Tempe

The only water utility to illustrate consistency with the CCPP is Tempe. While Cambridge suggests that the water is passive, there does not seem to be any real correlation to 90th percentile lead concentrations. The CCPP values for Milwaukee, NYC, and Providence do not provide an accurate representation of these utilities. For Milwaukee when lead levels decrease the CCPP rises to a more positive value, but then decreases back down to a mildly corrosive water. The CCPP values for NYC all suggest mildly corrosive water despite lead levels stabilizing between 11 and 12 µg/L. Lastly, Providence CCPP values indicate the water is scale forming despite 90th percentile lead concentrations exceeding the LCR by a significant amount.

4.13 McCauley's Driving Force Index

The McCauley's Driving Force Index (DFI) was developed in 1960 to show that large differences in the concentrations of calcium and carbonate alkalinity play a significant role in the precipitation of calcium carbonate (Dye, 1963). The cities analyzed from 2007 to 2018 were Cambridge, New York City, Tempe, and Washington, D.C. DFI values for Milwaukee were calculated from 2014 to 2018, and DFI value for Providence were calculated from 2013 to 2018. The shortened time frame was due to limited data availability and DFI values for Newark could not be calculated at all for the same reason.

To interpret DFI values, values that are less than 1 indicate that the water is undersaturated and $CaCO_3$ will dissolve and corrode the pipe. DFI values equal to 1 represent water that is balanced; $CaCO_3$ will neither precipitate nor dissolve. DFI values greater than 1 indicate that the water is oversaturated and $CaCO_3$ will precipitate.

Table 18. DFI Values for Each Municipality

Municipality	Cambridge		Milwaukee		NYC**		Providence		Tempe		D.C.**	
Year	DFI	90th*	DFI	90th*	DFI	90th*	DFI	90th*	DFI	90th*	DFI	90th*
2018	1.79	N/A	0.22	N/A	0.0051	11.0	4.10	11/22	0.14	12.0	0.17	3/2
2017	1.88	7.0	0.21	7.2	0.0046	11.0	4.33	14/17	0.29	N/A	0.17	3/3
2016	2.26	N/A	0.19	N/A	0.0073	11.0	3.45	13/16	0.16	N/A	0.23	2/3
2015	1.46	N/A	0.21	N/A	0.0044	12.0	4.32	9/15	0.50	8.40	0.20	2/4
2014	1.74	5.0	0.18	8.2	0.0023	11.0	4.38	10/16	0.43	N/A	0.18	2/4
2013	1.28	N/A	N/A	N/A	0.0024	11.0	4.21	13/30	0.61	N/A	0.15	4/6
2012	1.33	N/A	N/A	N/A	0.0018	10.0	N/A	14/25	0.60	6.50	0.18	3/4
2011	1.42	5.0	N/A	N/A	0.0019	6/13	N/A	15/21	0.47	N/A	0.18	5/5
2010	1.08	N/A	N/A	N/A	0.0015	19.0	N/A	21/20	0.55	N/A	0.17	7/9
2009	1.29	N/A	N/A	N/A	0.0015	10/6	N/A	16/30	1.03	4.50	0.17	6/7
2008	1.64	9.0	N/A	N/A	0.0015	11/8	N/A	14/21	0.64	N/A	0.17	7/8
2007	1.82	7.0	N/A	N/A	0.0018	15/9	N/A	20/21	0.96	N/A	0.22	10/11

*90th percentile lead concentrations in µg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

DFI Value Note: green = >1, yellow = 1, red = <1

90th Percentile Note: green = 0-10 µg/L, yellow = 10-15 µg/L, red = 15+ µg/L

Table 18 shows the DFI values calculated compared to the 90th percentile lead levels of the various cities assessed. New York City had the lowest DFI values out of all the cities looked at. New York City's DFI values ranged from 0.0015 to 0.0051. New York City's water had mostly moderate lead concentrations, ranging from 6 to 19 µg/L. Tempe's DFI values were all less than 1, except in 2009 when it was 1.03. The rest of Tempe's DFI values ranged from 0.14 to 0.96, predicting corrosion. However, the municipality's 90th percentile lead levels ranged from 4.50 to 12.0, with mostly low lead concentrations. Milwaukee and Washington, D.C. had similar results to Tempe. They both had low DFI values that predicted corrosion, ranging from 0.18 to 0.22 for Milwaukee and ranging from 0.15 to 0.23 for Washington, D.C. But both cities had low 90th percentile lead levels ranging from 7.2 to 8.2 µg/L for Milwaukee and 2 to 11 µg/L for Washington, D.C.

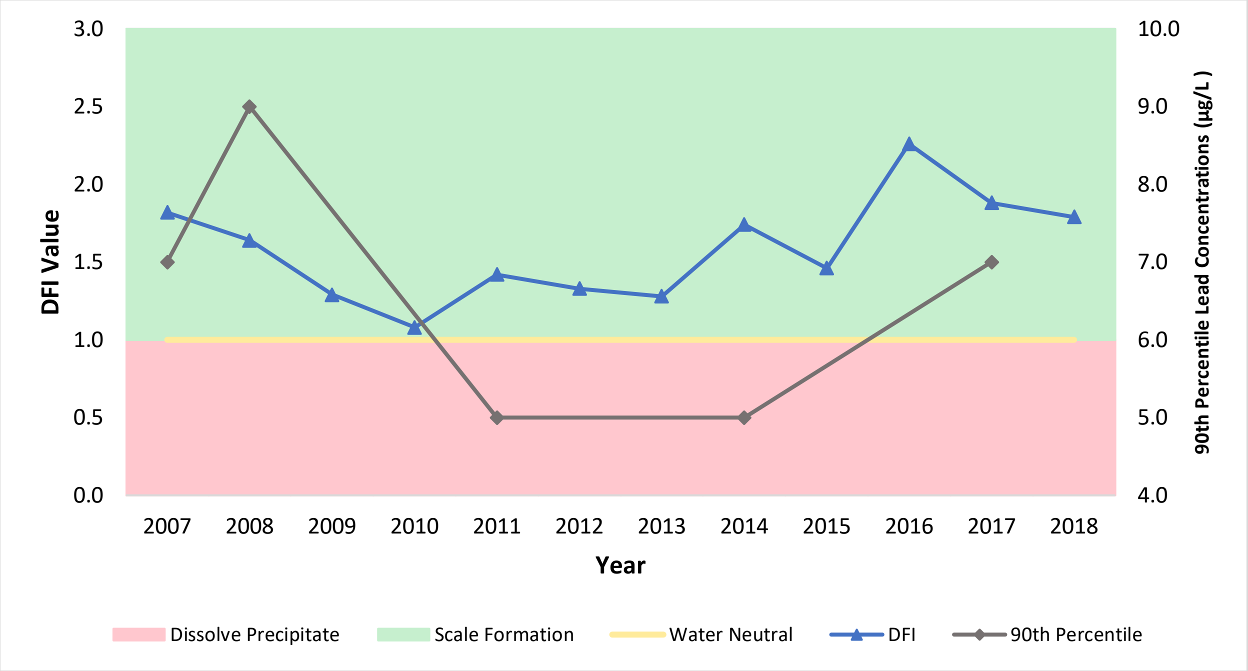


Figure 19. DFI and 90th Percentile Lead Concentrations for Cambridge

Figure 19 shows the DFI values over time compared to Cambridge's 90th percentile lead levels. The DFI indicated scaling for Cambridge, which had values ranging from 1.08 to 2.26. This corresponds with the city's 90th percentile lead levels which ranged from 5.0 to 9.0 µg/L. Even though the DFI correctly predicted non-corrosive water, it is interesting to note that when Cambridge's DFI values increased (indicating a higher scaling potential), the 90th percentile lead levels actually increased (while still remaining low). Providence had the highest DFI values out of all of the cities, which would mean that the water is conducive to scaling. However, Providence had the highest lead concentrations ranging from 9 to 30 µg/L.

Overall, it seems that the DFI is not the best corrosion index for drinking water systems. The DFI was only accurate for Cambridge and somewhat accurate for New York City. The errors in the DFI's corrosion predictions could be because the index uses carbonate alkalinity in its equation. However, drinking water usually has a higher amount of bicarbonate in it compared to carbonate. The imbalance between the two ions could be the reason for inaccurate predictions of the chemical reactions in the water.

4.12 Momentary Excess Index

The Momentary Excess (ME) index was developed in 1958 by Dye as one of the first ventures to predict the amount of calcium carbonate that forms in water (Rossum & Merrill, 1983). A summary of the ME values for each water utility are provided in Table 19.

Table 19. ME Values for Each Municipality

Municipality	Cambridge		Milwaukee		NYC**		Providence		Tempe		D.C.**	
Year	ME	90th*	ME	90th*	ME	90th*	ME	90th*	ME	90th*	ME	90th*
2018	0.60	N/A	-0.67	N/A	-3.04	11.0	5.82	11/22	-0.28	12.0	-0.51	3/2
2017	0.66	7.0	-0.59	7.2	-3.09	11.0	5.82	14/17	-0.25	N/A	-0.53	3/3
2016	0.93	N/A	-0.63	N/A	-2.53	11.0	4.52	13/16	-0.31	N/A	-0.43	2/3
2015	0.39	N/A	-0.62	N/A	-2.83	12.0	5.81	9/15	-0.16	8.40	-0.47	2/4
2014	0.73	5.0	-0.65	8.2	-3.65	11.0	6.03	10/16	-0.20	N/A	-0.48	2/4
2013	0.35	N/A	N/A	N/A	-3.65	11.0	5.15	13/30	-0.12	N/A	-0.49	4/6
2012	0.35	N/A	N/A	N/A	-3.68	10.0	N/A	14/25	-0.14	6.50	-0.46	3/4
2011	0.42	5.0	N/A	N/A	-3.81	6/13	N/A	15/21	-0.23	N/A	-0.44	5/5
2010	0.09	N/A	N/A	N/A	-3.72	19.0	N/A	21/20	-0.23	N/A	-0.45	7/9
2009	0.31	N/A	N/A	N/A	-3.78	10/6	N/A	16/30	-0.01	4.50	-0.45	6/7
2008	0.70	9.0	N/A	N/A	-3.73	11/8	N/A	14/21	-0.16	N/A	-0.47	7/8
2007	0.87	7.0	N/A	N/A	-3.82	15/9	N/A	20/21	-0.01	N/A	-0.42	10/11

*90th percentile lead concentrations in µg/L

**Average 90th percentile lead concentration values given twice per year (First half of year/Second half of year)

ME Value Note: green = > 0, yellow = 0, red = < 0

90th Percentile Note: green = 0-10 µg/L, yellow = 10-15 µg/L, red = 15+ µg/L

If the ME value is greater than 0, it is predicted that the water is supersaturated with $CaCO_3$ and will form a precipitate. ME values equal to 0 indicate neutral water where no reactions will take place. ME less than 0 suggests that the distributed water could dissolve scales on the pipe wall.

Of all of the water systems analyzed, only Cambridge and Providence had ME values greater than 0, with a range of 0.31 to 0.93 from the years 2007 to 2018 and 5.15 to 6.03 from 2013 to 2018, respectively. This index interpretation does not correlate with Cambridge's 90th percentile lead levels. As lead levels decreased from 2008 to 2011, the ME also dropped suggesting the water has become more neutral. Also from 2011 to 2017 the ME increased despite 90th percentile lead concentrations rising. For Providence, ME values all indicate that it will form a scale even though 90th percentile lead concentrations are well above the LCR action limit.

All the remaining facilities: Milwaukee, NYC, Tempe, and D.C. had negative values that these waters could dissolve protective scales. Tempe ME values were closest to zero for the years 2007 to 2018. Figure 20 depicts the relationship between the ME and 90th percentile lead concentrations for Tempe. In this example, as the lead levels increased from 4.5 to 12 µg/L, the ME value decreased: -0.01 in 2007 to -0.28 in 2018.

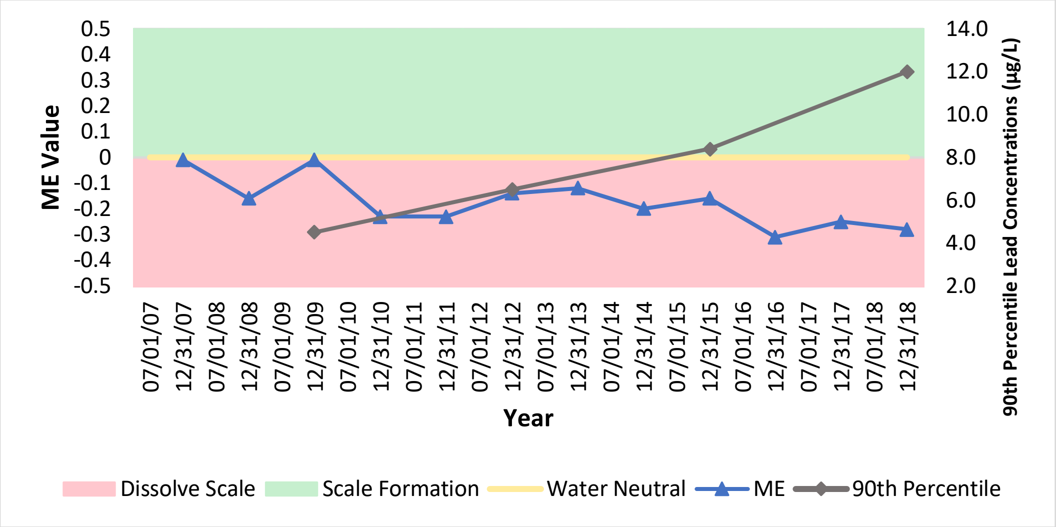


Figure 20. ME and 90th Percentile Lead Concentrations for Tempe

For Washington, D.C., the lead 90th percentile lead levels decreased from 10 to 2 µg/L over the course of 12 years. The ME, however, remains the same. NYC had the largest negative ME values with range of -3.82 to -2.53 between 2007 to 2018. Despite the LCR violation in 2010, where the 90th percentile lead concentration rose to 19 µg/L, the ME was unsuccessful in predicting this outcome. There also was no correlation between the ME for Milwaukee and 90th percentile lead concentrations. The ME stays relatively constant from 2014 to 2018 even though 90th percentile lead levels decreased from 8.2 to 7.2 µg/L.

It is interesting to note that like the DFI, the ME uses only carbonate (CO_3^{2-}) ions concentrations to calculate the relationship between calcium and the carbonate system in the water. Many of the water utilities analyzed have a much higher percentage of bicarbonate (HCO_3^-) ions in the water, which suggests that the ME leaves out an important variable when calculating if $CaCO_3$ would precipitate a scale.

5.0 Conclusions & Recommendations

After calculating index values for all of the utilities, we ranked each index on a five-point scale as accurate, moderately accurate, neutral, moderately inaccurate, or inaccurate. Using the rankings, we calculated an overall ranking for each index and determined which indices were most useful. We also developed recommendations on what corrosion indices water utilities should use and designed a corrosion control monitoring program for water utilities.

5.1 Conclusions about Corrosion Indices

This section summarizes the predictive ability of the corrosion indices with regard to lead concentrations in homeowner's taps. Table 21 shows whether each index does or does not accurately predict lead levels for each municipality. The water utilities are listed, and their corrosion control treatment strategy is noted. Using the results from Chapter 4, each index was evaluated for each municipality to determine if the index was useful for predicting lead concentrations.

Table 20: Ranking of Index Predictions

Utility		Milwaukee	Newark	D.C.	NYC	Cambridge	Providence	Tempe	Ranking (sum of points / maximum possible points)
		Treatment							
Type of Index	Index	Ortho	Ortho	Ortho	Ortho, pH adj.	pH adj.	pH & alk adj.	None	
$CaCO_3$ precipitation	LSI	0	N/A	0	0	3	0	1	0.17
	RSI	0	N/A	0	0	0	2	1	0.13
	S&DSI	4	N/A	N/A	0	4	0	3	0.55
	PSI	0	N/A	0	0	0	3	0	0.13
	CCPP	3	N/A	0	3	3	0	2	0.46
	DFI	0	N/A	0	0	3	0	1	0.17
	ME	0	N/A	0	0	3	0	1	0.17
	CSI	4	N/A	N/A	0	4	0	3	0.55
Corrosion of mild steel	L&SkI	4	1	0	0	0	3	1	0.32
	LR	0	1	0	0	0	3	1	0.18
Galvanic corrosion	CSMR	4	2	0	0	0	4	1	0.39
Aggressiveness of water	AI	3	1	0	2	3	0	4	0.46

Note on Rankings: 0 = index was inaccurate, 1 = index was moderately inaccurate, 2 = index was neutral, 3 = index was moderately accurate, 4 = index was accurate

The definitions of accuracy were as follows:

- An index was defined as accurate (ranking of 4) if it met at least one of the conditions listed a-c and also met condition d:
    a) It indicated corrosion, aggressiveness, or $CaCO_3$ would dissolve and 90th percentile lead levels exceeded the EPA Action Level (15 μg/L)
    b) It indicated no corrosion, non-aggressive or neutral water, or $CaCO_3$ scaling and 90th percentile lead levels were less than 10 μg/L
    c) It predicted moderate corrosion and 90th percentile lead levels were between 10-15 μg/L
    d) Index values changed to indicate more or less corrosion/aggressiveness/scaling and lead levels were simultaneously increasing or decreasing (followed trends)
- An index was defined as moderately accurate (ranking of 3) if it met at least one of the conditions listed a-c and also met condition d:
    a) It indicated corrosion, aggressiveness, or $CaCO_3$ would dissolve and 90th percentile lead levels exceeded the EPA Action Level (15 μg/L)
    b) It indicated no corrosion, non-aggressive or neutral water, or $CaCO_3$ scaling and 90th percentile lead levels were less than 10 μg/L
    c) It predicted moderate corrosion and 90th percentile lead levels were between 10-15 μg/L
    d) Index values did not follow lead concentration trends
- An index was defined as neutral (ranking of 2) if the following condition was met:
    a) It was accurate for 40 to 60% of the time period assessed and inaccurate for the other percent of the time period
- An index was defined as moderately inaccurate (ranking of 1) if it met at least one of the conditions listed a-b and also met condition c:
    a) It indicated corrosion, aggressiveness, or $CaCO_3$ would dissolve and 90th percentile lead levels were less than 10 μg/L
    b) It indicated no corrosion, non-aggressive or neutral water, or $CaCO_3$ scaling and 90th percentile lead levels were higher than 15 μg/L
    c) Index values did follow lead concentration trends
- An index was defined as inaccurate (ranking of 0) if it met at least one of the conditions listed a-b and also met condition c:
    a) It indicated corrosion, aggressiveness, or $CaCO_3$ would dissolve and 90th percentile lead levels were less than 10 μg/L
    b) It indicated no corrosion, non-aggressive or neutral water, or $CaCO_3$ scaling and 90th percentile lead levels were higher than 15 μg/L
    c) Index values did not follow lead concentration trends

The ranking for each index was determined as the sum of the rankings for each utility divided by the maximum sum of rankings that could be obtained. For example, for the LSI, the sum of the rankings was 4. The maximum possible sum (if all utilities were ranked at “4”) would be 24 since there were 6 utilities for which this index was calculated. Therefore, the ranking is calculated as 4/24 = 0.17. The ranking could range from 0.0 for an index that was inaccurate for all utilities to 1.0 for one that was accurate for all utilities.

After calculating the ranking for each index, the Calcium Saturation Index (CSI) and the Stiff & Davis Index (S&DSI) were determined to be the most accurate indices, with rankings of 0.55. The CSI provided accurate results for Milwaukee, Cambridge, and Tempe. The CSI predicted no corrosion for Milwaukee and the city had low 90th percentile lead levels. Likewise, Cambridge had CSI values predicting no corrosion and relatively low 90th percentile lead levels. For Tempe, the CSI received a ranking of 3, indicating moderate accuracy because as 90th percentile concentrations increased to moderate levels, the CSI showed no change. It is interesting to note that the two water utilities that had inaccurate rankings (NYC and Providence) these facilities have higher 90th percentile lead concentrations. This could suggest that the CSI is limited in its applicability.

The Stiff & Davis Stability Index (S&DSI) was the other most accurate index. Like the CSI, the S&DSI had an accurate prediction for Milwaukee and Cambridge, predicting $CaCO_3$ scaling and the cities had low 90th percentile lead concentrations. Tempe had a moderately accurate corrosion prediction. The S&DSI predicted scaling for Tempe and there were low lead levels. However, Tempe's 90th percentile lead levels increased over time and the index did not reflect this trend. It is interesting to note that the S&DSI was designed for waters with total dissolved solids over 10,000 mg/L. In all of the water utilities analyzed, the TDS never reached this concentration. Therefore, the results of the S&DSI could in fact be confounding or inapplicable to this project.

The indices that were least accurate in predicting corrosion were the Puckorius Saturation Index (PSI) and the Ryznar Saturation Index (RSI), each with rankings of 0.13. The PSI had only one moderately accurate prediction and the rest were inaccurate for the water municipalities while the RSI was neutral for Providence and moderately inaccurate for Tempe. As acknowledged in Chapter 2, the PSI was designed for cooling towers, which makes sense as to why it was perhaps not as accurate in predicting the corrosion potential of distributed waters. On the other hand, the PSI was intended to be more accurate than the LSI, but this was not the case for our study. The RSI was also adapted from the LSI, but our results indicate that the modifications may not have been as successful as intended.

Table 21 is organized by the different treatment methods that water utilities use to control corrosion to see if there are any correlations between index accuracy and treatment methods. Many indices were either moderately inaccurate or neutral for Tempe, with only one index determined to be inaccurate. Tempe does not use any treatment to prevent corrosion in their water. This does not explain why a majority of the indices predicted moderate inaccuracy, as there are no additional chemicals in the water to induce corrosion. Milwaukee, Washington, D.C., Newark, and New York City all have an orthophosphate treatment, and had many inaccurate predictions from the indices (except for Newark, for which only four indices were able to be calculated due to limited water quality data). Milwaukee, Washington, D.C., and New York City all had ten or more indices calculated for them, increasing the amount of data available for drawing conclusions about the most accurate indices. There is no obvious trend for how corrosion treatment affects the accuracy of the corrosion indices (e.g., that a particular index was accurate if orthophosphate was used but inaccurate if pH adjustment was used).

Overall, there exists a number of shortcomings in the indices that were evaluated. One of the major factors was a lack of a variable for phosphate concentrations. For the water departments that used orthophosphate for their corrosion control treatment program, phosphate ions can play a significant role in the reactions that take place within the distributed water to precipitate out lead-phosphate scales. Further studies would be necessary to understand the correlations between phosphate-based inhibitors and lead concentrations in the water to formulate a new or update an existing index. The CSI and S&DSI were determined to be the most accurate indices, but still had rankings of only 0.55, which is not satisfactory to recommend these indices for use by all utilities. The LSI, which has become the standard corrosion index for many water utilities, was only accurate in predicting scaling potential for one of the municipalities, moderately inaccurate for another, and inaccurate for the rest. A shortcoming in the data used is the fact that it is difficult to collect data within the distributed water system. Most facilities collect data on the water leaving the water treatment plant. As the water flows through the piping systems numerous reactions take place that change the chemistry of the water. As such, the water samples collected at the tap can be different from the initial samples leaving the plant.

5.2 Recommendations

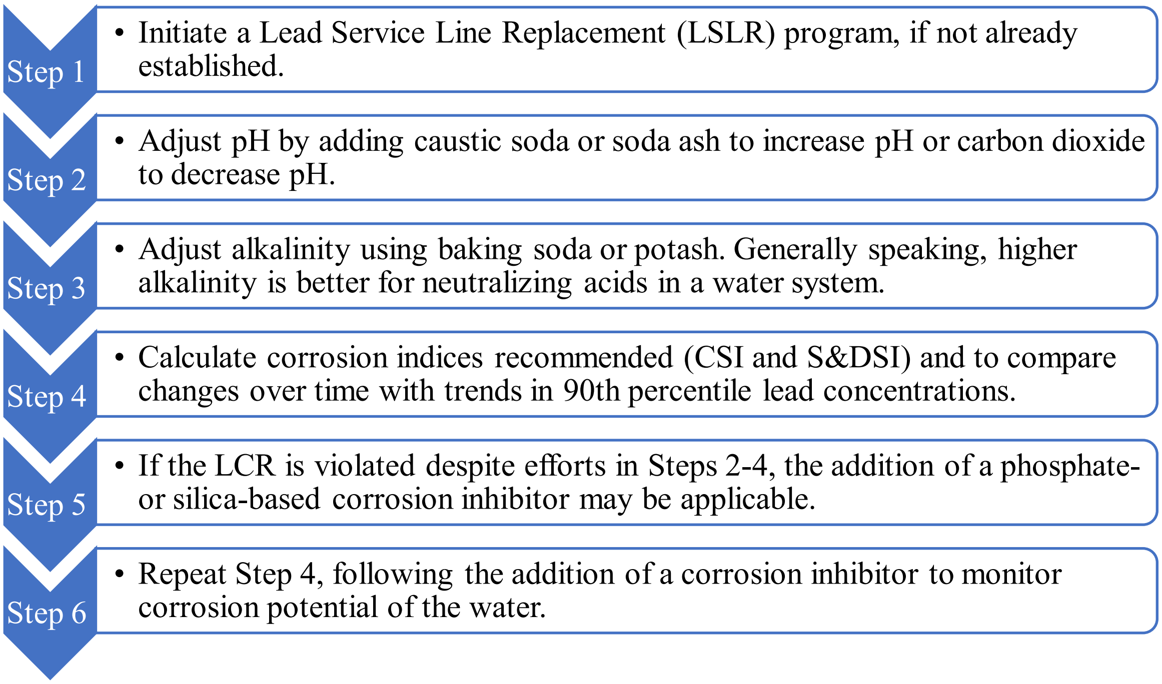
We designed a corrosion control monitoring program that can be useful for water systems. The corrosion indices use a large number of different variables, and the two most accurate indices found in this study (CSI and S&DSI) use similar variables. Both the CSI and S&DSI use alkalinity, calcium, conductivity, pH, temperature, and ionic strength. The S&DSI overall is more simplified than the CSI, therefore, a water municipality may find it easier to use. Water utilities should also monitor the additives they use to control corrosion. If a water system adds orthophosphate or silica-based corrosion inhibitors, the system should also measure phosphate or silica residuals to ensure that the concentrations are high enough to indicate that the reactions have gone to completion. In our initial research, we believed that the Riddick Corrosion Index could be a very effective index for predicting corrosion because it accounts for several variables that are not used in other indices: carbon dioxide, chloride, dissolved oxygen (DO), nitrate, and silica. Higher levels of DO in water can increase the rate of corrosion reactions in the water. High chloride concentration can promote corrosion in iron, copper, and steel, making it an important factor to consider during corrosion monitoring. Because the Riddick Corrosion Index utilizes these variables, we wanted to include it in our study of corrosion indices. However, most water quality reports do not include these variables and we were not able to obtain enough data to calculate Riddick index values for the water systems.

In terms of the frequency of monitoring, the Optimal Corrosion Control Treatment (OCCT) report written by the EPA provides a summary of the most common water parameters linked to corrosion prevention. In Chapter 2, we provided a table with a list of the major variables that contribute to corrosion control. These include: alkalinity, calcium, chloride, DO, hardness, pH, sulfate, and temperature. While alkalinity, calcium, pH, and corrosion inhibitors (phosphate- or silicate-based) are the standard water quality parameters listed for sampling twice every six months, it is highly recommended that monitoring of these water quality parameters occur every month (Office of Water, 2016).

With the water quality parameters that they measure, water utilities should calculate corrosion index values. The S&DSI is a simpler equation to calculate than the CSI. Utilities can calculate values for these indices and use them to monitor corrosion in the water. Water utilities should be aware that the corrosion index values may not be correct. They should compare index values to 90th percentile lead concentrations and see if the index values correlate with lead levels. If index values predict non-corrosion, but the numbers change to become closer to corrosion and 90th percentile lead levels also increase over time, then the water utility should review its corrosion control treatment methods. The index could also predict corrosion when 90th percentile lead levels are below the EPA limit. The water system should look at index values for past years and see if the index value changes over time. If the index predicts more corrosion over time, the water utility should think about adjusting their corrosion treatment.

5.3 Steps for Corrosion Monitoring and Prevention

We designed a corrosion monitoring and prevention program that water utilities can use. It should be noted that if a water municipality already uses a corrosion index that is not one of our recommended indices specified below and the index successfully predicts lead concentrations, they can continue to apply such practices as they see fit. If a utility is struggling to find the optimal corrosion index for their corrosion monitoring program, we have developed a step by step process below to aid in this matter.



Step 1
- Initiate a Lead Service Line Replacement (LSLR) program, if not already established.

Step 2
- Adjust pH by adding caustic soda or soda ash to increase pH or carbon dioxide to decrease pH.

Step 3
- Adjust alkalinity using baking soda or potash. Generally speaking, higher alkalinity is better for neutralizing acids in a water system.

Step 4
- Calculate corrosion indices recommended (CSI and S&DSI) and to compare changes over time with trends in 90th percentile lead concentrations.

Step 5
- If the LCR is violated despite efforts in Steps 2-4, the addition of a phosphate- or silica-based corrosion inhibitor may be applicable.

Step 6
- Repeat Step 4, following the addition of a corrosion inhibitor to monitor corrosion potential of the water.

Figure 21. Steps for Corrosion Monitoring and Prevention

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