Optimization of Phosphorus-Based Corrosion Control Chemicals Using a Comprehensive Perspective of Water Quality

Project #4586

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Optimization of Phosphorus-Based Corrosion Control Chemicals Using a Comprehensive Perspective of Water Quality

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FOREWORD

The Water Research Foundation (WRF) is a nonprofit corporation dedicated to the development and implementation of scientifically sound research designed to help water utilities respond to regulatory requirements and address high-priority concerns. WRF's research agenda is developed through a process of consultation with WRF subscribers and other water professionals. WRF's Board of Directors and other professional volunteers help prioritize and select research projects for funding based upon current and future industry needs, applicability, and past work. WRF sponsors research projects through the Focus Area, Emerging Opportunities, Tailored Collaboration, and Facilitated Research programs, as well as various joint research efforts with organizations such as the U.S. Environmental Protection Agency and the U.S. Bureau of Reclamation.

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A broad spectrum of water issues is addressed by WRF's research agenda, including infrastructure and asset management, rates and utility finance, risk communication, green infrastructure, food waste co-digestion, reuse, alternative water supplies, water loss control, and more. The ultimate purpose of the coordinated effort is to help water suppliers provide a reliable supply of safe and affordable water to consumers. The true benefits of WRF's research are realized when the results are implemented at the utility level. WRF's staff and Board of Directors are pleased to offer this publication as a contribution toward that end.

Charles M. Murray
Chair, Board of Directors
Water Research Foundation

Robert C. Renner, PE
Chief Executive Officer
Water Research Foundation

ACKNOWLEDGEMENTS

This project is the culmination of years of development of the author's approach to distribution system water quality control. There are many people to thank whose input helped to form the approach and also helped to carry out this project.

Eric Kiefer, Manager of the North Shore Water Commission water treatment plant in Glendale, Wisconsin, is an "early adopter" (Rogers 2003) of ideas and technologies. He has involved the PRS Monitoring Station in two Water Research Foundation projects (Project #4286 and this project, Project #4586) as well as in making a critical operational change at the water treatment plant. His involvement with the PRS Monitoring Station has called the technique to the attention of the Water Research Foundation and others in the drinking water field.

Kevin Shafer, Executive Director of the Milwaukee Metropolitan Sewerage District and Chairman of the Water Environment Research Foundation Board, initiated this project in a quest for minimizing phosphate contributions from municipal drinking water to wastewater treatment facilities. Timothy Bate, P.E., Director of Planning, Research and Sustainability at the Milwaukee Metropolitan Sewerage District, also worked to initiate the project and attended planning meetings. He retired during this project and left Matthew Magruder, Environmental Research Manager, in the project. Matt went on to aid in collecting data from the wastewater treatment facilities in this study and to edit Chapter 12 on phosphorus removal from wastewater, giving a big boost to the development of that material.

Two other Wisconsin wastewater treatment facility managers took an interest in this project and volunteered time to planning the wastewater approach and to editing Chapter 12. Tom Steinbach, manager of the Oconomowoc, Wisconsin wastewater facility, and Sam Warp, manager of the Marshfield, Wisconsin wastewater facility, both donated time and excellent ideas for development of the wastewater chapter.

Continuing with support from the wastewater side of the water equation, this project could not have been carried out without the generous grant from the Water Environment Research Foundation and the involvement of Walter Graf, Program Manager.

On the drinking water side of the water equation, this project also would not be possible without the generous grant from the Water Research Foundation. Jonathan Cuppett, Project Manager, helped pave the way for making this project a reality and keeping it on track.

Water Research Foundation Project Advisory Committee members, Jeff Swertfeger, Assistant Superintendent of the Greater Cincinnati Water Works, and Zeke Campbell, Superintendent of Water Quality in the Denver Water Utility, donated their time to commenting on project progress reports every three months and on the draft manuscript of the final report. Their comments were invaluable in helping to communicate the ideas in this project.

The project team consisted of twelve Wisconsin water utilities. It has been requested that the utilities remain anonymous. Managers, operators, engineers, and chemists from these utilities all participated in project meetings and in carrying out the detailed work in gathering the distribution system data. Project meetings began about six months before the original grant proposal was submitted and continued throughout this multi-year project. Meeting discussions became a great exchange of ideas and were important in shaping the outcome of this project. These utilities and personnel donated financial support, labor, and planning time; they were the engine keeping this project moving forward.

Federal and state drinking water regulators also took an interest in this project and donated time to participate in project meetings and in editing the report manuscript. Miguel del Toral, Regulations Manager for the U.S. Environmental Protection Agency (EPA) of Region 5 Groundwater and Drinking Water Bureau in Chicago also arranged for the donation of water analyses from the EPA laboratory in Chicago. With this donation, the project was able to carry out profile sampling in two residences of five Lake Michigan water systems.

At the State of Wisconsin regulatory level, Steve Elmore, Director of the Department of Natural Resources Bureau of Drinking Water and Groundwater, and Mark Nelson, Water Supply Specialist with a focus on the Lead and Copper Rule, both participated in this project in its planning stages and throughout by attending project meetings and offering comments on project activities. Mark Nelson retired during this project; Bridget Kelly took his place at the Bureau and actively participated in this project. Cathrine Wunderlich, Chief of Public Water Engineering, and Adam DeWeese, Chief of Public Water Supply, along with Bridget Kelly, all became involved in reading the draft report and setting aside time to discuss aspects of the findings. This project has greatly benefited from this direct involvement and interest of drinking water regulators.

On the corporate side, Jason Peters, Vice President of Product Development at Blue Earth Labs LLC, participated in project meetings and in editing the report manuscript. In addition, he made arrangements for his company to support disinfection by-product sampling at one of the sites where his company's product, Clearitas®, was utilized.

Dr. J. Barry Maynard, currently retired geology professor from the University of Cincinnati, has analyzed the chemical scales on the PRS Monitoring Station metal plates since 2006 when the first PRS Monitoring Station was installed. His insight into chemical scales in drinking water systems has added an important dimension to the use of PRS Monitoring Stations and his analyses have uncovered key aspects of lead and copper release mechanisms.

Dr. Andrew Jacque, P.E., Founder and Chief Scientist of Water Quality Investigations, LLC, has made tremendous strides in uncovering how microorganisms participate in water chemistry and in shaping water quality. The report author, Abigail Cantor, and Dr. Jacque, met many years ago in a mutual quest for improved methods for measuring the population of microorganisms in water and on pipe walls. They have collaborated on many projects since that time, during which time Dr. Jacque has expanded the possibilities of microbiological materials measurement and interpretations of the data.

Dr. Kevin Little, statistician and Founder of Informing Ecological Design, LLC, has been an important mentor to Abigail Cantor on the use of statistical techniques for the analysis of drinking water monitoring data. Dr. Little was the first to suggest that the Shewhart Control Charts be used for this purpose. He has also introduced other concepts regarding data presentation and statistical programming language. This quantity of data could not be handled without the techniques that he promotes.

Rob Spence, vice-president of the Rundle-Spence Company -- plumbing, heating, well, and septic equipment distributor -- and mechanical engineer, took on the task of improving the design of Process Research Solutions' Monitoring Station and assembling the stations for water utilities starting around 2009. He has made it possible to easily produce and install a monitoring station in a distribution system to get a water quality monitoring program underway.

EXECUTIVE SUMMARY

KEY FINDINGS

- If planning to use orthophosphate, perform a phosphorus environmental impact analysis in coordination with the wastewater treatment facility
- It should never be assumed that orthophosphate use is applicable to all water systems or that its use provides guaranteed protection from exposure to lead or copper
- The comprehensive perspective of water quality includes routinely improving infrastructure, adopting an ongoing biostability improvement program, and maintaining an ongoing corrosion control plan

OBJECTIVES

When controlling lead and copper release from piping materials into drinking water, choices are limited. Orthophosphate addition and pH/alkalinity adjustment are the two commonly used lead and copper control strategies and are the focus of the Lead and Copper Rule. Both methods are utilized to create a protective chemical barrier on metal surfaces that inhibits further corrosion of the metal. The science behind these methods is well understood. But, how are these chemical interactions carried out in actual water systems where many other chemical and microbiological interactions are occurring at the same time? This question was explored in this project.

The objectives of this project were:

- To measure the effects of lead and copper orthophosphate and carbonate compounds in the complex chemical and microbiological environment of drinking water systems
- To observe the effects on lead and copper orthophosphate and carbonate compounds as some of the chemical and microbiological factors were removed from the water environment. This was accomplished by removal of pipe wall accumulations and by creation of a water environment where microorganisms could not grow excessively.
- To assess the impact of phosphates on the environment and on wastewater treatment facilities after the phosphates have left the drinking water system

BACKGROUND

Phosphorus-based chemicals have a long history of use as additives in drinking water systems, especially in pulling calcium, iron, and manganese compounds off of system structures and holding the metals in solution (sequestration). Other phosphate chemicals successfully act in an opposite manner by dropping metals out as insoluble compounds on metal surfaces that can, in some cases, inhibit corrosion of those surfaces.

In 1991, phosphorus-based chemicals took on even more importance in drinking water systems. This was the year that the Lead and Copper Rule was first published. Historical use of phosphates in drinking water systems and years of phosphate-oriented research led up to the publishing of the Rule, with emphasis on the use of orthophosphate for control of uniform corrosion of lead.

In 2017, the United States Environmental Protection Agency (EPA) is poised to rewrite and republish the Lead and Copper Rule. EPA documents imply that a greater focus will be placed on the use of orthophosphate. For lead control, there are suggestions that the dosage should be increased to around 3.5 mg/L as PO_4 from current common dosages of 0.3, 1, and 3 mg/L as PO_4. In addition, a new emphasis will be placed on copper corrosion control. Regarding copper corrosion, many water systems not now using orthophosphate may be required to begin orthophosphate addition.

As an alternative to orthophosphate addition for lead and copper corrosion control, the Lead and Copper Rule also allows for alterations to alkalinity and pH of the water. Manipulation of alkalinity, pH, and orthophosphate concentration for lead and copper corrosion control come from a fundamental concept of how lead and copper are released into water from piping materials. The Lead and Copper Rule is based on this fundamental concept and maintains that either lead or copper carbonates or lead or copper orthophosphates will form a uniform barrier on pipe walls to inhibit further lead or copper corrosion and release.

However, analyses of system water and pipe wall accumulations in actual water systems show a more complex composition than described by the carbonate- or the orthophosphate-solubility models. This project explored whether lead or copper orthophosphate and carbonate compounds could continue to provide corrosion control in the presence of these observed chemical and microbiological interactions actually occurring in water systems.

In bringing more of the observed complexity into this study of water systems, components of system water and of pipe wall accumulations were grouped into three general categories for organizational purposes:

1. Uniform corrosion products, including not only carbonates and orthophosphates but also oxides, chlorides, and sulfates
2. Water biostability parameters, including microbiological populations, the presence of biofilms, the presence of nutrients for microorganisms (organic carbon, nitrogen, and phosphorus compounds), and the presence of disinfection
3. Chemical scale formation and dissolution parameters, including a number of metals in both dissolved and particulate form, such as iron, manganese, and aluminum

In addition, this project looked at the fate of phosphates after they leave the drinking water system. At the same time that drinking water systems are becoming more dependent on phosphorus-based water treatment products, there is an urgency to decrease the release of phosphorus to waterbodies since phosphorus creates a number of environmental issues. Therefore, it is now imperative that an assessment be made to determine how wastewater treatment facilities will be impacted by additional phosphorus contributed from drinking water.

APPROACH

This project involved the following tasks:

- Gather existing information on each water system
- Characterize each existing water system using comprehensive monitoring techniques, including special distribution system monitoring stations

- Clean each water system with uni-directional (high velocity) flushing and, optionally, a biofilm-removing chemical while monitoring. To the extent possible, control factors that can influence excessive growth of microorganisms.
- Continue monitoring as the water system comes to a new steady state of lead and copper release

Data from flowing system water, monitoring station test chamber stagnating water, and test chamber metal plate accumulations were used to determine the relationships between lead and copper release and their various possible influencing factors.

RESULTS/CONCLUSIONS

This project set out to determine whether development of passivating barriers on pipe walls for corrosion control can be successfully carried out in water systems where many other chemical and microbiological interactions occur at the same time.

It was found that passivating barriers are not guaranteed to form on pipe walls. Lead and copper carbonates, expected by the carbonate solubility models used as a foundation for the Lead and Copper Rule, formed on the test chamber metal surfaces, but many other chemical compounds and biofilms formed as well. A high rate of lead and copper release was measured initially in the test chambers from the bare metal surfaces. The rate of lead and copper release dropped over time – from one month to one year – in the different water systems, most likely as carbonate barriers formed. Then, other factors influencing chemical scale and biofilm development appeared to become more dominant in controlling the quantity of lead and copper released. In water systems, there are few pipes that remain as bare metal; most pipes develop complex structures of chemical scales and biofilms. It is doubtful that a passivating film could physically form a uniform barrier against the pipe wall, much less compete with the other influencing factors.

In studying the accumulations on the metal surfaces in the test chambers, there was not just the one lead or copper carbonate compound expected by the carbonate solubility models. Instead, there were mixtures of types of lead or copper carbonate compounds, as well as lead or copper oxides. There were also other elements, such as iron, manganese, aluminum, phosphorus, and sulfur. In addition, there were thermodynamically unstable amorphous compounds observed on the plates, not just the thermodynamically stable crystalline compounds assumed by the equilibrium-based carbonate solubility models. There were also chemical scales observed containing lead and copper that had the potential to crumble into the water and transport lead or copper as particulate matter, another aspect not considered in the carbonate solubility models. To add to this chemical complexity, a presence of biofilms was quantified on each metal surface.

Given the lack of correlation to lead and copper release in this project, and the complex nature of the metal surface accumulations observed, the models of lead and copper carbonate solubility used by the Lead and Copper Rule to predict lead and copper release do not adequately represent the set of circumstances actually found in drinking water distribution systems.

This is not to say that the lead and copper carbonate solubility concept should not be considered. Instead, this is an observation that carbonate solubility is only one of many factors that control the release of lead and copper in water distribution systems. The major water quality parameters of the carbonate concept, alkalinity and pH, must always be considered in an evaluation of lead and copper control along with two other groups of water quality parameters identified on the metal plates – parameters related to chemical scale formation and biostability of the water.

Forming passivating barriers with orthophosphate addition was also studied. As with a carbonate-based passivating barrier, it was physically difficult to form a uniform barrier against metal surfaces, and to compete with the other influencing factors, where other chemical scales and biofilms were also forming. Only one water system showed adequate formation of the desired lead and orthophosphate mineral, pyromorphite. That water system, though, released lead where fifty percent was in particulate form, not known to be controlled by pyromorphite, and had a strong relationship of lead and copper release to a microbiological nitrification process occurring seasonally in the distribution system.

In addition, three of the water systems dosing a phosphate corrosion control chemical showed trends between increasing lead and/or copper with increasing phosphorus in the water. This was either because of sequestration by the polyphosphate fraction of the corrosion control chemical or it was from the sloughing of biofilms and organically-bound phosphorus and metals.

This does not mean that orthophosphate is not a viable tool for corrosion control. It should always be considered in a comprehensive approach to corrosion control, but placed within proper context. It should never be assumed that its use is applicable to all water systems or that its use provides a guaranteed protection from exposure to lead or copper for consumers.

These project findings aside, orthophosphate addition and pH/alkalinity adjustment have been applied to water systems since the Lead and Copper Rule was published in 1991. There are many water systems that have achieved Lead and Copper Rule compliance using these techniques, and lead exposure around the country has been greatly reduced since the Rule was enacted. This project demonstrated that the reason a water system achieved a certain outcome for water quality may be difficult to pinpoint. The pH/alkalinity adjustment or orthophosphate dosing is most likely effective in specific water systems, but the effectiveness of orthophosphate and pH/alkalinity adjustment may be an illusion in other water systems for a number of reasons:

- Several water quality parameters can play a role in both chemical and microbiological interactions, and the true reason that adjustment of the specific water quality parameter is effective for lowering lead and copper release has not been properly identified
- Other water system operations, such as carrying out a high velocity flushing program, reducing system residence time, better eliminating nutrients, or filter cleaning, are occurring simultaneously to the presumed corrosion control strategy and are actually the real influencing factors on corrosion control
- Follow up sampling of the outcome of the corrosion control strategy is inadequate and not representative of actual effectiveness

In terms of other influencing factors in the water systems, a strong relationship was found between particulate lead and copper release and the presence of particulate iron, manganese, and aluminum. In addition, multiple pathways by which microorganisms and their life cycles can cause microbiologically influenced corrosion systemically in a water system were identified.

To control these influences, some of the water systems were cleaned of large quantities of pipe wall iron, manganese, and aluminum particulates by means of high velocity, uni-directional flushing. In addition, the biostability of the water was improved by removing biofilms with the high velocity flushing, decreasing nutrients entering the water system with well rehabilitation and cleaning, and conducting water treatment filter rehabilitation and cleaning. Water systems that underwent these system hygiene activities in this project had lower lead and copper release in the monitoring station test chambers and in Lead and Copper Rule compliance sampling.

In general, the findings of this project emphasized the benefits of a comprehensive perspective for control of distribution system water quality issues, including lead and copper release. This perspective considers that water quality is shaped by complex interactions of drinking water, which is a potpourri of natural and treatment chemicals and naturally-occurring microorganisms, and pipe wall accumulations of various chemical scales and biofilms. No scientific formula can predict the characteristics of the final water quality. All distribution system water quality issues (discolored water, disinfection byproducts, presence of pathogens, release of lead and copper, etc.) are interrelated; they are all manifestations of the complex interactions between a complex solution of water and a complex composition of pipe wall accumulations.

APPLICATIONS/RECOMMENDATIONS

The Lead and Copper Rule is relatively straightforward to carry out. The comprehensive perspective of water quality is not. How can practitioners who have a multitude of water system operational demands and budget constraints control lead and copper release by applying the comprehensive perspective? The following is a list of recommendations:

Routinely Improve Infrastructure

- Develop a plan to remove lead and galvanized iron service lines
- Develop a water main replacement program
- Develop and carry out routine high velocity flushing of water mains
- Use chemical cleaning aids, where applicable, and use them cautiously
- Clean other water system components, such as storage tanks and filters

Adopt an Ongoing Biostability Improvement Program

- Understand the role that microorganisms play in shaping water quality and interacting with water chemistry
- Perform routine biostability tracking and improvement for source water, wells, filters, storage tanks, and high capacity pipe lines
- Prevent microbiological nutrients (organic carbon, nitrogen compounds, and phosphorus compounds) and microbiological populations from entering the water system
- Provide adequate disinfection throughout the water system
- Reduce residence time of water in the system

Maintain an Ongoing Corrosion Control Plan

- Do not define the corrosivity of water based on pH and alkalinity alone or based on predictions of the carbonate-solubility models. They do not adequately represent the set of circumstances found in water systems. The comprehensive perspective must be incorporated into insights regarding water system lead and copper release.
- Keep an updated desktop study and timeline for each water utility as demonstrated in this report. See Chapter 2.
- Perform a routine distribution system water quality indicator study using frequently visited sites, such as the Total Coliform Rule sampling sites, with disinfection

concentration and turbidity data. Troubleshoot operations when disinfection concentrations are low or turbidity is high. See Chapters 4 and 11.

- Study the water in problematic buildings identified by Lead and Copper Rule compliance sampling or customer complaints. The profile sampling used in this study is one good sampling method. See Chapter 3.
- If possible, routinely gauge lead and copper release from a special monitoring station, pipe loop, or accessible building. See Chapters 5 to 11.
- Consider using orthophosphate or pH/alkalinity adjustment in water systems under certain circumstances, but with continuation of water system hygiene protocols
- If planning to use orthophosphate, use a product with little to no polyphosphate fraction
- If planning to use orthophosphate, use a dose adequate to form the desired phosphate minerals within the existing pipe wall accumulations
- If planning to use orthophosphate, perform a phosphorus environmental impact analysis in coordination with the associated wastewater treatment facility. See Chapter 12.

READING THIS REPORT

Because of the amount of material in this report, it is recommended that Chapter 1, Chapter 13, and Chapter 14 be read first as an overview.

When following recommendations in Chapter 14, details of maintaining an ongoing corrosion control plan can be found in individual interior chapters.

SUMMARY

This report challenged common understandings of lead and copper corrosion control. The goal of the project was not to tear down institutional concepts, but to build up a larger perspective – to look at lead and copper release more comprehensively, to treat the problems and not the symptoms, and to add more tools to the toolbox.

RELATED WRF RESEARCH

- Controlling Lead in Drinking Water, project #4409
- Impact of Phosphate Corrosion Inhibitors on Cement-Based Pipes and Linings, project #4033
- Optimizing Corrosion Control in Water Distribution Systems, project #2648

CHAPTER 1
INTRODUCTION

In control of lead and copper release from piping materials into drinking water, choices are limited. A common method is to add orthophosphate to the water. The science behind orthophosphate's ability to inhibit metals corrosion is well understood. But, how are orthophosphate chemical interactions carried out in actual water systems where many other chemical and microbiological interactions are occurring? Can knowledge of the real-world interactions aid in optimizing the use of orthophosphate? These questions were explored in this project.

HISTORY OF PHOSPHORUS-BASED CHEMICALS IN DRINKING WATER

Phosphorus-based chemicals have a long history of use as additives in drinking water systems. An article from 1957 in the *Journal of the American Water Works Association* described uses of polyphosphate at the time (Larson 1957). Practical uses of the chemical revolved around the ability of polyphosphate to hold (sequester) metals in water. It was used for removing minerals from clogged screens and water-bearing formations in wells, removing and preventing the formation of iron and calcium scale on plumbing fixtures, and cleaning accumulations off of interior water main walls when combined with a mechanical pipeline scouring technique.

Polyphosphate was also used in industrial and municipal applications for controlling iron corrosion (Hatch 1941). It was theorized, at the time, that the chemical could also control lead corrosion and was tested in this scenario (Hatch 1941). Lower lead concentrations were found in these specific tests of polyphosphate solutions in contact with lead tubing, however the mechanism by which the lower lead release occurred was misunderstood. At that time, it was thought that the polyphosphate was adsorbed onto metal surfaces or formed a complex on metal surfaces that inhibited the corrosion of metals, such as iron, steel, or lead (Hatch 1941).

Others could not reproduce the benefits of corrosion control using polyphosphates. They were not found to be effective as corrosion control agents (for iron) in stagnant or nearly stagnant water, such as in dead ends or service lines (Larson 1957). Testing in the 1980's found that polyphosphates, instead of inhibiting corrosion, could accelerate it for copper and lead (AwwaRF and DVGW 1996). At that time, polyphosphates became better understood. Investigations showed that polyphosphates, a polymer of orthophosphate ions, eventually breaks apart and reverts to individual orthophosphate ions. It is the orthophosphate ion and not the polyphosphate molecule that provides corrosion control (Holm and Schock 1991; AwwaRF and DVGW 1996). The orthophosphate ion combines with the lead or copper ions in the water to create relatively insoluble compounds that have the ability to sit on the pipe wall and inhibit metals corrosion.

In 1991, phosphorus-based chemicals took on even more importance in drinking water systems. This was the year that the Lead and Copper Rule of the Federal drinking water regulations was first published (Code of Federal Regulations 2010b). Historical use of phosphates in drinking water systems and years of phosphate-oriented research led up to the publishing of the Rule with emphasis on the use of orthophosphate for control of uniform corrosion of lead (AwwaRF and DVGW 1996).

In 2017, the United States Environmental Protection Agency (EPA) is poised to rewrite and republish the Lead and Copper Rule. EPA documents imply that a greater focus will be placed on the use of orthophosphate (EPA 2016a; EPA 2016b). For lead control, there are suggestions that the dosage should be increased to around 3.5 mg/L as PO_4 from current common dosages of 0.3, 1 and 3 mg/L as PO_4 (EPA 2016a). In addition, a new emphasis will be placed on copper corrosion control. On behalf of copper corrosion, many water systems not now using orthophosphate may be required to begin orthophosphate addition (EPA 2016b).

A FUNDAMENTAL PERSPECTIVE OF LEAD AND COPPER CORROSION

Alternative to orthophosphate addition for lead and copper corrosion control, the Lead and Copper Rule also allows for alterations to alkalinity and pH of the water. Manipulation of alkalinity, pH, and orthophosphate concentration for lead and copper corrosion control come from a fundamental concept of how lead and copper is released into water from piping material.

Corrosion of metal occurs by means of a flow of electrons similar to a battery (AwwaRF and DVGW 1996; Peabody 2001). When water contacts metal piping, the pipe provides dynamically changing microscopic locations of anodes and cathodes. Electrons in the metal flow between the anodic and cathodic sites within the solid metal.

Just like a battery, at the anodic sites, the solid metal that has lost electrons is transferred to the adjacent water as a positive ion. In the water, the positively-charged metal ion pairs with oppositely-charged ions. The water can supply several negative-ion choices, such as oxygen and carbonate. By this method, a new dissolved compound is formed.

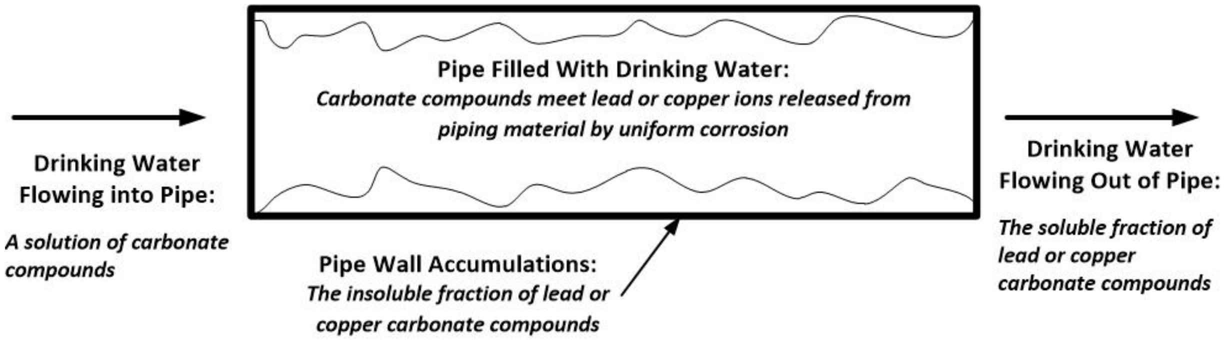
However, the new compound will not stay dissolved in the water if, by nature, it has a low solubility. With a low solubility, the new compound reaches a saturation point quickly and precipitates out of the water onto the metal surface. Some precipitated compounds can create a fine, uniform, non-porous barrier on the metal surface that, in turn, can inhibit the release of metal ions from the piping material into the water.

If the new compound that forms has a high solubility, the dissolved lead or copper concentration in the water increases and metal loss from the piping material continues.

(The process described above is called uniform corrosion. The term uniform corrosion refers to the fact that the anodes and cathodes are dynamically changing and each site on the piping has an equal chance of becoming an anode and losing solid metal to water. The metal is lost uniformly along the pipe surface.)

The Lead and Copper Rule is based on the fact that carbonates, typically found in water, can form compounds with lead and copper ions after they are released from piping materials. Figure 1.1 is a diagram of this concept. Water containing carbonate compounds flows into piping. In the pipe, the water comes in contact with lead and copper ions and form lead and copper carbonate compounds of varying solubility. The insoluble quantity of the lead or copper carbonate compounds can be found on the pipe walls; the soluble fraction of the carbonate compounds can be found dissolved in the water. The more soluble the compound, the more lead or copper is dissolved in the water. In this concept, lead and copper control is a matter of finessing the pH and/or alkalinity of the water to produce a more insoluble compound of lead or copper carbonates.

Alternatively, orthophosphate can be added to form insoluble compounds of lead or copper phosphates. Then, the pipe wall accumulations are composed of orthophosphate compounds, which are more insoluble than lead or copper carbonate compounds. Figure 1.1 can be redrawn with phosphates of lead or copper instead of carbonates.



Source: Courtesy of Process Research Solutions, LLC of Madison, WI.

Figure 1.1 A fundamental perspective of lead and copper release

However, analyses of system water and pipe wall accumulations in actual water systems show a more complex composition than described by the carbonate- or the orthophosphate-solubility models of Figure 1.1. It has been observed in previous investigations by this author that components of system water and of pipe wall accumulations can be grouped into three general categories for organizational purposes:

1. Uniform corrosion products, including not only carbonates and orthophosphates but also oxides, chlorides, and sulfates
2. Water biostability parameters, including microbiological populations, the presence of biofilms, the presence of nutrients for microorganisms (organic carbon, nitrogen, and phosphorus compounds), and the presence of disinfection
3. Chemical scale formation and dissolution parameters, including a number of metals in both dissolved and particulate form, such as iron, manganese, and aluminum

This project explored if lead or copper orthophosphate and carbonate compounds could continue to provide corrosion control in the presence of the various chemical and microbiological interactions actually occurring in water systems.

ENVIRONMENTAL IMPACT OF PHOSPHORUS

In addition, this project looked at the fate of phosphates after they leave the drinking water system. At the same time that drinking water systems are becoming more dependent on phosphorus-based water treatment products, there is increasing urgency to decrease the release of phosphorus to natural bodies of water which creates a number of environmental issues. Phosphorus causes excessive growth of algae and phytoplankton (EPA 2010) and can be the limiting nutrient that triggers this growth (B&V 2014). With the increased mass of dead plant material from the algae population, dissolved oxygen is depleted in the water bodies and other life can no longer thrive (EPA 2010).

In addition to destruction of the aquatic environment, water drawn for drinking water from affected bodies of water can experience water quality problems in the distribution system such as taste and odor problems, deadly cyanotoxins, and increased organic carbon concentrations with the potential for increased carcinogenic disinfection by-product formation (B&V 2014).

Discharge of phosphorus is regulated on federal and state levels. The United States' Clean Water Act requires that states and other regulating entities set goals for protection of individual bodies of water to maintain desired uses. The criteria for a body of water can be based on requirements for possible use as a public water supply or for recreational, commercial, or navigational purposes (EPA 2010).

Once goals and water quality standards are established for a body of water, point source discharges (individual discharge pipelines), such as from wastewater treatment facilities, to that body of water are regulated by means of the National Pollution Discharge Elimination System (NPDES) permitting process (EPA 2010). Because the phosphorus discharge limit is dependent on individual state regulations and the needs of individual bodies of water, discharge limits vary. Typical phosphorus discharge limits are seen to vary between 1 mg/L to 0.02 mg/L as P for the most sensitive bodies of water (B&V 2014).

Therefore, it is now imperative that an assessment be made to determine how the environment and each wastewater treatment facility will be impacted by additional phosphorus contributed from the drinking water.

EXPLORING THE ROLE OF PHOSPHORUS IN DRINKING WATER SYSTEMS

In summary, the objectives of this project were:

- To measure the effects of lead and copper orthophosphate and carbonate compounds in the complex chemical and microbiological environment of drinking water systems
- To observe the effects on lead and copper orthophosphate and carbonate compounds as the water system complexity is controlled by removal of pipe wall accumulations and by creation of a water environment where microorganisms cannot grow excessively
- To assess the impact of phosphates on the environment and on wastewater treatment facilities after they have left the drinking water system

To carry out the objectives, the project involved the following tasks:

- Gather existing information on each water system.
- Characterize each existing water system using comprehensive monitoring techniques, including special distribution system monitoring stations.
- Clean each water system with uni-directional (high velocity) flushing and, optionally, a biofilm-removing chemical while monitoring. To the extent possible, control factors that can influence excessive growth of microorganisms.
- Continue monitoring as the water system comes to a new steady state of lead and copper release.

This report on the completed tasks is organized as follows:

- Chapters 2, 3, and 4 describe the water systems studied in this project using existing information.
- Chapter 5 describes the comprehensive monitoring technique used to characterize the distribution system water quality for the participating water systems.
- Chapters 6 to 11 describe the results of the comprehensive monitoring.
- Chapter 12 describes the assessment of the impact of drinking water phosphate-dosing on wastewater treatment plant facilities and the environment.
- Chapters 13 and 14 discuss conclusions and recommendations from this study.

CHAPTER 2
PARTICIPATING WATER SYSTEMS

The first task of any water system investigation is to gather existing system information to characterize the system components to be studied (EPA 2016a). Existing system information of the participating water utilities is the focus of this chapter.

This project involved information from twelve water utilities. Eight of the water utilities were studied for lead and copper release trends from special distribution system monitoring stations before, during, and after system cleaning efforts. The four remaining water systems contributed existing information to the project. Five of the twelve water systems, the systems which use Lake Michigan as source water, participated in profile sampling of two residences in each water system.

Six wastewater treatment facilities associated with the drinking water utilities in this project were also studied to conceptualize the impact of phosphate-based lead and copper control chemicals on meeting wastewater phosphorus discharge limits.

Table 2.1 lists the twelve water systems and their general characteristics by which they can be grouped. Table 2.2 is a re-sorted list of the water systems of Table 2.1 showing the order in which data are presented in this report.

Table 2.1
Water systems participating in project #4586

Water System ID	Type of Facility	Water Source	Presence of Lead Service Lines	Use of Phosphate Corrosion Control Chemical	Provided Existing Data	Ran Distribution System Monitoring with Monitoring Station	Performed Residential Profile Sampling
A	Municipal	Lake Michigan	Yes	Yes	Yes	Yes + did in the past	Yes
B	Municipal	Lake Michigan	Yes	No	Yes	Yes	Yes
C	Municipal	Lake Michigan	Yes	Yes	Yes	Yes + did in the past	Yes
D	Municipal	Groundwater	Yes	Yes	Yes	Yes	No
E	Campus	Groundwater	No	No	Yes	Yes	No
F	Campus	Groundwater	No	No	Yes	Yes	No
G	Campus	Groundwater	No	Yes	Yes	Yes	No
*H1 and H2	Campus	Groundwater	No	Yes	Yes	Yes	No
I	Municipal	Lake Michigan	Yes	Yes	Yes	No	Yes
J	Municipal	Lake Michigan	Yes	Yes	Yes	No	Yes
K	Municipal	Groundwater	Yes	No	Yes	No + did in the past	No
L	Municipal	Groundwater	No	No (did in the past)	Yes	No + did in the past	No

*Water Systems H1 and H2 are two campuses served by one water system

Table 2.2
Order of water systems in data presentation

Water System ID	Type of Facility	Water Source	Ran Distribution System Monitoring with Monitoring Station
A	Municipal	Lake Michigan	Yes + did in the past
B	Municipal	Lake Michigan	Yes
C	Municipal	Lake Michigan	Yes + did in the past
I	Municipal	Lake Michigan	No
J	Municipal	Lake Michigan	No
D	Municipal	Groundwater	Yes
K	Municipal	Groundwater	No + did in the past
L	Municipal	Groundwater	No + did in the past
E	Campus	Groundwater	Yes
F	Campus	Groundwater	Yes
G	Campus	Groundwater	Yes
*H1 and H2	Campus	Groundwater	Yes

*Water Systems H1 and H2 are two campuses served by one water system

WATER SYSTEM DESCRIPTIONS

The water systems participating in this project are described below.

Municipal Lake Michigan Systems

Water System A is a treatment plant filtering Lake Michigan water. The treatment plant is owned by three water systems that individually oversee their distribution systems. Data in tables of this report describing Water System A are a summation of the three distribution systems' characteristics.

This confederation was started in 1961 when the water treatment plant was built. The distribution systems are tested as one for the Lead and Copper Rule. The Lead and Copper Rule compliance sampling showed the systems to be out of compliance for lead in 1992 and 1995. A polyphosphate/orthophosphate blend where orthophosphate was 50% of the total phosphorus in the product (50/50 poly/orthophosphate blend) was then added to control the lead system-wide.

In 2008, a decision was made to switch the disinfection chemical from free chlorine to chloramine. This was done to make the water compatible with water from a nearby city that would be used in an emergency situation. This was a pro-active decision because there has never been an emergency situation where the nearby city's water was used. In order to make the switch, special distribution system monitoring stations (described in Chapter 5) were installed to characterize the original system's water characteristics, to monitor the water quality, including lead and copper release, frequently during the change of disinfection chemical, and to monitor the water quality over time after the change.

In addition, off-line tests were run using the monitoring stations in a different configuration to compare phosphate-based corrosion control chemicals. A 10/90 poly/orthophosphate blend was found to be more effective at lowering lead levels than the 50/50 blended product and a 70/30 blended product. The orthophosphate kept the lead concentration lower with less particulate lead release and within a more narrow range of concentrations. So, the phosphate corrosion control product was switched two and one-half months before the disinfection chemical. The 10/90 poly/orthophosphate chemical specification has been used since that time.

Lead and Copper Rule sampling in 2009, about ten months after the chemical changes, showed the same water quality responses that the off-line tests and the distribution sampling predicted. That is, average and maximum lead levels were greatly reduced with the new chemical regimen.

During the monitoring of the distribution systems in 2008 through 2010 and in simultaneous and repeated sampling of four residences with lead service lines, a high degree of particulate lead was measured that was not found at the entry point to the distribution system. It was concluded that existing pipe wall debris interacted with the system water to increase the transfer of lead in particulate form into the water. Water system cleaning has been discussed for these systems since that time but very little activity in this respect has been completed. For this project, some water main flushing was conducted by one of the three systems. The monitoring of this system in this project gives feedback on the status of water quality seven years after the major changes made in 2008.

Water System B was originally a groundwater system from 1886 to 1957. By 1957, a transmission line had been built to bring Lake Michigan water to a central treatment facility. Ozone as a primary disinfectant was added to the treatment train in 2000. A second transmission line from Lake Michigan to the treatment plant was added in 2005.

The water system exceeded the lead Action Level of 15 µg/L in 2011. An investigation was performed in 2013 that focused on the causes of the lead increase and recommended methods to control and monitor the lead and associated water quality parameters in the water system.

It was found that the prevalence of lead water service lines connected to privately-owned galvanized iron water service lines and other galvanized iron premise plumbing was a significant factor related to elevated lead at consumers' taps. The adsorption and accumulation of lead on galvanized iron pipe scales with eventual crumbling of the lead-laden scale into the water has been acknowledged in the technical literature as a major form of lead transport in premise plumbing (McFadden et al. 2011). Plans are being made for lead and galvanized iron service line removal.

A second factor affecting lead release in the system was the contribution of iron and manganese from past use of wells and from unlined cast iron water main to scale formation on lead service lines. An analysis of lead service line scales found crumbly scales of iron, manganese, and lead. Only standard hydrant flushing had been performed over the years to clean water mains; the pipe wall chemical analyses showed that this cleaning activity was not sufficient to remove system debris deposited decades ago when groundwater was used. During this project, an engineered uni-directional (high velocity) flushing program was designed and carried out for this water system.

A third factor in lead release found in the water system was a microbiological component. There were reported indications that microbiological activity increased in the distribution system just after the ozone process was placed online in 2000 with an increase in corroded valves and meters. The installation of the new transmission line in 2005 also appeared to coincide with increased lead and copper release. Additional water system modifications were made in 2010. Exceeding the lead Action Limit occurred in 2011. This will be discussed further in Chapter 6 and later.

Water System C treats Lake Michigan water using two separate processes. The first treatment plant is conventional filtration and was put on-line in 1963. In 1999, a microfiltration plant was placed into service. The distribution system receives a mix of water from the two plants.

This water system was studied using a special distribution system monitoring station (described in Chapter 5) at a high water age location in the distribution system in 2011 and 2012.

Even though this water system has never been out of compliance with the Lead and Copper Rule, when the system is routinely tracked with a monitoring station, it is seen that high and erratic releases of particulate lead occur in the test chambers. High velocity, uni-directional flushing of water mains was discussed as a remedy for this water quality behavior. However, resources have not been available for this purpose.

This water system also has the potential to produce biofilms and corrode metals when conditions are right. This was a significant finding in the past test chamber data. There was a complaint from an industry in 2012 with this problem. The problem was also observed in a water utility building in 2015.

A 60/40 poly/orthophosphate product has been added since 1996 to this water system in a low orthophosphate dosage. A chemical analysis of a lead service line in 2012 showed that no pyromorphite, the lead phosphate compound that is intended to protect the lead pipe walls, existed in the pipe wall scales. Instead, aluminum predominated in the scale with the source being the Lake Michigan water and the alum coagulant used at the conventional treatment plant. The aluminum compounds sorb existing lead compounds in the scale and are poised to both transport particulate lead upon scale disruption and to release dissolved lead into the water when environmental conditions, such as pH, re-solubilizes the aluminum compounds.

Water System I is a large system using Lake Michigan water since 1872. The first filtration plant was built in 1939. A second treatment plant was built in 1962. In 1996, orthophosphate as phosphoric acid was added for corrosion control. In 1998, ozonation was added for primary disinfection. Ozonation can break apart naturally-occurring organic carbon compounds into compounds more accessible for microbiological growth (Escobar and Randall 2001). Chlorination before the filters at both plants was discontinued at some point after the ozone was installed in order to create biological filters for better dissolved organic carbon removal.

Water System J is a smaller system using Lake Michigan water. The treatment plant was added in 1973. A 60/40 poly/orthophosphate product is used for corrosion control.

Municipal Groundwater Systems

Water System D began operation in 1914. In 1986, an area just across an adjacent river was annexed to the city and the water systems, each with 3 wells, were connected together in 1991. Early on, a unique iron and manganese removal plant was installed for the wells on the original city property. The system was called a Vyredox system where water was aerated as it was pumped from the ground and reinjected into the ground to use the aquifer as a filtration medium for the oxidized iron and manganese. The system also depended on naturally-occurring iron bacteria in the aquifer to help with the removal of dissolved iron and manganese from the water. The result was greatly lowered capacity of wells as the aquifer clogged with oxidized iron and manganese and bacterial growth. The water ultimately pumped from the wells after years of using this system had very high iron and manganese concentrations and was loaded with microorganisms and nutrients, especially organic carbon. An ozone oxidation and pressure filtration system replaced the Vyredox system in 1995. However, the removal efficiency for iron and manganese was low due to the high levels entering the plant. There were several other issues with the finished water. Over the years, there were episodes of being out of compliance with the Lead and Copper Rule resulting in the introduction of a poly/orthophosphate blend product and there were discolored water complaints from consumers. In 2006, the wells on the annexed city area were found to have high manganese concentrations, so a 100% polyphosphate product was added to that water in order to sequester manganese. The types of water are mixed in the distribution system to varying degrees. An investigation into the water quality issues began in 2012. The wells were investigated and rehabilitated as much as possible which lowered the iron and manganese concentrations entering the treatment plant. The treatment plant was renovated from 2014 to 2016, replacing ozone with chlorine oxidation and pH adjustment with a calcite contactor. After pressure filtration for oxidized iron and manganese removal, the water flows to a granular activated carbon contactor for dissolved organic carbon removal. Water mains have undergone high velocity flushing in 2016. This project was used as an opportunity to monitor as the water system was cleaned.

Water System K was founded in 1893. Over the years, a number of well fields were developed. In 1986, two of the wells had high iron. A polyphosphate was added to sequester the iron. In 1992, a radon and hydrogen sulfide removal plant was added using air stripping and an iron and manganese removal plant was added using oxidation and pressure filtration on a combined flow from the wells. This replaced the use of polyphosphate chemical addition. Originally, pH was adjusted above 8 because the utility was advised to do so for corrosion control.

For wells grouped at two other distribution system entry points, aeration was added for hydrogen sulfide and radon removal.

In 2005, the water system was found to be out of compliance for lead. An investigation was performed and found that the lead was being carried to the consumers in particulate form by means of manganese particulates in the water. In addition, there were indications in the investigation that there was a microbiological aspect to the system corrosion and that a high pH would render the free chlorine disinfection less effective. Upon recommendations from the investigation, the pH was no longer elevated by caustic soda addition. A uni-directional high velocity flushing program was initiated for water mains. Lead and Copper Rule compliance sampling performed in 2008 found the water system back in compliance. Continued high velocity flushing during warm weather periods has brought the lead concentrations even lower. Lead and Copper Rule compliance sampling in 2016 exhibited a very low 90th percentile lead concentration (5.5 μg/L).

Copper concentrations are below the copper Action Level of the Lead and Copper Rule but are desired to be lower for wastewater treatment plant discharge considerations. Studies using a special distribution system monitoring station (described in Chapter 5) have identified possible influences for increasing copper release in the water system to be high chloride levels, possibly from road salt infiltration into the wells, and microbiologically influenced corrosion.

Water System L is a groundwater system with no lead service lines. In 2008 to 2011, a water quality investigation and studies using a special distribution system monitoring station (described in Chapter 5) recommended high velocity flushing of water mains. This was carried out. It was also recommended that one problematic well with high iron and high microbiological populations be rehabilitated and possibly an iron removal plant be built. This is in process in 2016. The use of a 70/30 poly/orthophosphate blend was found to not be as effective at lowering copper levels in an off-line re-configured monitoring station test against an orthophosphate product where 100% of the phosphorus was orthophosphate. It was recommended that the phosphate chemical be switched to an orthophosphate product. Then, with the distribution system monitoring station installed for routine tracking, bring the phosphate levels down slowly to an optimum level or determine if the dosage could be eliminated altogether. In 2012, before this slow approach could occur, a third party abruptly stopped the phosphate feed and it has stayed off.

It was also found in the studies that high chloride and microbiologically influenced corrosion appear to play a role in elevating copper concentrations similar to Water System K. High nitrates have been found in area wells and are increasing in the Water System L municipal wells;

nitrates could also be causing the higher release of copper. The 90th percentile copper concentration remains below but close to the Action Level.

Campus Groundwater Systems

Water System E is a campus water system where the owner also owns all the buildings served by the water system. These are large buildings with complex plumbing systems. Originally, the water source was an adjacent lake with a water treatment plant built in 1969. In 2005, wells were drilled and a connection of piping from the new well house to the existing water main was made even though the wells were not yet contributing water to the system. In 2006, the new wells and iron removal plant were placed in service. During this transition period, the surface water plant produced water in the morning to fill the elevated tank and sent treated groundwater to the tank in the afternoon. A dramatic increase in pinhole leaks in copper pipes inside buildings was experienced. An investigation found inadequacies with the new filter's ability to remove iron and manganese before it entered the distribution system. The investigation also found high populations of microorganisms especially in locations that leaks had occurred. It was recommended to perform water main and building plumbing flushing, not to allow water to stagnate in piping, and to keep a good disinfection barrier. There was also concern about the mixing of the two types of water with fluctuating characteristics that could disturb existing pipe wall scales. Labor and budget shortages prevented recommendations from being carried out. By 2012, the pinhole leak issue was worse and a new investigation began. After the second investigation, the filter was rehabilitated and began to keep iron and manganese out of the distribution system. An added granular activated carbon cap also removed dissolved organic carbon, a nutrient for microorganisms. Disinfection was kept at an appropriate level. A low dosage of a biofilm-cleaning chemical, Clearitas®, was dosed into the system water. Clearitas has a similar chemical composition as sodium hypochlorite but different chemical structure and properties. The chemical can break apart biofilm material on pipe walls. It was necessary to use this chemical as chlorine disinfection was apparently not sufficient to remove biofilms which were found inside pipes throughout the campus.

A special distribution system monitoring station (described in Chapter 5) was installed in this project to gauge the progress of the system cleaning. A routine of building main flushing, hot water tank blowdown, and softener cleaning was also put in place. Water mains, which are in a simple configuration, are also cleaned with a high velocity flush once or twice a summer, but do not appear to have a large quantity of debris accumulated.

Water System F first opened as a school in 1962 and had one well. In 1975, the campus was modified to accommodate a larger population. In 1983, a second well was drilled. By 1994, one well had been taken out of service and another one drilled. In 2006, another well and a 200,000-gallon reservoir were added to the water system. After that, pinhole leaks began to develop and hot water heaters also failed at a higher rate. By 2011, the two newer wells served the campus. The number of pinhole leaks increased. A water quality investigation found a high degree of microbiological activity. At the time of the investigation, construction was finishing on a new building. The new building was included in the investigation and it was found that the new plumbing system had already developed a biofilm problem and a few pipes had already developed pinhole leaks.

As recommended in the investigative report, the wells were inspected and rehabilitated. The well investigation concluded that the poor-quality water was coming from one of the wells where bacteria and fungi were found. Features in the borehole showed that poor quality water was short-circuited from surface influences to the lower portion of the well. Karst geology, that is, fissures in limestone rock, was suspected as the problem. The lower portion of this well was filled in and abandoned. Both wells were cleaned. Other cleaning activities included initiation of a low dosage of the biofilm-removing chemical, Clearitas®, into the system water, installation of new water mains, cleaning of the reservoir, and routine building plumbing maintenance as described for Water System E.

Water System G is a campus system that began with two wells in the 1960's. Well 3 was drilled in 1997 and Well 4 was drilled in 2007. The Action Level for copper was first exceeded in 2008; the Action Level for lead was first exceeded in 2012. A water quality investigation began in 2013 and a large presence of microbiological activity was found. The problem was found to initiate in the wells, so the wells were rehabilitated in 2013. Similar to Water Systems E and F, cleaning activities besides well rehabilitation included initiation of a low dosage of biofilm-removing chemical into the system water, high velocity flushing of water mains, cleaning of a reservoir, and routine building plumbing maintenance.

Water System H is a water system that serves two campuses of large buildings. Well 1 pumps directly to the distribution system and runs from 3 pm to 11 pm as called by the water tower level. Well 2 pumps to a reservoir where water is boosted directly to the distribution system. The water system was out of compliance with the Lead and Copper Rule for lead in 2011. A water investigation was performed. Similar to the other three campus systems, it was found that water quality problems in this system come from poor water quality in the wells. Cleaning activities included initiation of a low dosage of biofilm-removing chemical into the system water, high velocity flushing of water mains, and routine building plumbing maintenance. Well rehabilitation is occurring in 2017.

WATER SYSTEM CONFIGURATIONS

All water systems studied in this project are located in Wisconsin where utility data are collected on many aspects of operation for regulatory control. The data have been made available to the public and easily accessible by means of the Internet or by regulatory personnel.

The Wisconsin Department of Natural Resources (WDNR) stores and makes available data which describe the water system for each utility – the water sources, water treatment chemicals added, water treatment processes, the locations where the water enters the distribution system, and water storage in the distribution system.

This information is repeated in more detail in the Wisconsin Public Service Commission (WPSC) annual reports that each utility must submit. The WPSC oversees the setting of water rates and requests annual financial reports from the municipal water utilities. In addition, they request various descriptions and operational data in order to determine if water rates are fairly set. As side-benefits of this effort, the water system data in WPSC reports have become important for utility planning, engineering designs of system components, setting goals for efficient system operation, and quickly understanding the general features of a water system. This project uses the data to understand the general features of each water system and compare them. The following information is presented in this report using data from 2015:

- Population served
- Number of customers
- Water audit
    - Total pumpage

    - Wholesale customer sales
    - Retail customer sales
    - Water used for flushing, fire protection, and pipe freezing protection
    - Piping breakage loss
    - Leakage and other unaccounted-for loss (Total pumpage – sales and estimated known losses listed above)
    - % Unaccounted-for water loss (Leakage and other unaccounted-for loss/Total pumpage)
- Water sources
    - Main
    - Emergency
- Entry points to the distribution system
    - Main
    - Emergency
- Water treatment processes and chemicals
    - Treatment plant identification
    - Intake chemicals, if relevant for surface water plants
    - Primary disinfection methods, if relevant for surface water plants
    - Water treatment processes
    - Water treatment chemicals used in the processes
    - Secondary disinfection methods
    - Corrosion control chemicals
    - Other chemicals
- Water stored in the system
    - Volume of water stored in standpipes, reservoirs, and elevated tanks
    - Number of storage facilities (not stated in this project)
- Water main inventory
    - Type of material
    - Diameter of pipes by material (not stated in this project)
    - Length of pipes by material in feet
- Water service line inventory
    - Type of material
    - Diameter of pipes by material (not stated in this project)
    - Number of service lines by material

Information, as described above, regarding four of the water systems (Systems E, F, G, and H) studied could not be obtained from WPSC because they are not typical municipal water systems and do not set water rates. The four systems are campuses where the water system and all buildings have the same owner.

Water pumpage data for the four campus-type water systems were obtained from WDNR monthly operations data. Water utilities complete daily water pumpage and chemical use forms that are submitted to WDNR monthly characterizing the water treatment facilities operations.

Tables 2.3 to 2.12 list and compare the data for the participating water utilities.

Table 2.3
2015 utility size for project #4586 participants

Water System	Population Served	Number of Customers
A	35,149	11,765
B	105,000	35,742
C	109,000	30,266
I	864,653	161,104
J	18,400	5,509
D	4,230	1,797
K	19,451	7,886
L	18,199	6,768
E	1,600	1
F	1,500	1
G	1,700	1
H		2

Table 2.4
2015 pumpage in 1000 gallons for project #4586 participants

Water System	Groundwater	Surface Water	Purchased Water	Total Pumpage
A	0	1,285,923	0	1,285,923
B	1,054	6,496,991	0	6,498,045
C	0	4,614,951	0	4,614,951
I	0	35,872,390	0	35,872,390
J	239,978 to industry	796,226	0	1,036,204
D	164,531	0	0	164,531
K	757,767	0	0	757,767
L	719,032	0	0	719,032
E	47,786	0	0	47,786
F	61,480	0	0	61,480
G	42,504	0	0	42,504
H	77,878	0	0	77,878

Table 2.5
2015 percent unaccounted-for water loss for project #4586 participants

Water System	% Unaccounted-for Water Loss
A	2.4
B	6.4
C	7.7
I	15.9
J	11.6
D	11.3
K	15.8
L	2.5
E	no data
F	no data
G	no data
H	no data

Note: Regarding unaccounted-for water loss, other benchmarks for non-revenue water are available and should be explored in characterizing a water system (Sayers et al. 2016).

Table 2.6
Water sources for project #4586 participants

Water System	Main Water Source	Backup Water Source
A	Lake Michigan	Lake Michigan
B	Lake Michigan	9 wells
C	Lake Michigan	Lake Michigan
I	Lake Michigan	Lake Michigan
J	Lake Michigan	Lake Michigan
D	6 well	wells
K	15 wells	wells
L	5 wells	wells
E	2 wells	wells
F	2 wells	wells
G	4 wells	wells
H	2 wells	wells

Table 2.7
Lead service lines for project #4586 participants

Water System	Number of Lead Service Lines	% of Total Service Lines That are Lead
A	3,126	26
B	2,252	6
C	8,907	30
I	77,000	48
J	1,236	23
D	107	6
K	76	1
L	0	0
E	0	0
F	0	0
G	0	0
H	0	0

Table 2.8
Water treatment for Water Systems A, B, and C

Plant Name	Intake Chemicals	Primary Disinfection	Treatment	Treatment Chemicals	Secondary Disinfection	Corrosion Control Chemicals	Other Chemicals
Water System A: Central Treatment Facility	Polymer for mussel control. Was previously sodium hypochlorite and then potassium permanganate.		Flocculation, sedimentation, rapid sand filtration	alum, polymer, optional powdered activated carbon	UV, chloramine	LPC-132: 10/90 poly/ortho blend	Fluoride
Water System B: Central Treatment Facility	Chlorine Gas	Ozone	Flocculation, Sedimentation, Sand Filtration	HyperIon 1050A, a polyaluminum hydroxychloride as coagulant, Carbon Dioxide, Sodium Bisulfite	Sodium hypochlorite	None	Fluoride
Water System C: East Filter			Flocculation, Sedimentation, Rapid Sand Filtration	Alum	Gas Chlorine	Carus 8400: 60/40 poly/ortho blend	Fluoride, potassium permanganate if needed for taste and odor
Water System C: Microfiltration			Membrane Filtration		Gas Chlorine	Carus 8400: 60/40 poly/ortho blend	Fluoride

Table 2.9
Water treatment for Water Systems I and J

Plant Name	Intake Chemicals	Primary Disinfection	Treatment	Treatment Chemicals	Secondary Disinfection	Corrosion Control Chemicals	Other Chemicals
Water System I: Plant 1		Ozone	Flocculation, sedimentation, rapid sand filtration, anthracite filtration	Coagulant	Chloramine	Phosphoric acid	Fluoride
Water System I: Plant 2		Ozone	Flocculation, sedimentation, rapid sand filtration, anthracite filtration	Coagulant	Chloramine	Phosphoric acid	Fluoride
Water System J: Treatment Plant		Gas Chlorine	Flocculation, Sedimentation, Rapid Sand Filtration, Activated Carbon Filtration	Coagulant	UV, Gas Chlorine	Aquadene SK7641: 60/40 poly/ortho blend	Fluoride

Table 2.10
Water treatment for Water System D

Plant Name	Intake Chemicals	Primary Disinfection	Treatment	Treatment Chemicals	Secondary Disinfection	Corrosion Control Chemicals	Other Chemicals
Water System D: Central Facilities			pH adjustment with calcite, oxidation, iron and manganese removal, granular activated carbon	liquid chlorine	liquid chlorine	Aquadene SK7543: 80/20 poly/ortho phosphate	
Water System D: 3 Individual wells directly to system					liquid chlorine	Aquadene SK7699: 100/0 poly/ortho phosphate	

Table 2.11
Water treatment for Water Systems K and L

Plant Name	Intake Chemicals	Primary Disinfection	Treatment	Treatment Chemicals	Secondary Disinfection	Corrosion Control Chemicals	Other Chemicals
Water System K: Central Treatment		Sodium hypochlorite	Aeration, Iron/manganese removal	potassium permanganate, polymer	Liquid chlorine	None	Fluoride
Water System K: Booster Station #1			Aeration		Liquid chlorine	None	Fluoride
Water System K: Booster Station #2			Aeration		Liquid chlorine	None	Fluoride
Water System L: EP1					Gas Chlorine	None (used to use 50/50 poly/ortho blend)	Fluoride
Water System L: EP2					Gas Chlorine	None (used to use 50/50 poly/ortho blend)	Fluoride
Water System L: EP3					Gas Chlorine	None (used to use 50/50 poly/ortho blend)	Fluoride
Water System L: EP4					Gas Chlorine	None (used to use 50/50 poly/ortho blend)	Fluoride

Table 2.12
Water treatment for Water Systems E, F, G, and H

Plant Name	Intake Chemicals	Primary Disinfection	Treatment	Treatment Chemicals	Secondary Disinfection	Corrosion Control Chemicals	Other Chemicals
Water System E: Central Facilities			Iron and manganese filtration with granular activated carbon cap	Sodium permanganate	Sodium hypochlorite	None	Clearitas
Water System F: individual wells					Sodium hypochlorite	None	Clearitas
Water System G: individual wells					Sodium hypochlorite	LPC-AM: 70/30 poly/ortho blend	Clearitas
Water System H: individual wells					Sodium hypochlorite	AquaMag: 70/30 poly/ortho blend	Clearitas, Fluoride

LEAD AND COPPER RULE COMPLIANCE DATA

To add more insight into the history of each water system, Lead and Copper Rule compliance data can be very informative. Changes in 90th percentile lead and copper concentrations over time can pinpoint a time period to study for possible operational changes that affected the water quality. Other statistics derived from Lead and Copper Rule sampling period data can also indicate positive or negative water quality trends.

Figure 2.1 is an example of a historical utility plot of copper concentration data statistics for each Lead and Copper Rule monitoring period since 1991 when the Rule was initiated. The Rule can require two monitoring periods a year: 1 – January through June and 2 – July through December. When a water system is deemed in compliance with the Rule, monitoring is required once every three years in the warmer semester, monitoring period 2. If out of compliance, a water system must demonstrate a 90th percentile lead or copper concentration less than the published Action Level (15 µg/L for lead and 1300 µg/L for copper) for two semesters in a row and again in a semester a year later. The Action Level is shown on the plot as a dotted line. In addition, the statistics for each monitoring period dataset are shown.

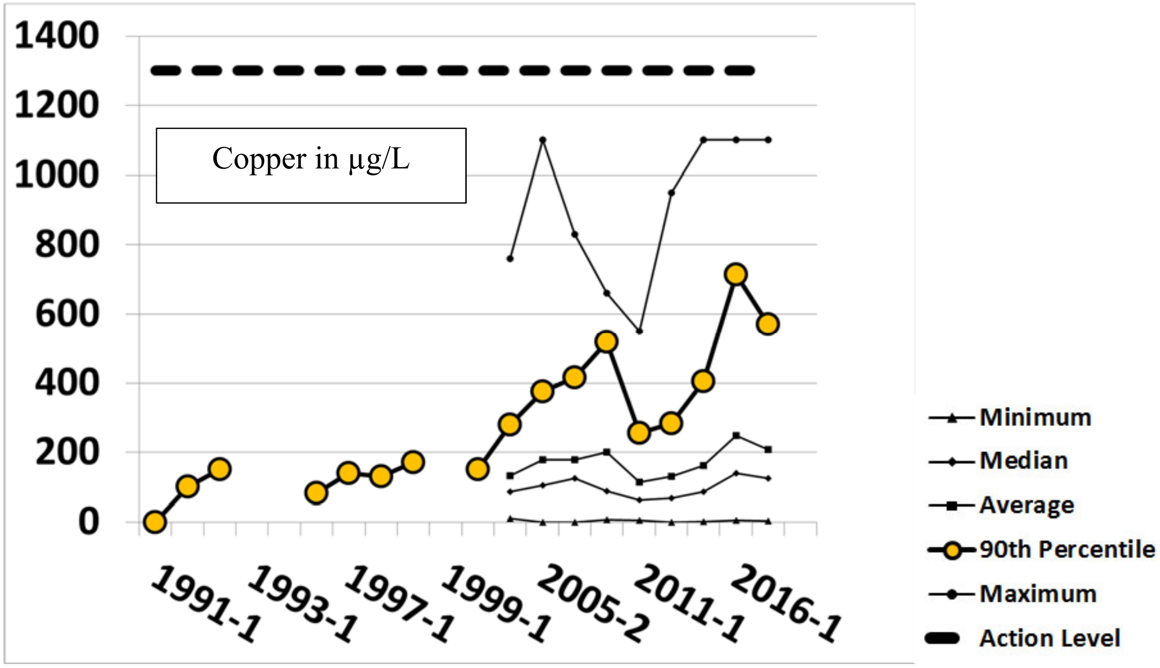


Figure 2.1 Example of plot of historical utility Lead and Copper Rule data

In Figure 2.1, the water utility never went out of compliance for copper. However, an upward trend of copper occurred starting in 2002 through 2016 with a sudden drop in 2011. While this was not a regulatory issue, it was an operational one signaling a slow degradation of water quality. A study of operational changes between 1999 and 2002 when the trend began was warranted.

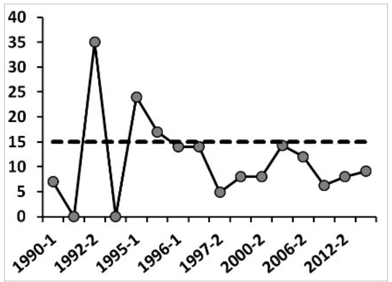
Lead and Copper Rule compliance sampling data were obtained for each utility starting from the Rule's initiation in 1991 through the end of this project in 2016. The WDNR collects data on water quality as prescribed by Federal and State drinking water regulations in order to assess utility compliance with the various regulations. The data are stored electronically and the WDNR website allows public access to downloading data in spreadsheet form. Until 2000, the

WDNR only stored the 90th percentile value for lead and for copper for each compliance monitoring period. This is the value that determines utility compliance with the Lead and Copper Rule. Ninety percent of the data collected in a monitoring period are lower than this value. Two different sets of data can have the same average but one dataset may have higher values; the 90th percentile method identifies those utilities that have the potential to produce the higher concentrations of lead and copper in the drinking water.

After 2000, the WDNR began to post all data in each compliance monitoring period and not just the 90th percentile value. With those datasets, other statistics have been calculated such as the minimum, average (mean), median (50th percentile), 90th percentile, and maximum values. These statistics are also plotted for each utility as shown in Figure 2.1.

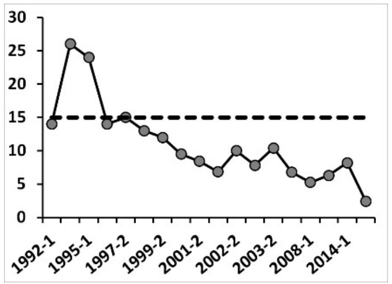
Figures 2.2 to 2.7 show and describe the history of each water system's compliance with the Lead and Copper Rule for lead and for copper. For these graphs, the 90th percentile concentration history is shown in relation to the Action Level.

Water System A



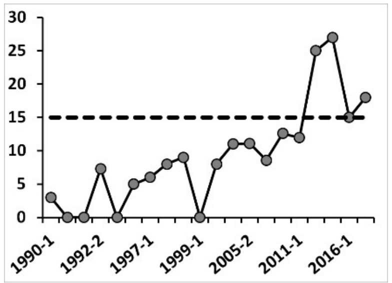
-1992 above Action Level
-1995 above Action Level
-1997 in compliance; 50/50 poly/orthophosphate added
-2003,6 close to Action Level
-2008 change to orthophosphate and chloramine
-2009 further drop in 90th percentile

Water System I



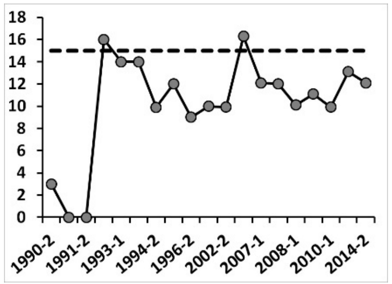
-Above Action Level at first
-Adds 1.9 mg/L as PO4 of 100% orthophosphate
-Has not been above Action Level since 1997

Water System B



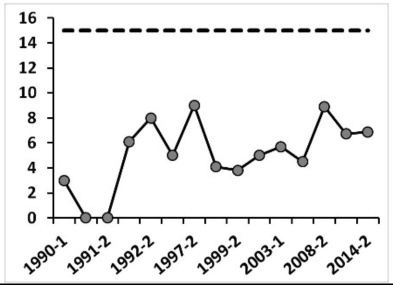
-2000 Ozonation added; lead increase begins
-2005 Large transmission line added
-2011 Begin above Action Level with accelerated increase
-2016 Cleaning brings lead down but biostability issue not yet resolved

Water System J



-Above Action Level in 1992 and 2005
-Adds 60/40 poly/orthophosphate blend
-Hovers just below Action Level

Water System C

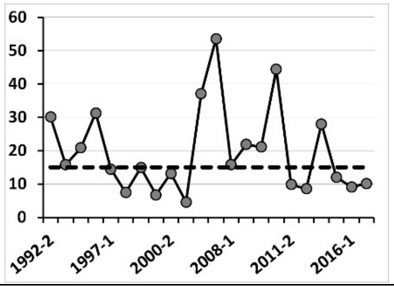


-Never above Action Level
-Adds a low dose of 60/40 poly/orthophosphate blend

● 90th Percentile
▬ Action Level

Figure 2.2 Lead and Copper Rule compliance data for lead in µg/L for municipal Lake Michigan water systems

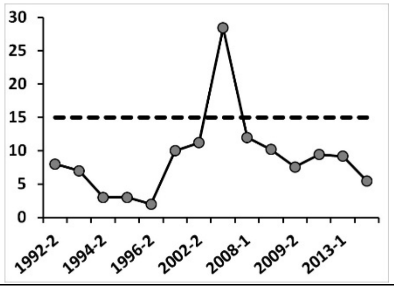
Water System D



-Over Action Level several times, the latest in 2012

-2016 below Action Level after extensive cleaning and treatment modifications; these are not yet completed

Water System K



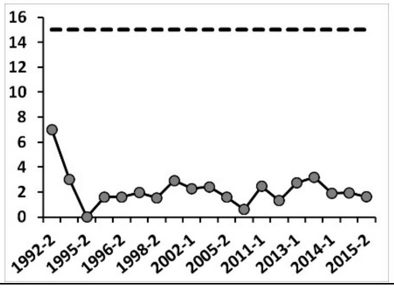
-Over Action Level in 2005; investigation in 2006

-Extensive uni-directional flushing in 2007

-Under Action Level in 2008

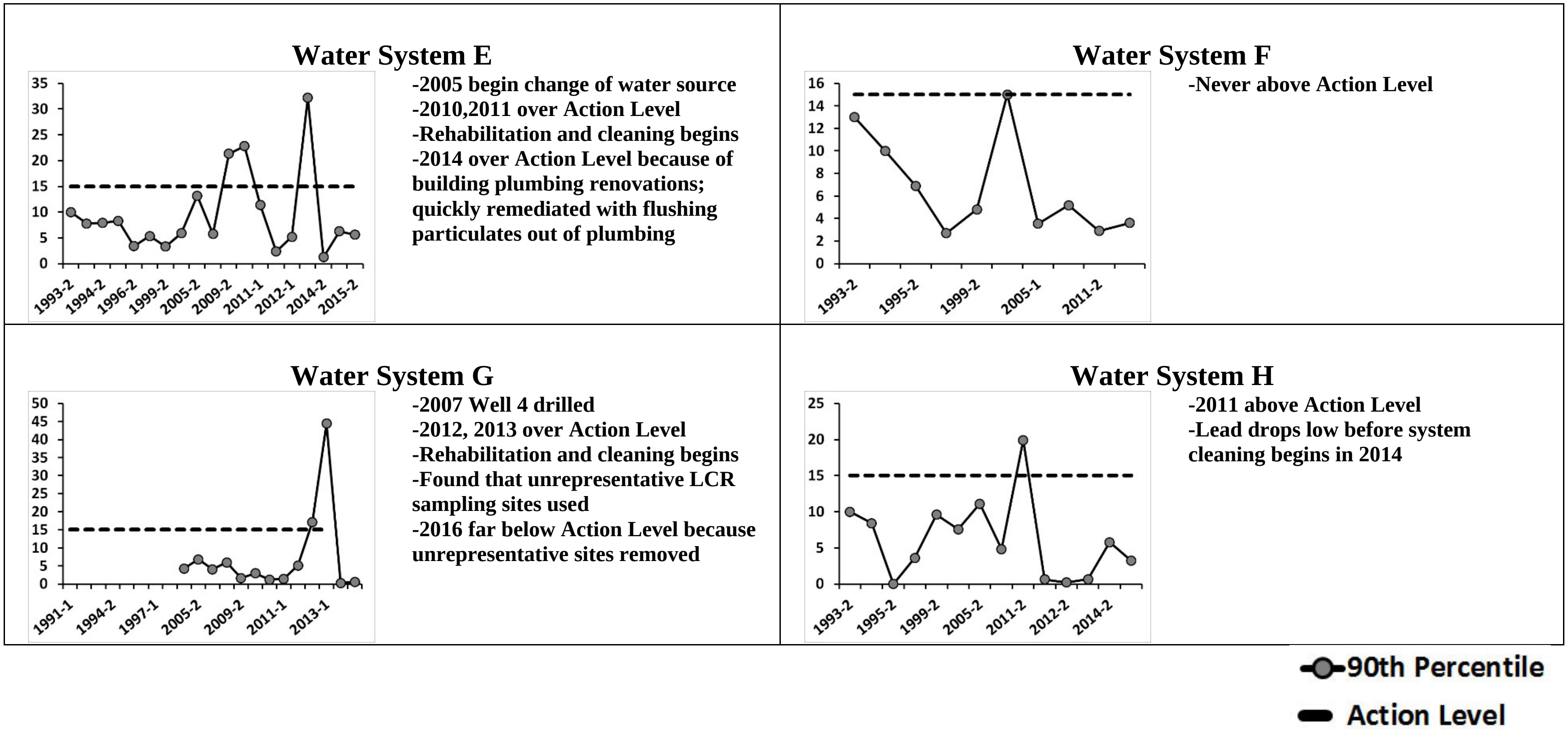
-In 2016, 90th percentile is 5.5 µg/L with flushing only

Water System L



-Never above Action Level

Figure 2.3 Lead and Copper Rule compliance data for lead in µg/L for municipal groundwater systems



Water System E

-2005 begin change of water source
-2010,2011 over Action Level
-Rehabilitation and cleaning begins
-2014 over Action Level because of building plumbing renovations; quickly remediated with flushing particulates out of plumbing

Water System F

-Never above Action Level

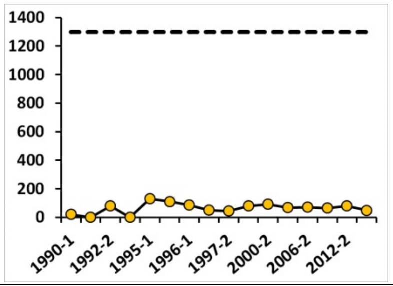
Water System G

-2007 Well 4 drilled
-2012, 2013 over Action Level
-Rehabilitation and cleaning begins
-Found that unrepresentative LCR sampling sites used
-2016 far below Action Level because unrepresentative sites removed

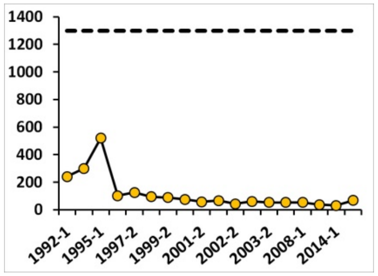
Water System H

-2011 above Action Level
-Lead drops low before system cleaning begins in 2014

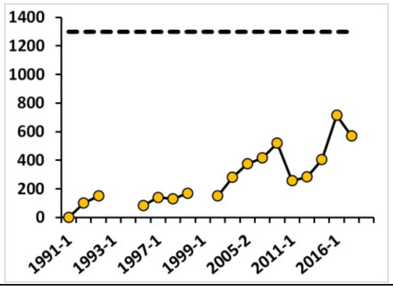
Figure 2.4 Lead and Copper Rule compliance data for lead in µg/L for campus water systems


Water System A

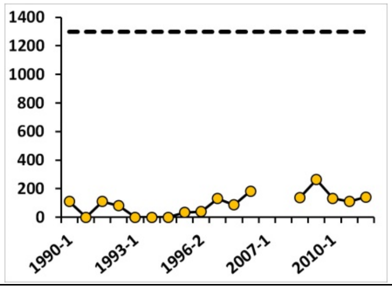
-Never has exceeded the Action Level


Water System I

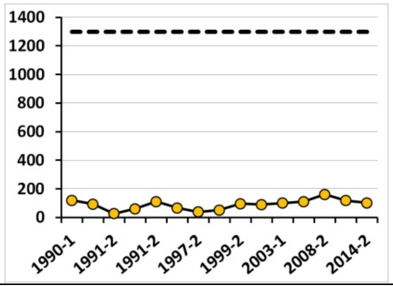
-never has exceeded the Action Level


Water System B

-Never has exceeded the Action Level
-Ozonation added in 2000
-2002 copper levels slightly higher
-2005 large transmission line added
-Copper continued to increase; cleaning is ongoing; newly identified biostability problem is not yet resolved


Water System J

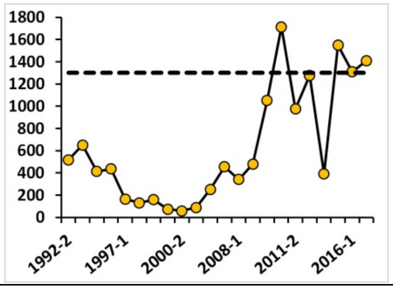
-Never has exceeded the Action Level


Water System C

-Never has exceeded the Action Level

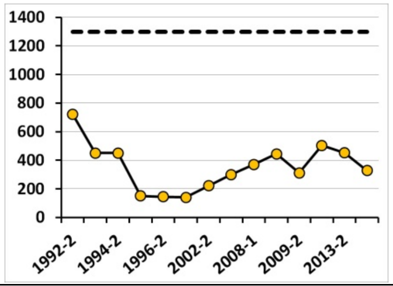
-●- 90th Percentile
▬ Action Level

Figure 2.5 Lead and Copper Rule compliance data for copper in µg/L for municipal Lake Michigan water systems



Water System D

-Has exceeded or been close to exceeding Action Level several times
-Extensive cleaning ongoing
-2015,2016 above Action Level
-Cleaning continues; polyphosphate being removed from corrosion control product



Water System K

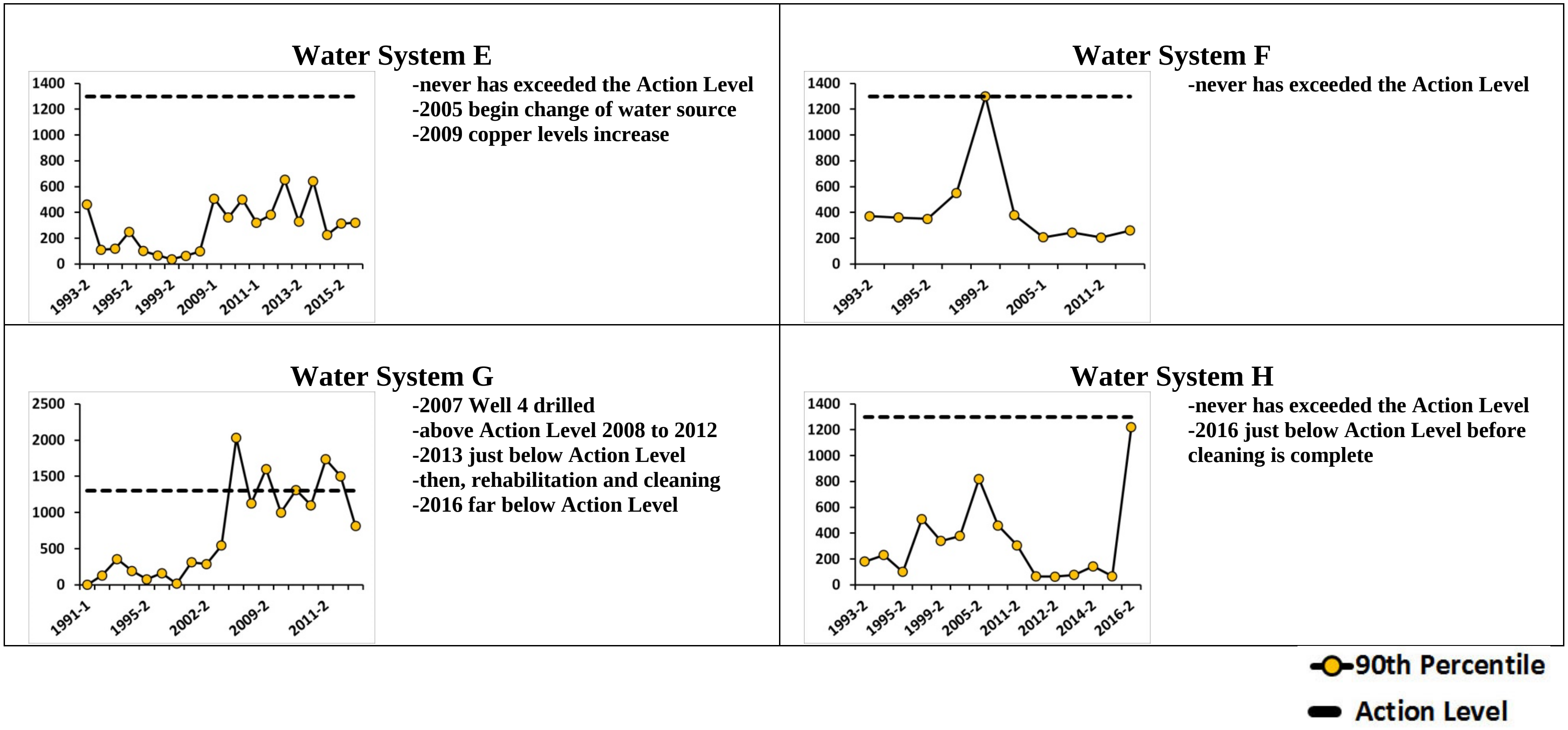
-Never has exceeded the Action Level

Water System L

-There was erroneous data on the public website for this system so no graph is shown. Water System L has a 90th percentile copper concentration that is below but close to the Action Level of 1300 µg/L.

-●- 90th Percentile
▬ Action Level

Figure 2.6 Lead and Copper Rule compliance data for copper in µg/L for municipal groundwater systems



Water System E

-never has exceeded the Action Level
-2005 begin change of water source
-2009 copper levels increase

Water System F

-never has exceeded the Action Level

Water System G

-2007 Well 4 drilled
-above Action Level 2008 to 2012
-2013 just below Action Level
-then, rehabilitation and cleaning
-2016 far below Action Level

Water System H

-never has exceeded the Action Level
-2016 just below Action Level before cleaning is complete

Figure 2.7 Lead and Copper Rule compliance data for copper in µg/L for campus water systems

WATER SYSTEM TIMELINES

To summarize the history of each water utility, timelines were constructed incorporating Lead and Copper Rule data trends, operational and regulatory information, and summary information from engineering reports. Timelines are very important for theorizing why water quality changes may have occurred.

A timeline was constructed for each water utility in varying detail. Much of the historical information was obtained from the WPSC annual reports where water system construction and maintenance activities are reported to justify expenditures. Other information, such as treatment chemical changes, was obtained from utility personnel, previous engineering reports, and WDNR operational data.

A utility timeline is less detailed for older events, such as noting major construction or operational changes. As a timeline becomes more current, more details are added – chemical product changes, chemical dosage changes, major or systemic customer complaint events, regulatory compliance issues.

Tables 2.13 to 2.24 list, over several pages, the timelines for each utility. The timelines become very important in explaining unique changes in time-based data as in interpreting changes on the Lead and Copper Rule compliance data graphs or in interpreting any ongoing system monitoring data.

SUMMARY

Key aspects of the participating water systems have been described in this chapter. It is important to understand the general configuration of a water system in order to study its water quality. Water source, treatment processes, chemicals used, system storage, and materials of construction all can influence the water quality that the consumers receive.

Lead and Copper Rule compliance data, taken every six months to every three years over time since 1991 can serve to pinpoint periods in time where operational changes may have affected lead or copper release trends and possibly additional distribution system water quality changes.

Finally, it is informative to compile a timeline of events at a water utility, listing configuration changes, operational changes, compliance issues, and major customer complaints. Using the timeline, the reason for water quality changes in certain time periods may be illuminated.

For the water utilities participating in this project, the story of their water quality begins here.

Table 2.13
Water System A timeline

Date Range	Event
1961	Plant built
2000	Adding poly/ortho phosphate blend for corrosion control
4/2008 - 9/2008	Offline chemical comparison study of phosphate products using PRS Monitoring Station
4/2008 - 9/2008	PRS Monitoring Station study of original water system where free chlorine disinfection and 50/50 poly/orthophosphate chemical were used
9/2008 - 11/2008	PRS Monitoring Station study of change to 10/90 poly/orthophosphate while still using free chlorine (see previous offline tests)
11/2008-4/2009	PRS Monitoring Station study of change to chloramine disinfection
11/2009	PRS Monitoring Station study of steady states of water system after big changes and use for process control
5/2010	Lowered phosphate dosage slightly
7/2010	Begin raising dosage back up to original dosage

Table 2.14
Water System B timeline

Date Range	Event
1886 to 1957	Well water system
1955	Raw water transmission line from lake to filter plant built
1956	Intake 1 built
1957	Raw water pumping station and conventional filtration plant are operational. Lake Michigan now used as the water source.
1972	Various treatment changes made by this year: fluoride changed from powder to liquid hydroflurosilicic acid; potassium permanganate had been used at raw water pumping station but was changed to chlorine; chlorine dioxide and ammonia was used for brief periods at the filter plant but is now free chlorine disinfection.
1990	Finished water free chlorine residual increased from 0.40 ppm to 0.55 – 0.60 ppm
1991	Switched from alum to polyaluminum hydroxychloride (Hyperion 1050A) as coagulant
1992	Powdered activated carbon feed stopped.
2000	Ozone on-line; begin to have trouble with copper pressure reducing valve components; now all are replaced with stainless steel
2005	2nd transmission line from lake to plant was built and in operation by June; treatment plant capacity was increased; a sodium hypochlorite system was installed to replace the use of gaseous chlorine
2006	Switched from chlorine gas to sodium hypochlorite
2007	Finished water free chlorine residual increased from 0.6 ppm to 0.70 – 0.75 ppm
2008	March: A carbon dioxide injection system was installed in the sodium hypochlorite carrier water to prevent scaling in the solution delivery line
2010	Variable frequency drives installed at lake water pumping station
2011	A section of one transmission line was replaced late in the year
2011	Filtration reservoir leak investigation
2011	Distribution system modeling
2011	Fluoride residual lowered to 0.70 – 0.80 ppm
2012	Lead service line harvested and chemical scales studied
2012	Increase in service leaks; Begin engineering planning study
2013	Break in 36" main
2014	January, February: Severe winter weather causing increased main leaks
2014	January, February: Severe winter weather causing increased frozen services
2014	March: Monitoring station installed and monitoring begins
2014	Summer: First year of uni-directional flushing
2015	Summer: Second year of uni-directional flushing
2016	January: End of distribution system study

Table 2.15
Water System C timeline

Date Range	Event
1895	Municipal water utility formed
1917	First filtration plant constructed with upgrades in 1926,1932, and 1951 (West Plant)
1928	Utility began using copper pipe for water services
1929	Filtration plant expansion from 8 MGD to 14 MGD
1949	Emergency intake constructed in the harbor
1952	Filtration expansion to 20 MGD
1964	East Filtration Plant constructed
1976	New 48” Lake Michigan intake placed in service
1996	Begin poly/orthophosphate addition
1997	Replaced filter media in East Filter Plant
1999	Microfiltration system added
2001	West Plant abandoned
2002	Expanded microfiltration plant to increase capacity by 50%
2006	A 0.75-million-gallon elevated storage tank constructed
2011	Ran PRS Monitoring Station for a year
2014	extreme cold weather with high number of main breaks
2014	extreme cold weather with high number of frozen services

Table 2.16
Water System I timeline

Date Range	Event
1871	Utility formed
1872	First system constructed of water intake, pumping system, and distribution mains
1888	Second intake added
1895	Third intake added; the first two intakes abandoned
1910	Chlorination with calcium hypochlorite begun
1915	Chlorination changed to liquid chlorine/chlorine gas system
1918	Fourth intake added
1939	Water treatment plant started -- coagulation, sedimentation, filtration, disinfection
Around 1960	Ammonia added to disinfect with chloramines
1962	Second treatment plant constructed
1994	Sand filter renovations; anthracite added to the sand filters
1996	Addition of orthophosphate for corrosion control implemented
1998	Ozonation with hydrogen peroxide addition put on-line for primary disinfection
before or around 2000	Chlorination before the filters at both plants was stopped to create “biological filters” for removal of dissolved organic carbon
2014	Repair of mains because of harsh winter

Table 2.17
Water System J timeline

Date Range	**Event**
1954	Treatment Plant built - upflow clarifiers with rapid sand filters 3.0 MGD capacity
1963	Treatment Plant addition – clarifiers replaced by flocculation/sedimentation basin
1973	Treatment plant addition – filter capacity added, floc/sed capacity added plant capacity now 6.0 MGD
1990	Changed coagulant from alum to a PAC product Gen Chem 1050A
1992	PO4 added for corrosion control
1992	Exceeded action level for lead
1998	Raw Water Pumping Station upgraded – new pumps and control
1998	Raw Water Pumping Station upgraded – new pumps and control
2000	Alternated intakes and added Cl_2 once per year to intakes for mussel control stopped practice in 2010
2000	GAC Media added to filters chlorination point moves from pre-filter to post-filter
2004	UV Disinfection added to treatment
2005	Exceeded action level for lead
2010	Swift Ave transmission main extended to north end of city
2011	Replaced 2 filter effluent flow control valves
2014	Cold winter and high number of main breaks
2014	engineering planning study begun
2014	High number of frozen services

Table 2.18
Water System D timeline

Date Range	Event
1914	Waterworks begins operation
1986	the area east of the river annexed to the city
1991	The 2 water systems connected together
1995	A Vyredox system for iron and manganese control at Wells 3,4 and 5 was replaced with an ozone oxidation/pressure filtration system
6/1997	Lead and Copper levels found to be lower
Jan/Feb 2000	Filter media replaced
5/2004	Lead first exceeded the Lead and Copper Rule Action Level.
2005	Well 6 drilled near Wells 1 and 2
6/2006	Switched from Aquadene to AquaMag. "Dirty water" complaints increased.
2006	Manganese found to be elevated in Well 2; polyphosphate feed adjusted to sequester its manganese which addressed customer complaints of discolored water; Well 2 use is minimized by designating it as the lag pump to Wells 1 or 6 lead
Apr/May 2006	Filter media replaced
2008	Consent order to replace lead service lines
5/2008	Temporary drop in lead and copper levels
12/2009	Copper first exceeded for Lead and Copper Rule
2010	Powdered lime use was stopped and liquid calcium hydroxide use began at treatment plant
Jun 2010	Switched from AquaMag to Aquadene
	SK7643 (30% ortho/70% poly) fed at treatment plant
	SK7699 (100% poly) fed at other wells
Jan 2011	Filter media replaced
Aug 2011	Lead and copper levels dropped below Action Level
Feb 2013	Filter media replaced
2012	Water quality investigation
2012	Water main flushing of west side of city
2013	well repair; water treatment study
2013	Water main flushing of east side of city
1/2014 - 3/2014	Breaks and freeze ups of service lines and water mains
2014 to early 2016	Renovation of water treatment plant with optimization in 2016
2016	High velocity water main flushing

Table 2.19
Water System K timeline

Date Range	Event
1893	Utility established
1904	Water utility purchased by the city
1923-1946	2 well fields developed
1947	1 more developed
1949	Northeast well field developed; Well 16 completed
1950	Well 17 of Northeast well field completed
1964	Well 18 in Northeast completed.
1955	Well 11 stopped production; converted into Booster Pumping Station
1960	Well 1 abandoned
1961	storage added
1966	Well 1A constructed
1968	another well field developed and Wells 19 and 20 completed; reservoir added
1969	Well 9 abandoned
1986	High iron in Wells 19 and 20; stopped using wells for a while; then, polyphosphates added and well usage resumed
1990	another well field developed with Wells 21 and 22 constructed
1992	water treatment facility on-line treating well water from 4 well fields to remove iron, manganese, radon, hydrogen sulfide, and adjust pH
1996	Approximate time that polyphosphates no longer used at Well 1 pump house
1996	Iron bacteria were found in a water tower that was being cleaned. The chlorine level at the entry points to the distribution system was increased from 0.5 mg/L to 0.7 mg/L in order to counteract any biofilms found elsewhere in the system.
2000	Well 3 abandoned; Well 7 abandoned; Well 16 abandoned
2002	Well 2 abandoned; booster station #2 switch from gas to liquid chlorine
	booster station #1 refurbished: addition of aeration, removal of caustic soda, switch from gas to liquid chlorine
2003	Well 23 drilled; Water treatment facility switch from gas to liquid chlorine; Wells 13 and 15 abandoned
2005	Above Action Level for lead
2006	Water quality investigation with recommendation to lower pH and high velocity flush water mains
2006	Stopped increasing pH with sodium hydroxide for corrosion control; High velocity flushing of water mains
2007	Below Action Level for lead
2010	Well rehabilitation
2011	Well rehabilitation for 3 wells; June began Lead and copper study; New water tower completed
2011	Additional high velocity water main flushing (this is done almost every summer since 2006)
2011	Several major distribution mains replaced
2012	Well rehabilitation for 2 wells
2013	No flushing
2014	1 well rehabilitation; Construction of new well 26; No flushing
2014	Large number of service line freeze-ups due to cold weather; Record number of main breaks due to cold weather
2015	High velocity flushing of water mains; Well 26 online

Table 2.20
Water System L timeline

Date Range	Event
1971	Well 7 added
1978	Well 8 added
1987	Well 9 added
1998	Well 5 added
2007	Well 10 added
2012	discontinued phosphate
2014	well reconstruction

Table 2.21
Water System E timeline

Date Range	Event
1969	Surface water treatment of adjacent small lake
	Water aerated and pre-chlorinated
	Upflow clarifier with aluminum sulfate, lime, coagulant aid, and powdered activated carbon addition
	Recarbonation after clarifier to decrease pH to 9
	Post-chlorination
	Sand filtration
	Clearwell
3/2005	Connection of piping from a new well house to existing water main made
3/2006	New well and iron removal plant placed into operation
	Aeration, prechlorination, potassium permanganate addition of raw well water
	Filters of anthracite impregnated with manganese dioxide (later found that proper media never supplied)
	Sodium hydroxide to increase pH to match surface water
	In transition period, surface water in morning and groundwater in afternoon
	Both cast and ductile iron pipe water mains; No lead service lines
2006	Dramatic increase in pipe leaks; were some routinely before but greatly increased; Investigation with recommendations
2012	Investigation after more pinhole leaks

Table 2.22
Water System F timeline

Date Range	Event
1962	Opened as a school; had one well
1975	Modified to accommodate a larger population
1983	Well 2 drilled
1993	Well 1 had been taken out of service
1994	Well 3 drilled
1998	Water softeners installed to prevent scaling in hot water systems
2006	Well 4 constructed and placed online
2006	A 200,000-gallon reservoir added
After 2006	A high degree of plumbing equipment replacement reported, including copper piping and hot water heaters
2011	An increase in pinhole leaks in copper pipe
2011	Wells 3 and 4 serve the campus
2012	Health Services Unit building opened after a long construction period
	The building was found to have biofilms throughout the plumbing before occupancy with some pipe failure
2012	Water quality investigation of campus
4/2013	Investigation of wells
Winter 2014	Repair of Well 4 and rehab of Well 3

Table 2.23
Water System G timeline

Date Range	Event
1960 to 1970	Wells No. 1 and 2 drilled
1997	Well No. 3 drilled
2007	Well No. 4 drilled
2008	Exceeded Action Level for copper; phosphate dosing increased
2009	Re-sampling showed lower copper
2012	Exceeded Action Level for lead and copper
2013	Investigation performed on water system; plans made for cleaning and monitoring in water system
2013	Water system continued to be above Action Level for lead and copper
9/2013	Wells No. 3 and 4 out of service for partial rehabilitation
11/2013	Wells No. 3 and 4 back on-line with low quality water blocked
9/2014	Monitoring station installed in distribution system and monitoring/flushing plan put into action

Table 2.24
Water System H1 and H2 timeline

Date Range	Event
2011	Out of compliance with LCR

CHAPTER 3
RESIDENTIAL PROFILE SAMPLING

Five of the participating water utilities (Systems A, B, C, I, and J) – all Lake Michigan water systems - selected two residences each for profile sampling. Profile sampling is a technique of lead and copper release assessment where sequential liters of stagnating water are drawn from a building's plumbing system. Analysis of each liter sample can describe where lead or copper reach higher concentrations relative to other locations in the plumbing system. That location is related to piping material, giving insight into the piping materials and locations in an individual building where lead or copper can be problematic. Lead and copper concentrations found by this method quite often show that the first draw liter of water as prescribed to be taken for Lead and Copper Rule compliance does not necessarily represent the maximum lead or copper concentration that could potentially reach the water consumers in that building (Cornwell and Brown 2015).

The following sampling protocol was used in this project for profile sampling of residences:

- Select two houses with a lead service line
- Using a hardness test strip, confirm that the kitchen cold water tap is not softened.
- Estimate the volume of water from the kitchen tap through the lead service line and determine the number of liter bottles required from sample tap to water main. Add 2 more liter bottles to obtain water samples from within the water main.
- Run water at normal flow rate at the kitchen tap until cold before stagnation, say 5 minutes. This helps to ensure that all sampling taps in all buildings began the experiment with fresh water from the water main. "Normal" flow rate is like filling a glass of water; it is not a flushing velocity, nor is it a trickle of flow.
- If possible, take flowing water samples for the following analyses: lead, copper, calcium, magnesium, iron, manganese, zinc, aluminum, cadmium, nickel, chloride, sulfate, fluoride, total phosphorus, orthophosphate, potassium, silica, sodium, and total alkalinity. Use "normal" flow rate to capture the sample in laboratory sample bottles.
- Check for automatic water use, such as ice makers, softeners, and humidifiers, and turn off.
- Stagnate the water 6 hours minimum or overnight.
- Keep the faucet aerator on as is expected in Lead and Copper Rule sampling.
- Using "normal" flow rate, take samples to reach from tap through lead service line into water main in separate one liter bottles. WIDE MOUTH bottles are to be used so that water flow into sample bottles can be similar to filling a glass of water. There should be no acid in any sample bottle in case a lab filtration of a portion of the sample can be performed. With the filtration, separate dissolved and total metals concentrations can be captured before acid preservation of the sample dissolves all metals.
- After stagnation sampling, if flowing water samples have not been taken before stagnation, take them now.
- Turn on automatic water use appliances before leaving the house.
- Send all bottles to the laboratory for analysis. Stagnation samples are to be analyzed for lead, copper, iron, manganese, zinc, aluminum, cadmium, and nickel.

- Perform this sampling in March or April 2015 while water is still cold from winter and water main flushing has not begun (Systems A and B did this), September or October 2015 (water is warmer from summer temperatures and flushing is either occurring or finished) and then again in November or December 2015 (water temperature has cooled and flushing was finished several months previously).

A video demonstrating profile sampling is available from the Milwaukee Water Works to explain the profile sampling to home owners and utility personnel. The video can be viewed at: https://youtu.be/t1Rmf7dcms0.

Fall and early winter sampling in 2015 was funded by the EPA and samples were analyzed in their Chicago laboratory. Funding was procured by Miguel del Toral, Regulations Manager in Region 5 EPA's office in Chicago.

It was not possible to perform sample filtration to differentiate between dissolved and particulate lead. However, Systems A and B paid for extra profile sampling before September 2015 and used a commercial laboratory. In those cases, lead was differentiated into dissolved and particulate fractions using laboratory filtration of a portion of each sample. The filtered sample portions were analyzed for dissolved lead and copper and the unfiltered sample portions were analyzed for total lead and copper. Particulate lead and copper concentrations were found by subtracting dissolved concentrations from total concentrations.

Flowing water was also sampled at each residence. The intent was to obtain a flowing water sample and then allow the water to stagnate for profile sampling. Sites C1, C2, A1, J1, J2, B1, and B2 were able to do this. Sites A2, I1 and I2 drew the flowing water sample just after the stagnation period. There were no flowing water samples at Sites A1 and A2 in April or August of 2015.

A longer list of parameters was run by the EPA laboratory in August/September 2015 sampling than in the November/December 2015 sampling. When ND (no detection) was reported on a laboratory report, the limit of detection was substituted for the result in the graphs in this chapter.

Site IDs for the residential profile sampling are listed below in Table 3.1.

Table 3.1
Project #4586 residential sampling sites

Water System	Site Code	Phosphate Addition
I	I1	yes
I	I2	yes
C	C1	yes
C	C2	yes
J	J1	yes
J	J2	yes
B	B1	no
B	B2	no
A	A1	yes
A	A2	yes

FLOWING WATER CHARACTERISTICS

Analyses of flowing water samples show that all five water systems have similar source water – Lake Michigan (Table 3.2).

All water systems add a phosphate product except System B (Sites B1 and B2). Phosphate products are listed in Table 2.8 and Table 8.1. In Table 3.2, Water System C had phosphorus below the detection limit of 0.012 mg/L as P even though phosphate was being dosed into the system water.

Table 3.2
Project #4586 residential sampling flowing water characteristics

Aug/Sep 2015	I1	I2	C1	C2	J1	J2	B1	B2	A1	A2
Calcium in mg/L	34.0	34.2	33.3	34.3	33.6	33.3	34.2	33.6		
Magnesium in mg/L	11.7	11.8	11.3	11.7	11.7	11.6	11.4	11.4		
Chloride in mg/L	14.3	15.2	13.1	13.3	14.7	14.6	13.6	13.6		
Fluoride in mg/L	0.61	0.52	0.60	0.58	0.67	0.63	0.63	0.61		
Phosphorus in mg/L as P	0.58	0.52	ND	ND	0.48	0.42	ND	ND		
Orthophosphate in mg/L as P									0.23	0.22
Potassium in mg/L	1.36	1.42	1.36	1.38	1.49	1.48	1.3	1.28		
Silica in mg/L as SiO2	1.95	2.13	2.02	2.02	1.69	1.62	2.19	2.15		
Sodium in mg/L	8.93	9.92	7.28	7.42	8.01	7.96	8.15	8.12		
Sulfate in mg/L	27.4	26.9	24.9	25.0	22.2	22.3	21.8	21.9		
Total Alkalinity in mg/L as CaCO3	100	100	100	100	100	100	110	110		

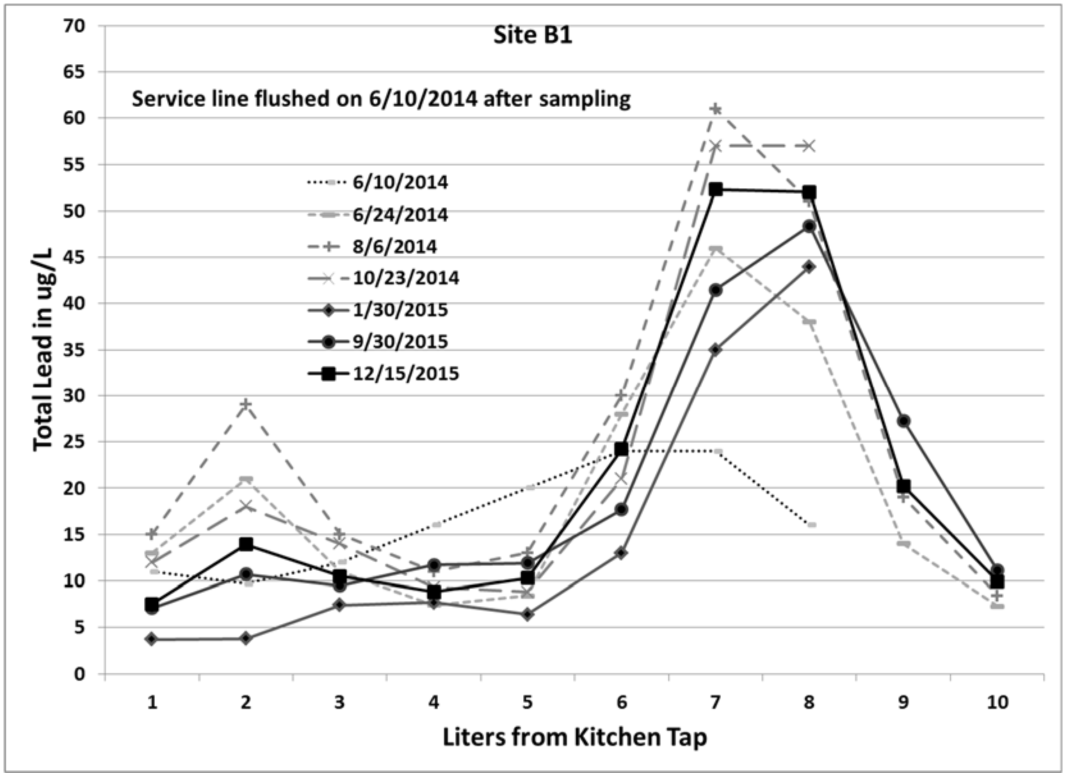
Nov/Dec 2015	I1	I2	C1	C2	J1	J2	B1	B2	A1	A2
Calcium in mg/L	33.7	33.9								
Magnesium in mg/L	11.9	12.0								
Chloride in mg/L	14.9	13.6	15.8	16.5	19.9	20.2	15.5	15	15	15.6
Fluoride in mg/L	0.49	0.46	0.69	0.57	0.71	0.71	0.73	0.71	0.75	0.74
Phosphorus in mg/L as P	0.50	0.52								
Potassium in mg/L	1.39	1.34								
Silica in mg/L as SiO2	2.45	2.35								
Sodium in mg/L	9.23	9.11								
Sulfate in mg/L	28.8	26.9	26.8	26.5	23.7	23.7	23.5	23.7	25.5	25.8
Total Alkalinity in mg/L as CaCO3	100	99	100	100	110	110	110	110	110	110

ND=no detection; concentration below the laboratory limit of detection

LEAD CONCENTRATIONS IN RESIDENTIAL PROFILES

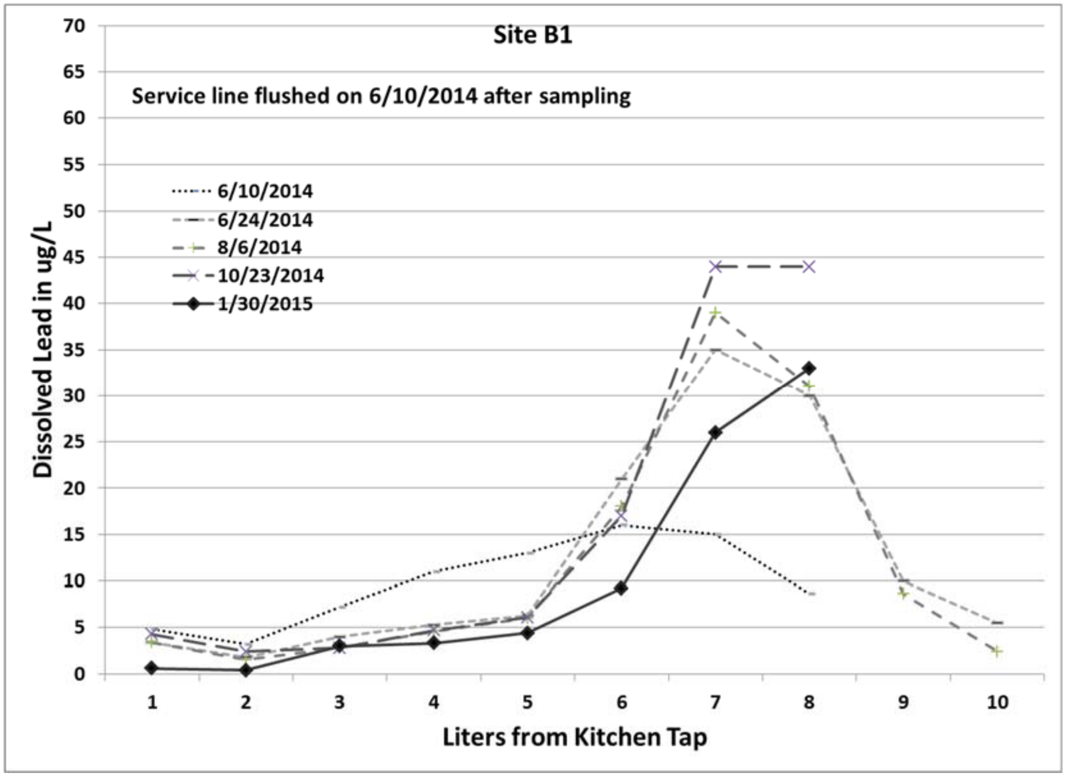
System B began sampling two residences in June of 2014 and was able to differentiate between dissolved and particulate lead in the earlier sampling periods.

In Site B1, after the first profile sampling, the lead service line was flushed. Instead of cleaning out particulate lead, the flushing resulted in higher dissolved lead. The lead in the lead service line was still elevated by the last sampling on 12/15/2015. See Figure 3.1 for total lead concentrations and Figure 3.2 for the dissolved and particulate lead fractions.



Liters from Kitchen Tap	Piping Material Associated with Sample
1	Galvanized iron pipe
2	Galvanized iron pipe
3	26% of length galvanized iron pipe and 74% copper pipe
4	Copper pipe
5	Copper pipe
6	4% of length copper pipe and 96% lead pipe
7	Lead pipe
8	21% of length lead pipe and 79% water main
9	Water main
10	Water main

Figure 3.1 Residential profile sampling: Site B1 total lead concentrations



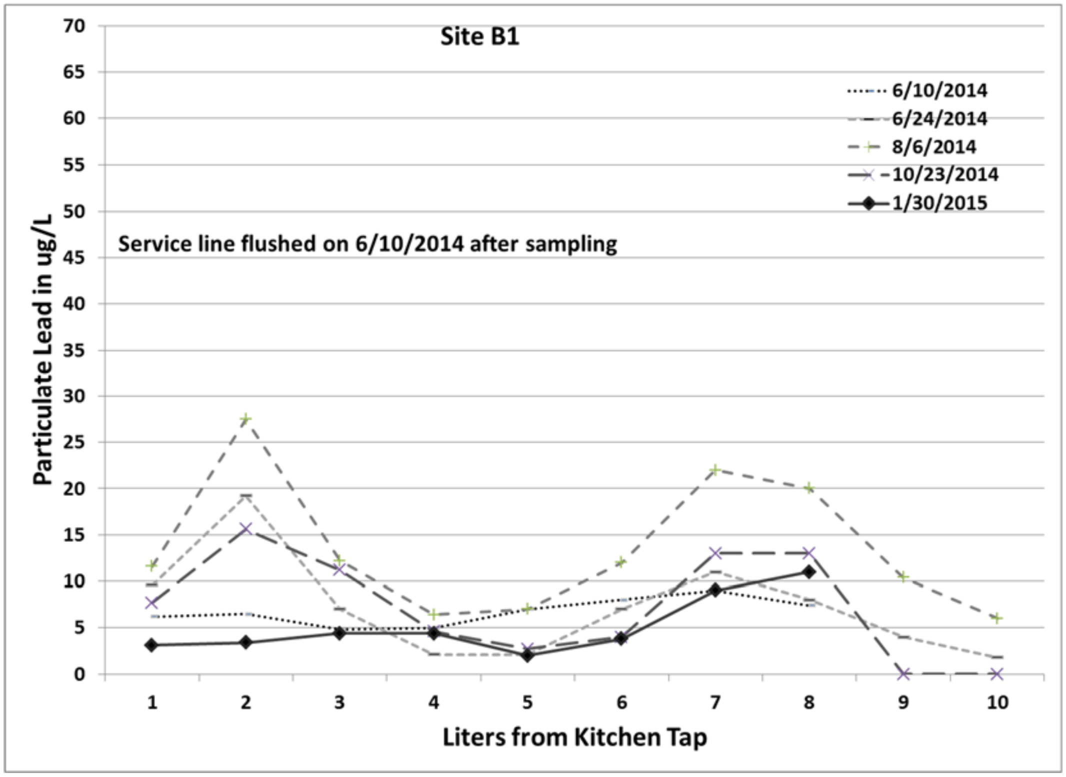
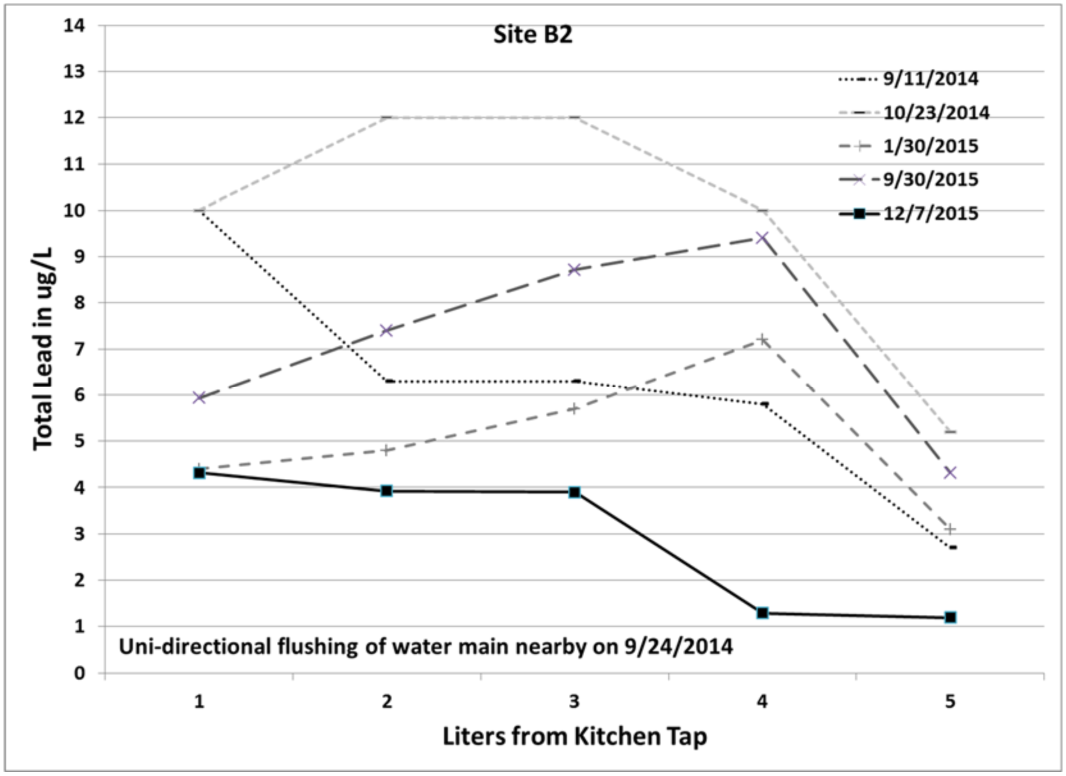


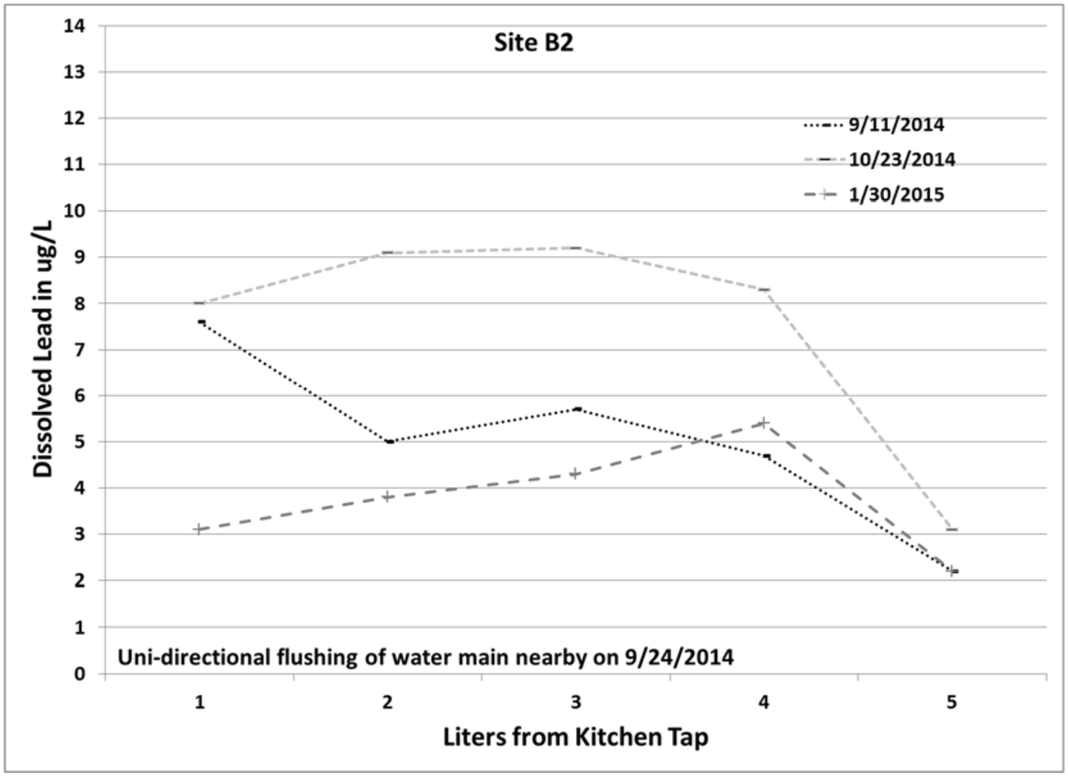
Figure 3.2 Residential profile sampling: Site B1 dissolved and particulate lead concentrations

For Site B2, the first sampling was performed before uni-directional flushing of water mains occurred nearby on 9/24/2014. Subsequent sampling showed elevated dissolved lead, but all levels had fallen to lower concentrations by the final sampling on 12/7/2015. The elevated lead concentrations never exceeded 15 µg/L. See Figures 3.3 and 3.4.



Liters from Kitchen Tap	Piping Material
1	Copper pipe
2	Copper pipe
3	48% of length copper pipe and 52% lead pipe
4	48% of length lead pipe and 52% water main
5	Water main

Figure 3.3 Residential profile sampling: Site B2 total lead concentrations



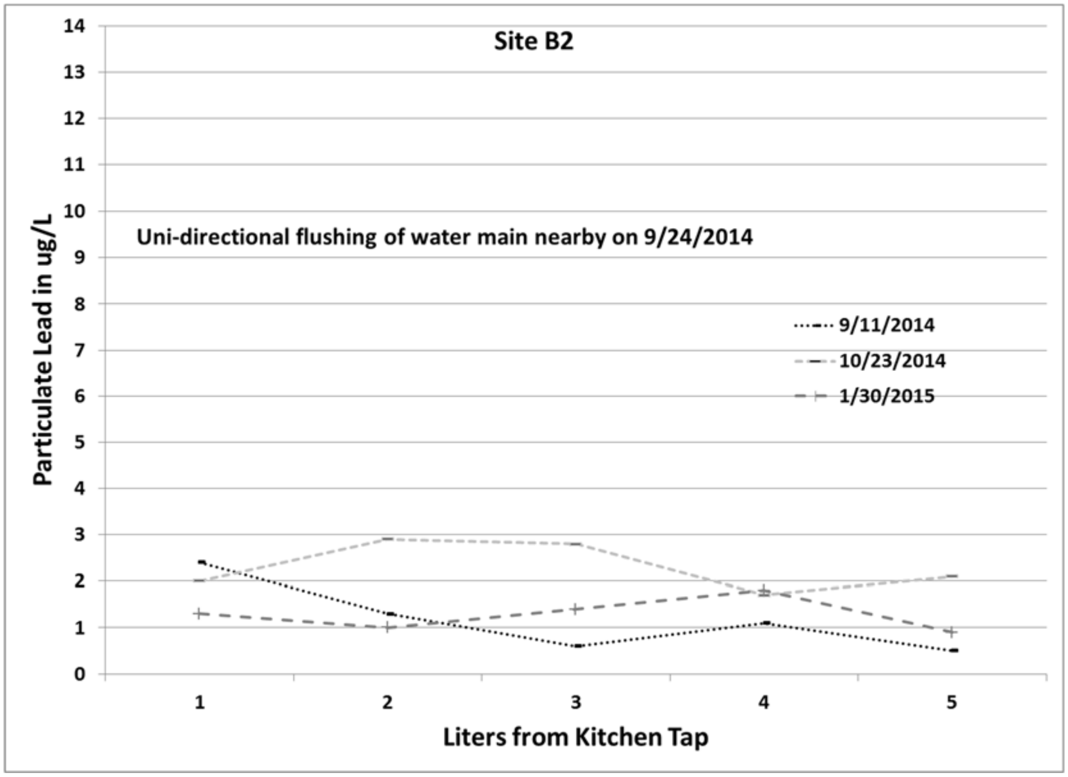


Figure 3.4 Residential profile sampling: Site B2 dissolved and particulate lead concentrations

System A performed profile sampling on two residences in April and August of 2015 using a commercial laboratory for analyses and then in November using the EPA laboratory. Uni-directional flushing of water mains occurred nearby both sites in May 2015. Lead concentrations were differentiated into dissolved and particulate forms in August and showed that a large percentage of lead was in particulate form. There was not enough information to determine if nearby water main flushing may have influenced the increase of the particulate lead concentration in the water or if some other factor may have been involved. Site A2 lead concentrations eventually fell to lower levels but Site A1 lead concentrations ended higher than in the first sampling. See Figures 3.5 and 3.6.

No water main flushing was performed in Systems I, C, and J. All of the residential profile lead concentrations dropped as the summer conditions entered into winter conditions. See Figure 3.7.

It should be noted that lead concentrations in lead pipe lines can still be excessive even when a phosphate product is used for control of lead release. Water Systems A and I use a high dose of mostly orthophosphate products and each system measured one home with lead levels over 15 µg/L. System J uses a lower dose of a poly/ortho blend and measured one home with lead levels over 15 µg/L. System B does not use a phosphate chemical and measured one home with lead levels over 15 µg/L. System C uses a low dose of a poly/ortho blend and found both residences with lead under 15 µg/L.

In these profiles, differentiation of lead into dissolved and particulate forms was done only in two systems. Therefore, nothing can be said about the nature of the lead in the other profiles or their potential mechanisms of release. It is interesting to note that System A, using a high dose of a mostly orthophosphate product, measured a high percentage of particulate lead profiled through both residences.

COPPER CONCENTRATIONS IN RESIDENTIAL PROFILES

Copper concentrations in profile sampling are highest near the sampling tap because residences commonly have more copper at that location. None of the residences sampled exhibited extreme copper concentrations. This can be seen in Figures 3.8 and 3.10.

In differentiating two sites' samples in System A into dissolved and particulate copper, dissolved copper appeared to predominate as opposed to a greater role played by lead particulates in the same residences. Refer to Figure 3.9.

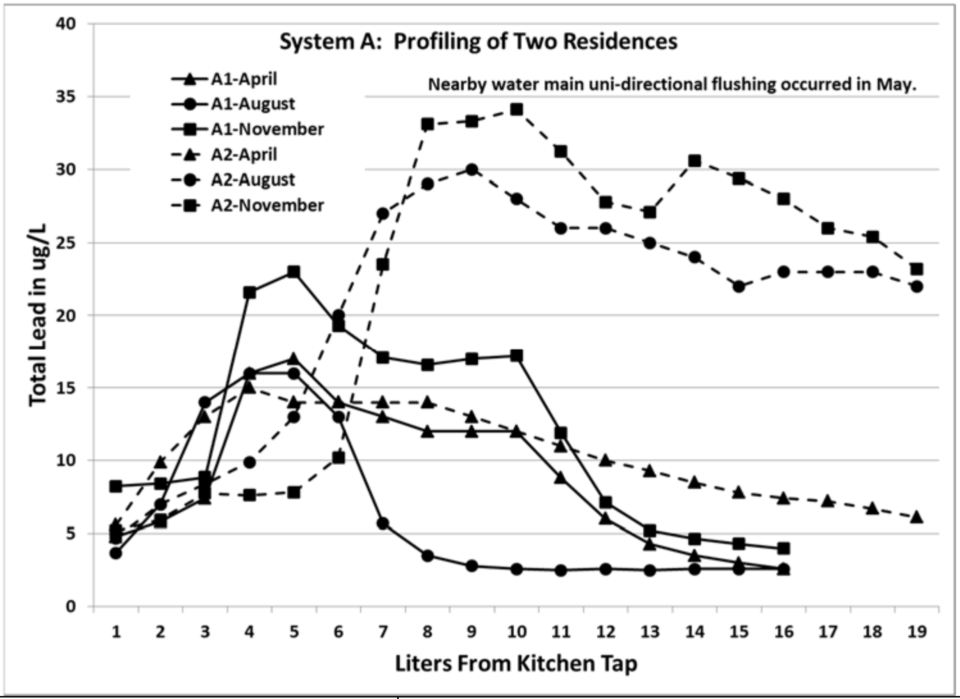
OTHER METALS' CONCENTRATIONS IN RESIDENTIAL PROFILES

Iron, manganese, and aluminum have been associated with adsorbing, accumulating, and transporting lead and copper in water systems (Schock et al. 2014). Iron was measured in significant concentrations in Sites I1 and A2 in August near the sampling faucet.

Manganese was not measured above the laboratory's limit of detection. Zinc was present in all residences, especially closer to the sample tap. Zinc indicates the presence of galvanized steel piping and certain metal alloys.

Aluminum was not measured above the laboratory's limit of detection. Cadmium and nickel were not measured above the laboratory's limit of detection.

Refer to Figures 3.11 to 3.14 for iron and zinc levels.



Site A1		Site A2	
Liters from Kitchen Tap	**Piping Material**	**Liters from Kitchen Tap**	**Piping Material**
1	Copper pipe	1	Copper pipe connected to galvanized pipe
2	Copper pipe	2	Copper pipe
3	Galvanized iron pipe	3	Copper pipe
4	Galvanized iron pipe	4	Copper pipe
5	Lead pipe	5	Copper pipe
6	Lead pipe	6	Lead pipe
7	Lead pipe	7	Lead pipe
8	Lead pipe	8	Lead pipe
9	Lead pipe	9	Lead pipe
10	Lead pipe	10	Lead pipe
11	Lead pipe	11	Lead pipe
12	Lead pipe	12	Lead pipe
13	Lead pipe	13	Lead pipe
14	Lead pipe	14	Lead pipe
15	Water main	15	Copper pipe
16	Water main	16	Copper pipe
		17	Copper pipe
		18	Water main
		19	Water main

Figure 3.5 Residential profile sampling: Sites A1 and A2 total lead concentrations

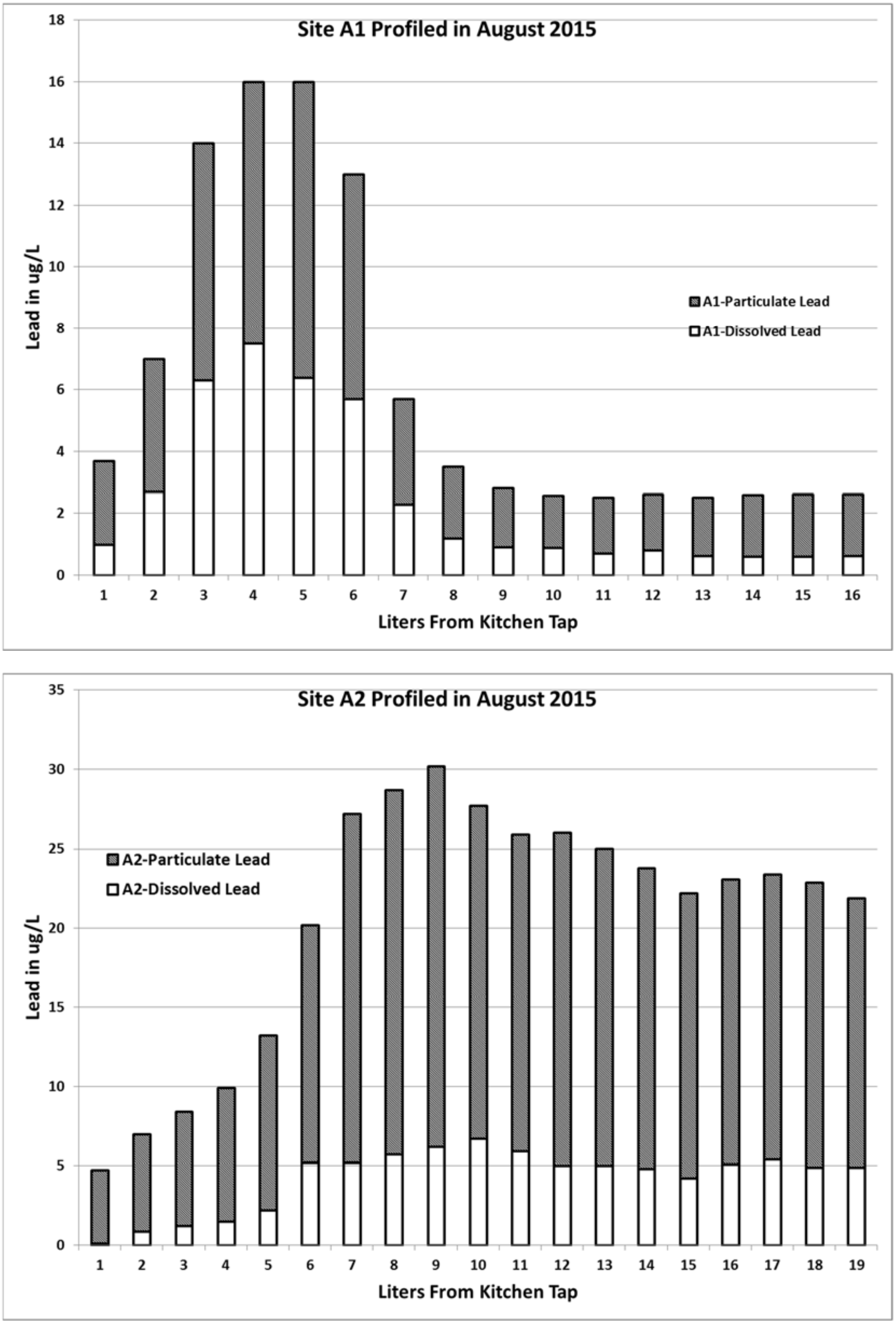


Figure 3.6 Residential profile sampling: Sites A1 and A2 dissolved and particulate lead concentrations

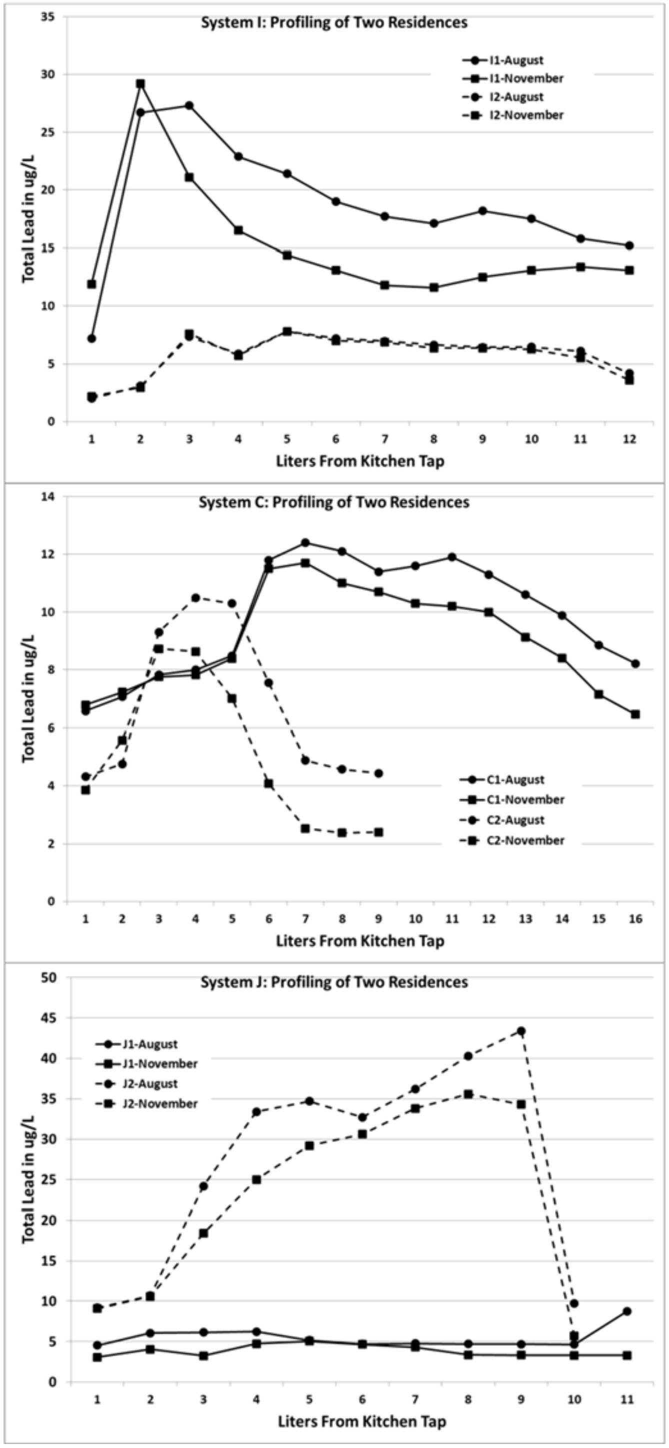


Figure 3.7 Residential profile sampling: Systems I, C, and J total lead concentrations

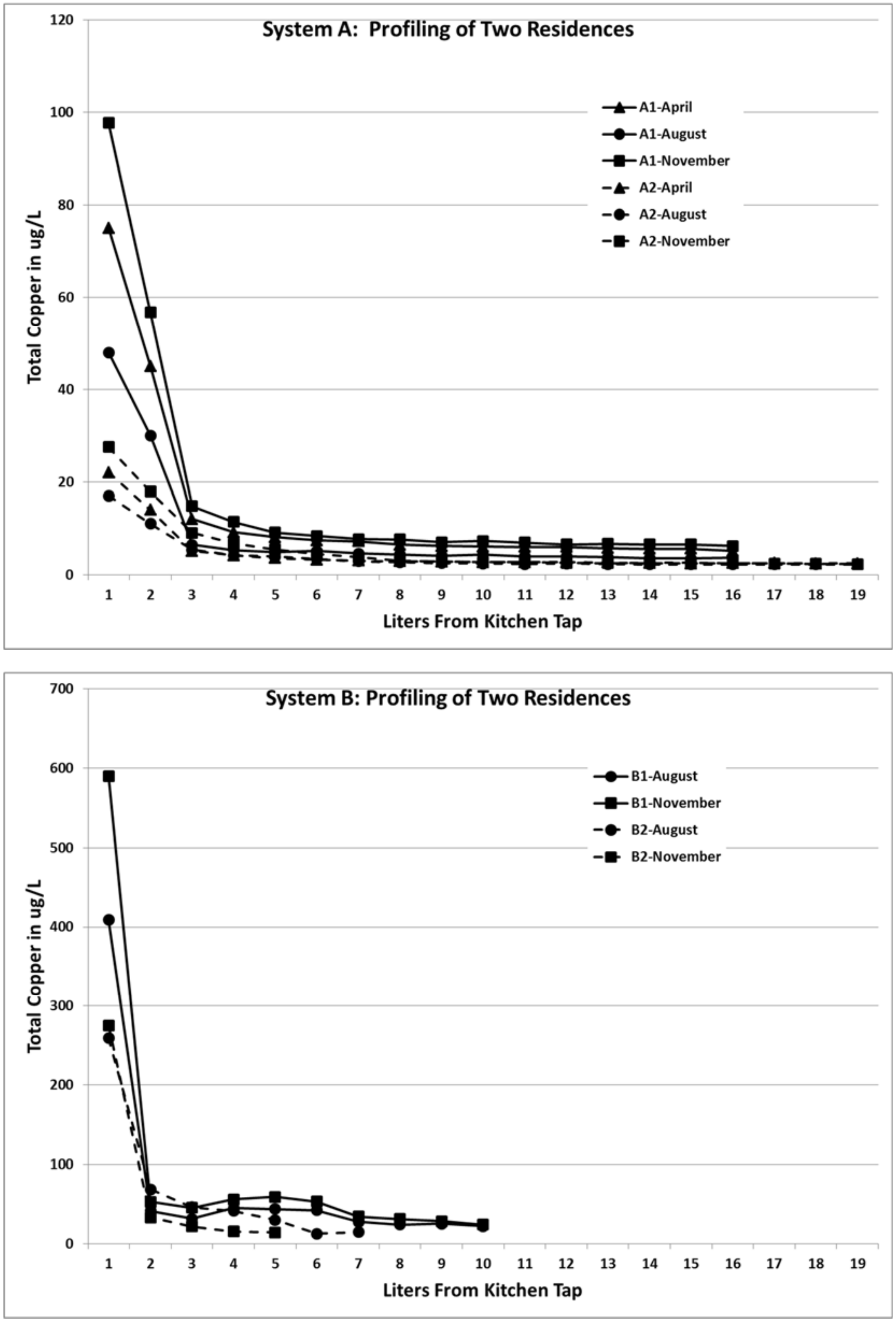
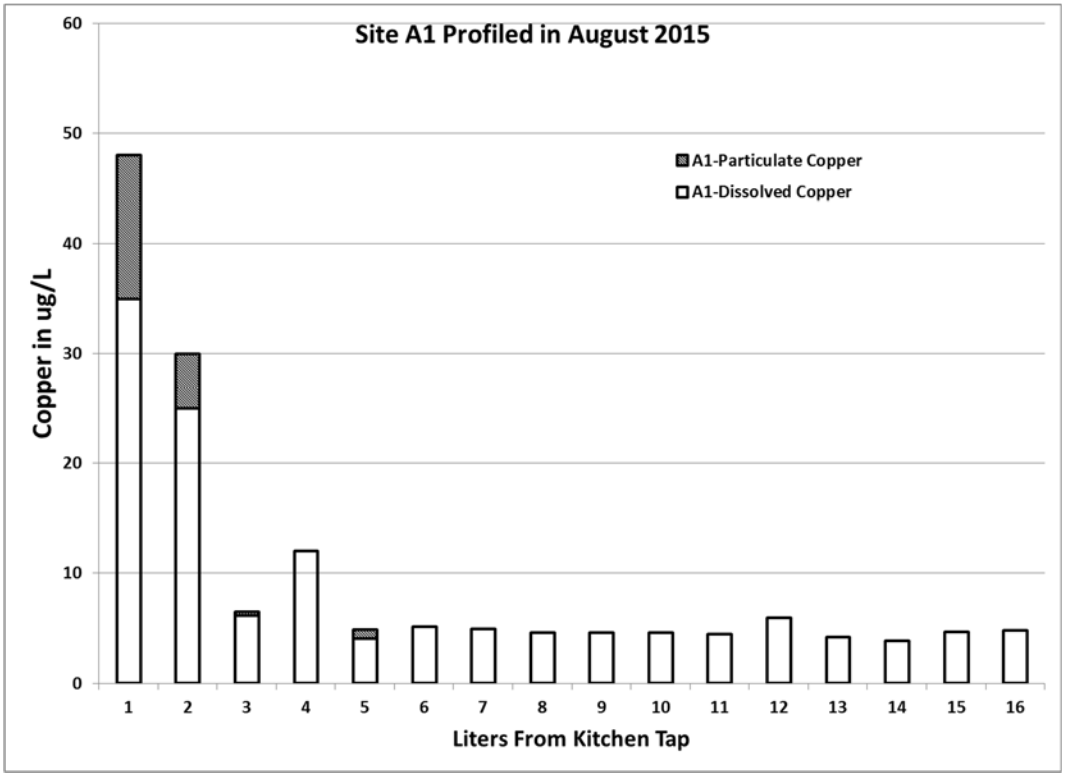


Figure 3.8 Residential profile sampling: Systems A and B total copper concentrations



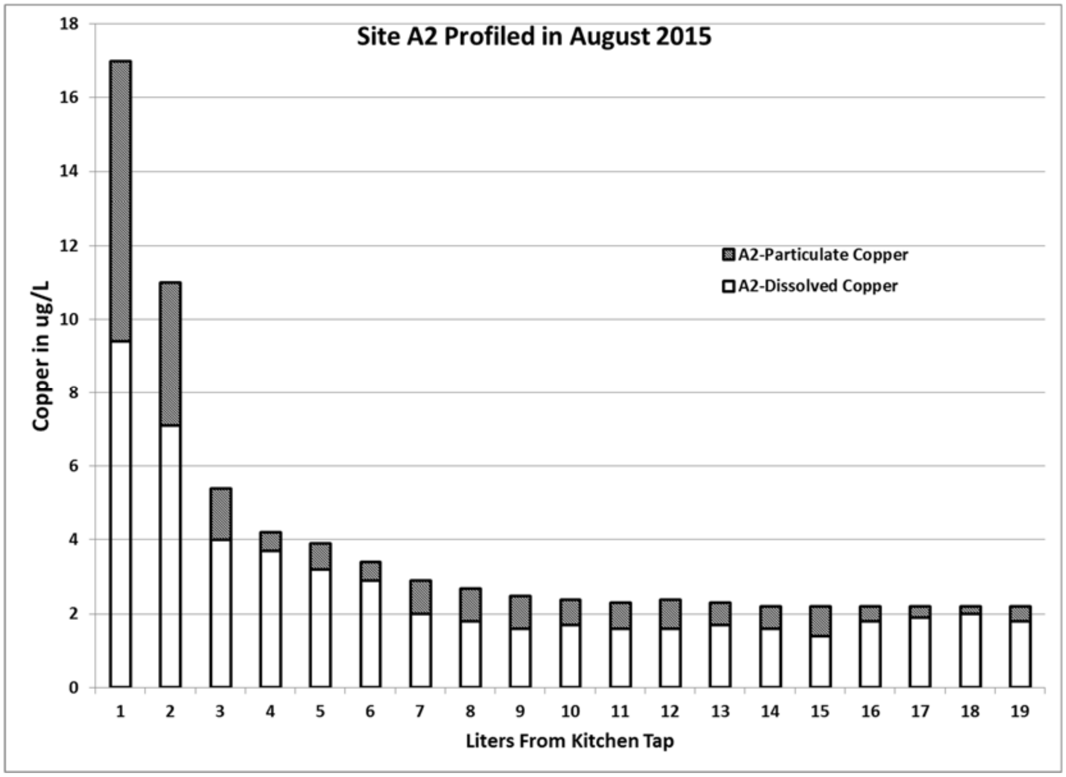


Figure 3.9 Residential profile sampling: Sites A1 and A2 dissolved and particulate copper concentrations

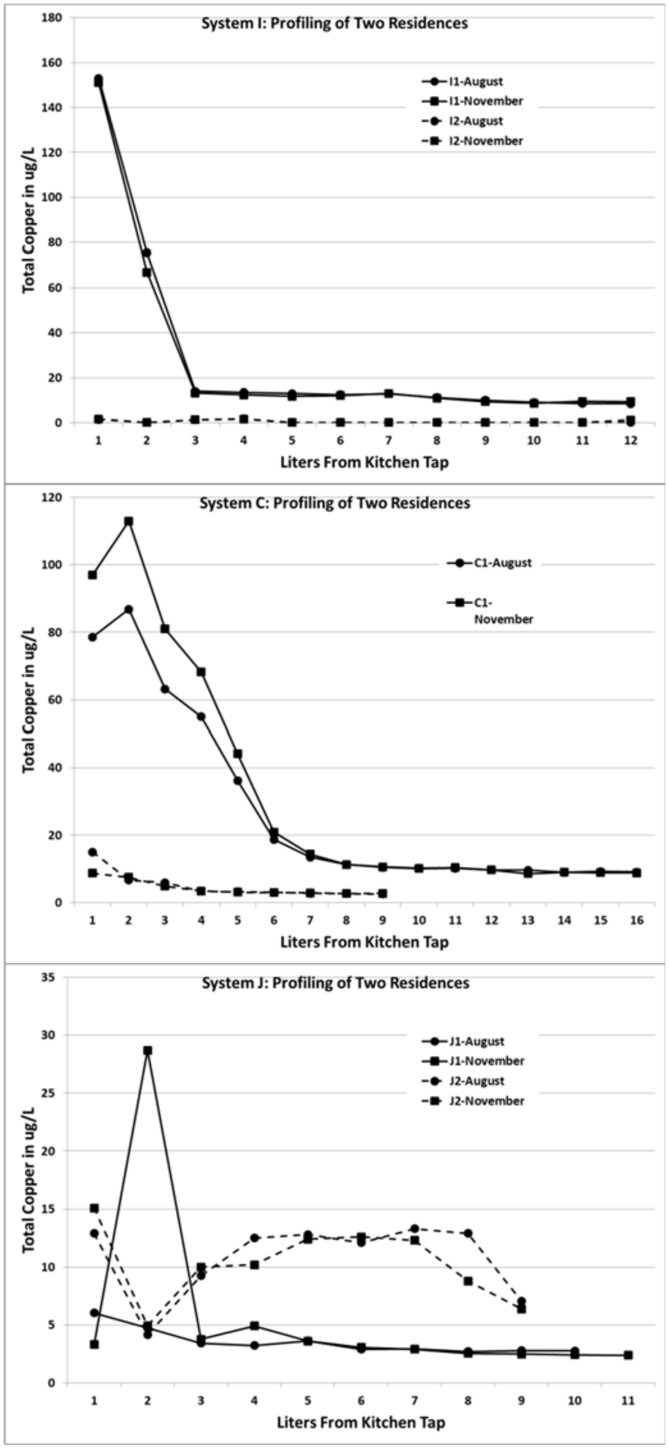


Figure 3.10 Residential profile sampling: Systems I, C, and J total copper concentrations

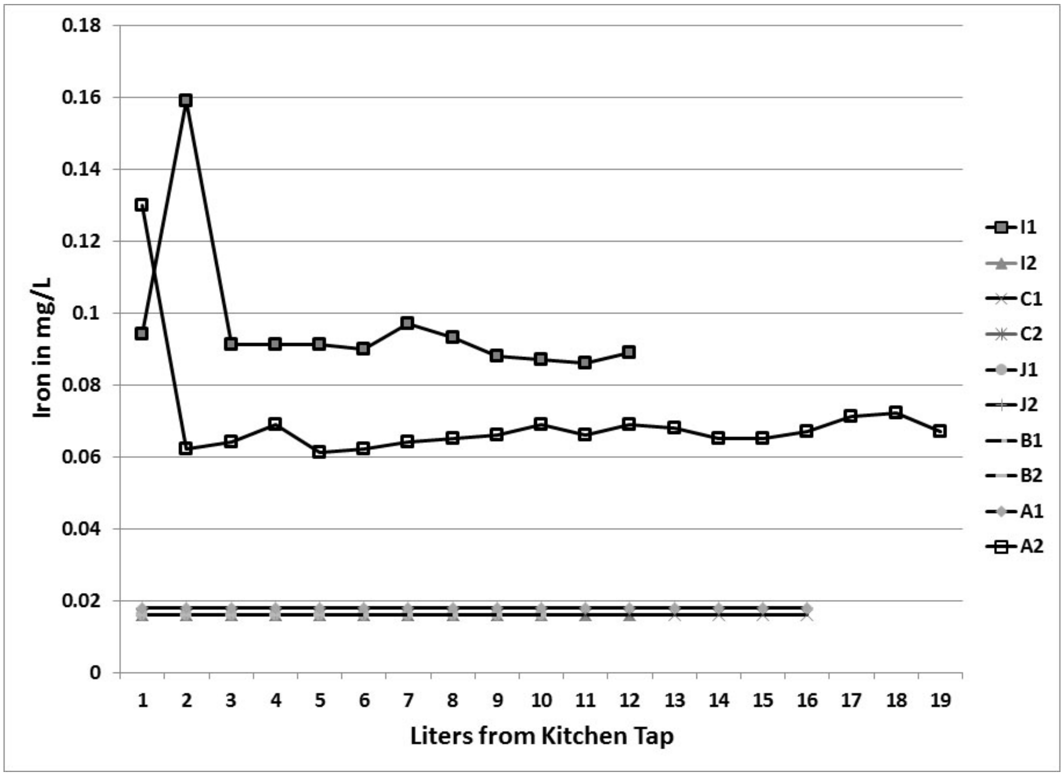


Figure 3.11 Residential profile sampling: Iron measured Aug/Sep 2015

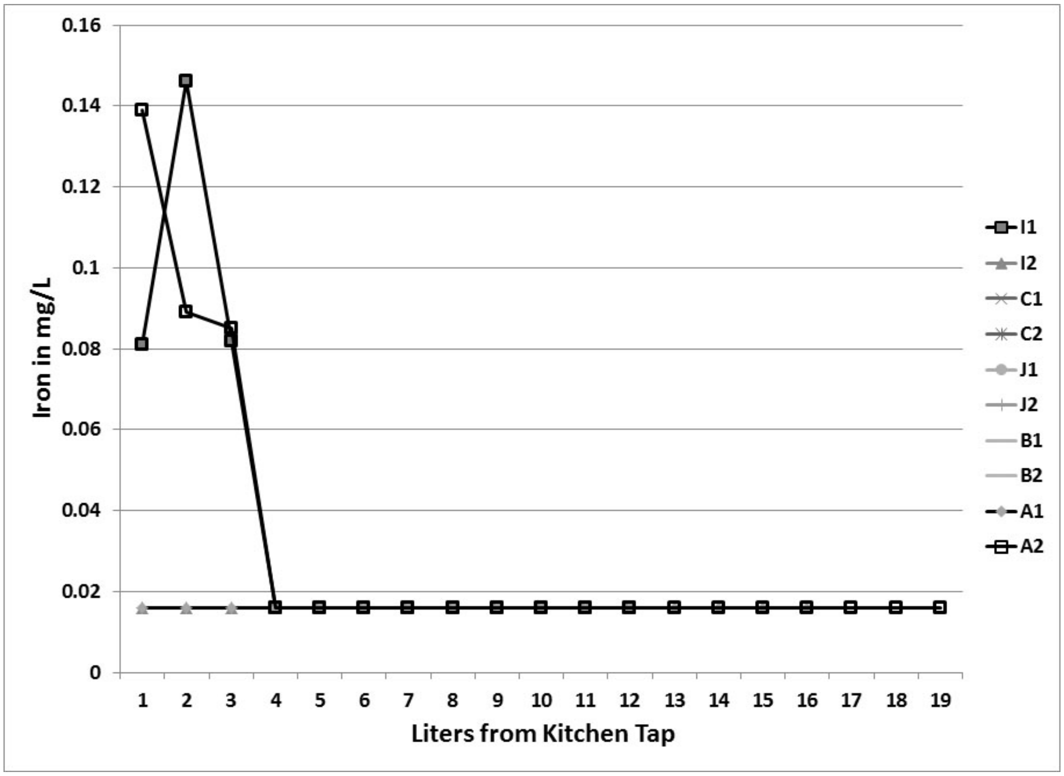


Figure 3.12 Residential profile sampling: Iron measured Nov/Dec 2015

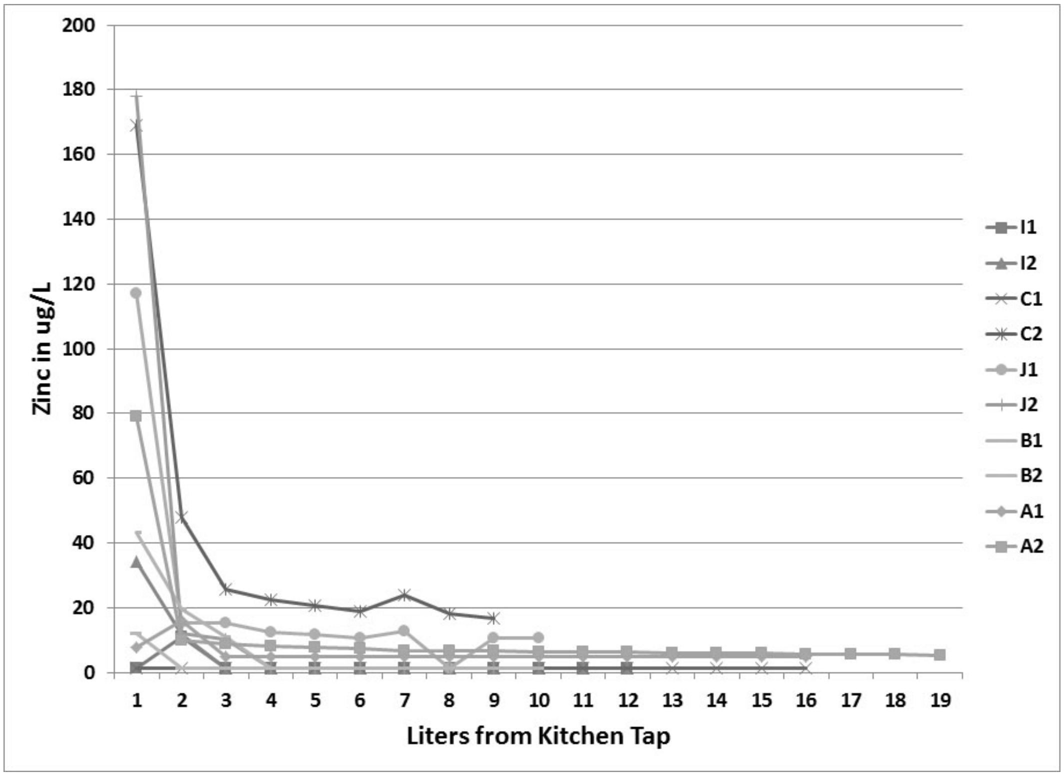


Figure 3.13 Residential profile sampling: Zinc measured Aug/Sep 2015

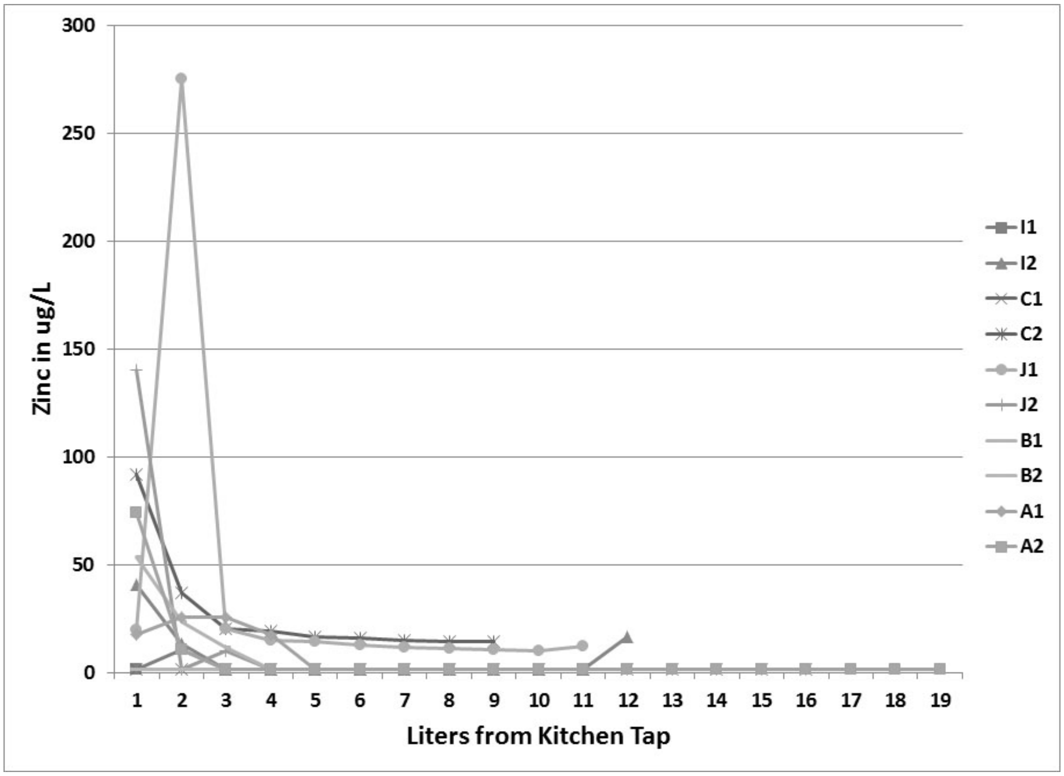


Figure 3.14 Residential profile sampling: Zinc measured Nov/Dec 2015

SUMMARY

Personnel from five water systems using Lake Michigan water performed profile sampling on two residences per water system to view the metals release in pipe sections from the kitchen tap through the building piping, lead service line and into the water main.

It was seen that high lead release could be experienced in water systems feeding phosphate-based chemical products as well as the one system not using phosphate.

Two water systems ran extra analyses to differentiate dissolved lead from particulate lead. Water System A had high particulate lead concentrations while Water System B had high dissolved lead. These findings will be compared to the distribution system monitoring data discussed later in this report.

Attempts at cleaning the water mains and the lead service lines created greater release of lead. In one system (Water System A), the greater release was in particulate form. In another system (Water System B), the greater release of lead was in dissolved form.

Copper release was not as dramatic as the lead release in these water systems.

Other metals were present, such as zinc from galvanized steel piping or metal alloys. There were not enough data to run correlative analyses of other water quality parameters with lead and copper release.

These characterizations of water quality at several critical residences in the water systems under study are important for later comparisons to general water distribution system monitoring results using a special monitoring station. The residential data help in validating the general results; the general results help in explaining the residential data.

CHAPTER 4

DISTRIBUTION SYSTEM DISINFECTION CONCENTRATIONS AND TURBIDITY MEASUREMENTS

This project explored the relationship between system cleanliness and biostability to lead and copper release from pipe material into water. Two easily accessible and economical field test parameters by definition represent system cleanliness and biostability.

Disinfection concentration is one of the parameters. When disinfection concentration is low at a location in a water distribution system, it means that the chemical has been used up. This is especially evident when the concentration is compared to the original dose at the entry points to the distribution system. The disinfection can be depleted by interactions with existing pipe wall chemical scale compounds or by interactions with existing microorganisms and biofilms in the system as well as bulk water chlorine demand compounds. Disinfection depletion is also a function of water age (residence time) in the water system with longer exposure to disinfection-depleting factors. If the pipe walls are clear of chemical scales and water and pipe wall debris devoid of microbiological populations and their organic secretions and if residence time in the water system is not excessive, disinfection concentration can be found to be at similar levels around the distribution system as was freshly dosed at the entry points to the distribution system. In this way, disinfection concentration is an indicator of the chlorine demand of the water and pipe wall accumulations, an indicator of the cleanliness and biostability of the water system. Although disinfection needs vary, anecdotally, if concentrations are below 0.3 mg/L free chlorine for chlorine disinfection or below 1 mg/L total chlorine for chloraminated systems, there are most likely not adequate levels of disinfection to defend against excessive growth of microorganisms.

Another easily obtainable water quality parameter is turbidity. Turbidity is a measure of particulates entrained in the water. Particulates can represent inert material such as sand, chemical scale particles such as particulate iron or manganese, microorganisms, or biofilm materials. In this way, turbidity is another indicator of water system cleanliness and biostability. Turbidity should not exceed 1 NTU in the distribution system based on a study of the potential to form biofilms in water systems (LeChevallier et al. 2015).

If disinfection concentrations and turbidities can be routinely tracked at set locations around the distribution system, then this is the equivalent of tracking the status of cleanliness and biostability over time and location. Problem locations or operational periods can be pinpointed and remedied.

Conveniently, one of the Federal drinking water regulations, the Total Coliform Rule, requires water utility personnel to select flowing water sampling sites around the distribution system to represent geographical changes in water quality. This regulation is focused on the weekly monitoring and monthly reporting for indicators of pathogenic microorganisms that could cause immediate illness to consumers. The presence of microorganisms (total coliform bacteria) that indicate possible contamination of drinking water by sewage is measured at these sites. In addition to the total coliform count, disinfection concentration is measured by many water systems. It is the disinfection concentration that was of interest in this project for reasons cited above. Some of the water system personnel participating in this project also added the measurement of turbidity during routine visits to Total Coliform Rule sites. Other already established distribution system regulatory sites or utility operational sampling sites can be used for this purpose as well.

In this project, Water Systems A, B, C, I, and L provided data so that disinfection concentration and turbidity could be plotted over time per sampling site. An example of the graph produced for both disinfection concentration and turbidity at each sampling site is shown in Figure 4.1. The type of graph is called a Shewhart Control Chart. Its features are explained in Chapter 5. For now, we can see from Figure 4.1 that the turbidity varied greatly at specific times. Inspection of the graph should be the motivation to study system conditions and operations at the date when the turbidity exceeded the upper boundary of a range where 99% of the data were statistically expected to fall.

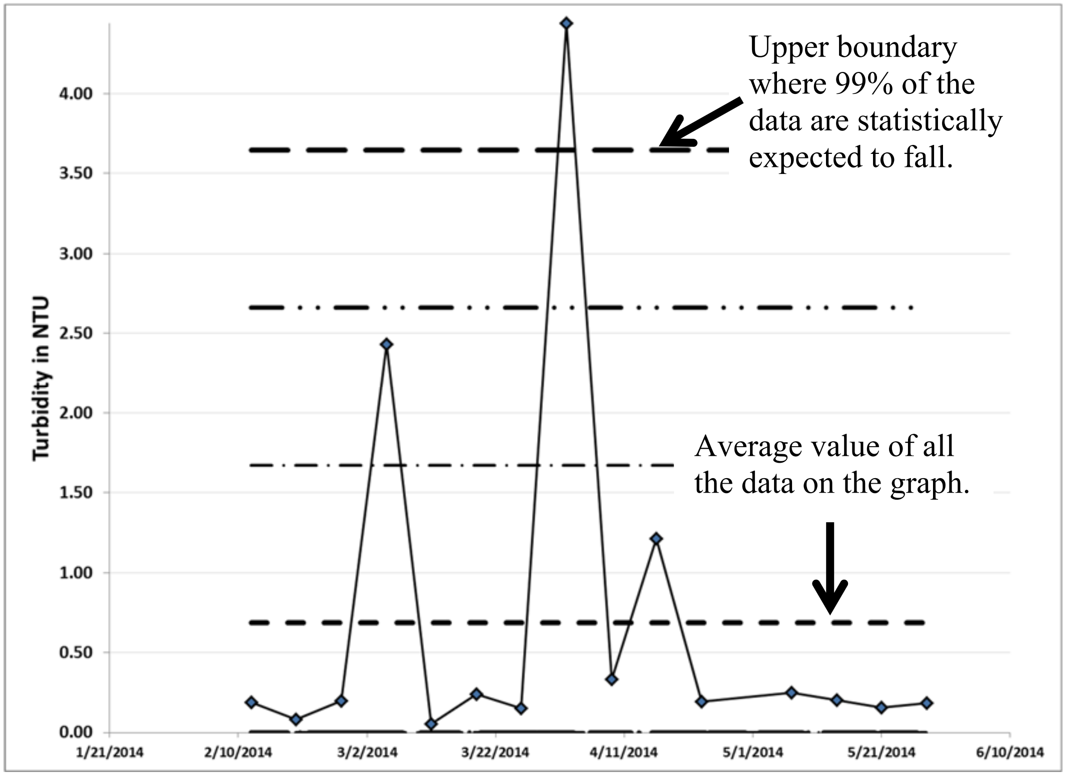


Figure 4.1 Example graph for each parameter at each TCR sampling site

Also, why did the turbidity in Figure 4.1 exceed the average value on two dates when all the other data stayed below the average? Since turbidity can represent chemical particulates in the water as well as microorganisms and biofilm material in the water, these graphs indicate a disruption to the cleanliness and/or biostability of the system. The graphs are guides to pinpointing the system conditions and operational issues at a specific time and location that affect water quality.

The data for each graph can be selected over specific time periods. For example, graphs of quarterly data may be of great interest. The quarters of a year coincide with seasons and water temperature. In comparing quarterly graphs, one may discover changes to cleanliness and biostability based on time of year.

Unfortunately, there is another consideration that may make a quarterly graph impractical. That consideration is the number of data points. The less data points, the less accurate the representative statistics are. With the Shewhart Control Charts, it is best to calculate statistics based on twenty or more data points (Wheeler and Chambers 1992). Using less data points is acceptable, but the statistics are less accurate. The charts are explained further in Chapter 5. For now, it is only important to consider how many data points are in a time period that one wishes to study.

In order to use enough data points, the comparative graphs in Figures 4.2 to 4.7 are based on the first (Semester 1) and second (Semester 2) six months of the year. Instead of studying each site graph, their statistics are compiled onto one graph. The statistics used are the average and the variability of results. The sites are sorted by increasing averages so that the sites with the highest and the lowest averages are evident. Site names are typically shown on the X-axis but are not shown in this report. For disinfection concentration, the sites with the lowest averages are of concern. For turbidity, the sites with the highest averages are of concern. These comparison graphs identify which sites should be studied and taken action on.

In addition to the averages, the comparison graphs in Figures 4.2 to 4.7 also show the degree to which the disinfection concentration or the turbidity varies at each site. The variation is shown by the symbols (“whiskers”) above and below each average connected with a line. The symbols represent the upper and lower boundaries where statistically 99% of all the data are expected to fall. Sites with wide expected variation should also be investigated; a steady proper dose of disinfection is desired at each site and a low steady turbidity at a site is preferred to one with erratic high jumps in particulate matter.

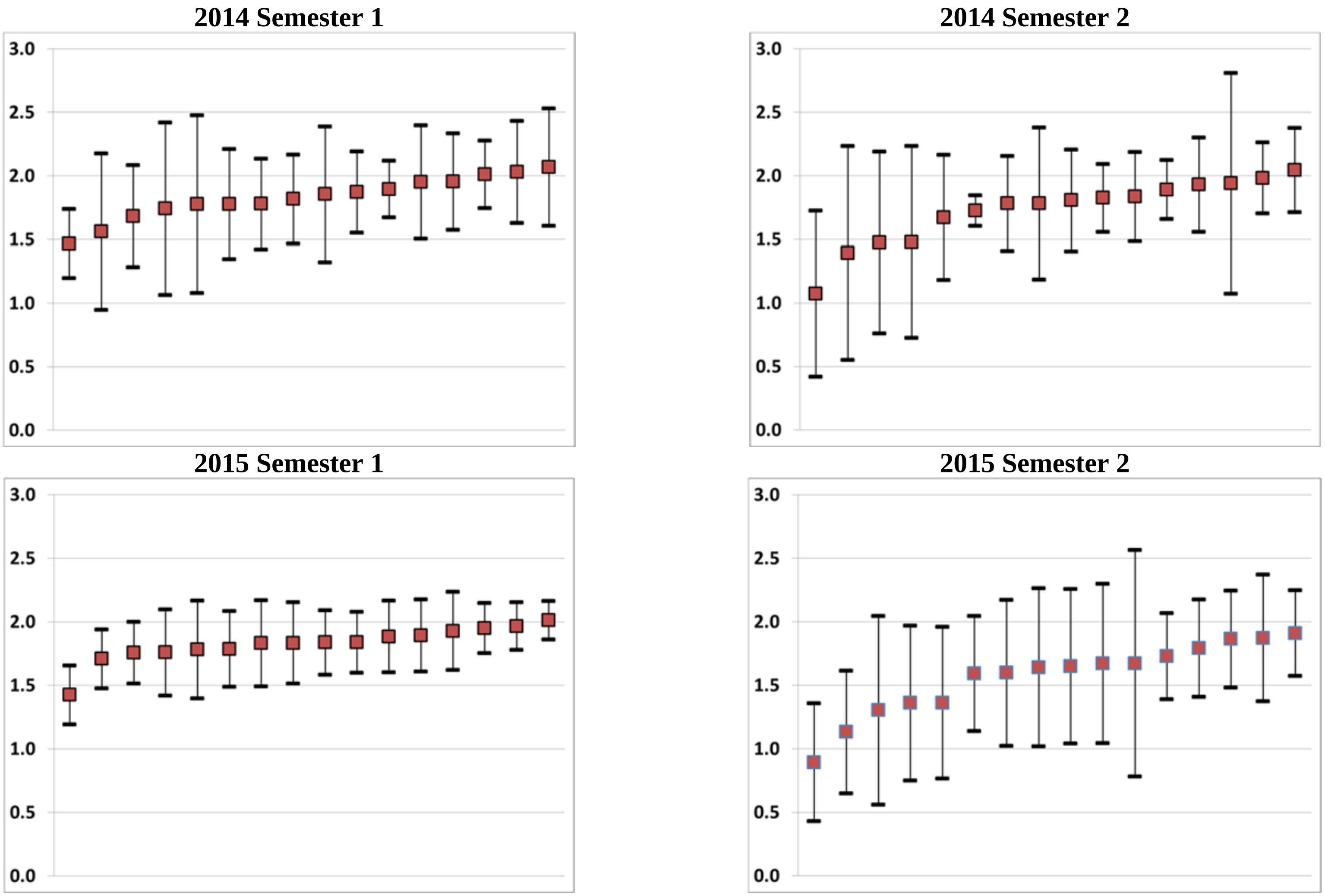
The graphs in Figures 4.2 to 4.7 not only allow for the comparison between sites in a given time period, but also allow for comparison between time periods. For example, in Figure 4.2, the first semester of 2014 can be compared to the second semester of 2014 and the first semester of 2015, etc. It can be determined if turbidity is dropping throughout the water system over time, for example.

Additionally, all of the sites can be compared on a time-series graph together. See Figures 4.8 to 4.13. Each time-series line belongs to a sampling site but the sites are not identified on this graph. Instead, the graph is used to view the overall minimum and maximum results of all sites over the time period and to determine if all sites are exhibiting similar behavior.

Figures 4.14 to 4.17 display the statistical comparison graphs for data covering a year-long time period. This demonstrates that disinfection concentration behavior and turbidity behavior can be compared between years as well as segments of a year. Figures 4.18 to 4.21 show the same data but as time-series in order to study general patterns for the complete water system.

In summary, disinfection concentration and turbidity data taken routinely at Total Coliform Rule sites and any other regularly visited distribution system sites can be tracked and studied to pinpoint operational events that have resulted in reduced water quality.

These graphs will be used in interpreting water system cleanliness and biostability in Chapter 11.



2014 Semester 1

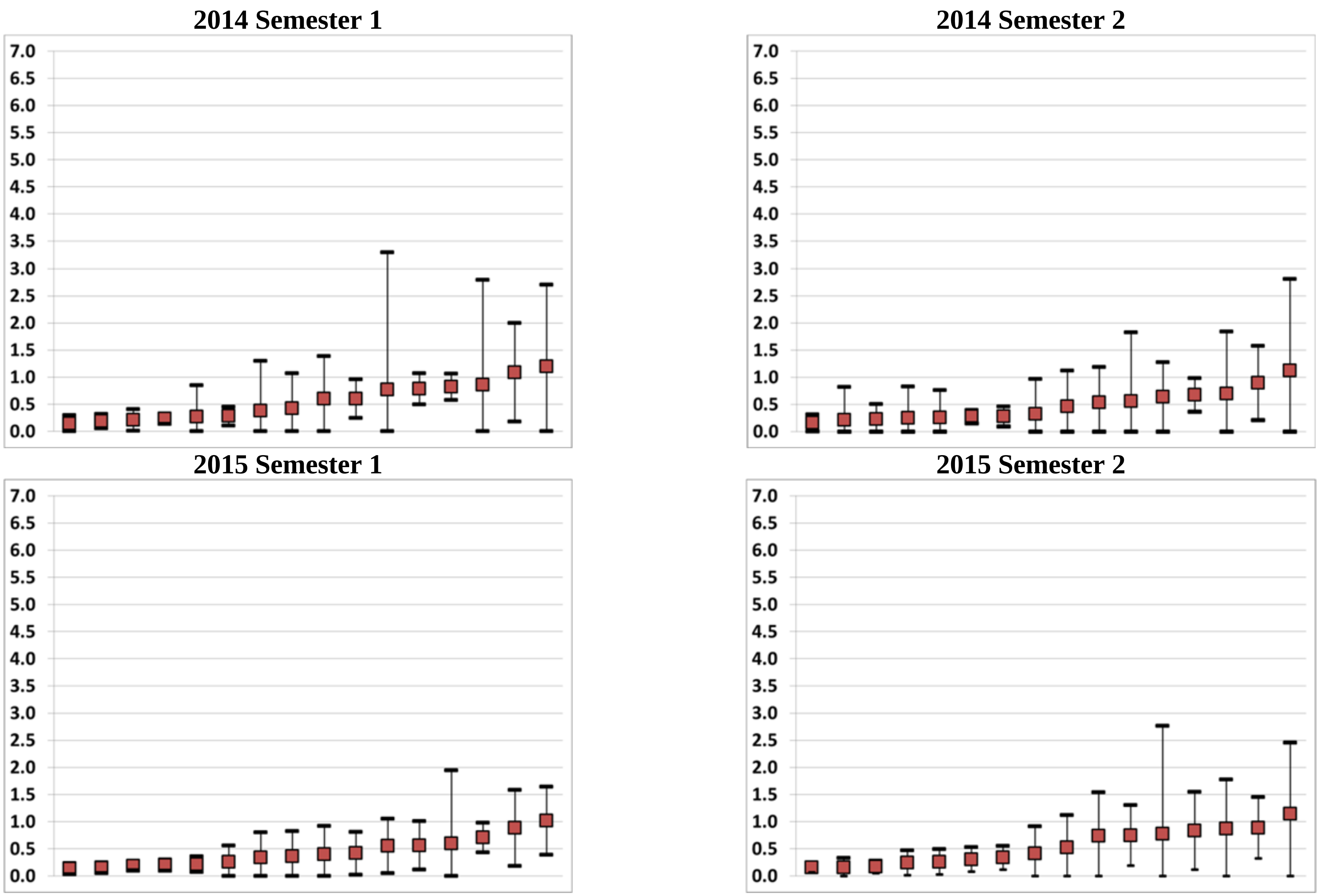
2014 Semester 2

2015 Semester 1

2015 Semester 2

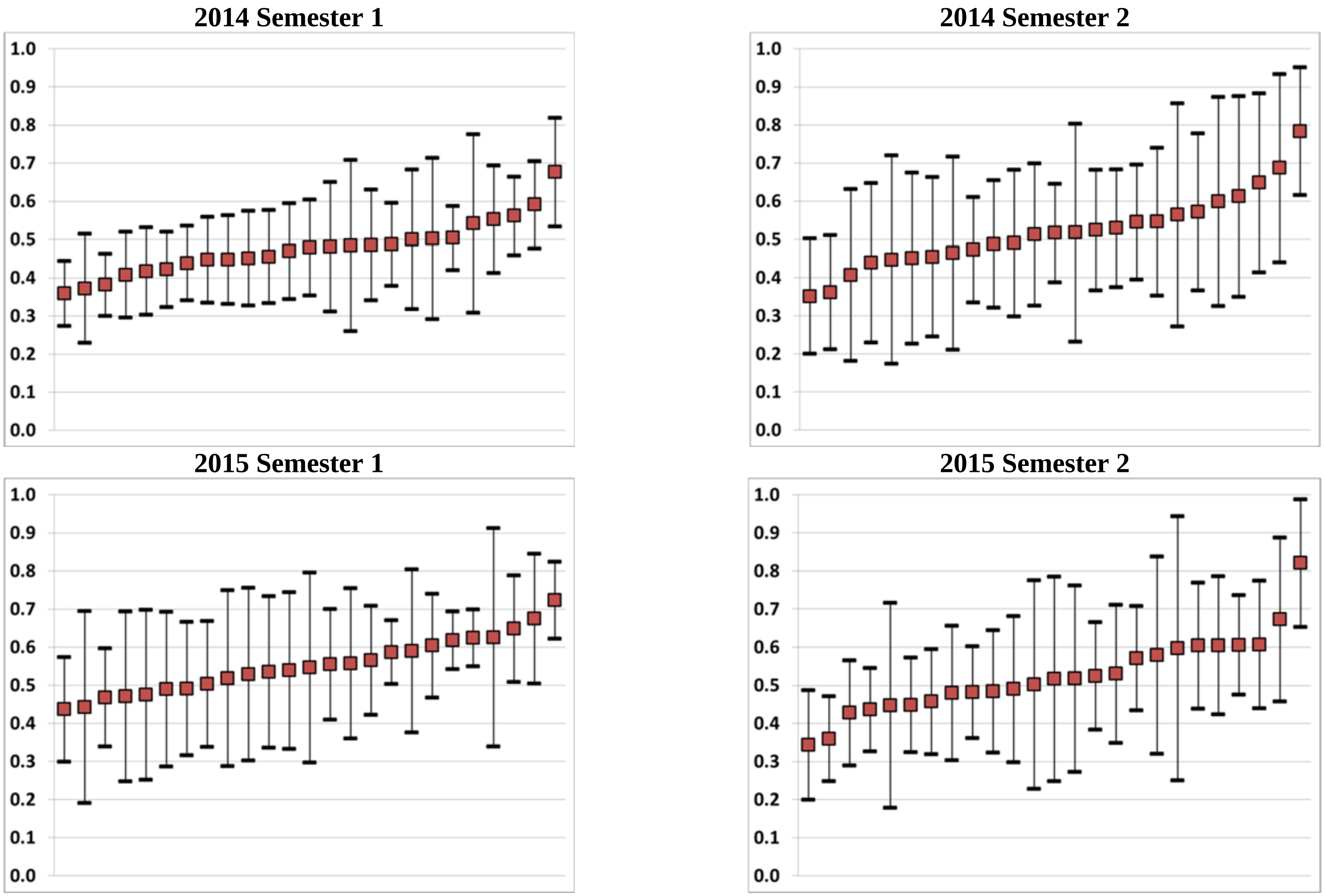
This graph shows the average concentration and variation of total chlorine at each Total Coliform Rule sampling site.
The x-axis would typically identify the sampling site associated with the data but are not shown here.
Each square with "whiskers" represents the average concentration at each sampling site.
The range between the upper and lower "whiskers" is the concentration range where statistically 99% of the concentrations will fall.

Figure 4.2 Water System A: Comparison of total chlorine in mg/L at Total Coliform Rule sites



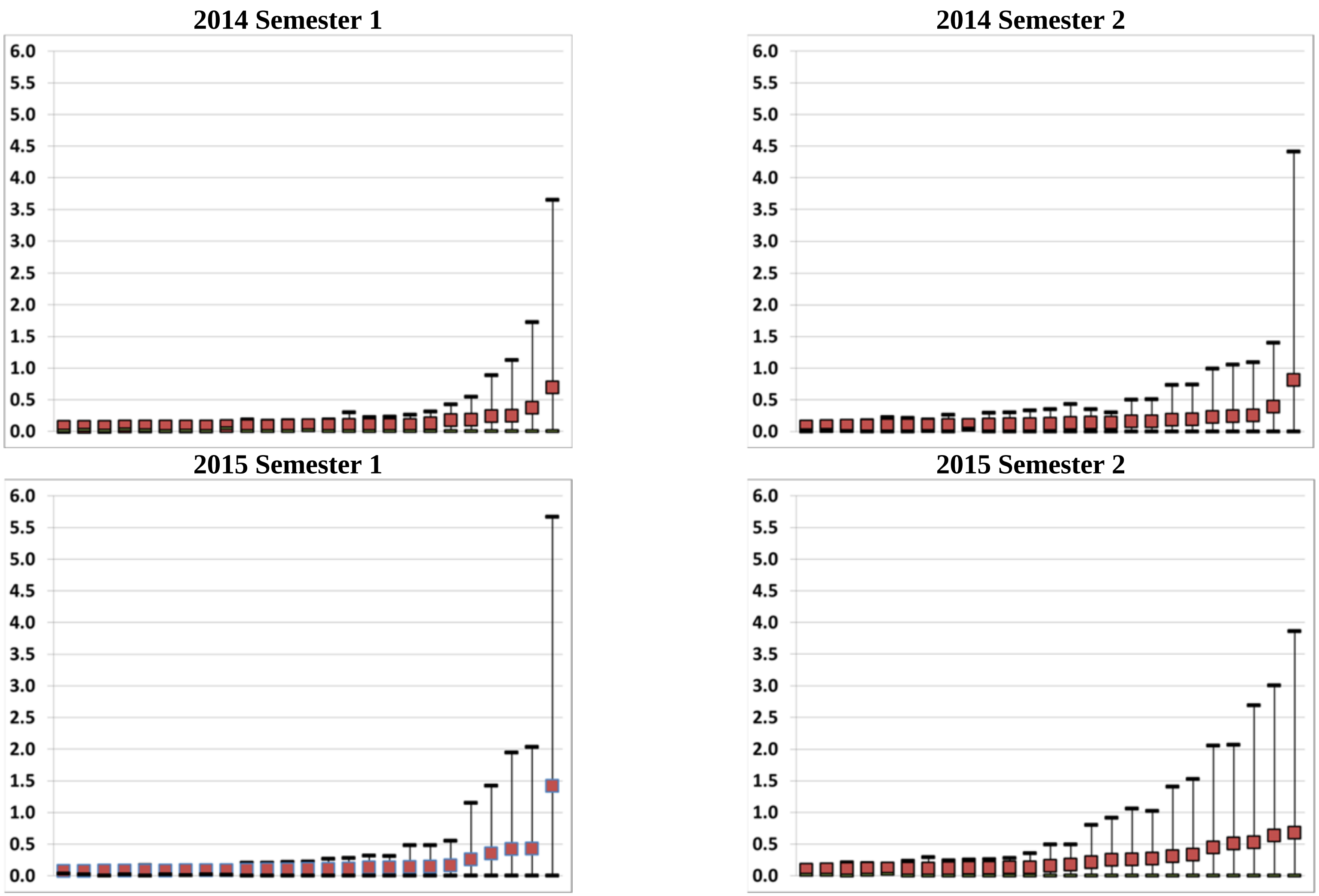
See notes in Figure 4.2.

Figure 4.3 Water System A: Comparison of turbidity in NTU at Total Coliform Rule sites



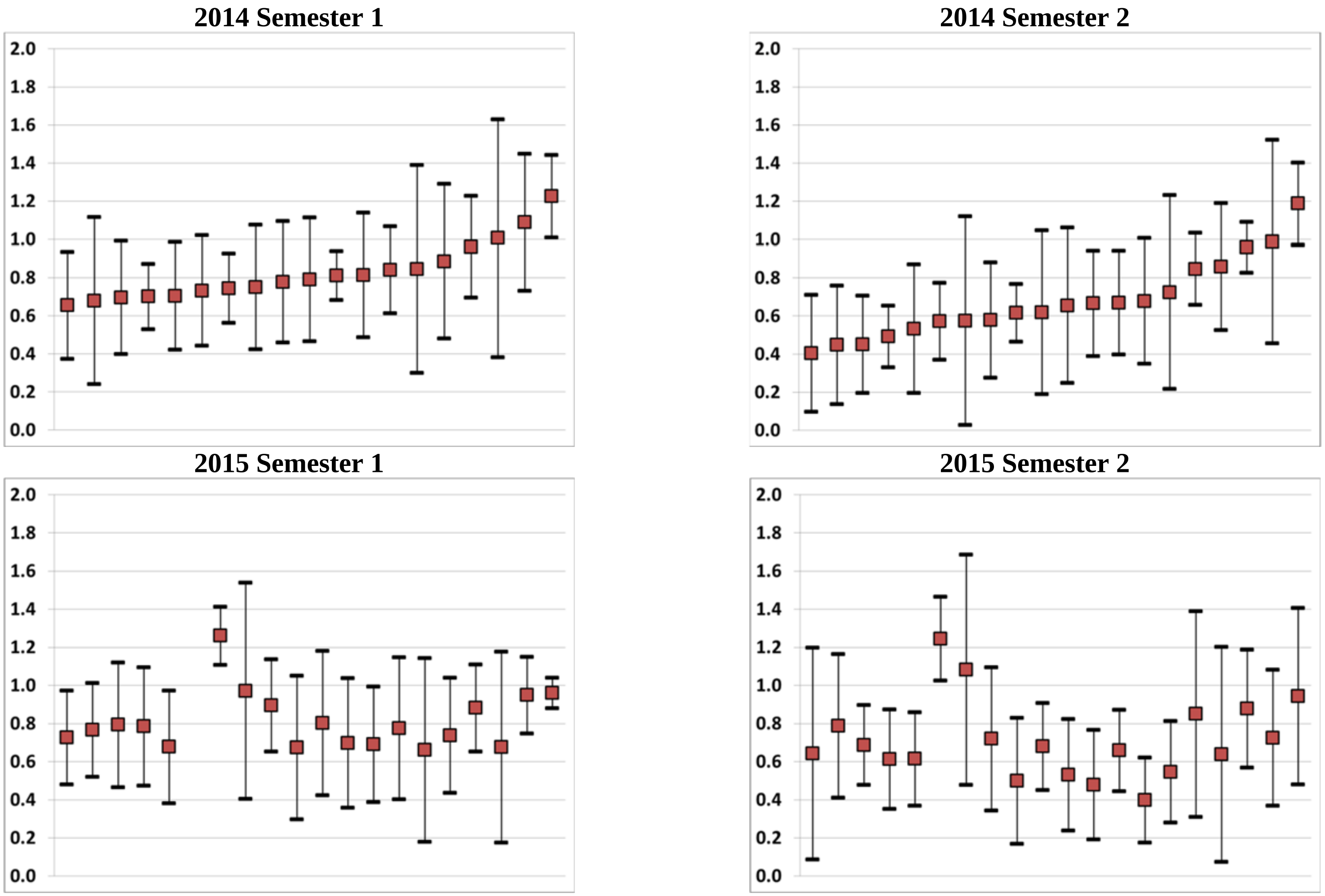
See notes in Figure 4.2.

Figure 4.4 Water System B: Comparison of total chlorine in mg/L at Total Coliform Rule sites



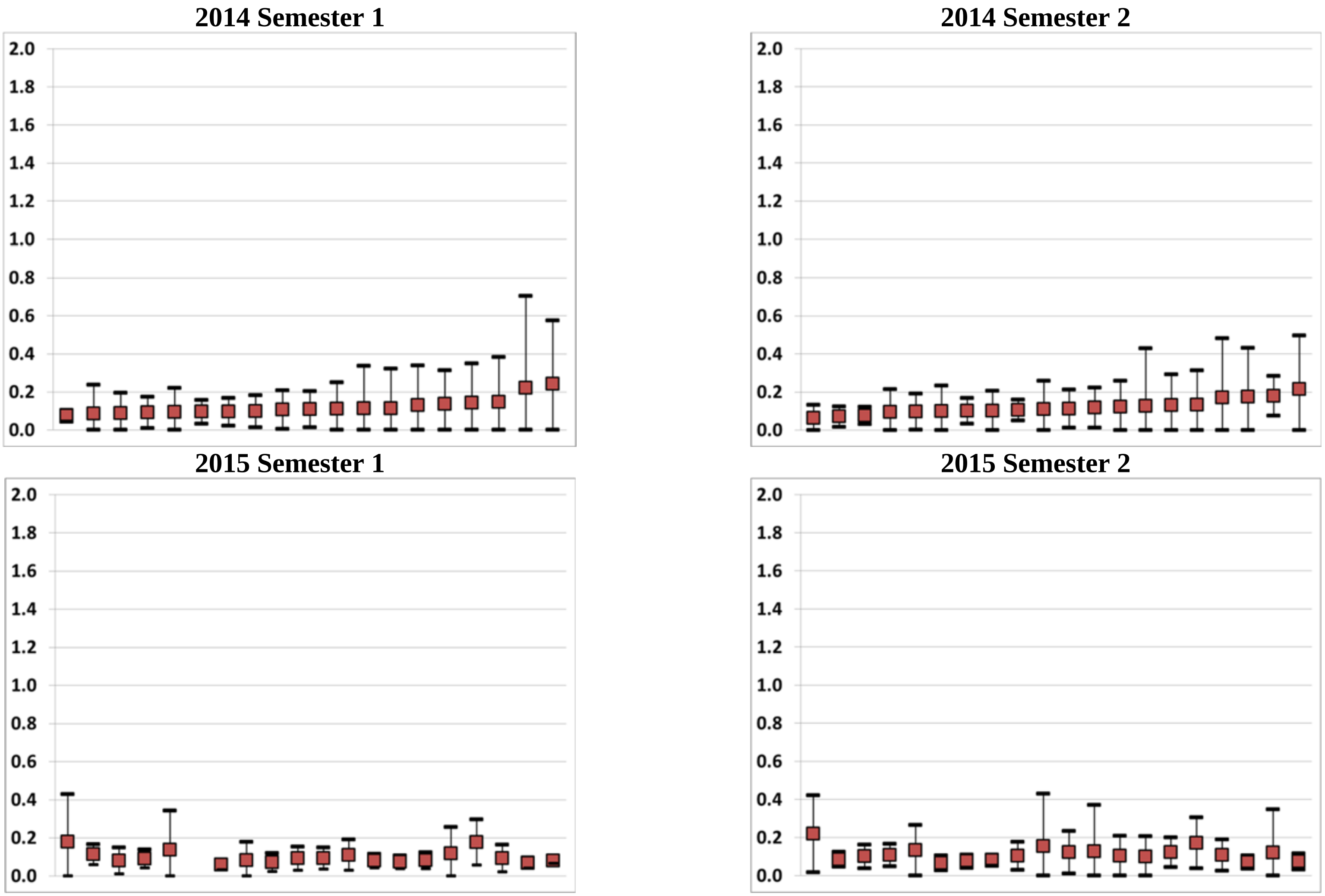
See notes in Figure 4.2.

Figure 4.5 Water System B: Comparison of turbidity in NTU at Total Coliform Rule sites



See notes in Figure 4.2.

Figure 4.6 Water System C: Comparison of total chlorine in mg/L at Total Coliform Rule sites



2014 Semester 1

2014 Semester 2

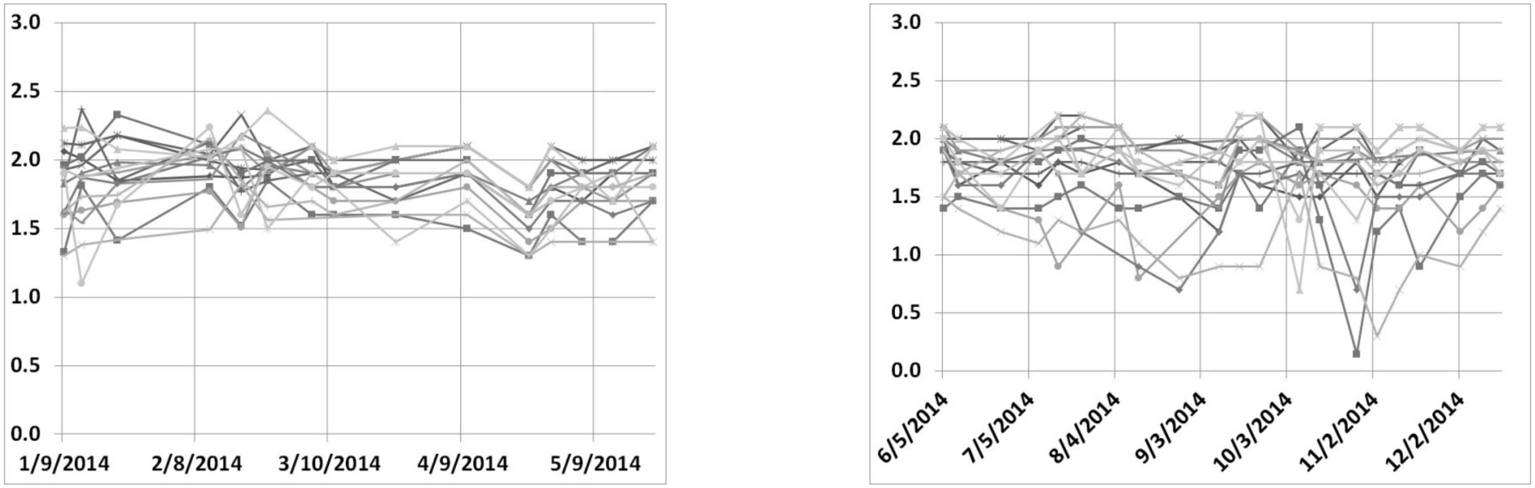
2015 Semester 1

2015 Semester 2

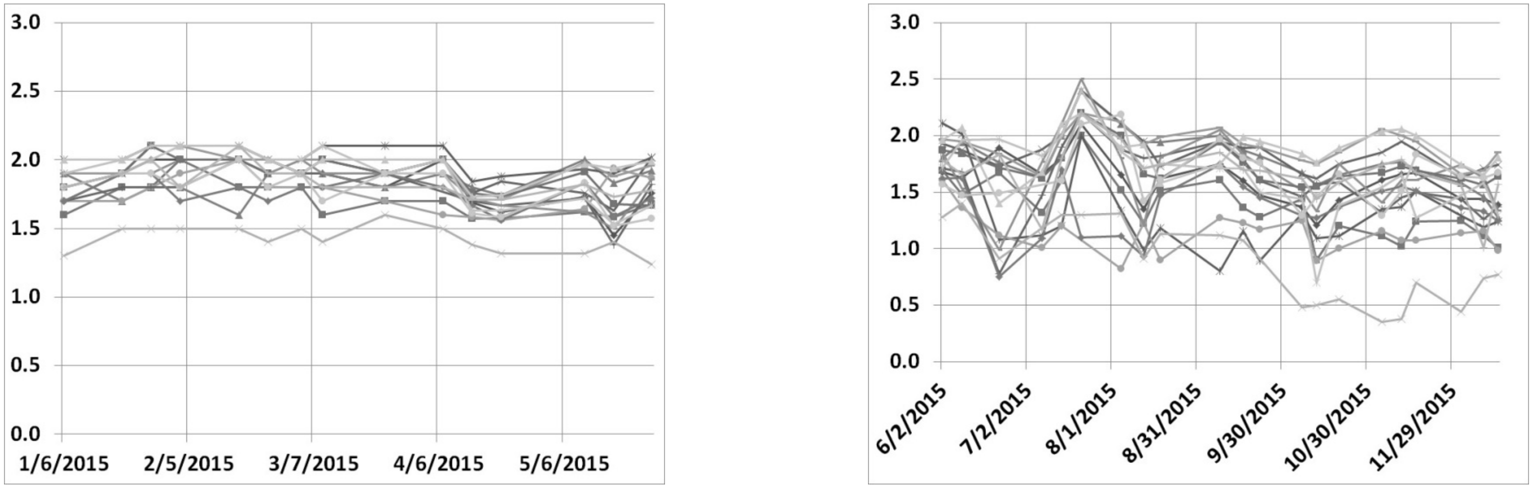
See notes in Figure 4.2.

Figure 4.7 Water System C: Comparison of turbidity in NTU at Total Coliform Rule sites

2014 Semester 1 | 2014 Semester 2

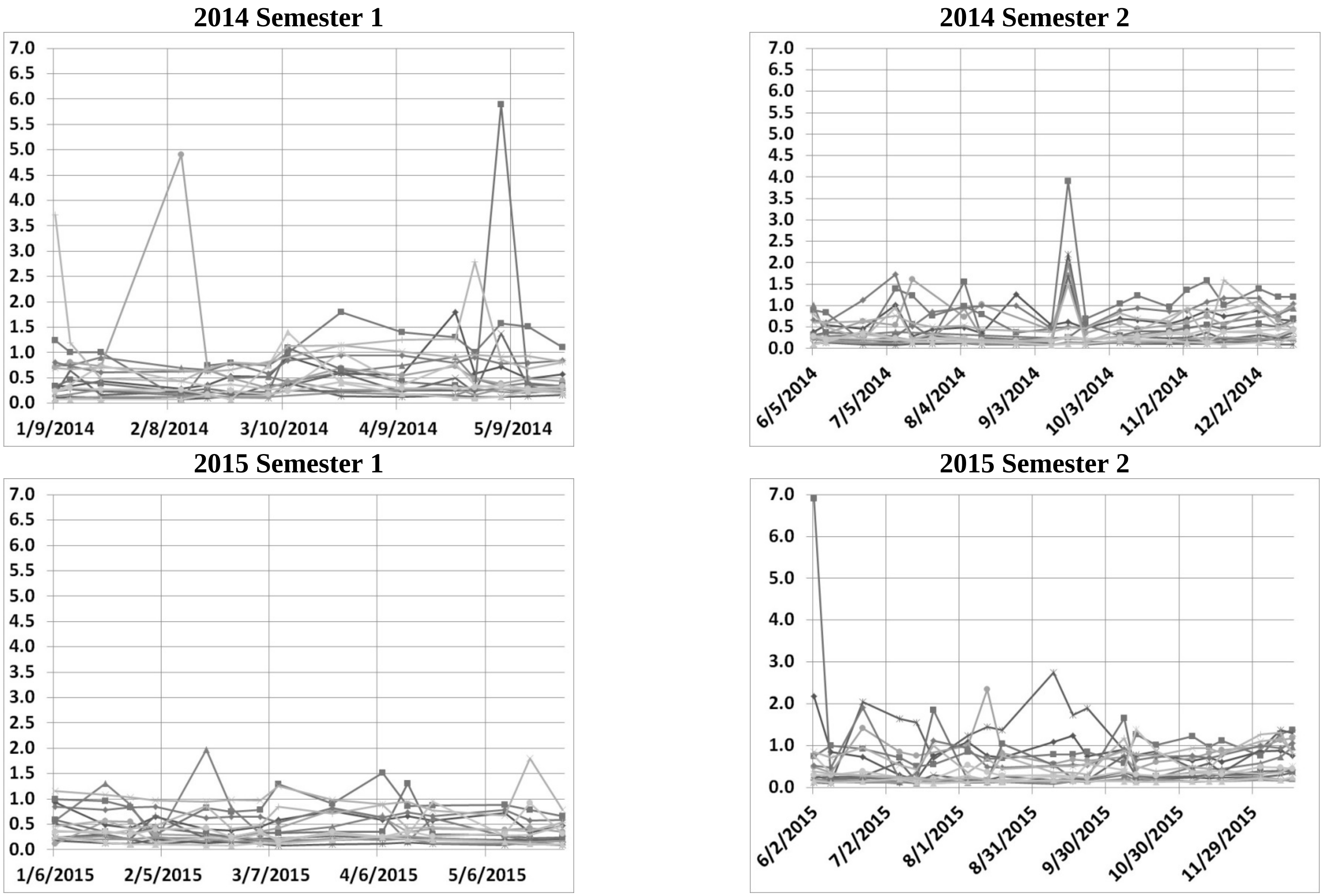


2015 Semester 1 | 2015 Semester 2



Each line represents data from a sampling site over time. Sampling sites are not identified here.
These graphs show whether or not there is overall conformity to the water quality trend in the water system.

Figure 4.8 Water System A: Comparison of total chlorine in mg/L at Total Coliform Rule sites over time



2014 Semester 1

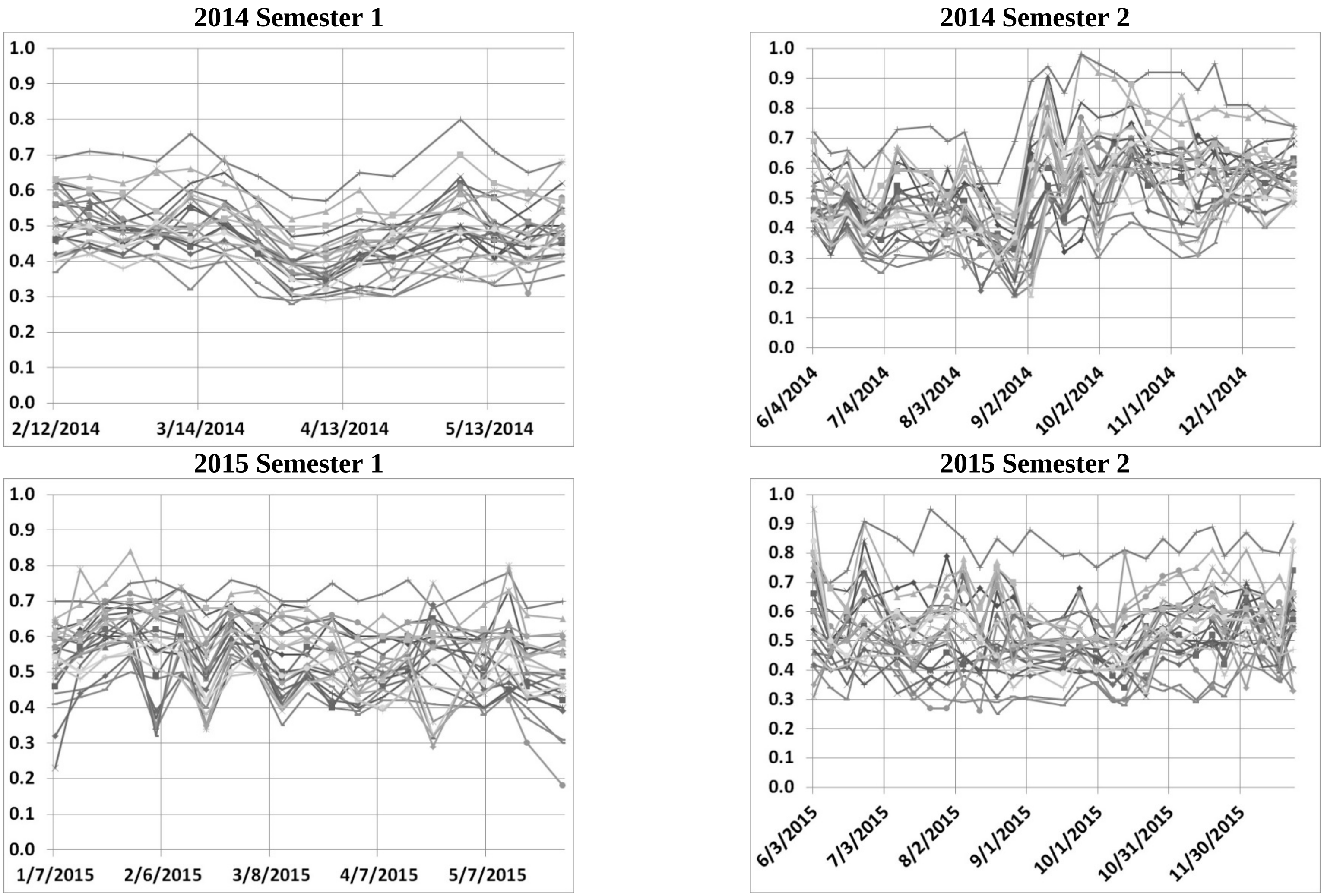
2014 Semester 2

2015 Semester 1

2015 Semester 2

See notes in Figure 4.8.

Figure 4.9 Water System A: Comparison of turbidity in NTU at Total Coliform Rule sites over time


2014 Semester 1

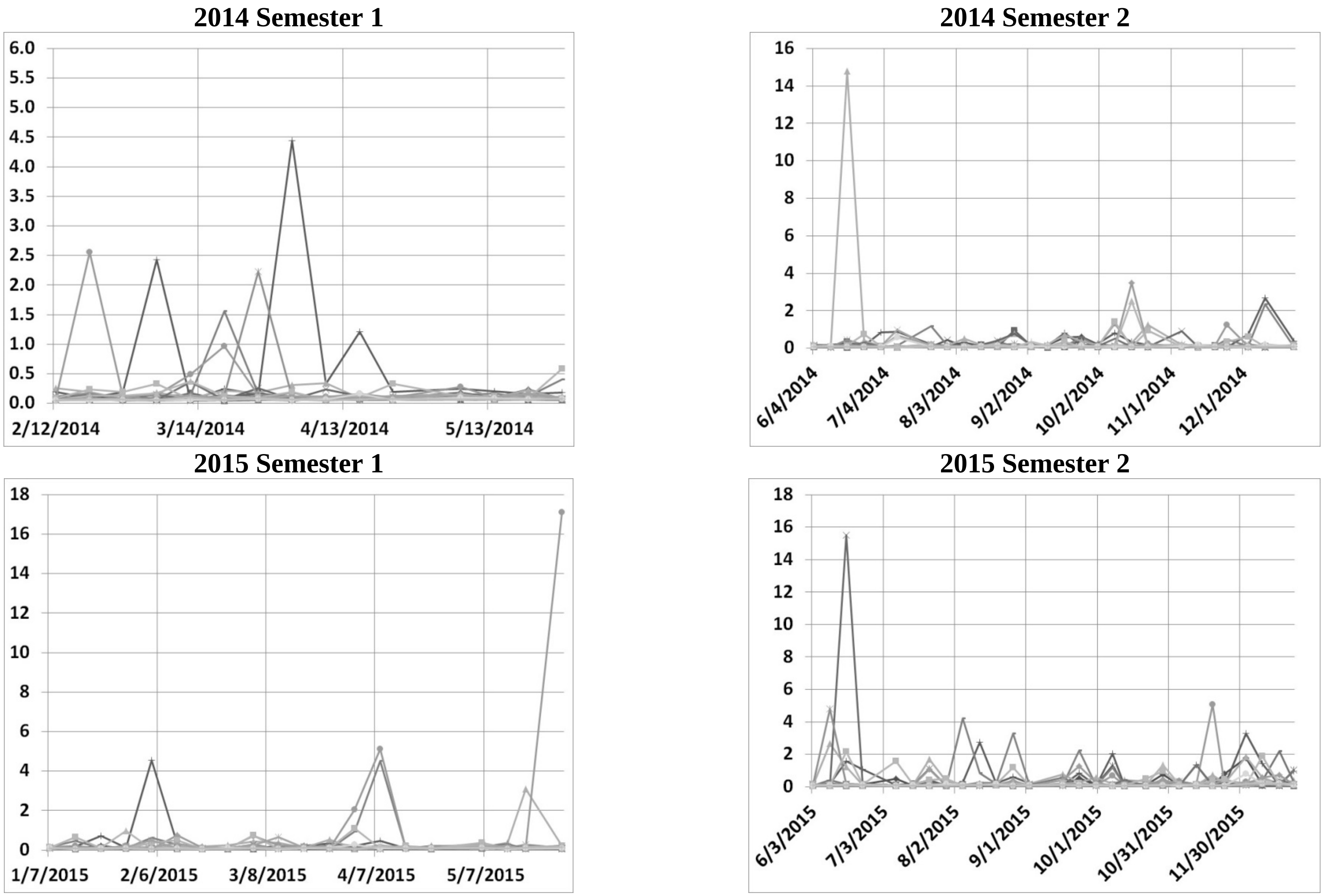
2014 Semester 2

2015 Semester 1

2015 Semester 2

See notes in Figure 4.8.

Figure 4.10 Water System B: Comparison of total chlorine in mg/L at Total Coliform Rule sites over time



2014 Semester 1

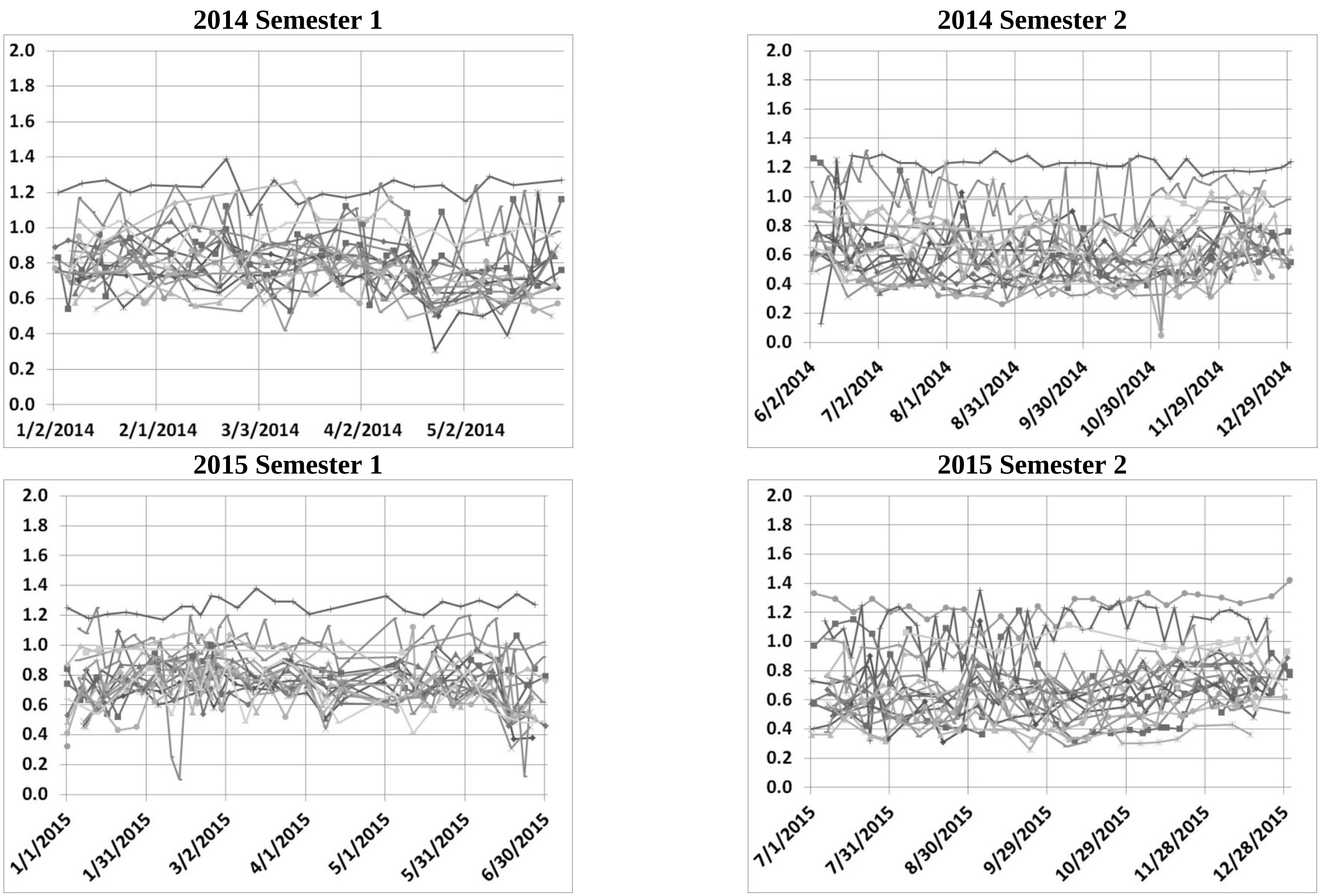
2014 Semester 2

2015 Semester 1

2015 Semester 2

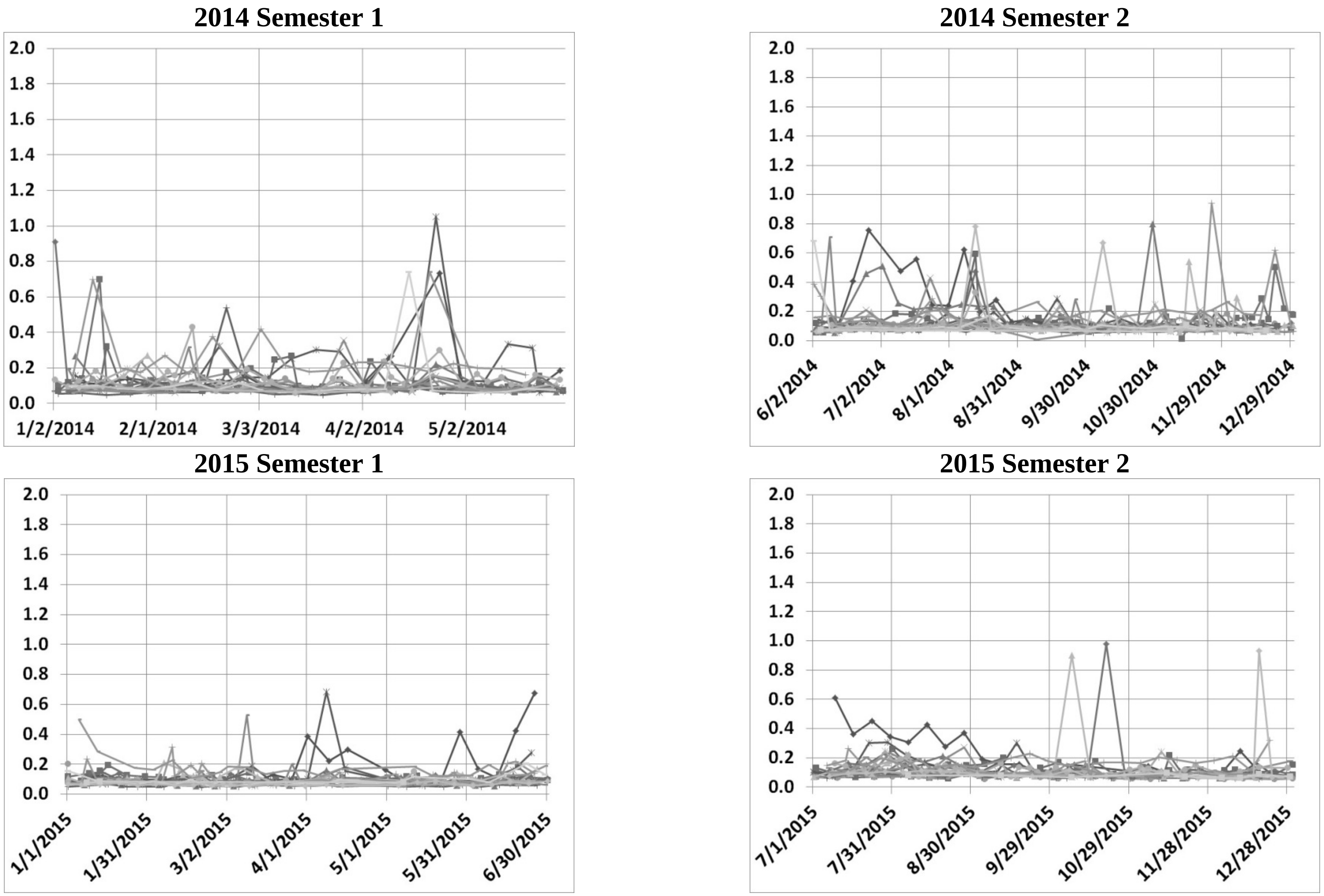
See notes in Figure 4.8.

Figure 4.11 Water System B: Comparison of turbidity in NTU at Total Coliform Rule sites over time



See notes in Figure 4.8.

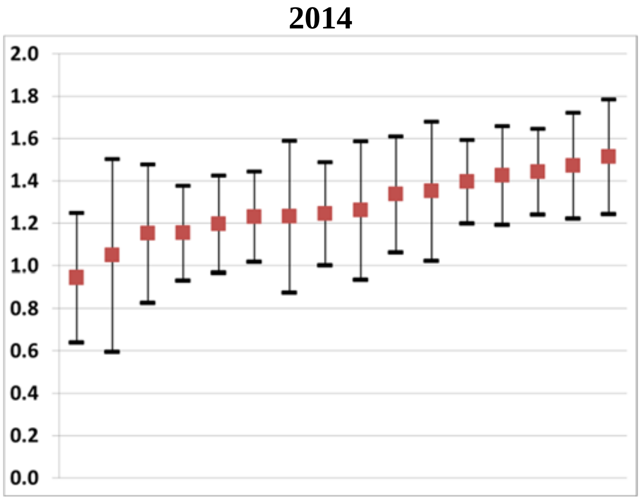
Figure 4.12 Water System C: Comparison of total chlorine in mg/L at Total Coliform Rule sites over time



See notes in Figure 4.8.

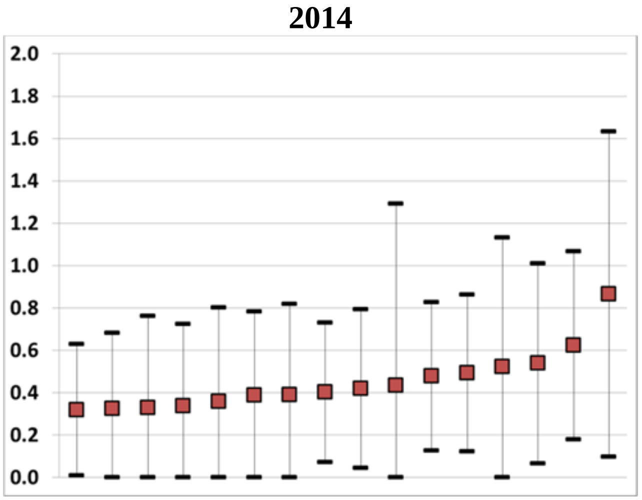
In this system, there was a question about consistent sampling protocol where spikes may represent less flushing before taking the sample.

Figure 4.13 Water System C: Comparison of turbidity in NTU at Total Coliform Rule sites over time



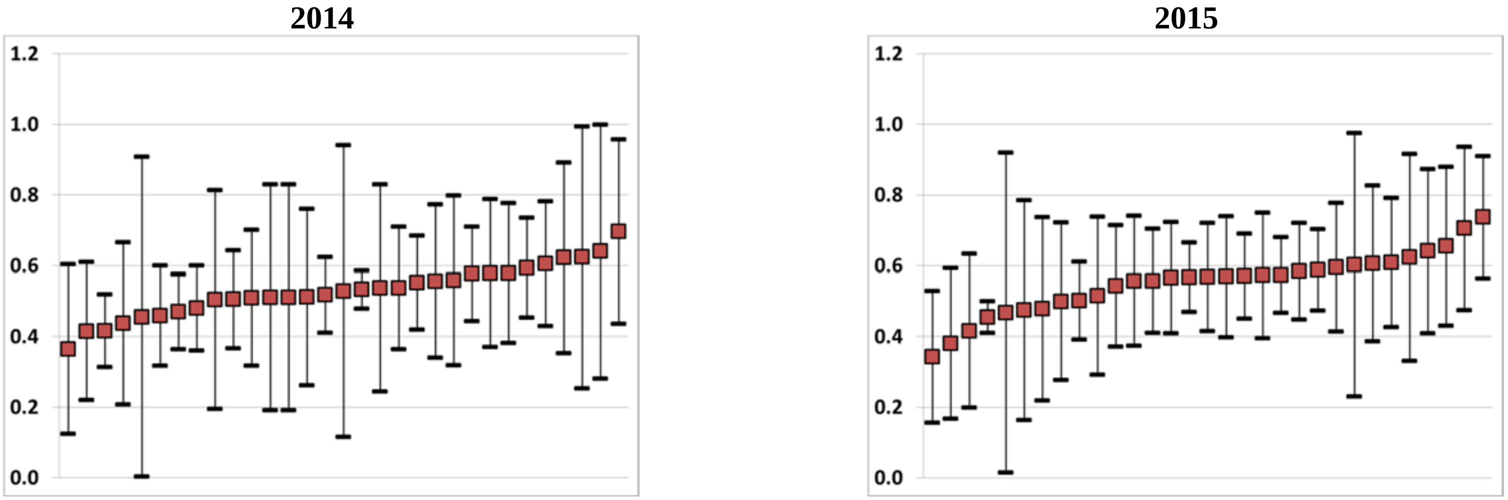
See notes in Figure 4.2.

Figure 4.14 Water System I: Comparison of total chlorine in mg/L at Total Coliform Rule sites



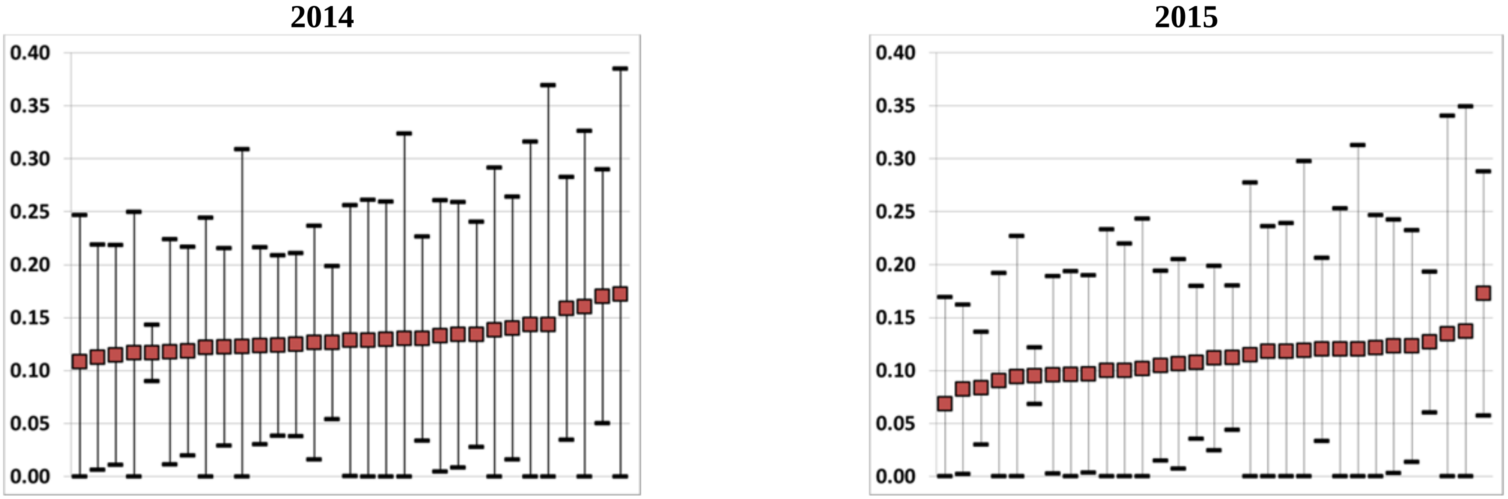
See notes in Figure 4.2.

Figure 4.15 Water System I: Comparison of turbidity in NTU at Total Coliform Rule sites



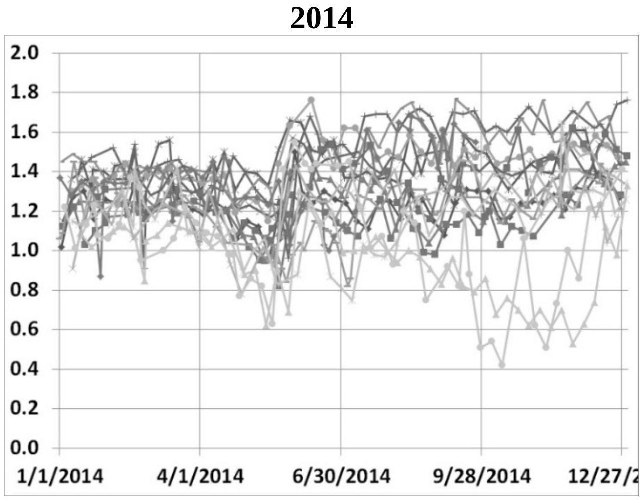
See notes in Figure 4.2.

Figure 4.16 Water System L: Comparison of total chlorine in mg/L at Total Coliform Rule sites



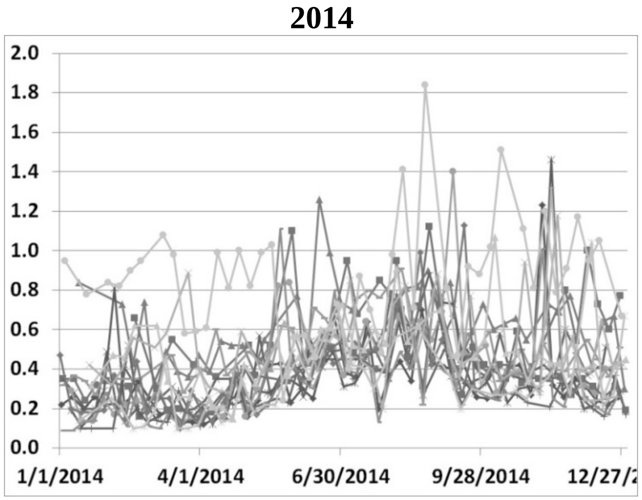
See notes in Figure 4.2.

Figure 4.17 Water System L: Comparison of turbidity in NTU at Total Coliform Rule sites



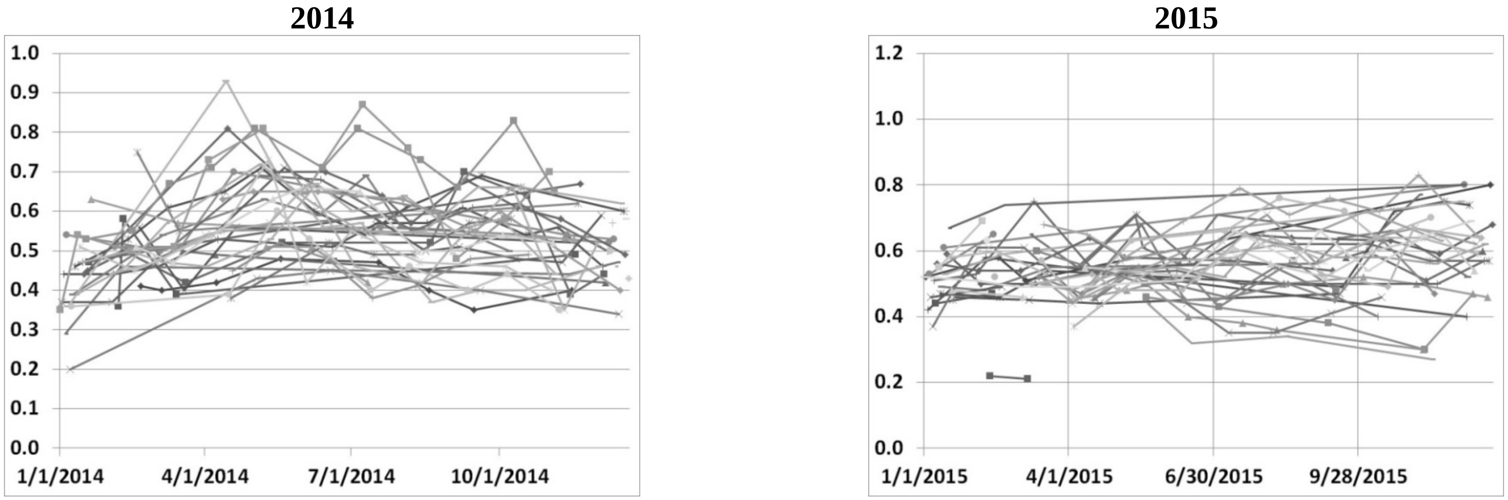
See notes in Figure 4.8.

Figure 4.18 Water System I: Comparison of total chlorine in mg/L at Total Coliform Rule sites



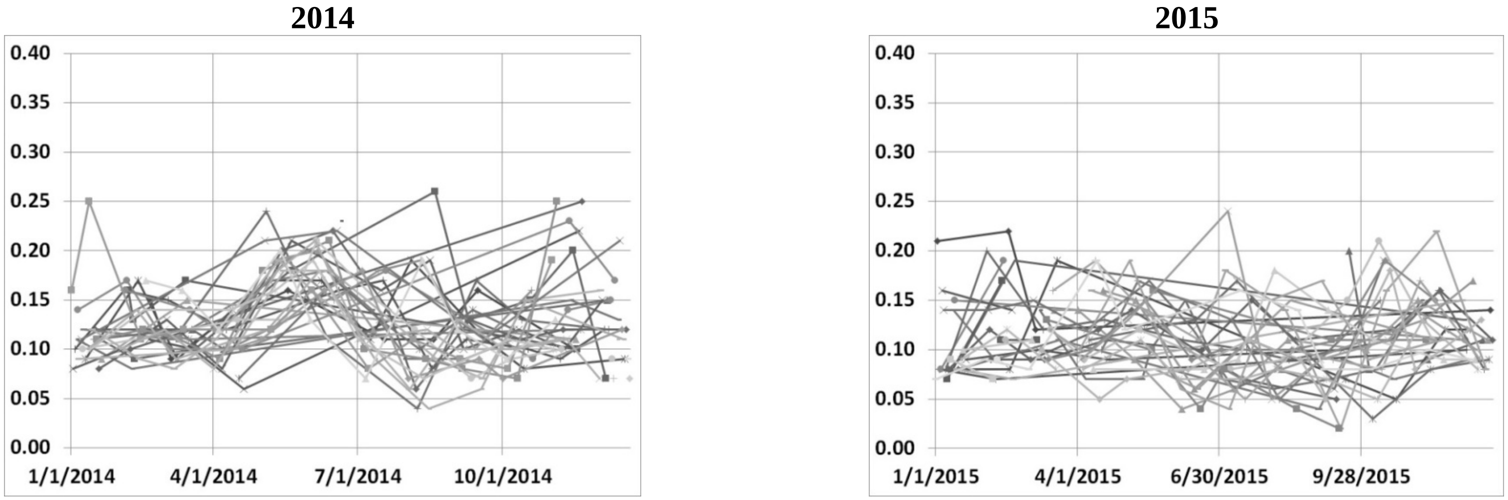
See notes in Figure 4.8.

Figure 4.19 Water System I: Comparison of turbidity in NTU at Total Coliform Rule sites over time



See notes in Figure 4.8.

Figure 4.20 Water System L: Comparison of total chlorine in mg/L at Total Coliform Rule sites over time



See notes in Figure 4.8.

Figure 4.21 Water System L: Comparison of turbidity in NTU at Total Coliform Rule sites over time

CHAPTER 5
DISTRIBUTION SYSTEM MONITORING TECHNIQUE

Now that the existing background information for the participating water utilities have been described in Chapters 2 to 4, the distribution system monitoring data gathered during this project will be discussed in Chapters 6 to 11.

This chapter describes how distribution system monitoring data were obtained and assessed.

DISTRIBUTION SYSTEM SAMPLING STRATEGIES

Sample Everywhere

Monitoring in a distribution system to assess a water system's potential for transferring lead and copper from metal components into the drinking water has always been fraught with dilemmas. Lead and copper release into the water varies over location in the distribution system and over time. Water utility personnel cannot visit every faucet in every building to sample and certainly cannot do that routinely.

Sample Critical Buildings

This is the reason that the EPA developed the strategy described for compliance sampling in the Lead and Copper Rule. Sampling sites are selected from residences most prone to have high lead levels such as the ones with lead service lines and ones with lead solder in copper piping. The number of sites for a utility is based on utility size. Compliance is based on comparing the 90th percentile concentration in the sample dataset to a regulatory Action Level that triggers action to modify the water or the system in order to lower lead and copper levels.

While this is a satisfactory strategy, there are issues with the technique. As discussed in Chapter 3 on residential profile sampling, the technique may not capture the highest lead or copper levels in a building. Most importantly, it is very difficult for water utility personnel to enter buildings to obtain samples. Property owners also tire of the sampling regime. For this reason, sampling can only be performed infrequently.

As data for analysis, lead and copper data from various buildings in a water system are challenging. It is difficult to justify comparing metals concentrations from endless variations of piping configuration, water usage, and water flow scenarios.

Even with these drawbacks, lead and copper data from critical sites in a distribution system can add to an understanding of lead and copper release in a water system. In Chapter 2, Lead and Copper Rule first-draw stagnation compliance data from critical residences were used to pinpoint time periods when major changes in water quality may have corresponded with operational changes. In Chapter 3, stagnation profile sampling of residences with lead service lines gave insight into the lead and copper contributions of various piping materials and to the effectiveness of phosphate corrosion control chemicals at specific locations.

Sample a Network of Sites over the Distribution System

The third strategy is to sample a network of sites geographically scattered around the distribution system. However, entering private property at routine intervals and working with a variety of sampling scenarios are still issues with this strategy.

In Chapter 4, a network of sites was used by measuring two flowing water quality parameters as indicators of water quality status. It was not possible to collect lead and copper stagnation concentrations at those sites, but a general indication of debris and microbiological activity at those sites was possible. This made it possible to pinpoint areas of the distribution system that had higher potential for a water quality issue, including lead and copper release, to occur.

Sample for the Extreme Scenarios

Another strategy defines the best and worst water quality scenarios in a distribution system in order to define the minimum and maximum lead and copper release in a water system. With this strategy, the water quality characteristics of a distribution system can be bracketed between two extremes – between the characteristics of the freshest water and the characteristics of the oldest water, that is, the water that has resided in the water system the longest time.

On one extreme, the freshest water with the highest concentrations of treatment chemicals can be found at the entry points to the distribution system. The effectiveness of the treatment chemicals is assumed to be at a maximum at these points. (Some water systems have only one entry point to the water distribution system; this is common for a surface water system with one treatment facility. Other water systems, such as ground water systems with multiple wells, can have many entry points.)

The opposite extreme of water quality parameters to the entry point of a distribution system are locations of high water age in the distribution system. Water age is another term for residence time of water. High water age locations occur at the farthest reaches of a distribution system, at dead ends, and in areas of low water usage. As water age increases, both added and naturally-occurring chemicals in the water have more time to interact chemically and microbiologically.

Other severe conditions in water distribution systems can also be good strategic choices to contrast with fresh water sites. Some of these sites occur where different water qualities blend together. This would be the case in a system with multiple water sources, such as in systems with multiple wells or in systems where groundwater supplements a surface water source. At these locations, water quality varies with multiple sources. The water quality swings can cause destabilizing conditions to existing chemical equilibriums and to existing pipe wall scales. These swings, in turn, can impact corrosion and metals release.

Areas of high release of metals in a distribution system may also be related to the age of the buildings in a neighborhood and the types of plumbing materials prevalent at the time the neighborhood was constructed. An inventory of system piping materials and age may provide better insight into selection of monitoring locations.

Customer complaints of discolored water, bad taste, or bad odor can additionally identify locations in the distribution system where corrosion of metals along with other water quality issues may be occurring. Such locations, especially if geographical patterns of complaints are evident, should also be considered when selecting critical sampling sites for routine monitoring.

Combining Strategies

A combination of strategies can be used for the routine tracking of lead and copper release directly or indirectly. The strategies are:

- Capture water quality at a subset of critical buildings in the distribution system
- Capture water quality in a network of sampling sites around the distribution system
- Capture water quality at the extremes of the distribution system

The combination strategy was demonstrated for this project with residential profile sampling, tracking of disinfection concentration and turbidity at Total Coliform Rule distribution system compliance sampling sites, and the use of a special monitoring station located at a high water age location. The high water age location sampling will be discussed after describing more fundamental concepts of monitoring in distribution systems.

TYPES OF WATER SAMPLES

Batch Reactors

After a sampling site selection strategy has been chosen, it must be determined whether flowing water or stagnating water should be captured for analysis. To understand when each type of sample is used, consider the brewing of beer as a frame of reference. To make beer, fresh ingredients with known characteristics are poured into a vat and then allowed to undergo chemical and microbiological changes for a period of time. At the end of the reaction period, the final product is withdrawn and analyzed to determine if the desired characteristics have been achieved. The brewing of beer is a batch process and the vat that holds the ingredients during the process is called a batch reactor.

Water pipes are also batch reactors. Fresh water flows into the pipe. Chemical and microbiological interactions occur during the time that the water is in the pipe. The water in the pipe can be withdrawn after a reaction period and analyzed to determine the outcome of the reactions. Examples of reaction outcomes in water are concentrations of lead, copper, and other metals and population of microorganisms.

Consumers of water in a system do not typically receive water fresh from a well or treatment plant. They receive water after varying degrees of chemical and microbiological interactions have occurred in the piping of the water distribution system and in their buildings. Therefore, the batch reactor concept aids in studying the water quality that the consumer receives.

Stagnating Water Samples

Buildings

Buildings connected to water systems are batch reactors. Fresh water flows in from a water main and then undergoes changes based on piping materials, residence time in pipes and tanks, flowrates, and quantity of water used. The Lead and Copper Rule uses residences with lead service lines or lead solder as the batch reactors in its sampling strategy. The Rule prescribes a minimum of six hours of reaction time, that is, six hours of water stagnating in the piping.

Pipe Loops

Given the problems already discussed with sampling from privately-owned buildings, an apparatus was devised to simulate a building piping system. It was called a "pipe loop apparatus" developed by the AWWA Research Foundation (AwwaRF, now renamed as the Water Research Foundation) in anticipation of the 1991 Lead and Copper Rule (EES 1990). The original apparatus consisted of one or more lengths of lead or copper pipe, each pipe able to hold at least one liter of water so that a one liter sample, similar to the Lead and Copper Rule residential compliance sample volume, could be obtained. The pipes were attached to non-reactive plastic pipe that connected to fresh distribution system water. Flow meters controlled the flow to each pipe. Water flowed from the distribution system, through the pipes and to waste, as occurs in building plumbing. The water flowing from the distribution system was controlled by a programmable timer opening and closing a valve to turn water on and off similar to the water usage pattern in a building.

The timer also allowed for a period of stagnation as described for reaction time in batch reactors. Because the Lead and Copper Rule calls for a minimum of six hours stagnation in residential plumbing before sampling, six hours became a common stagnation time used before sampling a pipe loop apparatus.

The original AwwaRF pipe loop apparatus was only used for corrosion control treatment chemical comparisons of entry point water; it was not used for routine monitoring of water quality at various locations around a distribution system. But even if it would have been used for distribution system monitoring, it would have been very awkward to place out in the water system because of its size.

Mini-Pipe Loops

Mini-pipe loops were developed to utilize the AwwaRF pipe loop concept as a means to monitor around a water distribution system (Cantor et al. 2000). They were originally constructed in 1996 at one-quarter the size of a standard pipe loop and skid-mounted. While the full-size apparatus might take up a large area at a water treatment plant, the mini-pipe loops were portable to about a 3 foot by 5 foot floor space in the distribution system. Copper mini-pipe loops were first used to place around a distribution system to monitor system water for effects of an added chemical (polyphosphate) that was thought to be increasing the copper levels in the water (Cantor et al. 2000). See Figure 5.1. This strategy successfully identified the chemical as the major influence of the copper problem and also identified when residences could be re-sampled to show lower copper concentrations after removal of the chemical. In 1999, mini-pipe loops were constructed for a research project to test the effects of chlorine addition on corrosion (Cantor et al. 2003a). See Figure 5.2. Three metals and three chemical treatments were studied using nine pipe loops. The complete apparatus fit into the corner of a small well house.

Source: Courtesy of Process Research Solutions, LLC of Madison, WI.
Figure 5.1 Mini-pipe loop used as a distribution system monitoring station in 1996

Source: Courtesy of Process Research Solutions, LLC of Madison, WI.
Figure 5.2 Mini-pipe loops of three metals for chemical treatment comparison in 1999

PRS Monitoring Stations

After the experiences with the mini-pipe loops, it became obvious that a distribution system monitoring station used as a routine gauge of water quality adds much insight into lead and copper and other metals release into water during routine water system operations and during system operational changes. Based on these experiences, criteria for an ideal distribution system monitoring station were developed. They were:

- Is relatively inexpensive
- Is easy to move from location to location
- Does not take up excessive space
- Is cushioned and isolated from vibrations that can interfere with pipe accumulation release
- Is straightforward to operate
- Can be used for either off-line chemical treatment comparison tests OR as a gauge of water quality around a distribution system
- Allows for routine collection of water samples
- Is easily accessible to water utility staff
- Has a uniform configuration
- Has uniform water flow rate and water usage
- Has a steady pressure
- Is capable of water stagnation for a uniform time
- Captures routine operation of the water system as well as treatment and operational changes that may occur over time
- Captures the interaction of pipe scales and films with the water
- Makes pipe film and scale analysis possible and economical so that the young scales developed during the monitoring period can be compared to older existing scales on actual water system pipe
- Does not destroy pipe film and scale during the metal sample preparation

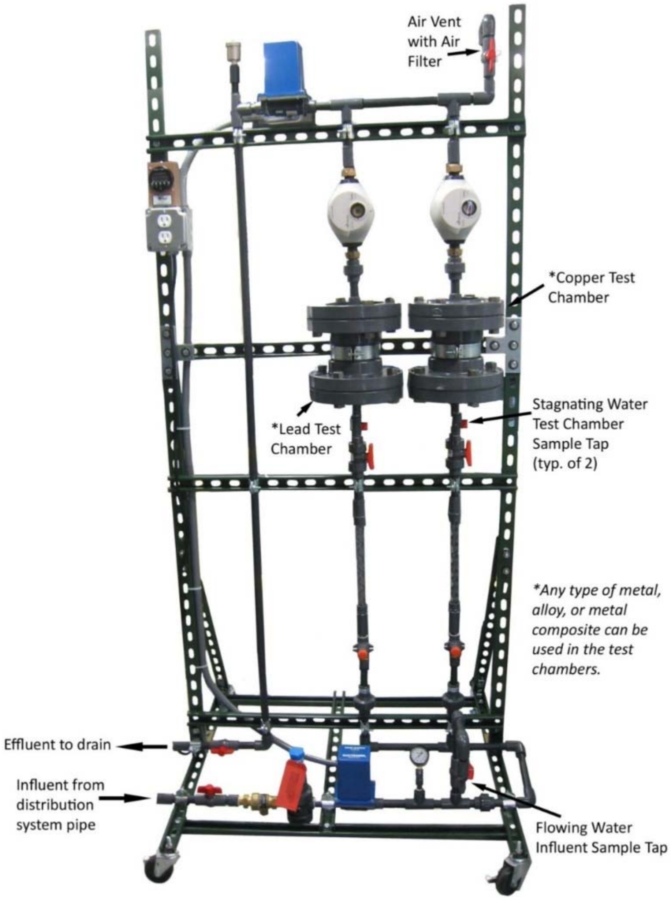
To meet these criteria, the mini-pipe loops were modified, in 2006, into the Process Research Solutions (PRS) Monitoring Station (Cantor 2009). See Figure 5.3. Instead of a piece of coiled pipe, stacks of metal plates that are secured in a section of larger plastic pipe are exposed to system water. The surface area of the metal plates to the volume of water held in the test chamber is similar to a 1.77-inch diameter pipe used as a pipe loop. This equivalent diameter pipe was the most economically and physically practical to achieve. See Figure 5.4 to view the metal plates stacked inside the test chambers before the chambers are sealed.

The PRS Monitoring Station is operated in the same way that standard or mini-pipe loops are operated. A timer controls the flow of water through the device as well as the time of stagnation. First-draw water samples are taken from the test chambers at the end of a prescribed stagnation period, collecting water that has been exposed to the metal surfaces.

These stations were used in eight water systems in this project to track the response of lead and copper material to the system water over time. Each monitoring station was placed at a high water age location to gauge an extreme scenario of lead and copper release in each water system.

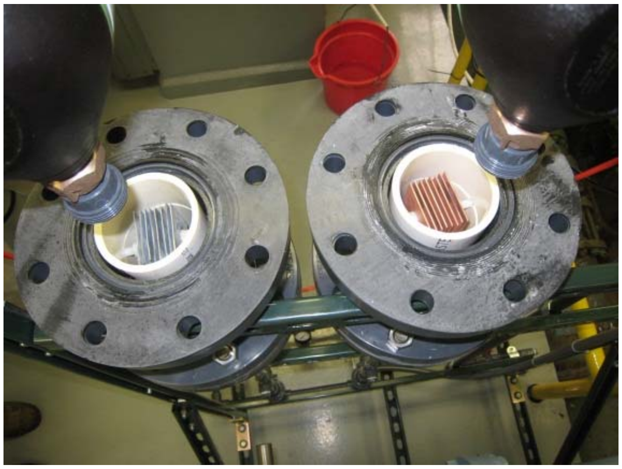
Flowing Water Samples

As in the beer-making analogy, the characteristics of the water flowing into the batch reactor are desired as well. With the PRS Monitoring Station test chambers acting as the “batch reactors” in this monitoring project, the associated flowing influent water samples characterized the “fresh ingredients” sent into the batch reactors. The samples were obtained from the influent sample tap on each monitoring station while water was flowing.



Source: Courtesy of Process Research Solutions, LLC of Madison, WI.

Figure 5.3 The PRS monitoring station, a standardized distribution system monitoring station



Source: Courtesy of Process Research Solutions, LLC of Madison, WI.

Figure 5.4 View of plates set inside and stacked in open test chambers in a PRS monitoring station

In addition, to contrast the high water age flowing water, flowing water samples from the entry points to the distribution systems were also obtained at the same frequency to characterize the "freshest" water in the system.

THE METAL SURFACE DILEMMA

In water distribution systems, all piping, whether in the distribution system or in the building piping, have varying degrees of existing chemical scales and biofilms that have built up over time. This is because all water is a complex solution of many naturally-occurring and added chemicals and a naturally-occurring potpourri of soil and air-borne microorganisms. Chemical scales precipitate onto the pipe walls over time; they are intertwined by biofilm development from microorganisms as the water environment allows. It is the interaction of the pipe wall debris with the adjacent water that shapes water quality, including lead and copper release.

To represent actual system pipes, the original AwwaRF pipe loop apparatus was intended to hold old lead pipes harvested from the distribution system and carrying decades of chemical scales and biofilms on their surfaces. This is good in theory; however, experimental dilemmas arose. When old pipes harvested from water distribution systems were used, there was no control over how representative each harvested pipe may or may not have been in the distribution system. In addition, metal particulates from the debris on the old pipe walls would be disturbed and interfere with the metal concentration data for a long period of time (AwwaRF and DVGW 1996).

Having new metal surfaces is equally problematic in that lead and copper transfer from the new metal surfaces is higher than after metal oxide and carbonate scales develop. The PRS Monitoring Station begins with new metal surfaces on the internal metal plates. The metal release from the plates is often high at first. To eliminate this unrepresentative data, monitoring of metal release in the test chambers typically is not begun until a month after the station is operating. Every water system is different as to how long it takes for lead and copper concentrations to stabilize.

However, an advantage of the PRS Monitoring Station over new metal in a pipe loop apparatus is that all the metal surfaces are in a configuration of a 2 inch by 2 inch by 1/16th inch thick metal plates. These metal squares are removed from the test chambers at the end of a monitoring project period and sent for both microbiological and chemical analysis. These are the same types of analyses performed on pipes harvested from distribution systems, but harvested pipes must be cut open in order to study their accumulations. The cutting operation can contaminate the surfaces to be studied. With the PRS Monitoring Station metal plates, they need no further processing before study. In this way, test chamber metal plates are studied and the chemical scales and biofilms are characterized. The metal plate scales have not had as much time to form as the scales on existing piping. When there have been opportunities to compare them with scales on existing piping, there are similarities but some of the compounds are farther away from their thermodynamically stable forms. The younger scales show the direction that the scales are heading and how fast they are aging. They also show similar extraneous elements and minerals as existing piping scales. And they show how phosphorus, when dosed into the water, is interacting with lead and copper.

To analyze the chemical scales on the metal plates, the scales are photographed and layers of scales visually identified. The following techniques are used to characterize the chemical scales on the metal surfaces:

- X-ray diffraction (XRD) determines the major compounds (minerals) on the metal surface

- X-ray fluorescence (XRF) or Energy Dispersive Spectroscopy (EDS) determines the bulk chemistry of the scale layers.
- Scanning electron microscopy (SEM) visually identifies crystal forms of compounds as well as detailed chemistry of a more localized area. The chemical composition found by SEM might not match that found by XRF/EDS because of the localized nature of the analysis.

The difference between these younger scales and mature scales that might exist in the distribution system are described by the scales' distance from the stable forms of lead and copper compounds as determined by a thermodynamic equilibrium state. Typical copper scales form in order of quick-forming and less stable compounds to slower-forming and more stable ones (closer to equilibrium). For cold water, cuprite (a type of copper oxide) forms first, then malachite (a copper carbonate) forms if alkalinity is high enough. Found mostly in hot water, tenorite (a copper oxide at a more stable higher oxidation state than cuprite) can form.

For lead scales, the succession is: litharge (a lead oxide), then lead carbonates such as cerrusite and hydrocerrusite, and then pyromorphite (a lead phosphate, if phosphate ions are available) and/or plattnerite (a lead oxide at a higher oxidation state if occurring).

Test chamber metal plates are studied microbiologically by means of submerging them in a lysing agent to release the biofilms. The cleaned metal plates are removed from the lysing agent and the final lysing solution analyzed for adenosine triphosphate (ATP), a measure of microbiological population. The result is reported in microbiological population per area of plate. This quantifies the degree to which biofilm has formed on the plates. It is especially informative in comparing the biofilm populations from plates of different metal types and different water systems. It is also informative in comparing the microbiological population in the water adjacent to the plates as a means to gauge the tendency of the microorganisms to stay on the plates in biofilms versus becoming entrained in the water.

With this chemical and microbiological knowledge of the scales and films developed during the monitoring period, factors shaping the water quality can be compared to the water quality data for more insight.

WATER QUALITY PARAMETERS

In flowing and stagnating water samples, various water quality parameters were measured based on a comprehensive strategy. That is, there can be many factors at work alone or simultaneously that cause the increase of lead or copper concentrations in the drinking water. Not knowing what nuances controlled the lead and copper concentrations in any given water system, quite a number of water quality parameters were measured in this project to determine if they either might influence the lead and copper concentrations or if they might be affected by the same factors controlling lead and copper.

The water quality parameters were organized into three main categories:

- Parameters involved in uniform corrosion of metals
- Parameters involved in the biostability of water
- Parameters involved in pipe wall scale formation or dissolution

Several water quality parameters can fall into more than one of these categories.

These categories were selected from studying accumulations on PRS Monitoring Station test chamber metal plates and also components in the test chamber stagnating water over the years where compounds appeared to fall into these three general categories. There is room to add any number of water quality parameters to these categories; using the categories to group water quality parameters is only an organizational method.

Regarding uniform corrosion of metals, several types of chemistry should be considered based on previous PRS Monitoring Station projects. Carbonate chemistry is the focus of the Lead and Copper Rule and must be studied in each water system. Chloride and sulfate appear to affect the dissolution of lead and copper and seem to have a complex chemistry. The chemistry of higher oxidation states must also be considered as it was discovered around 2002 that higher oxidation states can create a more stable lead compound that should not be overlooked (Lytle and Schock 2005). Phosphate chemistry is important because the Lead and Copper Rule relies heavily on the addition of phosphate to control lead and copper.

Regarding biostability, there is an accessible and affordable analysis available currently to track the population size of all microorganisms (with the exception of viruses) in a water system. That is the analysis for the energy molecule of living cells, adenosine triphosphate or ATP. The population size can be assessed in the context of concentrations of nutrients for encouraging growth of microorganisms – nitrogen, phosphorus, and carbon compounds. The population size can also be assessed in the context of disinfection concentration for eliminating microorganisms.

Regarding scale formation or dissolution, several metals in the water system were studied. Some metals can adsorb lead and copper, accumulate them on the surfaces of the metal scales or particulates, and eventually transport them through the water system to consumers' taps. Iron, manganese, and aluminum are known for this (Schock et al. 2014). There are plumbing related metals that indicate if other metals are also corroding in the water system: cadmium, chromium, cobalt, nickel, tin, and zinc. There are minerals related to the natural hardness or softening treatment of the water: calcium, magnesium, strontium, barium, potassium, and sodium. There are also other metals that occur naturally in the water that may be of interest to track, such as arsenic and vanadium. A panel of metals can be obtained from laboratories by means of a metals scan from an inductively coupled plasma mass spectrometer (ICP).

A measurement of any metal can be further fractionated into dissolved and particulate forms of that metal. To do this, a portion of a water sample must be filtered through a 0.45-micron filter (APHA et al. 1995). The metals analyzed in the unfiltered sample portion represent total metals concentrations. The metals analyzed in the filtered sample portion represent dissolved metals concentrations. Particulate metals equal total metals minus dissolved metals concentrations. Ideally, water samples should be field filtered immediately after obtaining the samples so that metals do not change from dissolved to particulate forms or vice versa or adhere to sample bottle walls (Cantor 2006). If this cannot occur, then lab filtration will have to suffice but with suspicion that metals may have changed form. The PRS Monitoring Station test chamber stagnation samples were field filtered using a new disposable syringe and syringe filter for each sample in all eight water utilities. The extra residential profile samples from two of the five participating water utilities were laboratory filtered.

General water quality parameters describing scale formation or dissolution are turbidity, the measurement of particulate solids entrained in the water, and conductivity, the measurement of dissolved solids in the water.

MONITORING FREQUENCY

The frequency of sampling should be based on the nature of a parameter's variation in a given water system. It is necessary to sample more frequently at first until the variation of a parameter is understood and an adequate frequency can be set.

Budget and labor availability for monitoring may force compromises in data-gathering frequency and number of parameters.

The frequency of monitoring parameters in this project was based on past experiences with PRS Monitoring Stations in a variety of water systems and within an affordable budget.

PROJECT #4586 MONITORING PLAN

Sampling Sites

The sampling strategy used in this project was to provide a combination of sampling sites, where possible. Residential profile sampling was performed in five of the water systems. Disinfection concentrations and turbidity at Total Coliform Rule sites were graphed where data were available.

PRS Monitoring Stations were installed in eight of the water systems, where Water System H utilized two stations, one for each campus served by the water system. For this monitoring, sites that were sampled are shown in Table 5.1.

Table 5.1
Sampling sites regarding the PRS monitoring station

Abbreviation	Description
EP	Flowing water at entry points to the distribution system
MS Inf	Flowing water at the influent sample tap of the PRS Monitoring Station; all of the stations in this project were located at high water age locations; this site represents flowing system water characteristics at a high water age location
MS Pb	Stagnating water in the lead test chamber
MS Cu	Stagnating water in the copper test chamber

In the campus water systems, there was access to the large buildings connected to the water distribution system. Because water system cleaning can release pipe wall accumulations into the drinking water and cause temporary water quality issues, the water quality in the buildings was tracked by measuring turbidity weekly at critical points in the building. Critical locations in buildings, especially large buildings, are shown in Table 5.2 based on past water quality investigations in building plumbing.

Table 5.2
Sampling sites regarding the building plumbing for turbidity measurements

Abbreviation	Description
EP	Entry point where water enters the building
Far CW	A cold water tap deep inside the building
Soft Out	Just after the water softener
HW Recirc	Hot water recirculation water near the water heater
Far HW	A hot water tap deep inside the building

All turbidity measurements made on flowing water from building plumbing

Water Quality Parameters

Water quality parameters measured in the project are listed under the three major categories of factors that can influence the release of lead and copper as discussed previously. They are listed in Table 5.3.

One laboratory was used in 2014 and 2015 for the metals analyses and then a second laboratory was used in 2016. The metals analyzed and their limits of detection (LOD) are shown in Table 5.4.

A portion of the stagnating metals samples from the PRS Monitoring Station test chambers were filtered in the field using new hand syringes and 0.45-micron nylon syringe filters for each sample.

Monitoring Frequency

The monitoring frequency of the water utilities using the PRS Monitoring Station in this project is shown in Table 5.5.

Monitoring Station Operating and Sampling Protocols

The operating and sampling protocols of the PRS Monitoring Station are paraphrased from the operations manual.

Preparation of the PRS Monitoring Station

After the monitoring station is set in location and attached to an influent water line and hosing is run from the station discharge to a drain, it is isolated from the water system and filled with a chlorine solution. This is to disinfect the station so that future water samples are not contaminated by microorganisms introduced during assembly, transport, and installation of the station. The chlorine solution is left in the station for 24 hours.

The next step is to prepare and install the metal plates in the test chambers.

Preparation of the Metal Plates for the Test Chambers

The PRS Monitoring Stations use stacks of metal plates installed in the test chambers to study trends in metal release into water. Each test chamber must have only one type of metal plate. For example, if it is desired to study lead and copper trends, one test chamber will hold 16 lead plates; the second test chamber will hold 16 copper plates.

Table 5.3
Water quality parameters related to categories of factors that shape water quality in distribution systems

Uniform Corrosion of Metals	Biostability	Scale Formation and Dissolution
Total Alkalinity	Adenosine Triphosphate (ATP) as a measure of microbiological population	Turbidity
pH	Free chlorine or monochloramine as the active disinfectant	Conductivity
Temperature	Total chlorine including the active disinfectant and the combined chlorine concentrations	Total, dissolved, and particulate concentrations of the following metals:
Conductivity	Dissolved organic carbon	Lead
Total Hardness	Ammonia nitrogen	Copper
Chloride	Nitrite/nitrate nitrogen	Iron
Sulfate	Total Phosphorus	Manganese
Total Phosphorus	Total alkalinity	Aluminum
Orthophosphate	pH	Cadmium
Oxidation/Reduction Potential (ORP)	Temperature	Chromium
	Oxidation/Reduction Potential (ORP)	Cobalt
		Nickel
		Tin
		Zinc
		Calcium
		Magnesium
		Barium
		Strontium
		Sodium
		Potassium
		Arsenic
		Vanadium

Table 5.4
Limits of detection for metals at two laboratories

Parameter	**Units**	**Limit of Detection for 2014-2015 Lab**	**Limit of Detection for 2016 Lab**	**Public Health Standard**	**Aesthetic Standard**	**Lifetime Health Advisory Limit**
Aluminum	µg/L	10	5	200		
Arsenic	µg/L	5.0	0.50	10		
Barium	µg/L		0.10			
Cadmium	µg/L	1.0	0.10	5		
Calcium	mg/L	0.1	0.15	No standard		
Chromium	µg/L	1.0	0.5	100		
Cobalt	µg/L	1.0	0.5	40		
Copper	µg/L	5.0	1.0	1300 (Action Level; non-enforceable goal)		
Hardness	mg/L as CaCO3	(calculated)	(calculated)	No standard		
Iron	mg/L	0.10	0.018		0.3	
Lead	µg/L	3.0	0.10	15 (Action Level)		
Magnesium	mg/L	0.10	0.15	No standard		
Manganese	µg/L	1.0	1.0	300	50	
Nickel	µg/L	2.0	0.50	100		
Potassium	mg/L	--	0.15			
Sodium	mg/L		0.15			
Strontium	µg/L	1.0	0.25			4000
Tin	µg/L	--	0.10			
Vanadium	µg/L	1	--	30		
Zinc	µg/L	5.0	5.0			

Note: Abrupt horizontal line changes on metals graphs are due to metals concentrations at the detection limit around 1/1/2016 when the laboratories were changed and the limits of detection from many metals also changed.

Table 5.5
Monitoring plan for project #4586 PRS monitoring stations

Frequency	**Flowing Influent Field Tests (also run on the entry point water to the distribution system)**	**Flowing Influent Lab Tests**	**Test Chambers Lab Tests**
Weekly	Flow meter totalizer readings, pH, temperature, ORP, turbidity, conductivity, total chlorine, free chlorine or monochloramine, orthophosphate, if relevant		
Bi-weekly		Total metals scan, ATP	Total metals scan, dissolved metals scan, ATP
Monthly		Total alkalinity, chloride, sulfate, DOC	
Bi-monthly		Total Phosphorus, Ammonia, Nitrite/nitrate	

Each metal plate is submerged for a short time in an organic acid detergent in order to clean off debris from the metal surface and to reduce any oxidized surface metal. Metal plates are then rinsed with deionized water and slipped onto the plastic rods that hold the metal plates in the test chambers. Plastic lock nuts secure 8 cleaned and rinsed plates separated by plastic spacers on a plastic rod. Two rods per test chamber are prepared in this way.

Installation of the Metal Plates into the Test Chambers

The rods with the plates are transported as soon as possible to the test chambers. The test chambers are drained of the disinfecting solution and opened from the top. The test chamber internals that hold the rods of plates are set in place along with the metal plates.

The test chambers are closed up. Fresh disinfecting solution is pumped into the monitoring station to clean out contamination from opening the test chambers for the installation of the plates. The disinfecting solution is held in the station and test chambers for 15 minutes.

The manual influent valve to the monitoring station is then opened and water from the water system is introduced into the monitoring station. The manual flow continues until disinfecting fluid is flushed out. Flow rates are set and checked for each test chamber at 0.5 gpm per test chamber at 30 psig unless it is necessary to set a lower operating pressure.

The water flow is turned off and the timer is programmed to operate one hour a day.

Operation of the Monitoring Station

The PRS Monitoring Station timer is set to allow flow through the station one hour a day at 30 psig and 0.5 gpm per test chamber.

The station is to be visited once a week where the recording of flow meter totalizer readings is of importance to document and insure that the flow rate and water usage is constant throughout the monitoring period. Flow rate is tweaked by means of a needle valve for each test chamber as informed by the totalizer readings.

Sampling the Monitoring Station

Ideally, flowing water samples should be taken during the automatic flow period from the influent valve to the monitoring station. The flow will turn off automatically as controlled by the timer. After six hours from when the flow has stopped, the operator returns to the monitoring station to take stagnation water samples from the test chambers.

Unfortunately, many water utility personnel cannot fit two visits to a monitoring station into their work day so an alternative sampling protocol is performed. In the alternative protocol, the operator visits the monitoring station six hours after the automatic flow has stopped. Totalizer readings are written down for the calculation of the average flow per day since the last visit. Then, the test chamber sample taps are wiped with alcohol to disinfect them and stagnation water samples are drawn from the test chambers. After taking the stagnation samples, the flow is turned on manually and the pressure checked. If needed, based on the totalizer readings, flow rates are reset or tweaked and confirmed with a timed test on flow as recorded by the totalizers. Flowing water samples are taken based on the monitoring plan from the alcohol-wiped influent sample tap to the monitoring station. The timer will then be set back to automatic operation, turning off the flow. Final totalizer readings are written down to start a new week of automatic operation.

Field analyses are performed on some of the flowing water samples as prescribed by the monitoring plan. If field filtration is to be performed on metals samples, a portion of each metals sample is filtered through a syringe and syringe filter into a separate sample bottle. Finally, water samples are labelled, packed, and sent to the laboratories for analysis.

Monitoring Schedules

Table 5.6 lists the periods of time that each water system operated the PRS Monitoring Stations and carried out the monitoring program.

Table 5.6
Monitoring periods for water systems using the PRS monitoring stations

Water System	Monitoring Station Startup Date	Monitoring Station Shut Down Date
A	07/21/14	01/05/16
B	03/31/14	01/05/16
C	07/13/14	01/05/16
D	04/30/14	09/05/16
E	04/16/14	10/05/15
F	08/26/14	06/13/16
G	09/30/14	[12/31/17]
H1	10/08/14	12/7/16
H2	10/08/14	12/7/16

DATA ANALYSIS

Data Management

Data from the PRS Monitoring Station and entry points to the distribution system were entered into spreadsheets and transferred and stored in a relational database by means of the data management software, My Monitoring Data®. This software is an interface between storing data in a Microsoft Access® database and pulling out specific data for analysis and reporting in a Microsoft Excel® spreadsheet. The software also keeps an accounting of last changes made to a data point and by whom. Any changes to data that have already been entered are also noted in a comment column associated with the data point. Data found invalid are not erased but are hidden from calculations, reporting, and graphing.

There were some conventions followed to keep data handling consistent. For example, when the laboratory reported no detection for a parameter, “nd” was entered into the computer for that data point instead of 0. When data were pulled out for data analysis, an entry of “nd” was automatically translated to the laboratory’s limit of detection for that analysis. This is because the parameter was at or below the limit of detection; it cannot be said that the value was 0.

Several parameters were calculated and certain conventions had to be set:

- Particulate metal concentration = Total metal concentration – Dissolved metal concentration
    - If dissolved metal concentration > total metal concentration and dissolved metal concentration – total metal concentration < 10% x total metal concentration, then particulate metal concentration = 0.001 (limit of detection does not apply here since

    - it is a calculated value. Zeroes can cause problems with some data analyses; instead the particulate concentration was stated as very small)
    - If dissolved metal concentration > total metal concentration, total metal concentration > 1.0, and dissolved metal concentration – total metal concentration > 10% x total metal concentration, then particulate metal concentration and dissolved metal concentration were left null. Laboratories have been consulted over these situations but the situation typically cannot be traced and may also be a sampling or filtering issue with metal particulates contaminating the dissolved metal sample.
- Larson-Skold Index = (chloride + sulfate concentrations)/total alkalinity
- CSMR = chloride concentration/sulfate concentration

Time Series Graphs

Each water quality parameter was plotted over time with all sampling sites graphed together for comparison of results. See Figure 5.5.

Graphs included markings for seasonal quarters of the year as many water quality phenomena are related to water temperature changes.

Graphs also included date markings for special events that occurred in the water system during the monitoring data collection. For example, if a well was taken off-line, water mains flushed, or biofilm-removing chemical dosed into the water, those events were signified relative to the time axis by a number referring to a list of system events.

Shaded Area Graphs

Dissolved and particulate fractions of each metal were graphed together in shaded area graphs. These graphs are similar to bar graphs where the two fractions add up to the total metal concentration. Instead of bars, data points for the dissolved metal are connected by a smooth curve over time and those for particulate metal concentrations are connected to each other as well. The area between the two curves is shaded black giving a dramatic visual effect as to the degree of particulate metal in the water. See Figure 5.6.

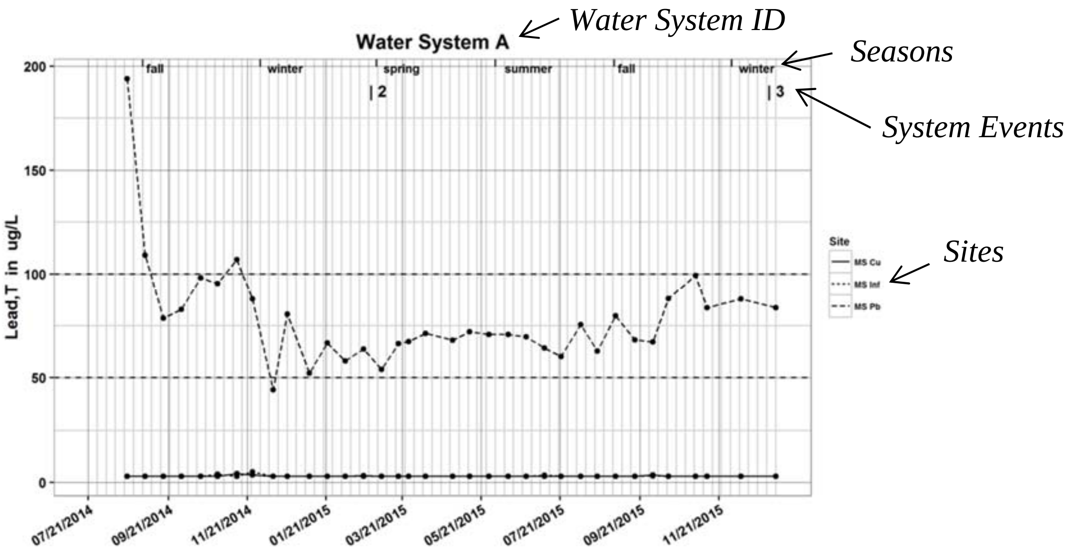


Figure 5.5 Example time-series graphs showing total lead concentration at three sites

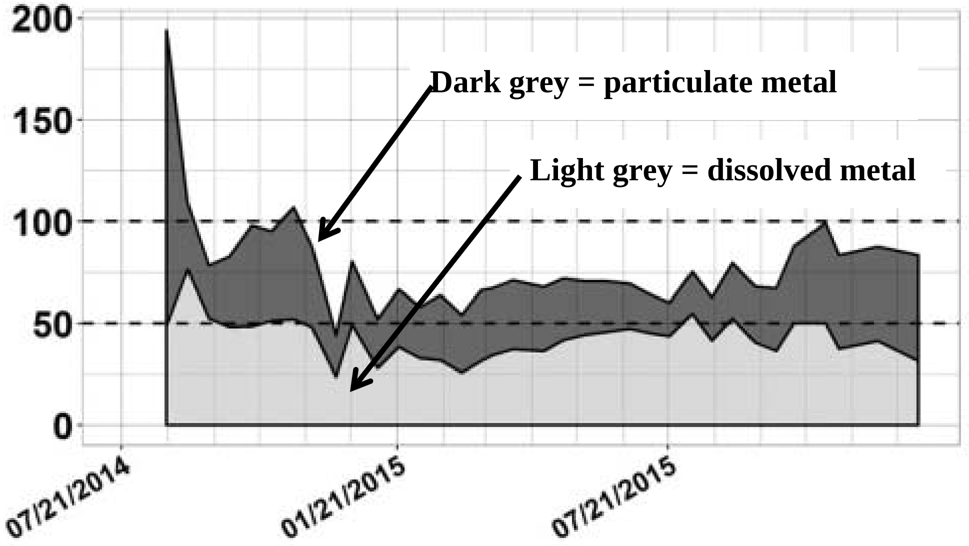


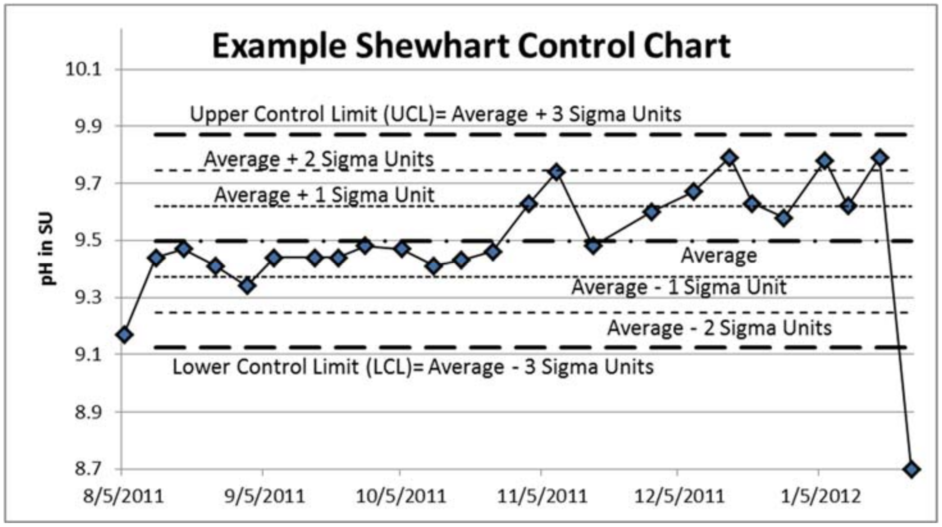
Figure 5.6 Example shaded area graph showing dissolved and particulate lead concentrations at a PRS monitoring station lead test chamber

Shewhart Control Charts

There is a method that can assist in determining which data points on a time-series plot are atypically high and which are atypically low. It can also identify other water quality trends indicating a changing water system. The method is to construct a Shewhart Control Chart. It is a data analytical technique that has been borrowed for water quality and water system data (Cantor and Cantor 2009; Cantor et al. 2012) from the field of industrial process control and improvement, called statistical process control. This technique was developed in the 1920's by Dr. Walter Shewhart of Bell Laboratories and was later integrated into many industries by Dr. W. Edwards Deming, a champion of process control and improvement (Wheeler and Chambers 1992).

The control chart is essentially a graph of data over time. Ease of interpreting the data is achieved by the guidelines plotted on the graph, which are plots of the Shewhart statistics calculated from the dataset. The statistics describe the expected variation of the data if the system remains operating under its existing conditions. Data points that fall outside of the lines of expected variation show that new factors are influencing the system. Other data patterns on the chart can show that changes to the status quo are beginning to occur (Wheeler and Chambers 1992).

Figure 5.7 summarizes the control chart's features. For Shewhart Control Charts, monitoring data are plotted over time. The average is drawn as a line through the data. A unit of variation, called a sigma unit, is calculated and then used to define the range (+/- 3 sigma units around the average) in which 99% of the data are expected to fall. Standard deviation is a type of a sigma unit. However, standard deviation can only be used on data from randomized experiments where each data point is independent of each other. In water quality monitoring, samples can only be taken sequentially over time like on an assembly line; the conditions at a previous sampling time might affect the conditions at the next sampling time. Therefore, the more general sigma unit is used. Refer to other references for a better understanding of the technique (Wheeler and Chambers 1992).



Source: Courtesy of Process Research Solutions, LLC of Madison, WI.

Figure 5.7 Summary of Shewhart Control Chart characteristics

For Figure 5.7, the following are defined:

- Average + 3 sigma units = Upper Control Limit = UCL
- Average – 3 sigma units = Lower Control Limit = LCL
- Between the UCL and the LCL = the expected range of the data. This is the range that will result from routine factors working on the system and 99% of the data points are expected to fall.

Patterns of atypical data can be found on the graph when:

- Data fall outside the 3 sigma unit lines
- At least 2 out of 3 successive values fall on the same side of the average and are 2 sigma units or greater away from the average
- At least 4 out of 5 successive values fall on the same side of the average and are 1 sigma unit or greater away from the average
- 8 or more successive points fall on the same side of the average line

Any data following the above patterns should trigger an investigation of system operations to determine the cause. If results are unfavorable, then corrections can be made to system operations. If results are favorable, then the continuation of such operating conditions could be beneficial.

A Shewhart Control Chart prepared for this project is shown in Figure 5.8.

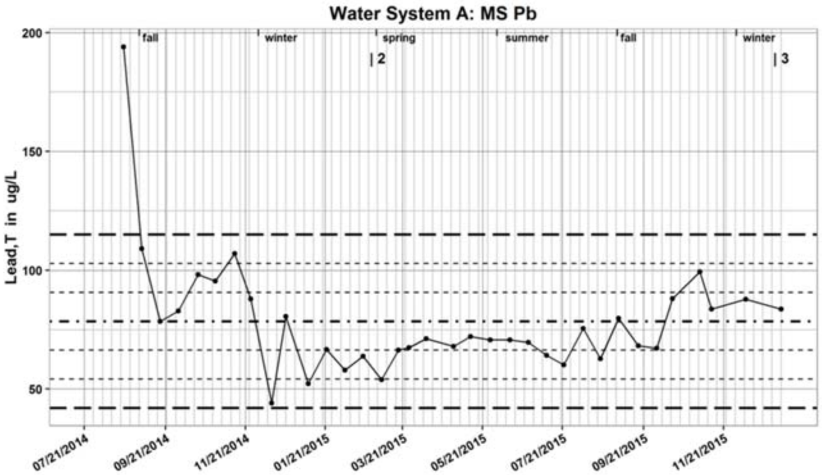


Figure 5.8 Total lead from Figure 5.5 at the lead test chamber graphed as a Shewhart Control Chart

In addition to the regular control chart, a second chart was drawn in this project to accentuate the data points that displayed trend patterns as defined by the Shewhart Control Chart rules. Refer to Figure 5.9.

The Shewhart Control Chart statistics were also used in this project to compare results between sites and between water systems. Besides the average, the "Upper Control Limit" (UCL) and the "Lower Control Limit" (LCL) were used for these comparisons. The UCL equals the average value plus 3 sigma units; the LCL equals the average value minus 3 sigma units. The difference between the UCL and the LCL is the range where 99% of the data points are expected to fall. Tables were made for each parameter listing the UCL, average, and LCL for each sampling site as shown in Table 5.7. "UCL" and "Highest Expected Value" and "LCL" and "Lowest Expected Value" were used as equivalent in meaning. The Highest Expected Value/UCL and the Lowest Expected Value/LCL should not be mistaken for the actual maximum and minimum results observed. Instead, these are statistical values as described previously.

Taking this comparison between sites a step further, these values were graphed as in Figure 5.10.

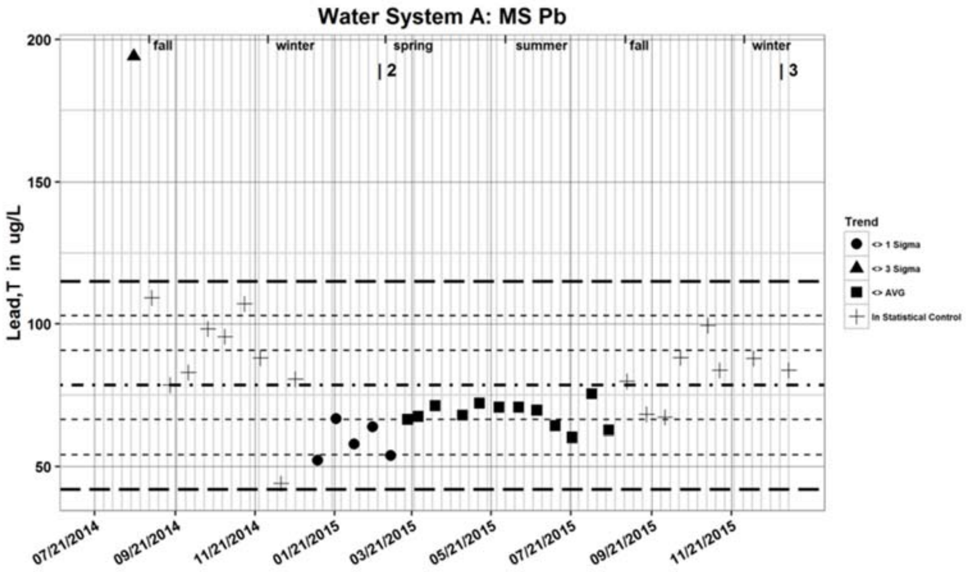


Figure 5.9 Figure 5.8 with data points highlighted for Shewhart Control Chart statistical status

Table 5.7
Shewhart Control Chart statistics summary of Figure 5.5

Lead, T: Comparison of Shewhart Control Chart Statistics by Site in µg/L			
Site	**UCL or Highest Expected Value**	**Average**	**LCL or Lowest Expected Value**
MS Cu	3.4	3.1	2.7
MS Inf	3.6	3.1	2.6
MS Pb	115.0	78.5	42.1

This is a table of the statistics representing average value and variation. This does not represent actual maximum and minimum results observed.

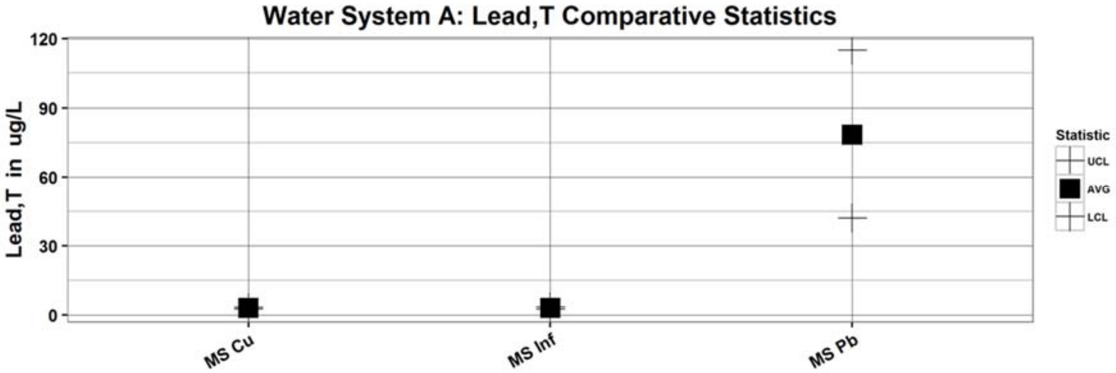


Figure 5.10 Graph of Table 5.7 Shewhart Control Chart statistics summary

Steady State Determination

In using the PRS Monitoring Station test chambers, or any other AwwaRF pipe-loop style apparatus, metals release data from new metal surfaces typically start at high concentrations because protective scales of metal oxides and carbonates have not yet been established on the clean metal surfaces newly in contact with system water. The dissolved metals concentrations fall over time as protective scales develop. Even though the scales do not have the time to develop to the degree that can be seen in the distribution system where pipe surfaces have been in contact with the water for decades, the metals' concentrations reach a smaller range of concentrations that can remain steady. Shewhart Control Charts of the dissolved metals release concentrations can be studied to determine where the concentrations have reached a point of "statistical control" and vary in a constant range.

An example is shown in Figure 5.11 where dissolved lead release is high and varies widely for several months. Figure 5.11(a) is the complete set of monitoring data from a lead test chamber on a Shewhart Control Chart. In Figure 5.11(b) data points in the Shewhart Control Chart that are in statistical control with each other are marked with a "+" symbol. The darker data points are atypical for this data set and represent the startup of a test chamber when protective scales are developing on clean metal surfaces.

When the initial data points are eliminated as in Figure 5.11(c), the Shewhart Control Chart shows all data points in what is considered statistical control with each other where rules of the control charts indicate no atypical trends are occurring.

Unfortunately, not all test chamber graphs fall so neatly into this exercise of pinpointing Shewhart Control Chart trends. Many times, the results of initial development of metal surface scales are confounded with water system events that can also influence the release of the metal under study. Many times, the selection of the steady state monitoring period is a subjective one based on knowledge of the system operations and events.

The steady state dissolved lead and copper concentrations are used in this study to compare to lead and copper release predicted by the EPA carbonate solubility models in Chapter 7.

Regression Trend Line

In Chapter 7, lead and copper release data are also compared to common corrosion indices to determine if the indices predict the degree that lead and copper will be released. The average steady state dissolved lead and copper concentrations are used as previously described. The indices used for comparison are dissolved inorganic carbon, calcium carbonate precipitation potential, the Langelier Index, the chloride to sulfate mass ratio, and the Larson-Skold Index. These are described in Chapter 7.

The metal concentration is plotted on the x-axis and the index is plotted on the y-axis. A linear regression line is fitted to the scatter of data points to determine if a metal concentration aligns with an index. If the data tend to form a linear relationship, the correlation coefficient, "r," will approach 1.0. If there is no tendency to form a linear relationship, r will approach 0.0. In the case of chloride to sulfate mass ratio, an exponential function had a higher correlation coefficient for the data point fit than did a linear function. In that case, an exponential line was used.

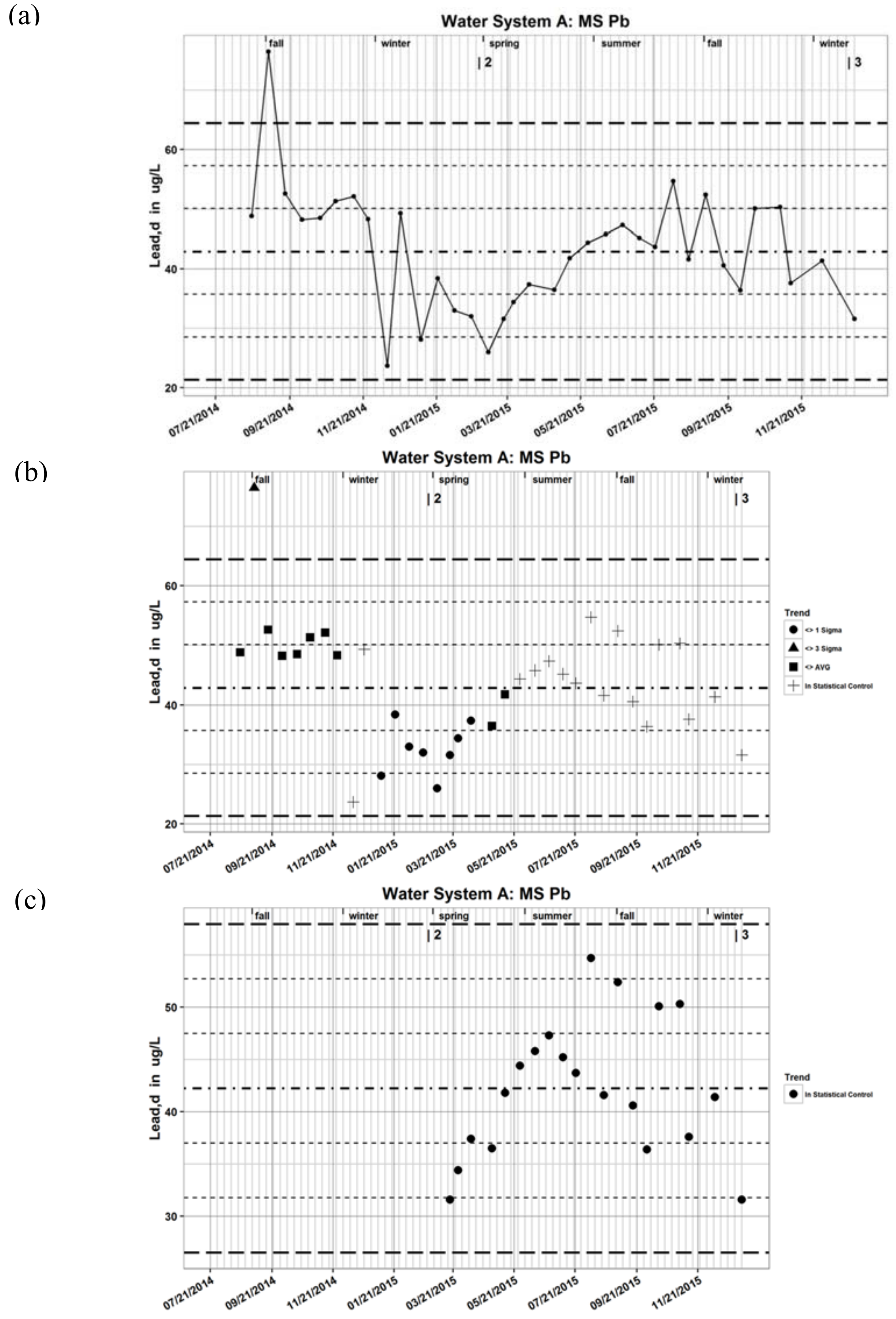


Figure 5.11 Determination of steady state release of dissolved lead from a PRS monitoring station lead test chamber

Correlations

Besides documenting the release of dissolved and particulate lead and copper in the PRS Monitoring Station test chambers, many other water quality parameters were analyzed as described previously. It was desired to determine which water quality parameters, if any, trended with the release of lead and copper. For this purpose, the Spearman Rank Correlation technique was utilized. This is appropriate for water quality monitoring data because the technique can be applied to "nonparametric" data. Water system data are nonparametric as described under the section, "Shewhart Control Charts," where one data point could influence a subsequent data point. The data are not considered independent and random.

The Spearman correlation is a technique that determines if two parameters are always increasing at the same time. If they are always increasing at the same time, they would have a perfect Spearman correlation coefficient of 1.0. If they increase together most of the time, they have a coefficient of a fraction of 1 and can range down to 0. The correlation also can discern if one parameter always increases while the other always decreases. If they always do this, they have a coefficient of -1. Fewer occurrences together would give negative fractions between -1 and 0. In this study, only coefficients between 0.6 and 1.0 and -0.6 and -1.0, the stronger trends, are acknowledged.

Conclusions drawn from the Spearman correlation coefficients should be made carefully. Common trends between two parameters do not prove causation. The two parameters may, instead, be characteristics of some other phenomena. For example, if lead release is trending with alkalinity of water, one should not assume that the lead release is the result of the increasing alkalinity. Instead, for example, an operational change of source water may be the real factor that increases both the alkalinity and the lead release. There can be many possible explanations that require more system study to decipher.

Time-aligned graphs of water quality parameters should also be inspected along with the correlation results. Sparklines are useful in this case. They are graphs without x and y axis labels that show the shape of the line connecting the data and the general trends of the data. When sparklines are created with data of multiple parameters over the same time period, they can be compared against each other to determine if trends are similar. Figure 5.12 is an example of sparklines that display two water quality parameters trending inversely with each other.

There are other reasons to inspect sparklines and other graphs instead of fully depending on Spearman Rank correlation coefficients. A trend pattern of one water quality parameter may be repeated in another water quality parameter at a later time period. Or, two water quality parameters may trend together only during a specific time period and trend oppositely or not at all in a different time period. These subtleties would be missed with a calculated correlation coefficient.

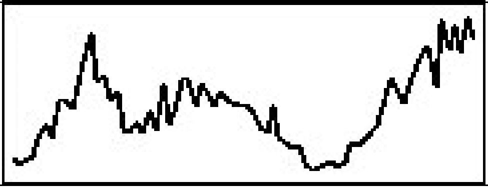
pH			
Turbidity			

Figure 5.12 Example of sparklines for data trend comparison

When studying the correlations in the PRS Monitoring Station data, flowing fresh influent water quality characteristics were compared to stagnating water quality characteristics. The correlations have been separated into:

- Correlations occurring within the flowing system water
- Correlations between flowing influent system water characteristics and resultant interactions that occurred in the stagnating test chamber water
- Correlations between water quality parameters that were released or changed together during the stagnation period in the test chamber

Box and Whisker Plots

Box and whisker plots, as shown in Figure 5.13, show how a set of data is distributed between the highest and lowest data point values. The data points are divided into four groups (quartiles). The grey box in Figure 5.13 encompasses the two inner groups with the black dividing line denoting the median (50th percentile) of the data set. The highest group includes values between the top of the grey box and the top of the "whisker," the vertical black line with a short, horizontal line as the maximum data point value. The lowest group includes values between the bottom of the grey box and the bottom of the "whisker." For the minimum data point value at the bottom of the whisker, the short horizontal line in Figure 5.13 is at 0.

The diamond shape locates the average value of all the data points. The black triangle locates the 90th percentile of all the data points. These plots were used on Lead and Copper Rule datasets in Chapter 11. All lead and copper concentration units in Chapter 11 on box and whisker plots are in units of µg/L.

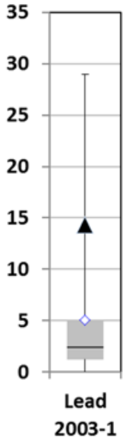


Figure 5.13 Example box and whisker plot for a set of Lead and Copper Rule data

Quality Control of Field Analysis Data

The analysis of water quality parameters must undergo quality control to assure accuracy and precision of the results. Water samples were sent to drinking-water certified laboratories where the analyses are subject to quality control techniques.

A number of water analyses were performed in the field. This was necessary because certain water quality parameters can change quickly from the time of sampling and with interaction with the air. Field tests used in this project were pH, temperature, total chlorine concentration, free chlorine or monochloramine concentration, conductivity, oxidation/reduction potential (ORP), and turbidity. For water systems adding a phosphate treatment product, orthophosphate concentration was analyzed in the field as a convenience.

Typically, no quality controls are run on field analyses. That is a shortcoming because the accuracy and precision of any test cannot be assumed. In this project, similar quality control techniques used in water laboratories were used on field analyses (APHA et al. 1995). For accuracy, a standard solution, where possible, was measured every week to determine how close the measurement came to the known value. Percent recovery of the standard was calculated as:

Percent Recovery = 100 * (Measured Value)/(Known Standard Solution Value)

Percent recovery was then graphed as a Shewhart Control Chart. The average percent recovery was used as the accuracy of the analysis with the UCL and LCL describing the accuracy range that was achieved.

Precision of an analysis was calculated by performing two measurements on the same sample. This was typically performed on the flowing water influent to the PRS Monitoring Stations every week. The absolute values of the differences between the first and second measurements were graphed as a Shewhart Range Control Chart (Wheeler and Chambers 1992) and the UCL used as the precision of the analysis.

The accuracy and precision of each analysis in each water system changed over certain periods of time. For example, the tests were typically not as accurate and precise at the beginning of the monitoring project as they were a few months later. Or, there were time periods when an analysis might become more problematic. The quality control statistics and graphs called attention to these issues so that they could be remedied.

In Tables 5.8 and 5.9, the precision and accuracy of field tests are listed for each water system’s monitoring effort where data from the complete monitoring period were combined for the calculation.

SUMMARY

Distribution system monitoring strategies and concepts were described in this chapter along with the specifics of this project’s monitoring plans and data analyses.

The highlights of these results are summarized and water system results compared in Chapters 6 to 11.

Table 5.8
Precision of field tests for project #4586 (+/- units shown)

Item Measured	Units	Water System							
		A	B	C	D	E	F	G	H
Free Chlorine or Monochloramine for System A	mg/L	0.08	0.09	0.03	0.02	0.11	0.13	0.12	0.15
Total Chlorine	mg/L		0.06		0.02	0.09	0.09	0.09	0.11
Conductivity	µS/cm	3.0	1.9	3.1	20	17	8.4	12	26
Oxidation/Reduction Potential (ORP)	mV	17	30	67		29	44	30	28
pH	SU	0.04	0.12	0.07	0.05	0.10	0.09	0.11	0.22
Orthophosphate	mg/L as PO_4	0.02		0.03	0.03			0.18	0.29
Temperature	deg C		0.04		0.13	0.23	0.13		
Turbidity	NTU	0.02	0.04	0.05	0.23	0.26	0.53	0.36	0.38/ 0.30

Table 5.9
Accuracy of field tests for project #4586 in %

Item Measured	**Water Systems and Their Average Accuracies**							
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Conductivity	104	99.9	100	100	99.7	100	100	97.3
ORP	100	93.8	100		104	104	103	102
pH	100	100	100	100	100	101	99.3	101
Orthophosphate	101		100	101			102	109
Turbidity	101	89.6		100	115	114	108	134

Item Measured	**Water Systems and Their Accuracy Values**							
	A		**B**		**C**		**D**	
	Lower Value	**Upper Value**	**Lower Value**	**Upper Value**	**Lower Value**	**Upper Value**	**Lower Value**	**Upper Value**
Conductivity	82.4	125.5	98.5	101	99.8	100	97.1	104
ORP	99.6	100	86.1	102	99.8	100		
pH	99.8	100	99.3	101	100	100	98.3	102
Orthophosphate	95.7	106			98.5	101	86.1	115
Turbidity	97.2	105	78.2	101			99.0	101

Item Measured	**Water Systems and Their Accuracy Values**							
	E		**F**		**G**		**H**	
	Lower Value	**Upper Value**	**Lower Value**	**Upper Value**	**Lower Value**	**Upper Value**	**Lower Value**	**Upper Value**
Conductivity	97.2	102	97.6	103	99.2	101	85.5	109
ORP	100	107	99.4	108	99.4	106	93.2	110
pH	99.8	101	99.1	102	95.5	103	98.5	103
Orthophosphate					91.5	112	86.1	132
Turbidity	95.4	135	91.2	138	94.4	121	0.0	281

CHAPTER 6
MONITORING STATION DATA

Lead and copper concentrations from stagnating water in the PRS Monitoring Station test chambers are exaggerated from what would actually be seen in the distribution system. The conditions under which the PRS Monitoring Station operates are equivalent to an abandoned building at an extreme location in the distribution system where water residence time is high. In addition, the metal in the test chambers starts with a clean un-oxidized surface and builds up chemical scales and biofilms during the monitoring period. The scales that do develop are much younger than the scales that exist in the distribution system. This allows more metal to transfer from the metal surface into the water than existing scales would.

Therefore, the metals concentrations measured in the stagnating water from test chambers must not be taken out of context. They are higher than would typically be seen in the actual distribution system. They serve to magnify the chemical and microbiological mechanisms that are shaping the water quality for the water system under study and to represent water quality trends.

In a PRS Monitoring Station test chamber, the following relationships have been observed:

- Lead concentrations < 100 µg/L are considered good; lead concentrations < 50 µg/L are considered excellent.
- Copper concentrations < 200 µg/L are considered good; copper concentrations < 100 µg/L are considered excellent.

When these goals can be achieved under the extreme conditions of a PRS Monitoring Station test chamber, the distribution system is typically experiencing very low lead and copper concentrations. These goal lines are drawn on lead and copper concentration graphs in this report.

LEAD

Flowing System Water

Besides the stagnating test chamber water, system water flowing into the PRS Monitoring Station is monitored. The monitoring results reflect the character of the actual system water at the monitoring station location in the distribution system. In this project, all monitoring stations were located at high water age (least fresh/high residence time) locations.

An important question to answer in any water system is: what concentration of lead can be measured in the system water that potentially enters buildings around the distribution system. Table 6.1 shows that system water average lead concentrations, all at high water age locations, were considered low (<5 µg/L) in the eight water systems.

But, two water systems showed a high variation in the lead concentration. System B had a highest expected concentration (a statistical concept discussed in Chapter 5) of 15 µg/L. That might be explained by the fact that the system had an initial issue with the influent line to the PRS Monitoring Station, where water stagnated in an unrepresentative manner. When this issue was discovered, the station influent line was kept flushed. In addition, in System B, there was a period where water main flushing was nearby and the high lead concentrations in the sampled system water occurred around at that time.

Table 6.1
Total lead concentrations in flowing system water in µg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	3.6	3.1	2.6
B	*15	5.3	0
C	4.6	3.3	1.9
D	4.5	2.7	0.9
E	3.4	3.1	2.7
F	7.8	3.1	0
G	*11	4.4	0
H1	3.5	2.3	1.0
H2	4.6	2.5	0.4

*System B data possibly reflects temporary unrepresentative flow in the influent line to the PRS Monitoring Stations; after the discovery of this issue, the influent line was kept flushed. In addition, water main flushing nearby may have contributed to higher lead levels. System G data represents some system cleaning operations.

System G experienced a highest expected concentration of 11 µg/L. The high system water lead concentrations occurred at the initiation of system cleaning efforts.

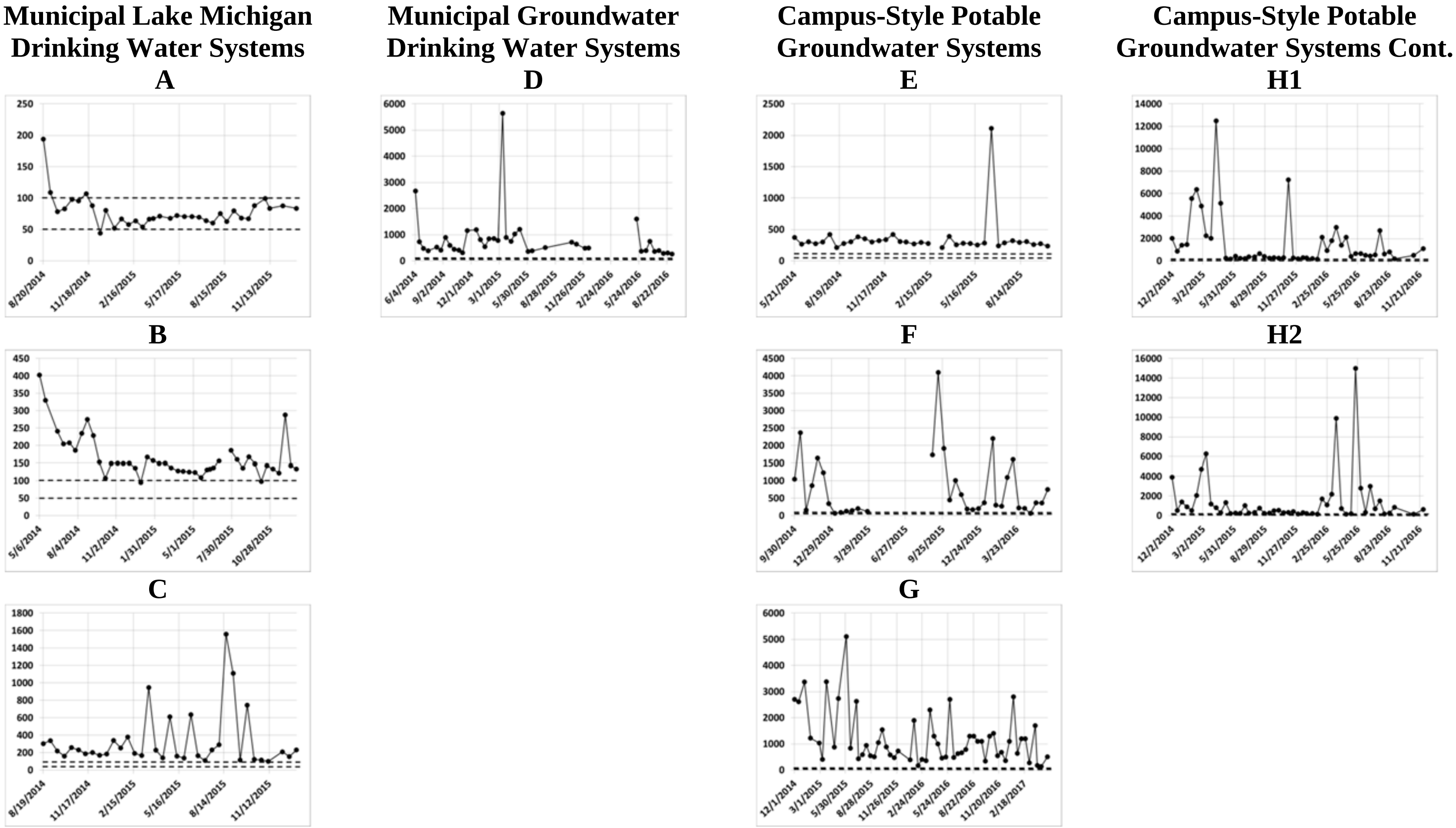
Stagnating Test Chamber Water

The total lead concentrations measured in stagnating water of the PRS Monitoring Station lead test chambers are shown in Figure 6.1.

On each graph, dotted lines are drawn horizontally at 50 and 100 µg/L of lead to show the concentration goals for release of lead in the lead test chambers. As previously mentioned, test chambers magnify the water system interactions. Based on past PRS Monitoring Station projects, releasing less than 100 µg/L of lead in a test chamber is representative of a water system under good lead control and good general water quality. Releasing less than 50 µg/L of lead in a test chamber is representative of a water system under excellent lead control and general water quality. Only Water System A had total lead concentrations in the target range. Water System B was close behind. All of the other water systems experienced greatly higher total lead release in the PRS Monitoring Stations.

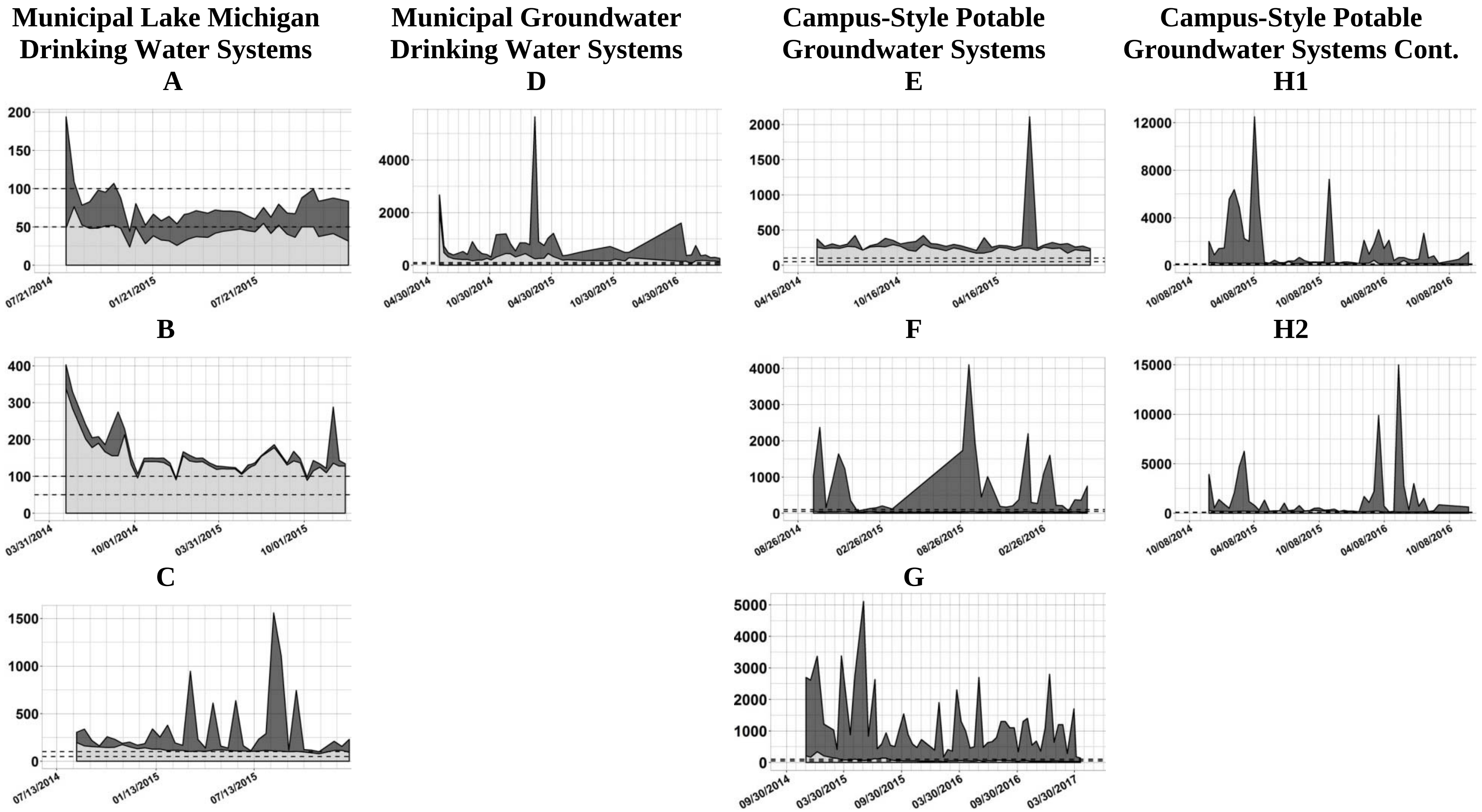
Figure 6.2 takes a closer look at the total lead concentrations, breaking the total concentration into its dissolved and particulate fractions of lead.

Water System A was seen to have dissolved lead concentrations meet the lower concentration range goal < 50 µg/L. However, the particulate lead concentration almost doubled the total lead concentration. So, even though the lead concentration ranges were satisfactory, the lead concentrations could have been cut by half if the particulate fraction was removed. A high percentage of particulate lead was also seen in this system during the residential profile sampling described in Chapter 3. In that situation, particulates of lead were shown to push the total lead concentration over the Action Level in an individual building while the water system was dosing orthophosphate to control dissolved lead.



1. F had a period of no monitoring during a water main replacement program.
2. D had a period of no monitoring while a new water treatment plant was optimized.

Figure 6.1 Total lead concentration released into PRS monitoring station lead test chamber stagnating water in µg/L



1. F had a period of no monitoring during a water main replacement program.
2. D had a period of no monitoring while a new water treatment plant was optimized.

Figure 6.2 Relative concentrations of dissolved and particulate lead fractions released into PRS monitoring station lead test chamber stagnating water in μg/L

Water System B had the lowest concentrations of particulate lead, the total lead being mostly in dissolved form. This was also found during the residential profile sampling described in Chapter 3.

All of the other water systems showed the potential to release concentrations of particulate lead at a level that dwarfed the dissolved lead concentrations.

The statistics for the dissolved, particulate, and total lead concentrations released in the PRS Monitoring Station lead test chambers are shown in Tables 6.2 to 6.4. Water Systems A, F, and G had average dissolved lead concentrations within the goal range of <100 µg/L. Particulate lead in all water systems significantly increased the total lead concentrations.

Table 6.2
Dissolved lead concentrations released into PRS monitoring station lead test chamber stagnating water in µg/L

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	64	43	21
B	201	146	92
C	147	121	96
D	573	297	22
E	309	235	160
F	52	35	18
G	149	82	15
H1	296	175	54
H2	293	191	89

Table 6.3
Particulate lead concentrations released into PRS monitoring station lead test chamber stagnating water in µg/L

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	59	36	12
B	66	21	0
C	889	204	0
D	1824	519	0
E	524	115	0
F	2624	748	0
G	3606	1182	0
H1	5172	1440	0
H2	6008	1340	0

Table 6.4
Total lead concentrations released into PRS monitoring station lead test chamber stagnating water in µg/L

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	115	78	42
B	251	167	83
C	1008	325	0
D	2248	816	0
E	773	350	0
F	2666	782	0
G	3688	1268	0
H1	5247	1593	0
H2	6097	1488	0

Total Lead = Dissolved Lead + Particulate Lead

COPPER

Flowing System Water

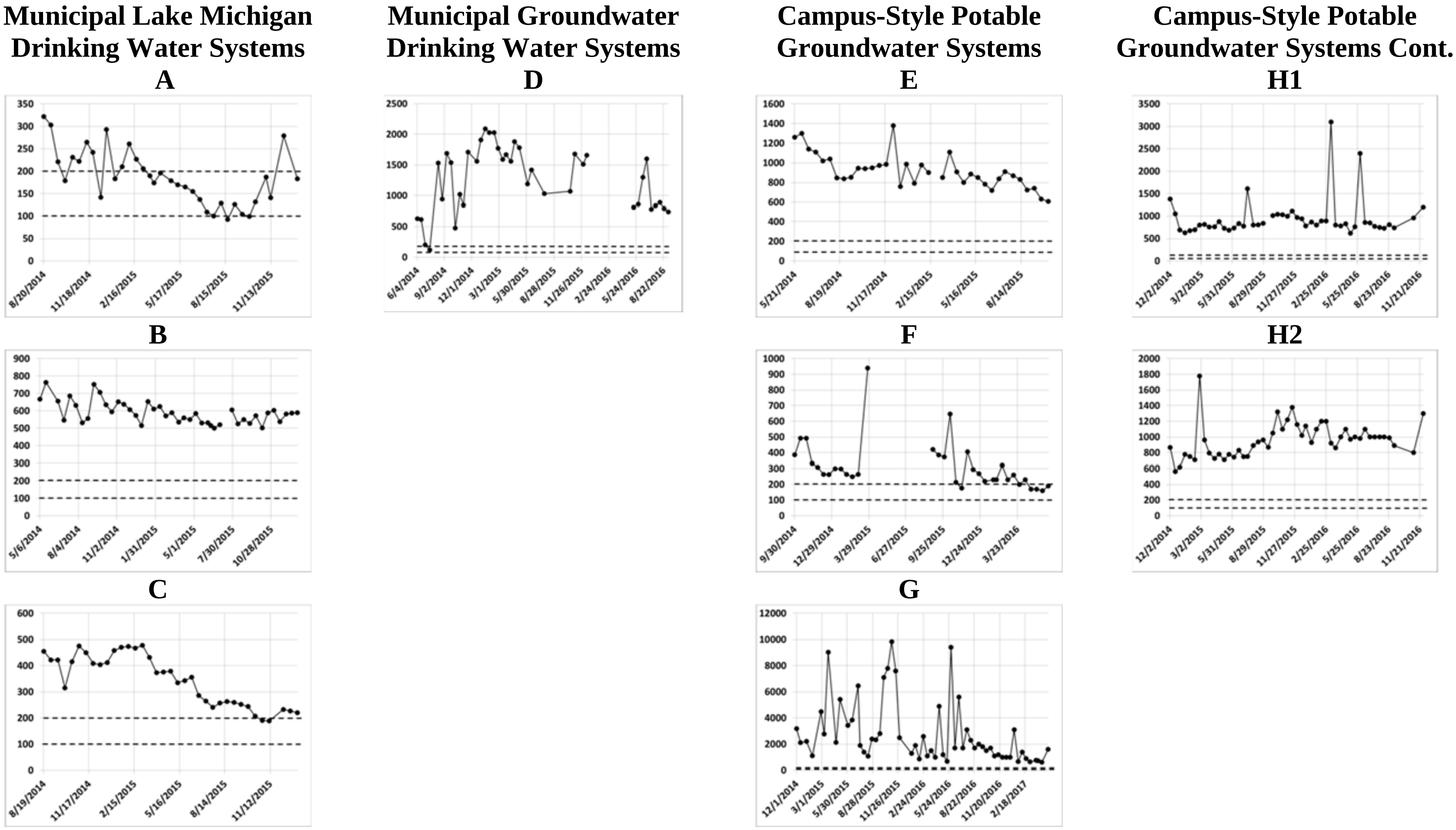
Table 6.5 shows the copper concentrations flowing in the system water at the high water age locations where the PRS Monitoring Stations were located. Anecdotally, concentrations <50 µg/L would be expected for system water copper levels. Water Systems D, G, and H have the highest concentrations of copper in the system water of the eight water systems.

Table 6.5
Total copper concentrations in flowing system water in µg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	5.5	5.1	4.6
B	33	11	0
C	24	16	7.6
D	166	90	14
E	53	27	0.5
F	18	9.1	0.2
G	1410	930	0
H1	79	48	17
H2	203	108	12

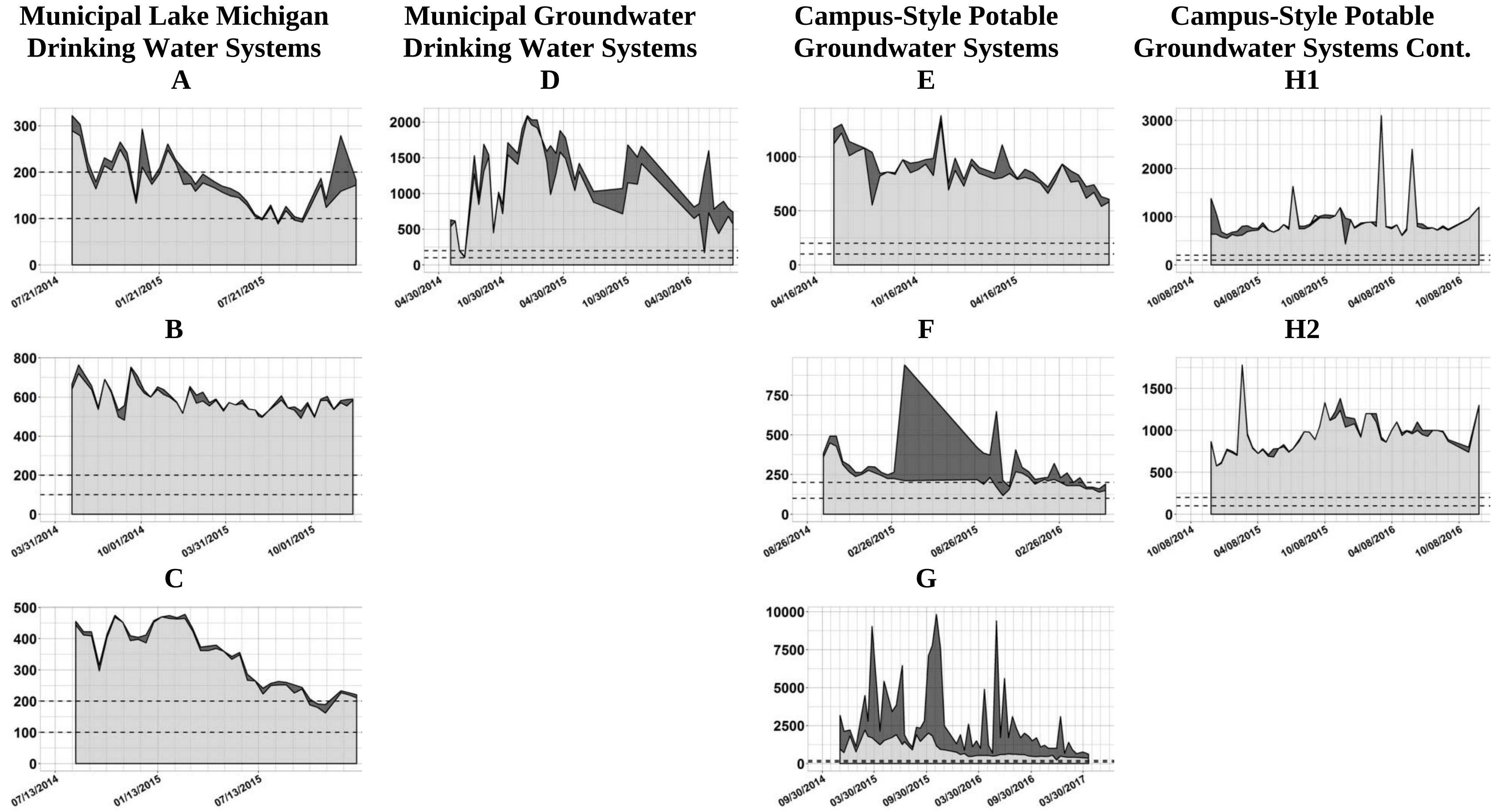
Stagnating Test Chamber Water

Figures 6.3 and 6.4 display the copper concentrations measured in the PRS Monitoring Station copper test chamber stagnating water.



1. F had a period of no monitoring during a water main replacement program.
2. D had a period of no monitoring while a new water treatment plant was optimized.

Figure 6.3 Total copper concentrations released into PRS monitoring station copper test chamber stagnating water in µg/L



1. F had a period of no monitoring during a water main replacement program.
2. D had a period of no monitoring while a new water treatment plant was optimized.

Figure 6.4 Relative concentrations of dissolved and particulate copper fractions released into PRS monitoring station copper test chamber stagnating water in μg/L

The goals for copper concentrations in a copper test chamber are <200 µg/L as satisfactory and <100 µg/L as excellent. These goals are drawn as dotted horizontal lines on the graphs. Water System A copper test chamber total copper release fell into the desired copper concentration range. Water System B hovered above the range. Water Systems C and F dropped into the range toward the end of the monitoring period. The other water systems released total copper in the copper test chambers at greatly higher concentrations than the desired range.

In Figure 6.4, Water Systems B, C, H1, and H2 released the lowest percent particulate copper concentrations in the copper test chambers. Water Systems A, D, and E released moderate quantities of particulate copper. (Water System A exhibited the same behavior in residential profile sampling described in Chapter 3.) Water System F released high particulate copper when water main construction began. Water System G routinely released high particulate copper concentrations in the copper test chamber.

The statistics for the dissolved, particulate, and total copper concentrations released in the PRS Monitoring Station copper test chambers are shown in Tables 6.6 to 6.8.

Table 6.6
Dissolved copper concentrations released into PRS monitoring station copper test chamber stagnating water in µg/L

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	248	169	89.2
B	714	576	438
C	413	336	259
D	1931	1038	146
E	1193	842	491
F	307	229	151
G	1674	1010	347
H1	1644	875	106
H2	1292	938	584

Table 6.7
Particulate copper concentrations released into PRS monitoring station copper test chamber stagnating water in µg/L

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	57	18	0
B	58	15	0
C	35	11	0
D	659	227	0
E	297	80	0
F	25	7.4	0
G	7949	2239	0
H1	251	71	0
H2	89	24	0

Table 6.8
Total copper concentrations released into PRS monitoring station copper test chamber stagnating water in µg/L

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	297	187	77.1
B	729	590	451
C	415	346	277
D	2158	1266	373
E	1211	918	625
F	575	313	51
G	8876	3191	0
H1	1680	937	194
H2	1326	958	590

Total Copper = Dissolved Copper + Particulate Copper

CORRELATIONS

As described in Chapter 5, many water quality parameters were measured in flowing system water and stagnating test chamber water in addition to tracking the dissolved and particulate lead and copper release in the test chambers. Common trends between lead and copper release and the other water quality parameters were studied visually using aligned time series graphs and mathematically using Spearman's rank correlation. Chapter 5 discusses the pitfalls of trending analyses, such as assuming cause and effect relationships or overlooking time lagged relationships. Nevertheless, it is informative to, at least, capture general relationships in order to form theories as to what mechanisms shape the water quality in an individual water system. Predictions of future water system behavior based on the theories must match measured observations of outcomes, otherwise theories must be changed. This is empirical science; it is a common industrial process control technique (Wheeler and Chambers 1992).

The overall narrative of water quality influences for each water system based on the observations and correlations are presented here. This project involved a great quantity of data, graphs, and correlations, which cannot all be discussed in this report. Some details of observed trending patterns are shown in Appendix A to accompany the narratives below.

Water System A

Two major seasonal events contributed to water quality characteristics in Water System A during the monitoring period. One event was alum dosing at the water treatment plant. Alum (aluminum sulfate) is used as a coagulant to lower the turbidity of the source water and was used in higher concentrations in cooler and colder temperatures of the year when the source water was more turbid. This introduced aluminum and sulfate into the water, each with their own patterns in the system water. Turbidity and pH were also related to the alum dosing. The second major seasonal event in this water system was nitrification. In the spring when temperatures began to rise, ammonia began releasing from the chloramine disinfection. Several weeks after the peak of ammonia release, the ammonia concentration diminished but dissolved organic carbon began to increase and peaked during the middle of summer. Dissolved lead released in the lead test chamber began to increase as ammonia was released; the dissolved lead diminished as the dissolved organic carbon diminished. Also initiated as the ammonia began to increase was the increase of nitrite/nitrate. This increase continued past the ammonia cycle and the dissolved organic carbon cycle on into the late autumn. Along with the nitrite/nitrate increase was an increase in dissolved copper release from the copper test chamber. Particulate metals measured in the system water and in the two test chambers trended with the nitrite/nitrate increase also. Here, turbidity, particulate iron, manganese, copper, and aluminum were measured in the upward trend. In addition, chloride, sulfate, and total phosphorus and particulate lead increased during this time period. Similar patterns have been seen for nitrification and lead and copper release in other PRS Monitoring Station projects in chloraminated water systems.

Water System B

Two phenomena were identified with Water System B that appeared to influence water quality. First, a crumbling manganese and iron scale on an existing lead service line had previously been identified by pipe wall scale analysis as a major source of capturing and transporting particulate lead in the water system. A uni-directional flushing program was carried out in the water system to remove the old scale. Flushing in the proximity of the PRS Monitoring Station in August 2014 sent higher particulate metals to the influent of the station; higher particulate lead and copper releases were measured at this time period along with measurements of elevated particulate iron, manganese, and aluminum. The particulate metals also peaked together in January 2015 – possibly from another system disturbance – and then again in September through December 2015.

Nitrification patterns were observed. The patterns were similar to those observed for chloraminated Water System A. That is, ammonia was released at the beginning of warmer temperatures, peaking in early summer. Several weeks later, dissolved organic carbon peaked. Nitrite/nitrate concentrations began an ascent as temperatures warmed which carried into late autumn.

Dissolved lead and aluminum release and dissolved solids concentration, in general, trended with the ammonia increase. Dissolved copper trended inversely with the ammonia release. Particulate lead, copper, and other metals were found to trend with nitrite/nitrate in the late summer and autumn.

It seemed odd to observe the nitrification patterns in a non-chloraminated water system and odd to see metals seemingly respond to this lower level of nitrification. A later study into the biostability of the system by others (communication with Dr. Andrew Jacque on 3/27/2017) found that the 2005 installation of a second water transmission line from the lake to the treatment plant appears to have influenced the microbiological activity in the water system. The residence time of water was greatly increased with the new transmission line and microbiological populations and biofilms increased before the treatment plant. Acetate, a simple organic carbon compound, and ammonia were found to be produced by the microbiological activity in the pipe and the specific microorganisms were identified by DNA analysis. In this way, the biostability study located the source of the ammonia, organic carbon, and nitrate patterns that were observed at the monitoring station where they were related to dissolved and particulate lead and copper release patterns.

Water System C

Water System C had pronounced particulate lead release in the lead test chamber. The lead release trended with particulate iron, manganese, and especially aluminum release. Particulate copper release in the copper test chamber trended with particulate aluminum.

Dissolved copper released in the copper test chamber trended inversely with dissolved aluminum release. The dissolved aluminum in the system water had a similar pattern as in Water System A, which uses alum (aluminum sulfate) as a coagulant as does Water System C. Sulfate concentrations followed opposite trends with dissolved aluminum as was seen in Water System A.

The nitrification patterns of ammonia, nitrite/nitrate, dissolved organic carbon, and lead and copper release were not observed in Water System C as they were in Water Systems A and B. Nitrite/nitrate concentrations did not increase over the summer and into the autumn as they did in Water System A. Instead, they increased in the later winter and early spring, occurring just before an increase in chloride. This is a curious finding and might be related to the spring snow melt period and the effect of road salt on Lake Michigan water within a mile of the shoreline. It is possible that particulate lead release followed the nitrite/nitrate concentration trend but other factors may be involved because the particulate lead release continued long after the end of the nitrate concentration peak.

Water System D

Water System D had a long history of elevated iron and manganese and microbiological activity because of the use of a unique water treatment technique used before 1995. During the monitoring program for this project, particulate lead and particulate copper release trended with particulate iron and manganese in the system water and co-releasing in the test chambers.

Dissolved copper and dissolved lead trended with total phosphorus. This may be the result of a high polyphosphate fraction of total phosphorus, which holds metals in water. Or, it may be from sloughing of phosphorus and metal-laden biofilm from pipe walls as nutrients were removed in the water system with the improved water treatment for organic carbon removal. There were also similar patterns for ammonia and nitrite/nitrate.

Alkalinity trended inversely with dissolved copper and dissolved lead – higher alkalinity meant lower dissolved copper and lead. This may have been a function of which wells were providing water to the monitoring station on a given sampling day. That is, the wells on the west side of the city fed a treatment plant where alkalinity would have increased slightly. That water had lower polyphosphate addition and other different water quality parameters than the east side wells.

In terms of biostability parameters and their effect on metals release in Water System D, nitrification patterns were not seen. Dissolved lead and copper trended with ammonia and nitrite/nitrate. These parameters trended inversely to dissolved organic carbon and microbiological population.

Water System E

Water characteristics fluctuated between system water from the iron and manganese removal filter and softened water early in the monitoring period in 2014. By 2015, all water to the station was softened. There was lower dissolved lead and copper release at that time.

The higher lead and copper release with fluctuating water quality characteristics may be a function of rapid water quality transitions where surface scales can re-solubilize and re-precipitate with changing water characteristics.

Chloride increased over the monitoring period probably due to the more continuous use of water softeners with their higher chloride output as the project progressed. Dissolved lead and copper release in the test chambers inversely trended with chloride in the system water. This is opposite to expectations where chloride is known to solubilize lead and copper from compounds on pipe walls. Since chloride concentration was related to the use of the softeners, one explanation is that the newly-installed softeners acted as a filter to the system water coming from the iron/manganese removal filter. The water directly from the iron/manganese removal filter was seen to be degrading in quality as measured by a continuously increasing turbidity after the filter. This would be an interesting turn of events since the original water softeners were observed to be discharging elevated microbiological populations and higher metals concentrations.

Dissolved manganese release in the water was similar in trends to particulate manganese release. Particulate lead released in the lead test chamber trended with the dissolved and particulate manganese release patterns as did particulate copper released in the copper test chamber.

Dissolved organic carbon in the system water decreased over time as did dissolved lead and copper release. This may be due to the softeners acting as a barrier to contaminants from the system water. However, microbiological populations increased in the test chambers by the end of the monitoring period.

As stated, turbidity after the main water treatment filter slowly increased over time indicating a need to clean the filter for better treatment efficiency and to insure that biofilms did not develop on the filter media. As the turbidity increased over time, the chlorine concentration in the system water decreased. It was suspected that the water quality improvement as measured in the test chambers would begin to degrade over time.

Water System F

Particulate lead released from the lead test chamber trended with particulate iron and manganese release, as has been seen in the other water systems. Particulate copper released from the copper test chamber also trended with particulate iron and manganese release.

Dissolved lead released from the lead test chamber was low and steady throughout the monitoring period. Dissolved copper released from the copper test chamber decreased over time, especially after distribution system rehabilitation.

Microbiological populations decreased after distribution system rehabilitation. Dissolved copper release trended with microbiological population. Dissolved lead release somewhat trended with microbiological population. Disinfection increased as the population decreased.

Water System G

Dissolved lead release and dissolved copper release decreased over time and were similar except that dissolved copper stayed at a higher level for a longer period and then dropped to the lower level.

Total phosphorus and dissolved copper trended together. Other dissolved metals followed similar patterns, such as calcium, magnesium, aluminum, iron, nickel, etc. Ammonia concentrations in the system water also followed this trend.

Particulate lead released from the lead test chamber trended with particulate iron and manganese release. Particulate copper released from the copper test chamber also trended with particulate iron and manganese release.

Dissolved lead and copper release trended with microbiological population as measured in the test chambers.

Water System H

Two campuses, each with their own PRS Monitoring Station, make up Water System H and receive water from the same wells. At both monitoring stations, particulate lead and particulate copper release trended with particulate iron and particulate manganese release. Dissolved lead and dissolved copper release trended with microbiological populations measured in the test chambers' water.

On Campus H2, dissolved lead release trended inversely with orthophosphate concentration in the water as well as trending directly with microbiological population.

METAL PLATE SCALE ANALYSIS

At the end of the monitoring periods in each water system, the internal metal plates were removed from the test chambers and sent for chemical and microbiological analysis of the scales and biofilms that had developed over the monitoring period. This is discussed in Chapter 5.

Tables 6.9 and 6.10 show the scale coverage on the plates. For Water System A in Table 6.9, scale coverage of 0.86 means that minerals had built up on 86 percent of the plate area. Fourteen percent of the plate area remained as bare metal at the time the plates were removed from exposure to the system water. In these water systems, scale formed more readily on lead surfaces (Table 6.9) than on copper surfaces (Table 6.10).

Tables 6.9 and 6.10 also list the general composition of the scales on the lead and copper plates. In x-ray diffraction analysis, minerals are identified. If a mineral has a peak higher than the other minerals, it is in greatest abundance on the plate. The other peaks are referred to as a percentage of the highest peak.

Minerals form in a succession from the least stable to the most stable as the compounds approach a thermodynamic equilibrium. In lead, litharge, a lead oxide, is the first to form. Then, the lead carbonates (cerussite and hydrocerussite) form. More stable minerals form under special conditions: plattnerite can form in a highly oxidizing environment; pyromorphite can form with a sufficient availability of orthophosphate ion.

In Table 6.9, the various combinations of litharge, cerussite, and hydrocerussite can be seen to have formed in the water systems. On the Water System A lead plates, these minerals were patchy and all exposed to the water as opposed to the carbonates overlying the litharge and preventing contact of the less stable compound with the water. Only Water System E showed the presence of the more insoluble plattnerite. Water System E had such a variety of lead compounds that it appeared it had been subjected to highly fluctuating oxidation potentials with changing precipitation and dissolution of compounds. Water System E was the water system where system water fluctuated between hard and soft water. Also, the scale was mostly of lead carbonate (cerussite) but it was very crumbly and prone to particulate lead release.

Water System D lead plate scales were oddly colored and will be discussed further as the metal plate scales are discussed in other chapters. Pyromorphite, found in Water System A, C, and E, is the desired mineral to form when adding orthophosphate for lead and copper corrosion control. It will be discussed further in Chapter 8.

For copper (Table 6.10), cuprite, a copper oxide, is the first mineral to form. Cuprite was the most common mineral found on the plates in this project. Tenorite, a copper oxide at a higher oxidation state, is more stable than cuprite and sometimes forms in cold water, although it is more likely to form in hot water. Only Water System F had a trace of tenorite. When alkalinity is sufficient, malachite, a copper carbonate, is the last mineral to form and is very stable. Water System E had a significant amount of the more stable mineral, malachite. For Water System D, cuprite was predominant with no malachite measured. However, the plates were green like the color of malachite. This will be discussed further as the metal plates scales are discussed in other chapters.

In addition to the identification and quantification of the minerals that formed on the lead and copper surfaces of the test chamber plates, other elements were found by other analytical techniques. Those findings will be discussed in later chapters.

Table 6.9

Major minerals on PRS monitoring station lead plates by x-ray diffraction

Water System	**Scale Coverage**	**Litharge**	**Cerussite**	**Hydrocerussite**	**Plattnerite**	**Pyromorphite**
		PbO	**$PbCO_3$**	**$Pb_3(CO_3)_2(OH)_2$**	**PbO_2**	**$Pb_5(PO_4)_3Cl$**
A	0.86	84		98		100
B	0.97	100	58	55		
C	0.99		100	28		35
D	1.00	70	60	100		
E	0.91		100		35	67
F	1.00	100	59			
G		Monitoring station will operate until June 2017				
H1	1.00	96	100	43		
H2	1.00	100	13	75		

Amounts are percent of largest x-ray diffraction peak for scale minerals
Scale coverage is (Pb metal peak on actual plate/Pb peak on pure metal)

Table 6.10

Major minerals on PRS monitoring station copper plates by x-ray diffraction

Water System	**Scale Coverage**	**Cuprite**	**Tenorite**	**Malachite**
		Cu_2O	**CuO**	**$Cu_2CO_3(OH)_2$**
A	0.33	100		
B	0.75	100		
C	0.93	100		
D	0.42	100		
E	0.63	100	2	13
F	0.89	49		100
G	Monitoring station will operate until June 2017			
H1	0.33	100		4
H2	0.43	100		2

Amounts are percent of largest x-ray diffraction peak for scale minerals
Scale coverage is (Cu metal peak on actual plate/Cu peak on pure metal)

SUMMARY

Lead and copper release trends were tracked in the stagnating water of PRS Monitoring Station test chambers in eight water systems. The concentrations of lead and copper release, although higher than actual water system release concentrations, indicated the release trends in the water system as operations and water chemistry changed over time.

The release patterns also indicated the degree that different forms of the metals – dissolved versus particulate – were found in the actual water system. Using trending analysis between a variety of other water quality parameters measured during the monitoring programs and the released metal forms, it was shown that different factors influence particulate lead and copper than influence dissolved lead and copper. In this project, factors co-trending with each metal fraction are summarized in Tables 6.11 and 6.12. Refer to Appendix A to study more trending details.

Regarding trending analysis, cause and effect are difficult to assign. Nevertheless, co-trending water quality parameters determined by graphical means and correlation calculations are the foundation of lead and copper release theories. It is seen that multiple factors work on the water system simultaneously shaping the final water quality, including lead and copper release.

More detailed aspects of the influencing factors are discussed in the following chapters:

- Chapter 7: Factors Related to Uniform Corrosion of Metals
- Chapter 8: The Influence of Phosphate on Corrosion of Metals
- Chapter 9: Factors Related to Biostability and Microbiologically Influenced Corrosion of Metals
- Chapter 10: Factors Related to Chemical Scale Formation and Dissolution and Their Influence on Metal Transport in Water Systems
- Chapter 11: Operations, Maintenance, and Cleaning of Water Systems and Their Influence on Metal Release

Table 6.11
Summary of factors co-trending with the release of dissolved lead and copper

Dissolved Lead

Parameter	Water System								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H1**	**H2**
Alkalinity				-					
pH	+								
Chloride					-				
Sulfate					+				
Iron									
Manganese									
Aluminum	+								
Nitrification	+	+							
Ammonia				+					
Nitrate				+					
Dissolved Organic Carbon				-	+				
Microbiological Population		+	+	-		+	+	+	+
Total Phosphorus	+		+	+					
Orthophosphate	+		+						-

Dissolved Copper

Parameter	Water System								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H1**	**H2**
Alkalinity				-					
pH	-								
Chloride					-				
Sulfate					+				
Iron									
Manganese									
Aluminum	-		-						
Nitrification	+	+							
Ammonia				+					
Nitrate				+					
Dissolved Organic Carbon	-			-	+				
Microbiological Population		+	+	-		+	+	+	+
Total Phosphorus	-		+	+			+		
Orthophosphate	-		+				+		-

+ = trended together; - = trended inversely

Table 6.12
Summary of factors co-trending with the release of particulate lead and copper

Particulate Lead									
Parameter	**Water System**								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H1**	**H2**
Alkalinity									
pH									
Chloride									
Sulfate									
Iron		+	+	+		+	+	+	+
Manganese	+	+	+	+	+	+	+	+	+
Aluminum	+	+	+			+	+		
Nitrification	+								
Ammonia									
Nitrate									
Dissolved Organic Carbon	-								
Microbiological Population									
Total Phosphorus									
Orthophosphate									

Particulate Copper									
Parameter	**Water System**								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H1**	**H2**
Alkalinity									
pH									
Chloride									
Sulfate									
Iron	+	+		+		+	+		+
Manganese	+	+		+	+	+	+		+
Aluminum	+	+	+			+			
Nitrification	+								
Ammonia									
Nitrate									
Dissolved Organic Carbon	-								
Microbiological Population			+						
Total Phosphorus									
Orthophosphate									

+ = trended together; - = trended inversely

CHAPTER 7
FACTORS RELATED TO UNIFORM CORROSION OF METALS

A fundamental aspect of lead and copper corrosion is a phenomenon called "uniform corrosion" which was described in Chapter 1.

This chapter explores aspects of uniform corrosion to determine how significant the phenomenon might be in controlling lead and copper release to the drinking water in the participating water distribution systems.

CARBONATE SOLUBILITY

Data

The focus of the Lead and Copper Rule is on the lead and copper carbonate compounds that are formed in the uniform corrosion process. The water quality parameters of pH, alkalinity, conductivity, hardness, and temperature control the formation of the lead and copper carbonate compounds and their solubility. Tables 7.1 to 7.5 list the statistics for these water quality parameters measured in the eight water systems studied. All parameters were measured in the system water flowing into the PRS Monitoring Station test chambers. This was a location of high water age in each distribution system.

Calculated Parameters

Using the water quality parameters listed in Tables 7.1 to 7.5, other uniform corrosion-related parameters can be calculated. Table 7.6 shows the calculated parameters for the participating water systems using the average values of parameters measured over the system monitoring periods. The calculation is performed using the RTW computer model (Tetra Tech and AWWA 2011).

Dissolved inorganic carbon (DIC) is the carbonate concentration in the water. Because the EPA lead and copper solubility models are based on solubility of lead and copper carbonate compounds, it is important to calculate the concentration of the carbonate in the water. DIC is somewhat synonymous with alkalinity. However, alkalinity is a combination of carbonates and other constituents in water that function to neutralize acids. DIC is calculated by knowing the alkalinity of the water as well as the other parameters previously mentioned. Early research in water system corrosion found that a DIC greater than about 10 but less than about 50 mg/L as carbon is important in lowering lead and copper corrosion (AwwaRF and DVGW 1996). In this study, the surface water systems A, B, and C were considered to have satisfactory concentrations of carbonate in addition to System D, which has shallow wells with lower alkalinity water. The other water systems have deeper wells with much higher alkalinity and DIC above what would be considered a satisfactory level.

Table 7.1
Conductivity in flowing system water at a high water age location in µmhos/cm (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average	Lowest Expected Concentration
A	333	308	283
B	308	299	290
C	344	305	266
D	980	516	51
E	588	504	420
F	673	618	563
G	581	522	462
H1	1120	815	509
H2	1104	819	534

Table 7.2
Total hardness in flowing system water at a high water age location in mg/L as $CaCO_3$ (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	144	135	126
B	146	136	127
C	150	138	127
D	117	92	66
E	159	27	0
F	355	316	276
G	306	272	238
H1	445	397	348
H2	434	394	353

Table 7.3
pH in flowing system water at a high water age location in SU (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average	Lowest Expected Concentration
A	8.1	7.9	7.8
B	8.1	7.9	7.6
C	7.9	7.8	7.7
D	7.9	7.3	6.6
E	8.3	7.9	7.5
F	7.7	7.5	7.3
G	7.8	7.5	7.3
H1	7.6	7.4	7.1
H2	7.7	7.4	7.1

Table 7.4
Total alkalinity in flowing system water at a high water age location in mg/L as CaCO3 (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	112	103	93
B	122	107	92
C	118	99	79
D	101	69	36
E	247	222	197
F	297	284	272
G	281	263	245
H1	329	309	289
H2	336	308	280

Table 7.5
Temperature in flowing system water at a high water age location in degrees C (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	15.2	12.6	9.9
B	14.7	12.5	10.3
C	14.8	13.1	11.3
D	20.9	17.5	14.1
E	15.4	12.7	9.9
F	12.5	10.7	8.9
G	11.9	10.6	9.3
H1	17.0	14.6	12.2
H2	20.6	15.3	10.1

The Calcium Carbonate Precipitation Potential (CCPP) and the Langelier Index have been suggested in corrosion literature as a basis for determining the corrosivity of water (Tetra Tech and AWWA 2011; APHA et al. 1995). These parameters quantify the degree to which calcium carbonate, a common constituent in water, will precipitate on the pipe walls. It was believed that calcium carbonate could form a protective layer on pipe walls to inhibit corrosion as was described for lead and copper carbonates. Early research showed that this was a misconception. Calcium carbonate forms a course, non-uniform, and porous scale and cannot inhibit corrosion of piping in water systems (AwwaRF and DVGW 1996). The EPA issued a corrosion guidance manual in 2016 that also recommended the practice of basing corrosivity of water on calcium carbonate precipitation be stopped (EPA 2016a).

Table 7.6
Calculated water quality parameters' average values in flowing system water at a high water age location (PRS monitoring station influent tap)

Water System	DIC mg/L as C	CCPP mg/L as CaCO3	Langelier Index
A	25	2.7	0.2
B	26	3.2	0.2
C	24	1.2	0.1
D	18	-11	-0.7
E	55	-4.6	-0.2
F	73	44	0.5
G	67	37	0.5
H1	80	60	0.6
H2	80	61	0.6
Value recommended by corrosion literature	*>10 and <50	*10 to 20	*>0

*DIC recommendation source: AWWA and DWVG 1996; CCPP and Langelier Index recommendation source: Tetra Tech and AWWA 2011; APHA et al. 1995
Values over the recommended value are shaded in the table.

CHLORIDE AND SULFATE SOLUBILITY

Data

Chloride and sulfate can also be significant factors in metal corrosion. Chloride and sulfate can be components of water treatment chemicals or constituents in the source water transferred from rocks and soil. Chloride can also enter the water supply as a residual from road salt. Compounds of lead and copper with chloride and sulfate are many magnitudes more soluble than lead and copper carbonate compounds. Chloride and sulfate concentrations found in the system water flowing into the PRS Monitoring Station are listed in Tables 7.7 and 7.8.

Table 7.7
Chloride concentration in flowing system water at a high water age location in mg/L (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	17	15	14
B	15	14	13
C	19	16	12
D	152	82	11
E	29	21	14
F	20	18	16
G	8.0	5	2
H1	114	77	41
H2	138	78	19

Table 7.8
Sulfate concentration in flowing system water at a high water age location in mg/L (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	29	25	22
B	24	22	20
C	27	25	23
D	12	7.9	3.7
E	10	9.0	7.5
F	27	22	17
G	19	14	9.0
H1	48	41	35
H2	54	39	24

Calculated Parameters

Various researchers have studied the corrosive effects of chloride and sulfate in context with other factors. One aspect of their chemistry is that they compete with carbonate to form compounds of lead and copper. If the carbonate is high relative to the chloride and sulfate concentrations, less-soluble carbonate compounds are formed more readily and increased solubility of lead and copper from chloride and sulfate compounds becomes less significant. In other words, the corrosivity of the water is dependent on “the proportion of corrosive agents to the inhibitive agents,” where chloride and sulfate are corrosive and carbonates are inhibitive (Larson and Skold 1958). The Larson-Skold Index has been used to express this competition. If the Larson-Skold Index is greater than 0.8, metals corrosion, including lead and copper, will be higher than desired (Masten et al. 2016). The calculated values for the water systems studied are shown in Table 7.9. Water System D had a Larson-Skold Index>0.8.

Table 7.9
Larson-Skold Index in flowing system water at a high water age location (PRS monitoring station influent tap)

Water System	Maximum Calculated Value	Average Value	Minimum Calculated Value
A	0.47	0.39	0.35
B	0.37	0.34	0.31
C	0.80	0.43	0.37
D	2.1	1.4	0.12
E	0.16	0.14	0.12
F	0.15	0.14	0.12
G	0.10	0.07	0.06
H1	0.70	0.40	0.26
H2	0.52	0.39	0.25

Larson-Skold Index = (Chloride + Sulfate)/(Alkalinity)
Larson-Skold Index recommendation source: Masten et al. 2016

The chloride to sulfate mass ratio (CSMR) was studied as a factor in galvanic corrosion in a water system, including corrosion of lead from lead solder and lead pipe connected to copper pipe (Nguyen et al. 2010). In addition, chloride compounds typically have a higher solubility than sulfate compounds. A higher CSMR indicates a greater potential for more soluble metal corrosion by-products. It was recommended that the CSMR be kept to <0.2 at best and <0.5 at most to prevent galvanic corrosion. A refinement of this recommendation advised to keep the CSMR <0.77 (Nguyen et al. 2011). The calculated values for the water systems studied are shown in Table 7.10. Water Systems D, E, F, and H have a CSMR>0.77. Water Systems A, B, C have a CSMR around 0.6. Only Water System G had a low CSMR.

Table 7.10
Chloride to sulfate mass ratio (CSMR) in flowing system water at a high water age location (PRS monitoring station influent tap)

Water System	Maximum Calculated Value	Average Value	Minimum Calculated Value
A	0.69	0.61	0.50
B	0.79	0.65	0.59
C	0.84	0.61	0.54
D	14	10	5.7
E	3.1	2.4	1.7
F	1.0	0.82	0.62
G	0.51	0.37	0.21
H1	2.6	1.9	1.3
H2	2.4	1.9	1.3

CSMR = Chloride/Sulfate
CSMR recommendation source: Nguyen et al. 2011

PHOSPHATE SOLUBILITY

Orthophosphate-based chemical products are used for lead and copper control as recommended and sometimes required by the Lead and Copper Rule. Orthophosphate ions form insoluble compounds with lead and copper and can create barriers on metal surfaces to inhibit the uniform corrosion process. Chapter 8 is dedicated to exploring the effects of orthophosphate on lead and copper release in the PRS Monitoring Station test chambers and they will not be discussed here.

SOLUBILITY UNDER HIGHLY OXIDIZING CONDITIONS

In 2005, it was acknowledged in the technical literature that the EPA solubility models and the Lead and Copper Rule had not taken into account the possible formation of a lead oxide that is highly insoluble (Lytle and Schock 2005). The lead oxide is the plattnerite mineral. It can only form when the lead ion has lost four electrons instead of the typical two. The only way four electrons can be lost is if the water environment is highly oxidizing. The oxidation/reduction potential (ORP) measures the oxidizing potential in the water environment. The higher the ORP, the more oxidizing the environment. If ORP is negative, it is a reducing environment. As an anecdotal guide, it is desired to see ORP values > 400 mV. Over 600 mV is excellent. All water systems had high average ORP values as seen in Table 7.11, although some water systems had periods of low values.

Table 7.11
Oxidation reduction potential (ORP) in system water at a high water age location in mV (PRS monitoring station influent tap)

Water System	Highest Expected	Average	Lowest Expected
A	782	704	627
B	739	642	545
C	758	532	306
D	No data		
E	671	514	358
F	732	572	411
G	749	524	300
H1	751	646	540
H2	732	589	446

EPA PREDICTED RELEASE OF LEAD AND COPPER

As stated previously, the Lead and Copper Rule is based on an idea that there is only one mechanism by which lead and copper are transferred from metal surfaces into drinking water (Code of Federal Regulations 2010b). In this concept, lead and copper are found in the water in dissolved form as soluble lead or copper carbonate compounds. The more insoluble fractions of the lead or copper carbonate compounds are assumed to form fine films on metal surfaces. These fine films can inhibit further transfer of metal ions between the metal surface and the water.

The carbonate solubility models behind the Lead and Copper Rule can be represented in graphical form. The graphs in Figure 7.1 are representations of the carbonate solubility model for prediction of lead release into water. In this model, water between pH 7 and 9 will have lower lead release than water with pH less than or greater than that range. There exists a pH somewhere within the range where lead release climbs to a maximum and then decreases as the pH continues to increase. In addition, DIC in a range of about 10 to 50 mg/L as carbon has the lowest lead release. Lower and higher DIC water types are predicted to release more lead.

The interplay between lead release and alkalinity (or dissolved inorganic carbon) and pH is based on the presence of two types of lead carbonates that are often observed coating leaded materials – cerussite ($PbCO3$) and hydrocerussite ($Pb3(CO3)2(OH)2$). Each type of lead carbonate exhibits its own solubility in water based on pH and alkalinity. Both carbonates become more soluble as pH decreases (water becomes more acidic). However, hydrocerussite is more soluble than cerussite at a pH less than 7.8. Theoretically, the more insoluble cerussite will form on the metal surfaces, inhibit the formation of hydrocerussite and control the lead solubility in the system. With alkalinity, the solubility of cerussite versus hydrocerussite varies based on pH. At a pH of 7, cerussite will be less soluble than hydrocerussite and will form on the metal surfaces, controlling the lead solubility in the water. At a pH of 8, hydrocerussite will theoretically dominate because it will be more insoluble than cerussite when the alkalinity is below 100 mg/L as $CaCO3$; above 100 mg/L, cerussite will control the lead solubility. (Communications with Dr. J. Barry Maynard on 4/19/17).

Figure 7.2 represents the carbonate solubility model behind the Lead and Copper Rule for copper. In addition, it has been proposed to be the basis of a Rule revision by which water systems will be deemed corrosive or non-corrosive to copper (Schock and Lytle 2014; Roth et al. 2016). From the figure, it is seen that the copper model, similar to the one for lead, predicts increasing copper release with lower pH and higher alkalinity. The shaded area on the graph delineates the alkalinity and pH combinations that are assumed to release copper over the Maximum Contaminant Level Goal (and coincidently, the Action Level) of 1300 µg/L. Those water systems will be assumed to always have elevated copper levels.

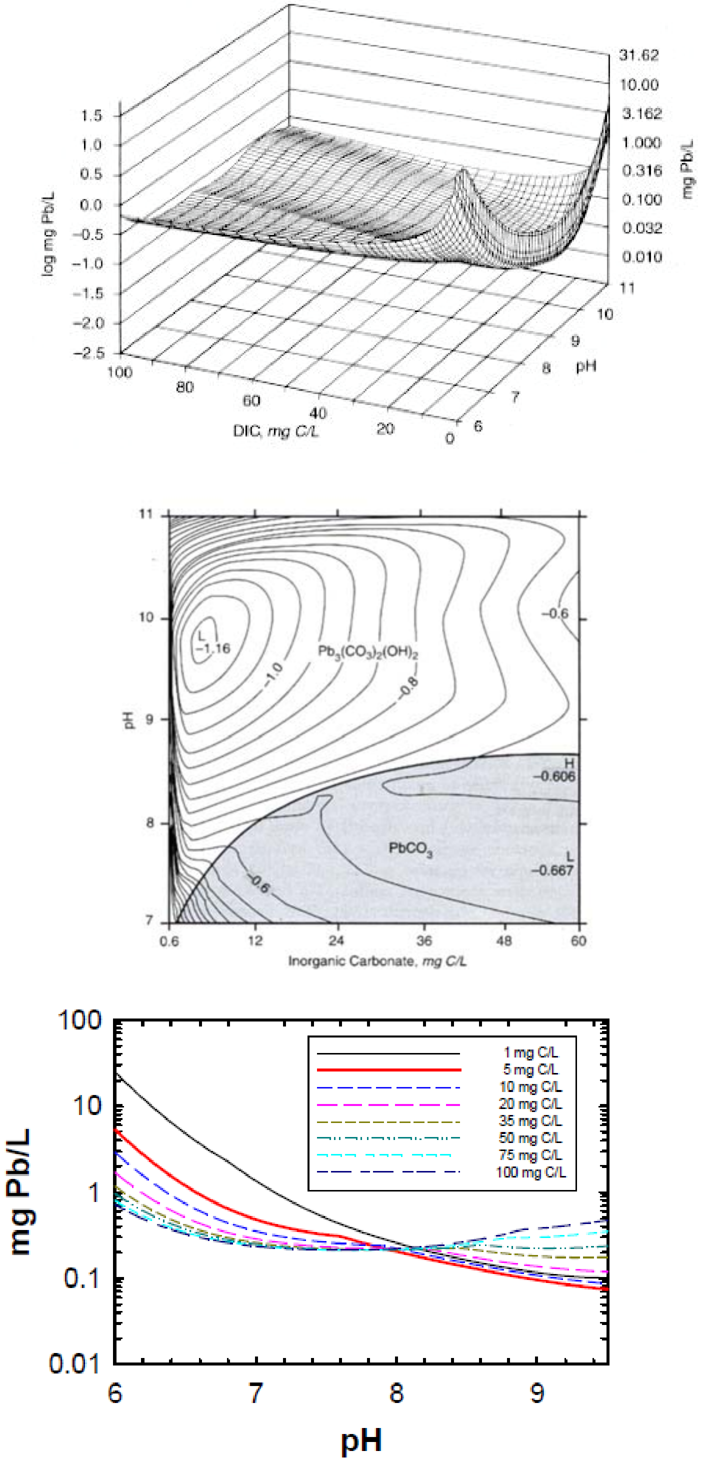
Steady State of Lead Release

The solubility model graphs can be used to predict the lead concentrations that would be expected in each of the project water systems. Then, the lead release data from the PRS Monitoring Station lead test chambers can be compared with the predictions. But, care must be taken to select the correct lead and copper release data. Of first consideration is that the EPA predictions are for dissolved lead concentrations only. The particulate lead concentrations measured in the eight water systems will not be used for comparison.

For the dissolved lead data, there was an initial time period when clean metal surfaces of the test chamber metal plates were first exposed to the system water. An explanation of uniform corrosion earlier in this chapter described a dynamic process of metals being released from piping material as ions, the metal ions forming new compounds in the water, and the rate and nature of the corrosion being controlled by the precipitation of the new compound as protective scales on the metal surfaces. These scales are typically composed of oxides and carbonates. Refer to Table 6.9 to see that oxides and carbonates did form in the lead test chamber. (Copper oxides and carbonates also formed as shown in Table 6.10.) Also, the dissolved lead concentrations measured in the PRS Monitoring Station test chamber stagnating water quite often show very high levels at first with a steep slope down to a lower steady state concentration range. Refer to Figure 6.2 Water Systems A, B, and D, to view the steep drop in dissolved lead concentration from clean metal newly exposed to water. (A similar copper release trend can be seen in Figure 6.4). The data to compare to the EPA solubility graphs are the dissolved lead concentrations measured in the stagnating lead test chamber water after a "steady state" concentration range has begun. From the monitoring station data, it is seen that a true steady state never occurs as each form of lead and copper is buffeted around by many factors over time. Nevertheless, the solubility model assumes that the water system is at equilibrium, so the most constant time period of measured monitoring data should be chosen for comparison.

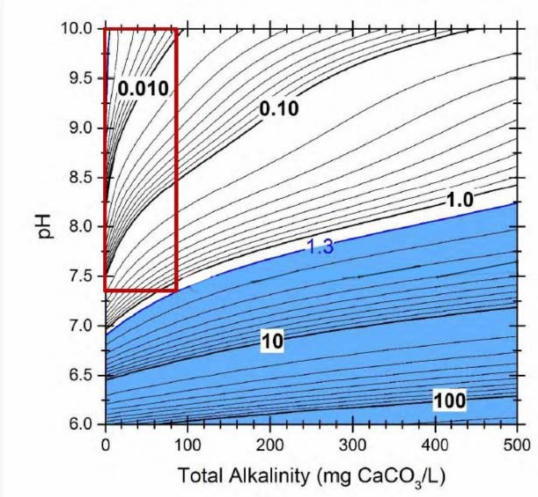
The determination of the steady state time period for monitoring station data was described in Chapter 5. A statistical method using Shewhart Control Charts was described. But, it was noted that many times the selection becomes subjective because of confounding water system events that buffet the lead concentrations up and down even during the initial scale formation period. Table 7.12 lists the number of days it took in each water system from the date of metal plate installation in the PRS Monitoring Stations until the dissolved lead concentrations exhibited the end of what appeared to be the initial scale formation period.

Table 7.13 lists the new dissolved lead statistics for each lead test chamber with the initial scale development period data removed from the data set and a more constant range of dissolved lead utilized for the statistical calculations.



Source: AwwaRF and DVGW 1996 (top and middle), and Brown et al. 2015, adapted from Schock and Lytle 2011 (bottom).

Figure 7.1 Representations of the EPA carbonate solubility model of lead



Source: Schock and Lytle 2014.

Figure 7.2 Representation of the EPA carbonate solubility model of copper

Table 7.12
Days to "steady state" for dissolved lead release in lead test chamber stagnating water

Utility Name	Days
A	240
B	176
C	247
D	76
E	35
F	370
G	371
H1	98
H2	55

Table 7.13
Dissolved lead concentrations released in lead test chamber stagnating water after "steady state" in µg/L

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	58	42	26
B	171	130	88
C	126	105	85
D	401	242	82
E	309	235	160
F	47	34	20
G	85	50	15
H1	298	173	48
H2	293	191	89

Steady State of Copper Release

The steady state release of dissolved copper from the PRS Monitoring Station copper test chambers was also determined. Table 7.14 lists the number of days it took in each water system from the date of metal plate installation in the PRS Monitoring Stations until the dissolved copper concentrations exhibited "steady state" behavior.

Table 7.14
Days to "steady state" for dissolved copper in copper test chambers

Utility Name	Days
A	353
B	302
C	37
D	104
E	119
F	175
G	511
H1	55
H2	55

Table 7.15 lists the new dissolved copper statistics for each copper test chamber with the initial scale development data removed from the data set and a more constant range of dissolved copper utilized for the statistical calculations.

Table 7.15
Dissolved copper concentration in copper test chamber after "steady state" in µg/L

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	195	122	49.4
B	633	549	465
C	413	336	259
D	1977	1116	255
E	1124	809	494
F	262	196	130
G	610	542	474
H1	1644	875	106
H2	1292	938	584

Comparisons between EPA Predictions and PRS Monitoring Station Lead and Copper Release Data

Figure 7.3 compares the average steady state dissolved lead release from PRS Monitoring Station lead test chambers to the EPA dissolved lead release predictions. There does not appear to be a relationship between the predictions and the actual release data. The relationship was explored again by comparing the test chamber data to average dissolved inorganic carbon concentration (DIC) for each water system in Figure 7.4. According to the carbonate solubility theory, dissolved lead release should be organized in some respect with DIC. The trend line and its correlation coefficient show that there was no linear relationship. Visually, the graph indicates that there were no other dependencies between the two variables.

Figure 7.5 compares the average steady state dissolved copper release from PRS Monitoring Station copper test chambers to the EPA dissolved copper release predictions. In this case, the lower DIC water systems appear to match the predictions. The higher DIC water systems are highly over-estimated.

The correlation of the lower DIC water with the predictions is confusing. In Table 6.11, nitrification and alum dosing were identified as two major factors that co-trended with dissolved copper release in this project with low DIC water systems. In addition, Figure 7.6 shows no relationship between steady state dissolved copper release and DIC, the water quality parameter underlying the carbonate solubility predictions. Therefore, the EPA predictions for copper release may coincidently correspond to the actual release at low DIC.

There are other indications that the EPA solubility model may not reflect reality. When the EPA model predictions are compared with predictions of lead and copper release from other standard solubility models, such as Phreeqc, there are discrepancies in the predicted concentrations. This comes from a difference in thermodynamic solubility parameters used in each model for species of carbonate complexes, such as for PbHCO3+. (Communications with Dr. Barry Maynard on 4/19/17).

The solubility models assume that the water/metal system is at equilibrium. However, studies of surface scale in this study have shown the presence of amorphous, thermodynamically unstable compounds of aluminum, iron, and manganese with their ability to adsorb other contaminants such as lead or copper. (This will be described in Chapter 10.) Non-equilibrium states are not accounted for in the solubility model. (Communications with Dr. Barry Maynard on 4/19/17).

Another observation of metal surfaces is that there is a diversity of lead and copper compounds that form and are present at the same time. The lead solubility cannot be predicted for such a mixed assemblage. (Communications with Dr. Barry Maynard on 4/19/17). This has also been acknowledged by others (DeSantis and Schock 2014). It is also seen in scale study results shown in Tables 6.9 and 6.10 for this project.

Comparisons between Calcium Carbonate Precipitation Indices and PRS Monitoring Station Lead and Copper Release Data

The role of calcium carbonate precipitation and lead corrosion was discussed earlier in this chapter. In summary, it was originally assumed that calcium carbonate, a common mineral in drinking water, could precipitate on the pipe walls and form a barrier to the uniform corrosion process. Researchers over several decades have proven this assumption incorrect. Nevertheless, it persists as a guide to lead and copper corrosion in the drinking water field (Tetra Tech and AWWA 2011; APHA et al. 1995).

Using the average steady state dissolved lead release data from the PRS Monitoring Station lead test chambers for each water system, lead release is compared to the calculated calcium carbonate precipitation potential in Figure 7.7. There is no correlation between the two parameters. In Figure 7.8, the exercise is repeated using the Langelier Index, of similar meaning to calcium carbonate precipitation potential. One data point that falls out of range with the other data points pulls the trend line into a stronger correlation. However, even though the correlation appears stronger, it is still below a correlation that could occur by chance.

The exercise is repeated for steady state dissolved copper release as seen in Figures 7.9 and 7.10. As with lead, there are no relationships between the indices and copper release.

Comparisons between Chloride and Sulfate Related Indices and PRS Monitoring Station Lead and Copper Release Data

Figures 7.11 to 7.14 compare steady state dissolved lead and copper release to the Larson-Skold Index and the Chloride to Sulfate Mass Ratio (CSMR). Similar to the calcium carbonate indices, there are no relationships between the metals release and the Larson-Skold Index regarding chloride and sulfate for the participating water systems.

In Figures 7.12 and 7.14, the CSMR has a strong fit using an exponential function. This does not confirm a connection between CSMR and galvanic corrosion but does put more weight on the fact that chloride compounds of metal are more soluble than sulfate ones.

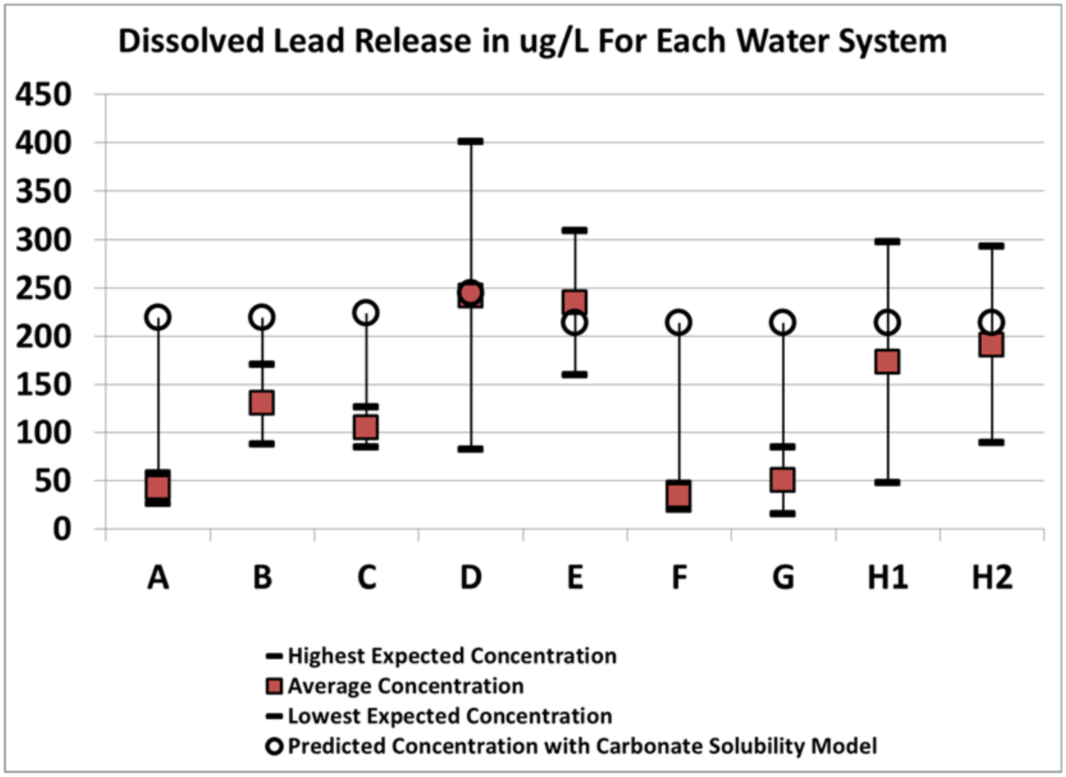


Figure 7.3 Steady state dissolved lead release into PRS monitoring station lead test chamber stagnating water compared to EPA dissolved lead release predictions

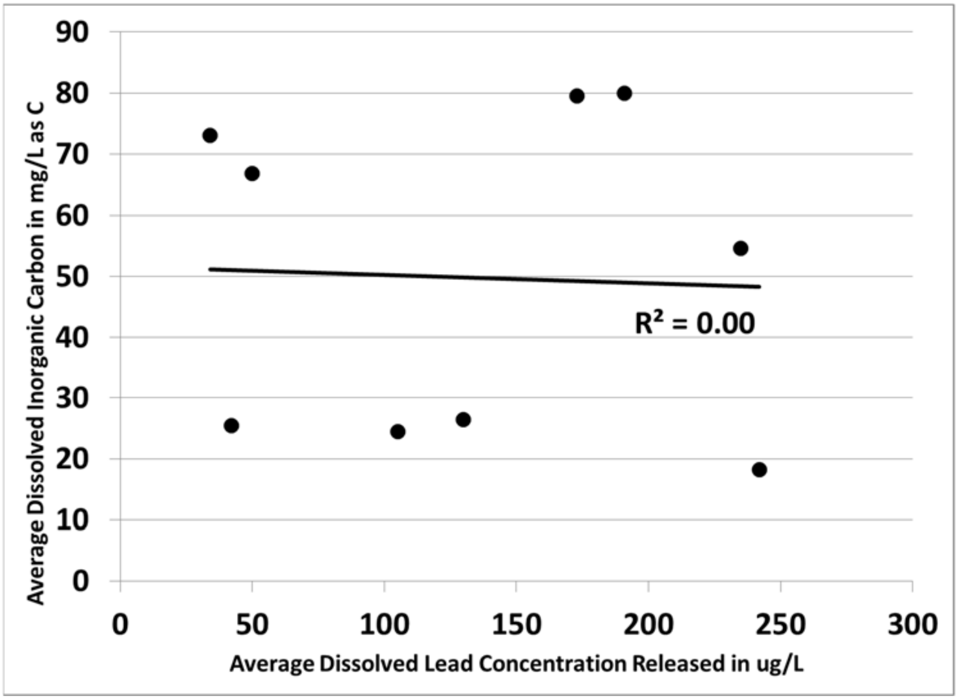


Figure 7.4 Steady state dissolved lead release into PRS monitoring station lead test chamber stagnating water in each water system compared to dissolved inorganic carbon concentration of the flowing system water

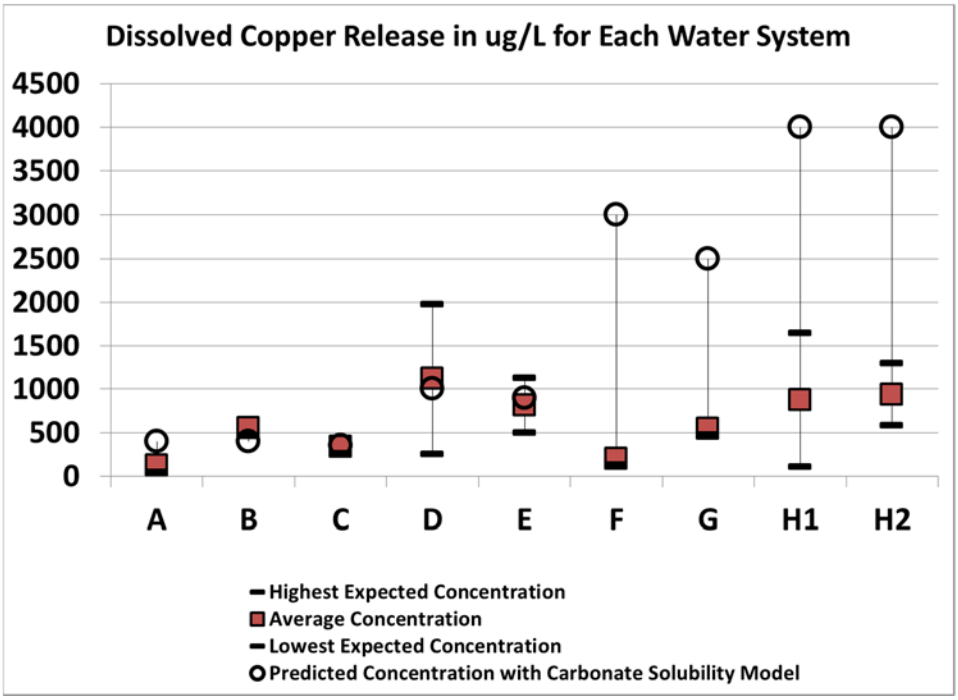


Figure 7.5 Steady state dissolved copper release into PRS monitoring station copper test chamber stagnating water in each water system compared to EPA dissolved copper release predictions

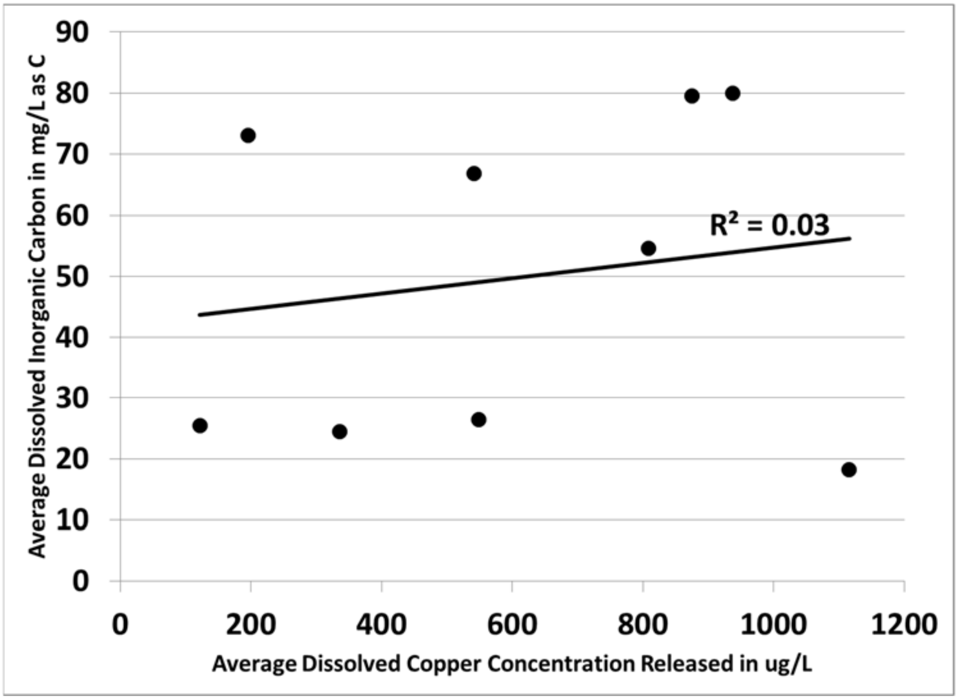


Figure 7.6 Steady state dissolved copper release into PRS monitoring station copper test chamber stagnating water compared to dissolved inorganic carbon concentration of the flowing system water

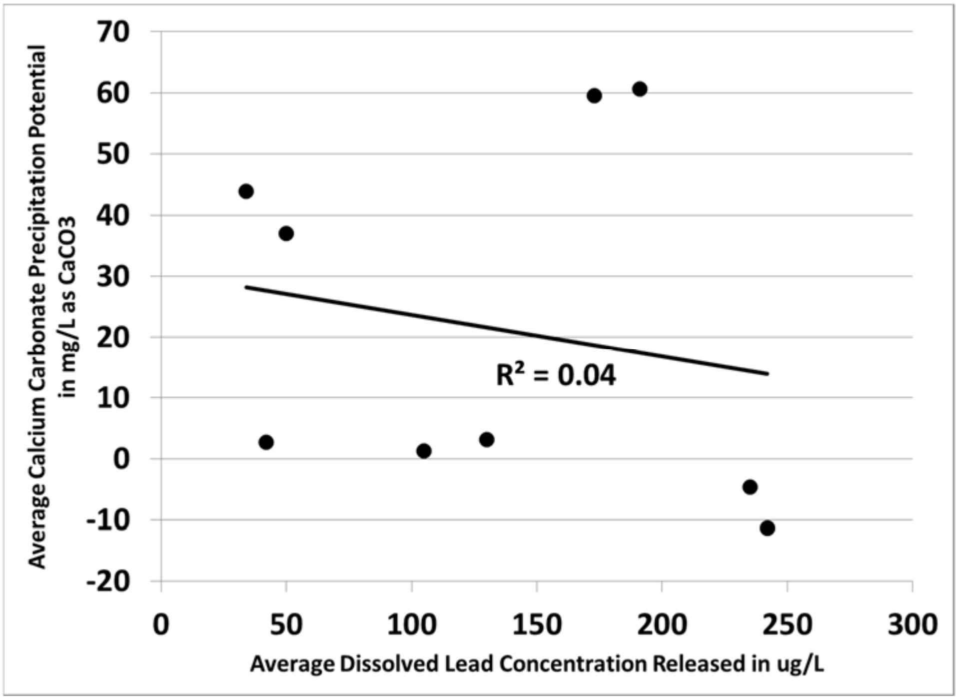


Figure 7.7 Steady state dissolved lead release into PRS monitoring station lead test chamber stagnating water compared to calcium carbonate precipitation potential of the flowing system water

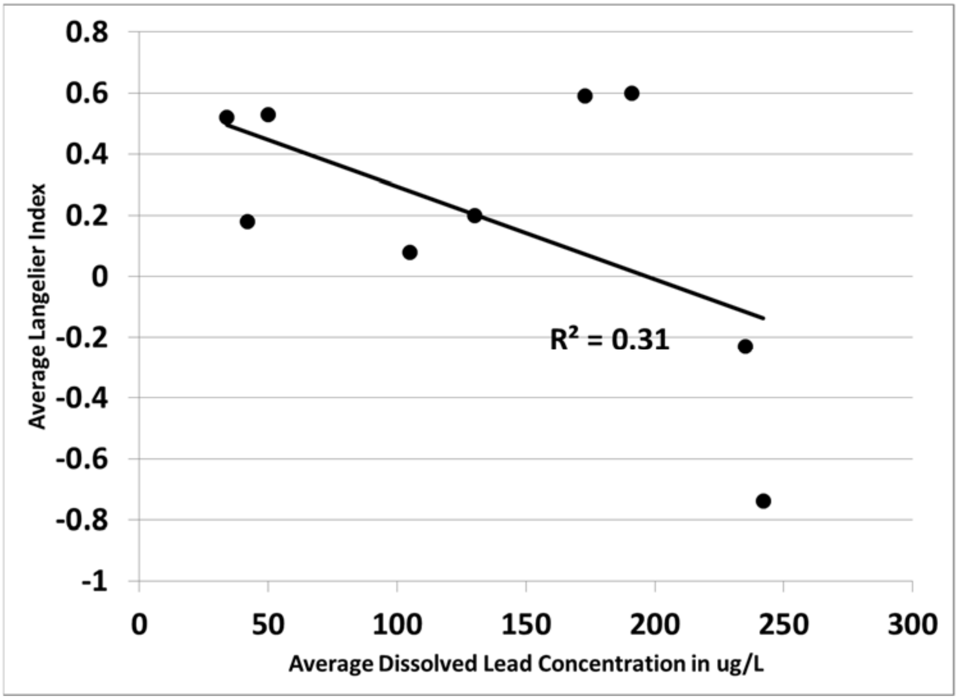


Figure 7.8 Steady state dissolved lead release into PRS monitoring station lead test chamber stagnating water compared to the Langelier Index of the flowing system water

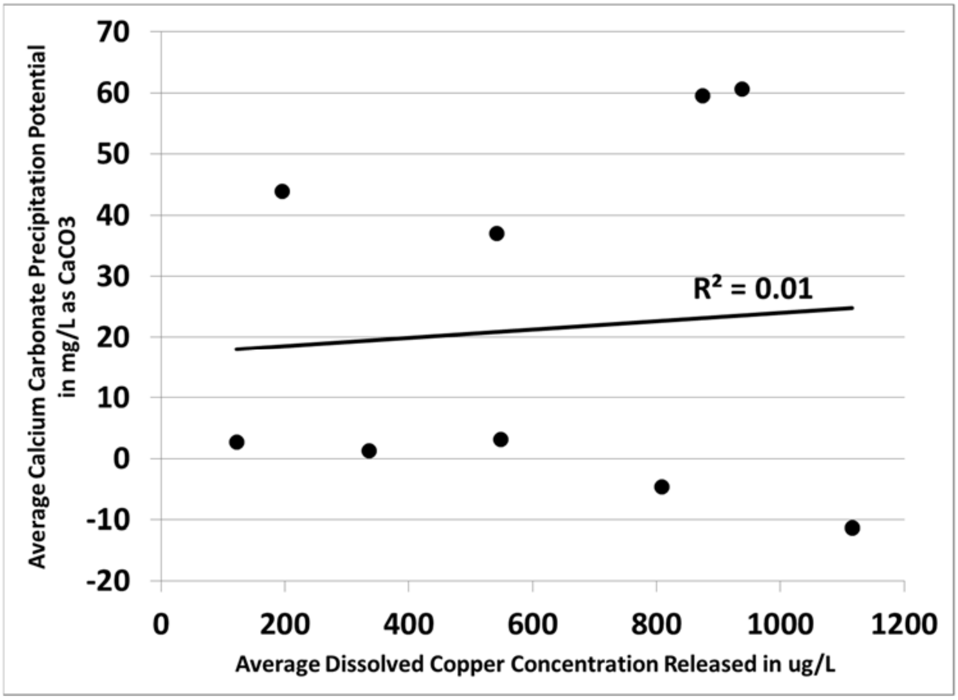


Figure 7.9 Steady state dissolved copper release into PRS monitoring station copper test chamber stagnating water compared to calcium carbonate precipitation potential of the flowing system water

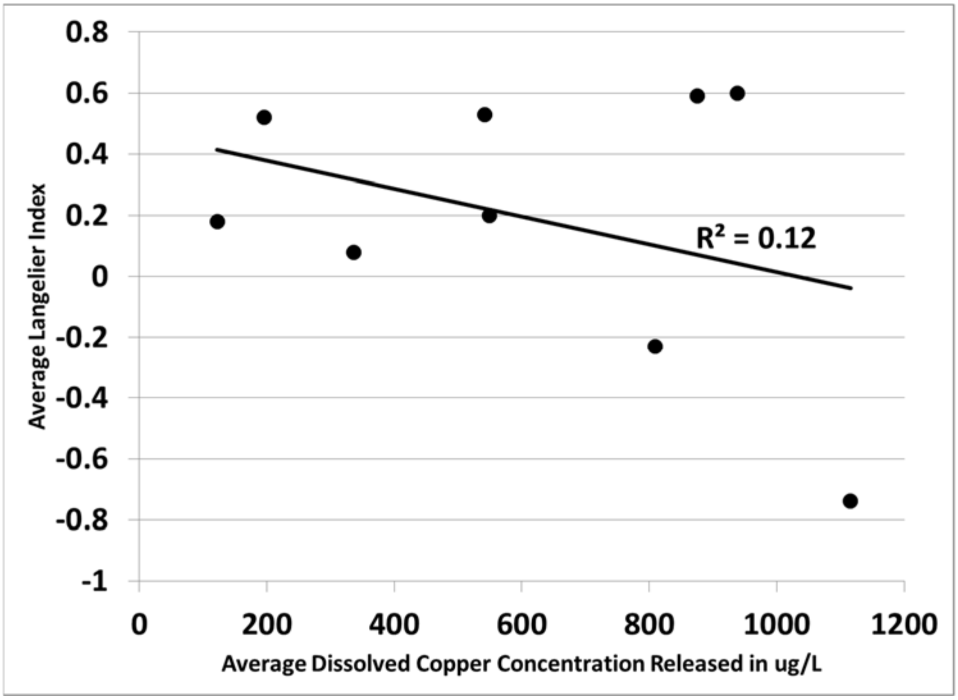


Figure 7.10 Steady state dissolved copper release into PRS monitoring station copper test chamber stagnating water compared to the Langelier Index of the flowing system water

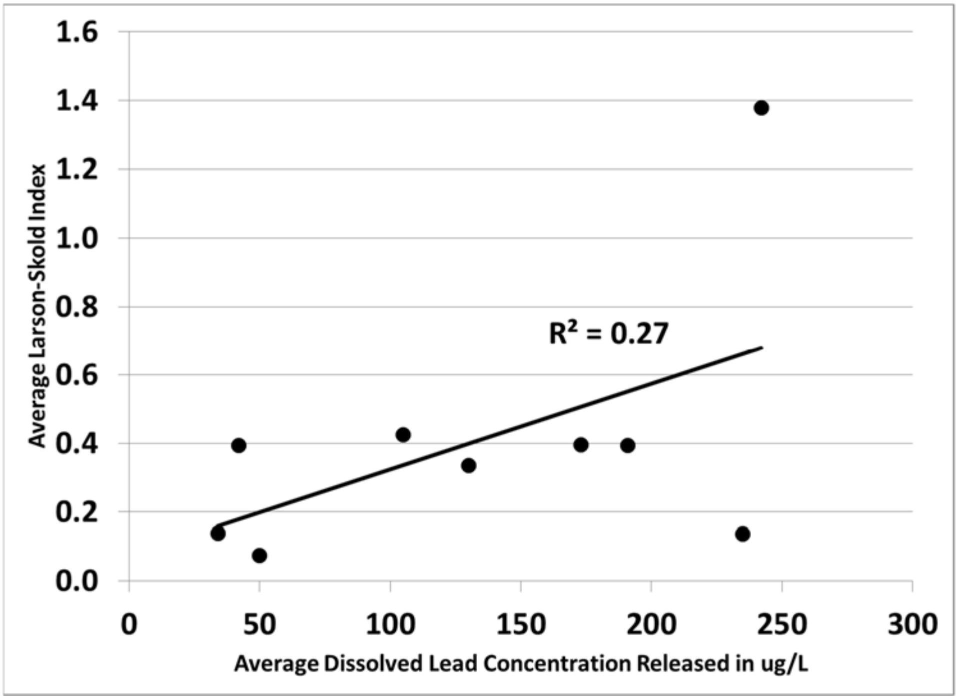


Figure 7.11 Steady state dissolved lead release into PRS monitoring station lead test chamber stagnating water compared to the Larson-Skold Index of the flowing system water

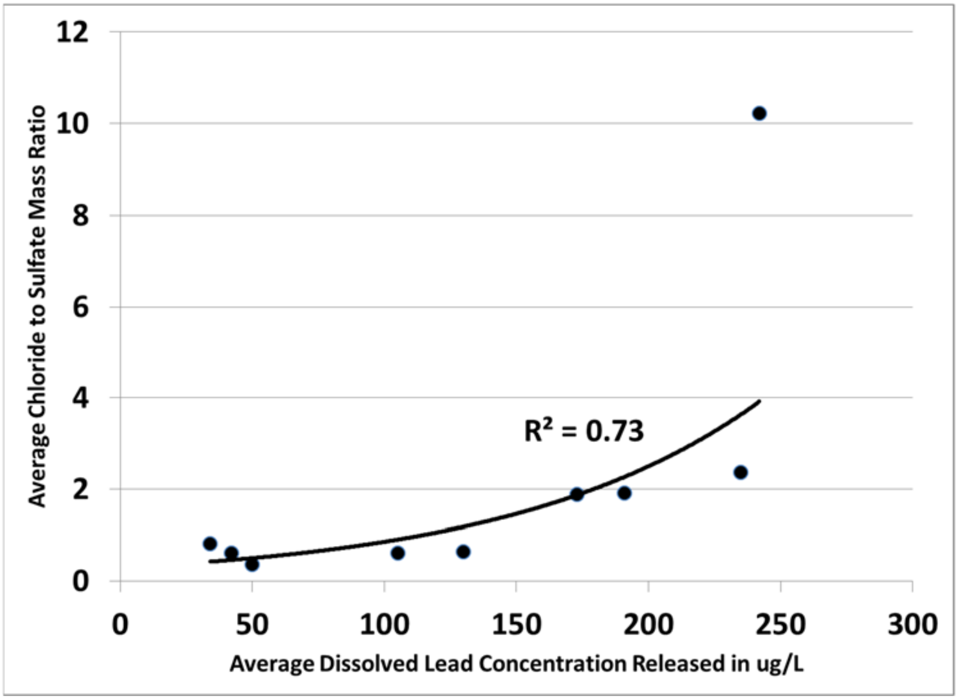


Figure 7.12 Steady state dissolved lead release into PRS monitoring station lead test chamber stagnating water compared to the chloride to sulfate mass ratio in the flowing system water

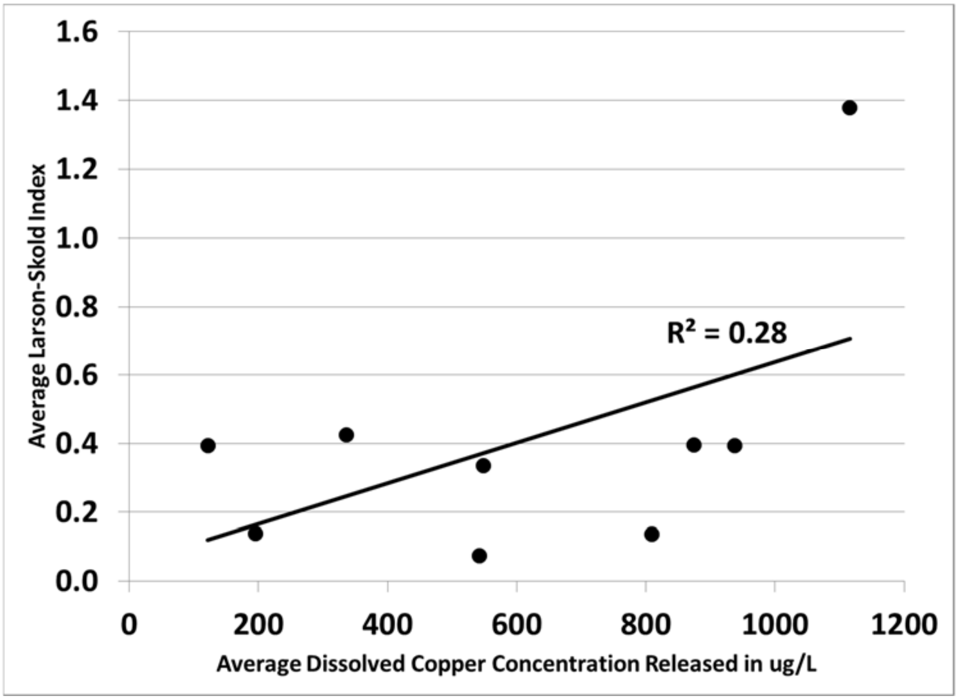


Figure 7.13 Steady state dissolved copper release into PRS monitoring station copper test chamber stagnating water compared to the Larson-Skold Index in the flowing system water

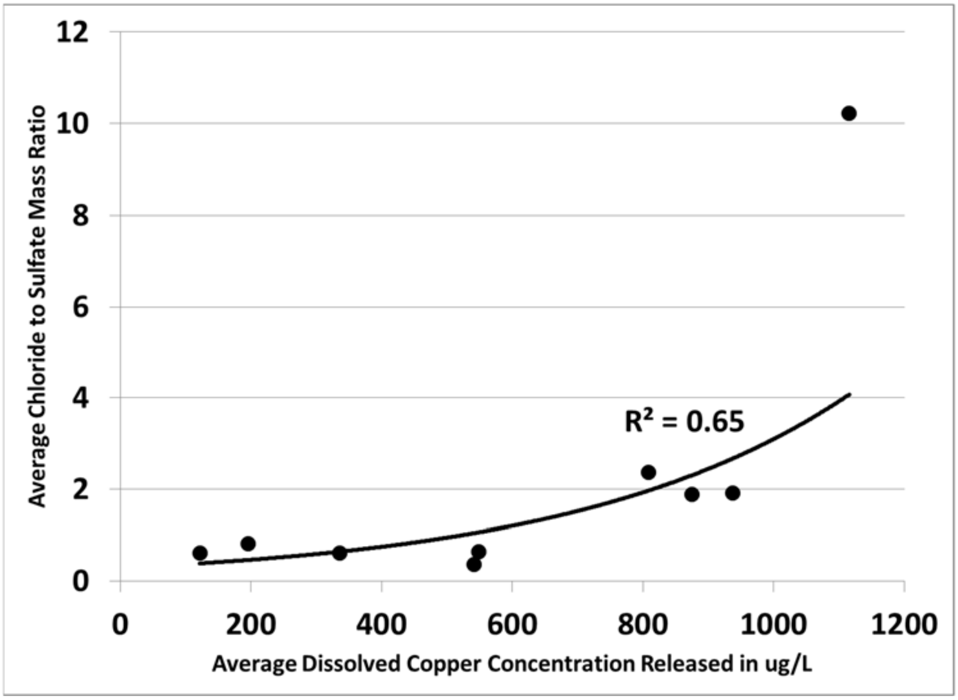


Figure 7.14 Steady state dissolved copper release into PRS monitoring station copper test chamber stagnating water compared to the chloride to sulfate mass ratio in the flowing system water

UNIFORM CORROSION ASPECTS OF THE METAL PLATE SCALES

Carbonate and oxide compounds of lead and copper found on the metal surfaces of the test chamber plates were described in Chapter 6 and Tables 6.9 and 6.10. These compounds are predicted to form using the thermodynamic equilibrium concepts described earlier.

Tables 7.16 and 7.17 list other components found in the scales on the metal plates. Water Systems A, B, and C use the same water source. However, from Table 7.16, Water System C had lower calcium incorporated into its lead plate scales than did Water Systems A and B. Water Systems B and C also had magnesium in the scales. The other water systems with harder water than Water Systems A, B, and C had very little calcium and magnesium in their scales. Water System E had the most calcium and magnesium of all the groundwater systems, but it was undergoing the installation of softeners that sent the characteristics of the system water swinging between hard and soft water.

From Table 7.17, less calcium and more magnesium built up on the copper metal plate surfaces than the lead plates for Water Systems A and B. For the groundwater systems, more calcium built up on copper plates than on the lead plates. Water System E, where influent water fluctuated between soft and hard water, a greater quantity of calcium and magnesium was found in the copper plate scale than on the lead plates. Chloride concentration was also greater on the copper plates than the lead plates for Water System E. Chloride was found on the copper plates of Water Systems A and C in about the same quantity. Water System B had slightly higher chloride content.

Table 7.16
Extraneous elements on PRS monitoring station lead plates by x-ray fluorescence or energy dispersive spectroscopy by weight %

Water System	Ca	Mg	Cl
A	7.99		
B	9.59	1.07	
C	1.85	0.123	0.094
D-yellow area	0.05		
D-blue area	0.57		
D-hydrocerussite	0.07		
D- Cerussite	0.40		
D-Litharge	0.00		
E	0.60	0.06	0.01
F	0.11		
G			
H	0.01		

Table 7.17
Extraneous elements on PRS monitoring station copper plates by x-ray fluorescence or energy dispersive spectroscopy by weight %

Water System	Ca	Mg	Cl
A	2.95	0.50	0.66
B	2.96	0.94	1.04
C	2.29	0.91	0.64
D-lower P area	0.27		
D-higher P area	0.96		
E	2.00	0.85	0.52
F	0.44		
G			
H	0.35		

This is a partial view of the chemical scale composition. It is only the part related to uniform corrosion. Chapter 8 describes the role of phosphorus in the scales. Chapter 9 describes a study of the biofilms that formed. Chapter 10 describes the other metals that composed the chemical scales and can possibly change their physical properties. These metal plates exemplify the complexity of metal surface accumulations.

CORRELATIONS

Water quality parameters were correlated with dissolved and particulate lead and copper release as described in Chapter 5. Results were described in Chapter 6 and Appendix A. The narrative continues here with a focus on uniform corrosion parameters.

For Water System A, there were time periods where the influent water to the monitoring station had higher pH and higher aluminum concentrations. These were times when sulfate concentration in the water was lower. This occurred during warmer weather months when less alum was required at the treatment plant to filter the lake water. The Larson-Skold Index trended with particulate lead released in the lead test chamber. During the colder months when sulfate level and alum use were higher, the Larson-Skold Index was higher and so was the particulate lead. With a higher Larson-Skold Index, increased dissolved lead was expected instead of increased particulate lead. The actual factors that produced the increased particulate lead may or may not be related to increased sulfate concentration; instead it may have something to do with the characteristics of the lake water and the treated lake water during the winter. As an example, there was higher turbidity and particulate iron during the same time period and these parameters also trended with particulate lead release.

In Water System B, conductivity trended with chloride concentration. That follows expectations because chloride is assumed to solubilize metals, creating higher dissolved solids concentration and its increased conductivity.

In Water System C, correlations identified a time period in the late winter and early spring when chloride concentration, nitrite/nitrate concentration, alkalinity, and ORP increased. Increased particulate lead was also measured during that time period.

Water System D received water from two different groups of water sources, swinging back and forth in water characteristics routinely. In Water System D, increased pH and lower alkalinity corresponded with increased nitrite/nitrate, total phosphorus, sulfate, and chloride, and increased dissolved metals. That is, alkalinity trended opposite of dissolved metals release in the test chambers. In this case, pH and alkalinity were indicators of water sources – water from the treatment plant with lower polyphosphate concentration and lower dissolved organic carbon versus water from three untreated wells with higher polyphosphate concentration and more biologically unstable characteristics. The alkalinity and pH were not necessarily dominant controlling factors in metals release.

Water System E also had swings in water characteristics during the monitoring period as water softeners were being installed. In addition, the system iron/manganese removal filter had been rehabilitated just before the monitoring period but had slowly degraded over the monitoring period as displayed by increasing turbidity after the filter. Correlations showed the release of dissolved lead in the lead test chamber increasing when the Larson-Skold Index decreased. This indicated that water softening, which increased the chloride in the water would have been operating when dissolved lead release was lower. When water was not being softened as indicated by lower chloride concentration, sulfate and hardness were higher. Peaks of ammonia and dissolved organic carbon occurred in the unsoftened water. Microbiological populations were higher when dissolved organic carbon was higher. Therefore, the new water softeners may have been acting as a barrier to parameters that could increase microbiologically influenced corrosion of metals. (This is interesting as older water softeners have been found to enhance parameters that increase microbiologically influenced corrosion of metals in past studies of building plumbing by this author).

In Water System F, influent alkalinity ran opposite to influent barium levels and this may have indicated changing water characteristics as the water supply alternated between two wells and water source mixtures. Lead and copper release were not correlated with any uniform corrosion water quality parameter.

No correlations with lead and copper and uniform corrosion parameters were found in Water System G also. Instead, high influent ORP appeared to be correlated with lower microbiological populations in the test chambers.

In Water System H, chloride and sulfate trended together but there were no implications for lead or copper release.

SUMMARY

There is an initial period of lead and copper release after the clean metal plates have been exposed to water where dissolved lead and copper concentrations are high and fall quickly over time. This is most likely a time when carbonate and oxide scales are forming on the metal surfaces as described in the solubility models, inhibiting uniform corrosion as scale coverage increases. The extent that carbonate and oxide scales form are measured by metal plate analysis at the end of each monitoring project.

However, uniform corrosion appears to take a minor role in lead and copper release after that initial time period. The following observations were made on the decreased influence of uniform corrosion after the initial exposure of metal to water:

- Dissolved lead release was not predicted by the carbonate solubility model graphs.
- Dissolved lead release did not show a dependency of dissolved inorganic carbon (DIC).
- Dissolved copper release showed a correspondence to predicted values for low DIC water but greatly diverged at higher DIC concentrations. The correspondence at the low DIC concentrations was called into question when the copper release was shown not to have a dependency on DIC. The prediction may have corresponded by chance especially when correlations with other water quality parameters were taken into account.
- The EPA solubility model appears to use different thermodynamic solubility parameters than other standard solubility models, such as Phreeqc which was used in this study.
- The solubility models assume that the water/metal system is at equilibrium. However, studies of surface scale can show the presence of amorphous, thermodynamically unstable compounds of aluminum, iron, and manganese with their ability to adsorb other contaminants such as lead, copper, radium, or arsenic.
- A diversity of lead and copper compounds form on metal surfaces. There are no models for predicting lead and copper release for such a mixed assemblage.
- Using the Spearman rank correlation and aligned time-series graphs to study trends, there were no common trends found between dissolved or particulate lead or copper and pH or alkalinity.

For chloride and sulfate, there was an exponential functional relationship to Chloride to Sulfate Mass Ratio. But, dissolved lead and copper release showed no dependency, in general, on the Larson-Skold Index where alkalinity is also considered. There were two water systems where lead and copper release did co-trend with the Larson-Skold Index. For Water System A where a pattern of alum use at the water treatment plant trended with a pattern of sulfate in the distribution system, higher particulate lead release trended with sulfate concentration and the Larson-Skold Index. For Water System E, where water characteristics fluctuated between hard and soft water, dissolved lead release was lower when water was being softened and the Larson-Skold Index was higher. Softened water had a higher Larson-Skold Index because of chloride addition from the softener. From these two examples, it can be seen that the index may just represent an operational scenario and not represent chloride or sulfate as a causative factor in lead and copper release.

Calcium carbonate precipitation was shown to not be a factor in lead or copper release as others have stated in the past (AWWA and DVWG 1996).

ORP did not show a direct relationship to lead or copper release. However, correlations tied it to trends with parameters related to biostability. This will be discussed further in Chapter 9.

In summary, uniform corrosion factors appear to be significant in the release of lead and copper when clean metal surfaces are first exposed to water. During this period, compounds of carbonates and oxides develop on the metal surfaces. Over time, other chemical compounds and microbiological products become ingrained in the metal surface debris, bringing other and possibly more significant influencing factors on lead and copper release.

Very important to the discussion of uniform corrosion is that it only deals with dissolved lead and dissolved copper. From Chapter 6, it can be seen that particulate lead and particulate copper can be quite a significant fraction of the total lead and copper that can reach consumers.

CHAPTER 8
THE INFLUENCE OF PHOSPHATE ON CORROSION OF METALS

Orthophosphate-based chemical products are used for lead and copper control as recommended and sometimes required by the Lead and Copper Rule. Orthophosphate ions can form very insoluble compounds with lead and copper and can create barriers on metal surfaces to inhibit the uniform corrosion process.

Water Systems A, C, D, G, and H dose various phosphate products into the drinking water (Table 8.1). In this project, the products used included polyphosphate as well as orthophosphate. Polyphosphate has been used historically in the drinking water industry to sequester iron, manganese, and calcium so that these minerals will not precipitate out on plumbing fixtures (Larson 1957). Much has been written about issues of using polyphosphate, a chemical that holds metals in water, when simultaneously trying to drop out lead or copper as a solid phosphate compound to form a protective barrier on pipe walls (Holm and Schock 1991; AwwaRF and DVGW 1996; Cantor et al. 2000; EPA 2016a). These are two competing interactions. Higher lead and copper concentrations have been found in the water, in some cases, when polyphosphate is present.

Several other types of phosphate products are allowable for lead control under the Rule (AwwaRF and DVGW 1996). There are orthophosphate products, such as phosphoric acid and sodium or potassium salts of orthophosphate. There are zinc orthophosphates which have fallen out of favor because of a negative impact of zinc at the receiving wastewater treatment plants.

Water System A uses a product where 90% of the phosphorus is orthophosphate. The other 10% is polyphosphate. The low polyphosphate fraction was intentional; a 100% orthophosphate product was desired. The product used is safer than using phosphoric acid and is economical. Water System D uses two phosphate products. One product is used on water that is treated for iron and manganese removal. The phosphate product is intended for corrosion control but 80% of that product is polyphosphate. A second phosphate product is used at three wells to sequester iron and manganese; here, the product is 100% polyphosphate. The two water types are routinely mixed in the water system. Water Systems C, G, and H use products that are 60 to 70% polyphosphate for corrosion control.

Table 8.1
Phosphate products used by participating water systems

Water System	Product	% by Wt. as P	% of P as Polyphosphate	% as P as Orthophosphate	Product Wt. in lb/gal
A	LPC-132	32.0	10	90	11.51
B	No phosphate added				
C	Carus 8400	31.7	60	40	11.20
D	Aquadene SK7699	21.0	100	0	11.01
	Aquadene 7543	30.0	80	20	11.51
E	No phosphate added				
F	No phosphate added				
G	LPC-AM	34.5	70	30	11.43
H	AquaMag	34.5	70	30	11.40

ORTHOPHOSPHATE AND POLYPHOSPHATE CONCENTRATIONS AT THE HIGH WATER AGE LOCATION

The dosage of phosphate products can be measured using a field analysis for orthophosphate and is typically expressed as concentration in mg/L as orthophosphate (PO_4). When polyphosphates are present, total phosphorus must be measured and the orthophosphate subtracted. The remainder is composed of more complex forms of phosphorus, such as the polyphosphate concentration. Total phosphorus cannot be analyzed in a field test and must be analyzed in a laboratory using an acid and heat digestion (APHA et al. 1995).

Total phosphorus is expressed in units of mg/L as phosphorus (P). To convert between the units of PO_4 and P in order to subtract the orthophosphate concentration from the total phosphorus concentration, the following formula applies:

$$\text{mg/L as P} = (\text{mg/L as PO}_4)/3.06$$

The conversion factor of 3.06 is the ratio of the molecular weights of PO_4 to P.

Table 8.2 displays the orthophosphate measured in the system water samples at the high water age locations where the PRS Monitoring Stations were located. Orthophosphate was only measured if a phosphate chemical was used in the system. Typical orthophosphate dosages discussed in the literature for lead control are found at 0.3 to 1.0 mg/L as P (0.92 to 3.1 mg/L as PO_4) (Sheiham and Jackson 1981; Gregory and Jackson 1984; Wagner 1989; Colling et al. 1992; Duranceau et al. 1997). Recent research calls for up to 1.14 mg/L as P (3.5 mg/L as PO_4) in order to control lead in a water system (EPA 2016a).

Table 8.2
Orthophosphate concentration in system water at a high water age location in mg/L as PO_4 (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.7	0.7	0.6
B	NA	NA	NA
C	0.2	0.2	0.1
D	2.2	0.8	0
E	NA	NA	NA
F	NA	NA	NA
G	0.9	0.4	0
H1	1.6	1.0	0.4
H2	1.3	0.9	0.5

Table 8.3 displays the total phosphorus measured in the water at the same locations. In this table, total phosphorus is expressed as mg/L as PO_4 so that it can be compared to the orthophosphate fraction measured and listed in Table 8.2.

The difference between the total phosphorus and the orthophosphate concentrations are the complex phosphorus compounds. They can be in organic form or they can be in polymeric form, such as with polyphosphate compounds. In Table 8.4, the orthophosphate concentration in Table 8.2 is subtracted from the total phosphorus concentration in Table 8.3 to calculate the possible polyphosphate concentration.

Table 8.3
Total phosphorus concentration in system water at a high water age location in mg/L as PO_4 (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.9	0.6	0.3
B	0.3	0	0
C	0.3	0.3	0.3
D	0.9	0.3	0
E	3.0	0.6	0
F	0.3	0	0
G	1.2	0.6	0
H1	2.1	1.2	0.3
H2	2.4	1.2	0

Table 8.4
Estimated polyphosphate concentration in system water at a high water age location in mg/L as PO_4 (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.2	0	0
B	NA	NA	NA
C	0.1	0.1	0
D	Unable to calculate because of alternating use of two products		
E	NA	NA	NA
F	NA	NA	NA
G	0.3	0.2	0
H1	0.5	0.2	0
H2	1.1	0.3	0

Table 8.5
Average % orthophosphate at high water age location (PRS monitoring station influent tap)

Water System	% Orthophosphate
A	100 (was originally 90)
B	No Phosphate Added
C	67 (was originally 40)
D	Unable to calculate because of alternating use of two products
E	No Phosphate Added
F	No Phosphate Added
G	67 (was originally 30)
H	79 (was originally 30)

In the water distribution system, the polyphosphate compound breaks apart into orthophosphate ions. Since the water samples studied here were from high water age locations, a decrease of polyphosphate and increase of orthophosphate would be expected at these locations. Table 8.5 shows the average percent orthophosphate measured at the high water age location compared to the percent orthophosphate in the product used.

ORTHOPHOSPHATE CONCENTRATION AT THE ENTRY POINT TO THE DISTRIBUTION SYSTEM

The orthophosphate concentrations at the entry points to the distribution systems varied from the concentrations seen at the high water age locations. Figure 8.1 displays these differences. In Water System A, the dosage dropped from an average of 0.72 to 0.66 mg/L as PO_4. This may be because the product was lost as the water flowed to the high water age location, precipitating out as intended. Water System A also used a product where 90% of the phosphorus was orthophosphate. There was little polyphosphate to break apart and increase the orthophosphate concentration. In the other water systems, orthophosphate concentrations increased from the entry points to the distribution systems to the high water age locations. These systems used products where polyphosphate can revert to orthophosphate and increase the orthophosphate concentration in the distribution system.

ORTHOPHOSPHATE CONCENTRATION OVER THE MONITORING PERIOD

Water Systems G and H modified the phosphate dosing during the monitoring period. Neither of the water systems have lead service lines. Regulators consulting on this project agreed that phosphate dosages could be altered in a water system if there were no lead service lines involved. In addition, both water systems had previously been investigated and found to have microbiological problems initiated in their wells and inoculating the distribution system. The remediation plan was to achieve biologically stable water (discussed in Chapter 9) and to clean existing biofilms and chemical scales from the system. To achieve biologically stable water, nutrients that encourage the growth of microorganisms must be removed from the water and that includes phosphorus. Therefore, the phosphate product dose was cut back slowly over time. Nevertheless, the orthophosphate dose remained measurable at the high water age location.

Figure 8.2 displays the orthophosphate concentration at the high water age locations over the monitoring period. Water Systems A and C showed the natural variation of dosed orthophosphate concentration in the distribution system. Water System D showed wide variability. One reason that the variability occurred was because of the two main sources of water that contributed to the system at different time periods, each water source with a different phosphate product, one with 0% orthophosphate.

PHOSPHORUS FROM BIOFILM SLOUGHING

For Water System G, the phosphate dosing was taken down slowly at first and reached a minimum level around 0.1 mg/L as PO_4, a level which occurred naturally in Water System C dosing. After several months, the orthophosphate concentration jumped back up. This was not because the dosing was increased again. This occurred naturally in the distribution system. It was theorized that the orthophosphate was being released from degrading biofilms; now that the microorganisms were starved of phosphorus and the population could not be supported, microorganisms began to die and biofilm material slough off the pipe wall. Another reason for the increase may have been an operational one. As old product was slowly dosed into the system, the orthophosphate fraction may have increased due to polyphosphate reverting to orthophosphate. In Water System H, there were two levels of phosphate dosing decrease. After each lower level was achieved, the elevated orthophosphate concentration in the distribution system occurred, giving more credibility to the biofilm sloughing theory.

PHOSPHORUS COMPOUNDS IN THE METAL PLATE SCALES

The success of covering metal surfaces with lead or copper phosphate compounds from the addition of a phosphate corrosion control chemical was determined by studying the chemical scales on the PRS Monitoring Station metal plate surfaces after the monitoring period was over. The goal with orthophosphate dosing is to create the mineral, pyromorphite, a lead phosphate compound, on lead surfaces. Table 8.6 shows the pyromorphite found in the lead plate scales. Table 8.7 shows the phosphorus found in both the lead and copper plate scales.

Water System A was very successful. It was the water system with a higher orthophosphate dose and no significant presence of polyphosphate in the water. An “appreciable” quantity of phosphorus was observed on the copper plates by means of x-ray fluorescence. On the lead plates, phosphorus was "exceptionally" high. A predominant mineral determined by x-ray diffraction was pyromorphite, the intended lead phosphate compound. The analyst suggested that lowering the phosphate dose should be considered since "adequate" quantities have been achieved in the developed scale. (That is, Table 8.6 shows pyromorphite as the predominant x-ray diffraction peak on lead plates from Water System A with 86% scale coverage (Table 6.9). (Metal plate analytical report from Dr. J. Barry Maynard in April 2016)

Water System C had a low quantity of phosphorus on lead plates and no significant phosphorus on copper plates.

Water System D had phosphorus on both lead and copper plates. However, the phosphorus was not formed into familiar minerals, such as the desired pyromorphite. Instead, the analyst theorized that the phosphorus on both the lead and copper plates was "bound through adsorption onto amorphous iron oxide or hydroxide." See Figure 8.3.

Water System E formed some pyromorphite, which occurred naturally since a phosphate chemical is not added.

Water System H phosphorus content was very low on the lead plates and was not found on copper plates. This was a system where the phosphate dosage was lowered intentionally. Water System G will be operating its PRS Monitoring Station until December 2017 at which time the metal plates will be studied.

Table 8.6
Major minerals on PRS monitoring station lead plates by x-ray diffraction

Water System	Pyromorphite $Pb5(PO4)3Cl$
A	100
B	no phosphate dosing
C	35
D	none present
E	67 (even though no phosphate dosing)
F	no phosphate dosing
G	Still running PRS Monitoring Station
H	none present

Amounts are percent of largest x-ray diffraction peak for scale minerals

Table 8.7
Phosphorus on PRS monitoring station lead and copper plates by x-ray fluorescence or energy dispersive spectroscopy in weight percent

Water System	Phosphorus on Lead Plates	Phosphorus on Copper Plates
A	9.50	4.66
B	0.31	0.12
C	0.88	0.01
D-yellow area	0.82	2.48
D-blue area	1.09	5.85
D-hydrocerussite	0.83	none
D- Cerussite	0.78	none
D-Litharge	1.68	none
E	0.03	0.38
F	none	none
G	Still running PRS Monitoring Station	
H	0.15	none

EFFECT OF PHOSPHATE ON LEAD AND COPPER RELEASE

In Figure 8.4, the lead and copper release in water systems dosing phosphate are compared to the release in water systems not dosing phosphate. Water systems dosing phosphate did not necessarily have lower dissolved lead or dissolved copper release than the non-phosphate systems. When particulate lead and particulate copper release was considered as seen in the total lead and copper release graphs of Figure 8.4, there also was no advantage to dosing orthophosphate compared to water systems not dosing orthophosphate. It is unknown if particulate lead or copper release would be worse if the orthophosphate was not present.

Water Systems A, D, and H had the highest orthophosphate dosages (Table 8.2) and yet their success at controlling lead and copper release was unpredictable in that the three systems experienced different lead concentrations in the water. In addition, Water System F, a higher alkalinity water system with no phosphate addition, had equally low dissolved lead, dissolved copper, and total copper release as Water System A. Lead and copper release in water systems appeared to be the result of a variety of factors and not just phosphate addition.

CORRELATIONS

No water system showed any correlation of increasing orthophosphate with decreasing lead or copper, dissolved or particulate. That is, no correlation coefficient between lead or copper forms and orthophosphate was less than -0.6.

Sparklines in Appendix A show that dissolved copper in Water System A was lower when orthophosphate increased but the phenomenon was part of a nitrification process that encompassed many water quality parameters; at the same time, dissolved lead increased with the increasing orthophosphate.

Water System D had correlations between increasing influent total phosphorus and a variety of dissolved metals released in both test chambers including dissolved copper from the copper test chamber. This may be a result of using a high polyphosphate percentage in the added phosphate product. It is equally possible that metals-laden phosphate was releasing from pipe walls based on the observation of amorphous iron/phosphorus/carbon compounds on the surfaces of the metal plates (Figure 8.3).

Water System B and E, both systems that do not add phosphorus over the natural levels, showed monitoring station influent total phosphorus trending with released particulate metals in the test chambers. Water System F, which also does not feed phosphorus, showed influent total phosphorus trending with various released dissolved metals in test chambers. Water Systems G and H showed influent total phosphorus trending with release of several particulate and dissolved metals.

Sparklines in Appendix A show dissolved copper increasing with increasing phosphate in Water Systems C, D, and G. Dissolved lead was shown increasing with increasing phosphate in Water Systems A, C, and D. Water System H2 had decreasing dissolved lead with increasing phosphate but there were many other factors shown to be at work as well.

Water Systems C and D showed influent orthophosphate trending oppositely from microbiological populations while orthophosphate and microbiological populations trended together in Water System G.

SUMMARY

With this study of the effect of orthophosphate on controlling lead and copper release, there is no clear picture that the chemical renders a water system safe from corrosion. There are no correlations that tie orthophosphate dosage to the lowering of lead or copper release in the five phosphate-dosing water systems.

The study of the scales formed when orthophosphate is dosed show that it does not form a perfectly consistent barrier over lead or copper surfaces. Instead, it is woven into a web of scales with many other metals and biofilms, if present at all.

With the exemplary Water System A water quality, one could argue that the higher dosage of orthophosphate and the absence of polyphosphate is required before the chemical can be effective. But even Water System A released an equal quantity of particulate lead as it did dissolved lead, the same particulate lead that had the potential to show up in residences to increase the lead concentration over desired levels (Chapter 3). It is also the same water system where the low released dissolved lead and copper levels were similar in magnitude to a high alkalinity groundwater system not dosing phosphate (Water System F). It is not known to what degree orthophosphate may mute particulate lead release in either Water System A or F.

Nevertheless, the monitoring data in this project give a more complex picture of what shapes water quality than merely being able to apply one chemical to all water systems for corrosion control.

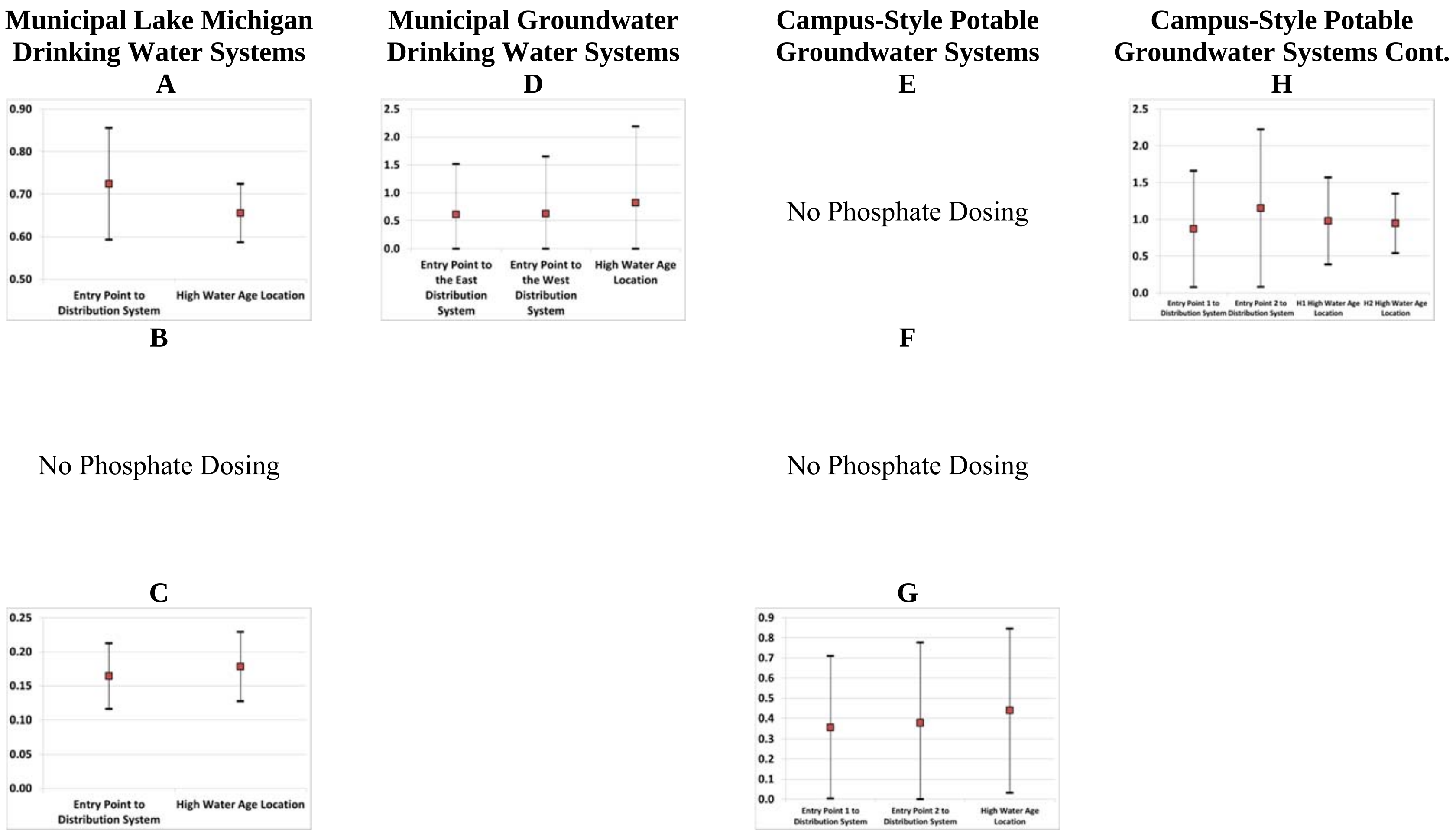


Figure 8.1 Comparison of orthophosphate concentration between the entry points to the distribution systems to the high water age locations in mg/L as PO_4

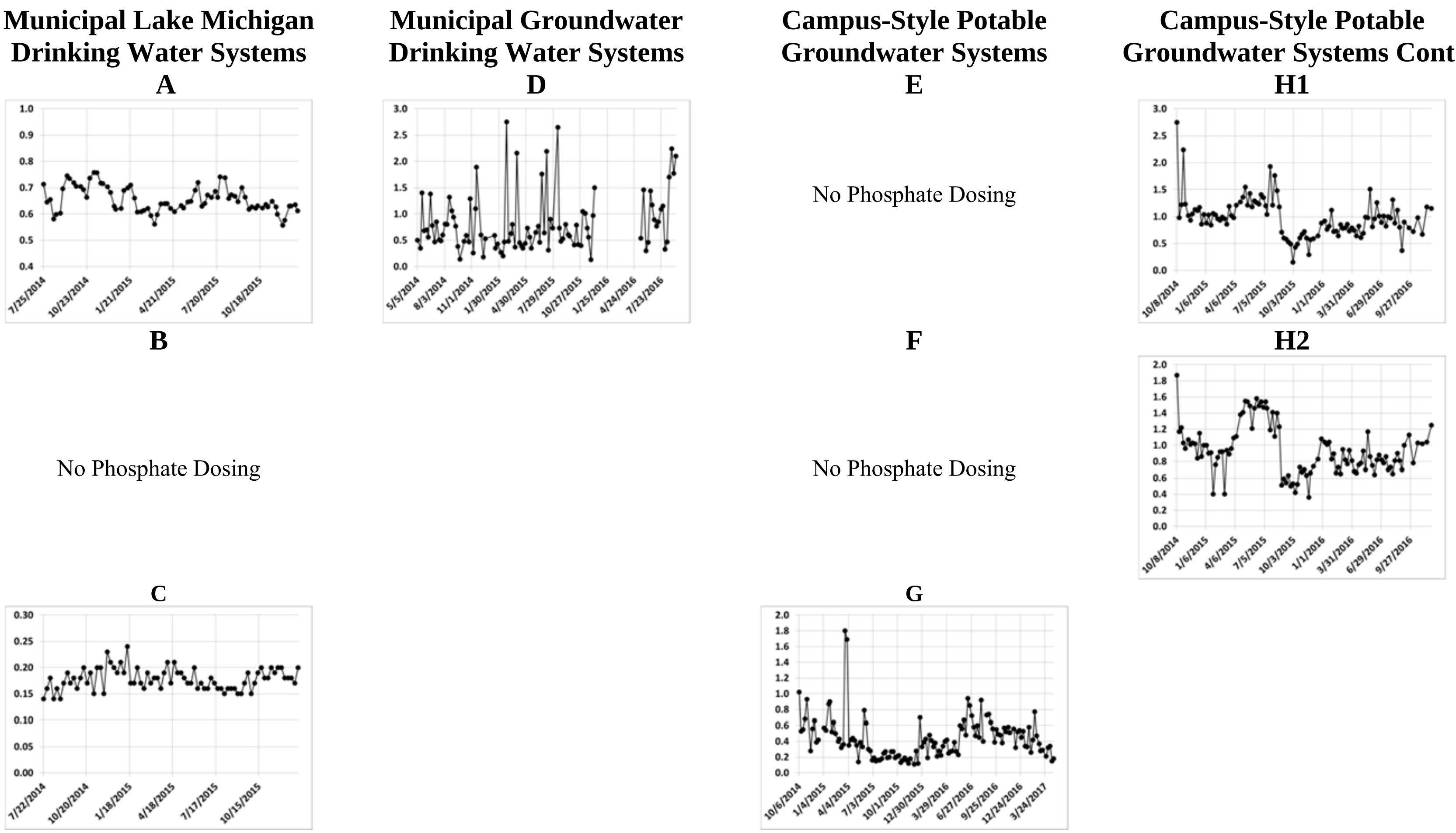
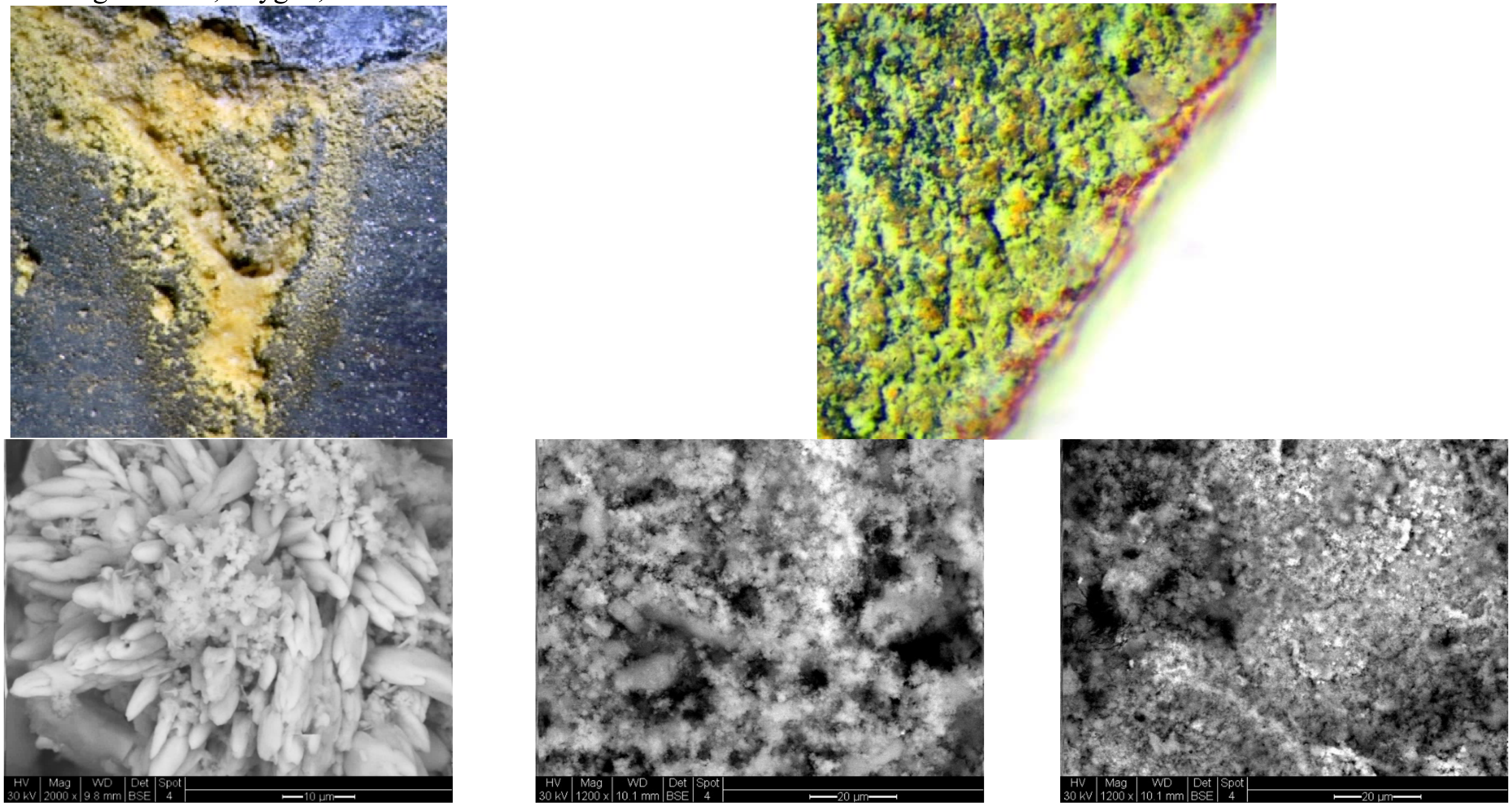


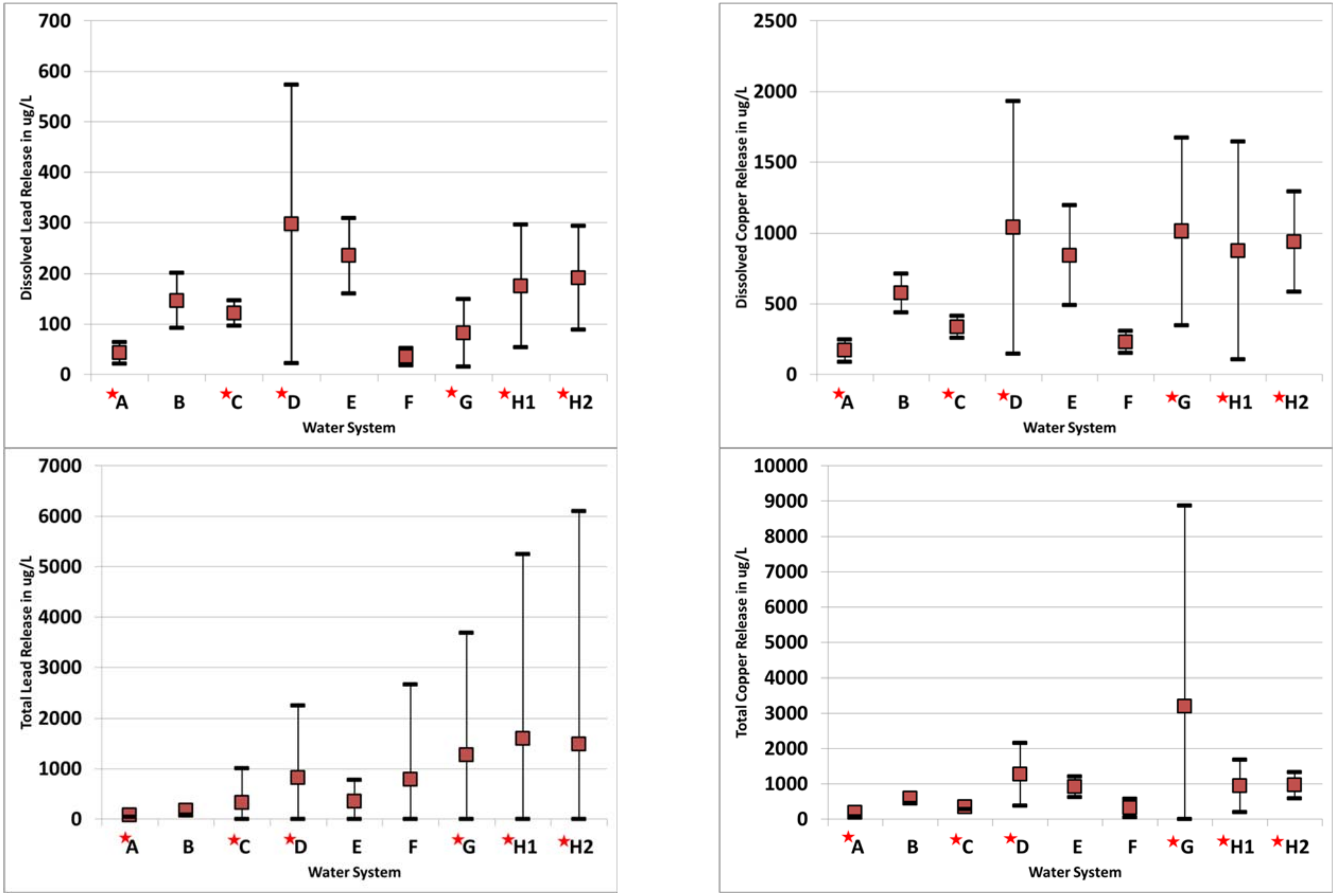
Figure 8.2 Orthophosphate concentration in flowing system water at the high water age locations (PRS monitoring station influent sample tap) over time in mg/L as PO_4

Lead Plates	Copper Plates
A mixture of cylindrical lead carbonate crystals, poorly developed phosphate crystal, and high carbon, oxygen, and iron.	A mixture of copper, phosphorus, carbon, oxygen, and iron



Source: Courtesy of Dr. J. Barry Maynard.

Figure 8.3 Water System D metal plates: Phosphorus bound to amorphous iron compounds



* = Water systems dosing orthophosphate for corrosion control
Total Lead Release = Dissolved lead release + Particulate lead release and the same for copper

Figure 8.4 Comparison of lead and copper release in water systems with and without phosphate dosing

CHAPTER 9
FACTORS RELATED TO BIOSTABILITY AND MICROBIOLOGICALLY INFLUENCED CORROSION OF METALS

Microorganisms are everywhere in the environment – the soil, the air, natural bodies of water - and are carried into water distribution systems. Microorganisms can thrive in water distribution systems, and under certain conditions, they can grow out of control (Bremer et al. 2001).

Several aspects of microbiological growth can cause corrosion of metal surfaces and solubilization of metal compounds. It is known that microorganisms can secrete acidic enzymes to attach to metal surfaces (Bremer et al. 2001) and that such localized acidity can corrode metal surfaces. It is also known that microorganisms can produce acidic waste products, such as hydrogen sulfide from sulfate-reducing bacteria, which forms a weak acid in water (Rittman and McCarty 2001; Madigan and Martinko 2006), another pathway to increased metal corrosion. Nitrifying microorganisms produce nitrates that can form highly soluble compounds of lead and copper and can possibly re-solubilize existing lead and copper films on metals surfaces. It is also known that there are iron-oxidizing bacteria that use electrons from iron and other metals as their food source (Rittman and McCarty 2001; Madigan and Martinko 2006), another pathway by which metal can be oxidized by microorganisms in a water system.

The key to lowering the potential for this microbiologically influenced corrosion is to keep the microbiological populations in balance. Factors that encourage the growth of microorganisms must be balanced against factors that discourage their growth. Successful balancing of factors is called “biostability” (Van der Kooij 1992; Volk and LeChevallier 2000; Zhang et al. 2002; LeChevallier et al. 2015).

In this chapter, measurements of water quality parameters that affect the biostability of the system water are displayed. Trends between biostability parameters and lead and copper release data are studied.

MICROBIOLOGICAL POPULATIONS

A method to quantify microbiological populations is to measure the concentration of adenosine triphosphate (ATP) in the water. ATP is the energy molecule of living organisms. The measured concentration of ATP in the water is somewhat proportional to the number of microorganisms living in the water. The ATP analysis is discussed in Chapter 5.

Only ATP from living microorganisms is captured in the analytical method by means of filtering the living microorganisms out of a water sample. Any ATP previously released from dead microorganisms is discarded in the water. The filtered living microorganisms become the sample to work with. They are exposed to a lysing agent which bursts the cells and releases the ATP into a liquid sample of the lysing agent. Another chemical compound is added to combine with ATP and emit light. The sample is placed in an instrument that can quantify the amount of light emitted and can correlate the measurement with ATP concentration.

Each type of microorganism has its own range of ATP concentrations per organism. As an estimate of microbiological population, an average ATP concentration per organism typically found in drinking water is used: 1000 microbial equivalents (ME) = 1 picogram (pg or trillionth gram) of ATP. While the actual type of microorganisms in the water is not known with this test, it is convenient to express the results as an estimated population number as it is useful for comparing and tracking the severity of microbiological growth in water systems.

A standard of the EPA is to consider less than 500 colony-forming units per mL of microorganisms as acceptable in drinking water as it is representative of enough disinfection to prevent excessive growth of microorganisms in the distribution system (Code of Federal Regulations 2010a). This refers to results of the Heterotrophic Plate Count analysis which only identifies heterotrophic bacteria. However, the test has been used as an indicator of total microbiological activity in water. Now, there is the ATP test that actually measures all microorganisms in the water (except viruses). The standard of achieving less than 500 ME/mL has been transferred to this new test by many practitioners. It becomes a more stringent criterion because all microorganisms are included in the ATP tests, not just the heterotrophic bacteria.

Table 9.1 shows the statistics for the estimated number of microorganisms measured in the system water of the participating water utilities at high water age locations. Very large populations were measured in most of the flowing system water. Only Water System E maintained populations under 500 ME/mL entrained in the system water.

Table 9.1
Microbiological population (ATP) at flowing system water at a high water age location in ME/mL (PRS monitoring station influent tap)

Water System	Highest Expected	Average	Lowest Expected
A	6,356	1,396	0
B	*340,104	64,226	0
C	2,633	733	0
D	8,183	2,087	0
E	157	54	0
F	30,590	7,166	0
G	48,414	8,315	0
H1	1,961	490	0
H2	960	288	0

*High ATP in Water System B influent water may be related to a stagnating influent water line to the monitoring station

Tables 9.2 and 9.3 show the microbiological populations found in the stagnating water of the lead and copper test chambers. Here, the degree that microorganisms grow in stagnating water versus flowing water (Table 9.1) is one indication of the biostability status of the water.

Table 9.2
Microbiological population (ATP) in PRS monitoring station lead test chamber stagnating water in ME/mL

Water System	Highest Expected	Average	Lowest Expected
A	4,431	1,704	0
B	26,069	5,578	0
C	14,351	5,320	0
D	246,193	90,044	0
E	3,813	1,263	0
F	82,688	26,458	0
G	180,714	54,582	0
H1	260,963	50,315	0
H2	266,630	87,025	0

Table 9.3
Microbiological population (ATP) in PRS monitoring station copper test chamber stagnating water in ME/mL

Water System	Highest Expected	Average	Lowest Expected
A	7,924	1,985	0
B	14,981	3,868	0
C	7,406	2,732	0
D	160,395	64,191	0
E	5,794	1,614	0
F	46,382	16,323	0
G	125,624	32,266	0
H1	140,342	24,640	0
H2	274,006	85,175	0

Having a low population of microorganisms entrained in the water, unfortunately, does not insure that excessive microbiological growth is not occurring. The environmental conditions, type of nutrients available, and type of microorganisms predominating in a water system may be more conducive to biofilm formation with little release of microorganisms into the water. Tables 9.4 and 9.5 compare microbiological populations adhering to the metal plates in the test chambers to populations in water flowing into the monitoring station and water stagnating adjacent to the biofilm-laden metal plates. Biofilm quantification on the metal plates was performed at the end of the monitoring period when metal plates could be removed from the test chambers and analyzed.

Table 9.4
Microbiological population (ATP) distributed between the water and the metal surface

Water System	In System Water	On Lead Surface	In Lead Test Chamber Water	On Copper Surface	In Copper Test Chamber Water
Units	ME/mL	ME/cm^2	ME/mL	ME/cm^2	ME/mL
A	440	4,000	320	8,800	680
B	2,100	3,220	128	10,200	900
C	350	71,000	920	15,000	430
D	643	522,659	13,640	108,883	8,151
E	40	76,600	600	265,000	1,000
F	115	15,900	1,071	34,100	215
G	Monitoring Station will be operating until December 2017				
H1	470	6,000	49,000	20,000	24,000
H2	280	6,000	85,000	67,000	83,000

From Table 9.4, the potential for biofilm formation can be quite high such as in Water System D. Biofilm formation potential can also vary by type of metal such as in Water System E where biofilm tends to form on copper surfaces versus lead. Biofilms can form and release large populations to the water as in Water System H. Or, biofilms can form and release very few microorganisms to water as in Water System E.

Table 9.5
Microbiological population (ATP) distributed between the water and the metal surface (%)

Water System	On Lead Surface	In Lead Test Chamber Water	On Copper Surface	In Copper Test Chamber Water
A	91.6	8.4	92.2	7.8
B	95.8	4.2	91.1	8.9
C	98.6	1.4	97.0	3.0
D	97.2	2.8	92.3	7.7
E	99.1	0.9	99.6	0.4
F	93.0	7.0	99.3	0.7
G	Monitoring station will be operating until December 2017			
H1	9.5	90.5	42.9	57.1
H2	5.4	94.6	42.2	57.8

Calculations based on data in Table 9.4; metal surface area in test chamber = 854.6 cm^2; volume of water in test chamber = 950 mL

In Table 9.6, it can be seen that microbiological populations in the test chambers are not necessarily equal to the incoming population. Sometimes, there can be an increase in population released from biofilm as in Water System D. There can also be a decrease in population held from the water by the biofilm as in Water System B.

Table 9.6
Microbiological population (ATP) entrained in water relative to influent water population

Water System	In System Water	In Lead Test Chamber Water	In Copper Test Chamber Water
A	1.00	0.73	1.55
B	1.00	0.06	0.43
C	1.00	2.63	1.23
D	1.00	21.21	12.68
E	1.00	15.00	25.00
F	1.00	9.31	1.87
G	Monitoring Station will be operating until December 2017		
H1	1.00	104.26	51.06
H2	1.00	303.57	296.43

Calculations based on data in Table 9.4; all values divided by system water population for each system

NUTRIENTS

In assessing biostability of water, the concentrations of nutrients available for microbiological growth must be monitored. The nutrients required in the largest quantities for microbiological growth are organic carbon compounds, nitrogen compounds, and phosphorus compounds. Tables 9.7 to 9.10 show the measured concentrations of nutrients in system water at a high water age location for the participating water utilities.

Table 9.7
Dissolved organic carbon (DOC) concentration in flowing water at a high water age location in mg/L (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	2.6	1.6	0.6
B	2.7	1.7	0.6
C	3.1	1.7	0.2
D	2.7	1.5	0.4
E	2.2	1.5	0.8
F	0.9	0.6	0.3
G	2.0	0.8	0
H1	1.0	0.6	0.1
H2	1.0	0.6	0.2

Table 9.8
Ammonia (NH_3) concentration in flowing water at a high water age location in mg/L as N (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.3	0.2	0.1
B	0.1	0	0
C	0.1	0	0
D	0.1	0	0
E	0	0	0
F	0.1	0	0
G	1.0	0.2	0
H1	0.1	0	0
H2	0.1	0	0

Table 9.9
Nitrite/nitrate (NO_3+NO_2) concentrations in flowing water at a high water age location in mg/L as N (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.5	0.4	0.3
B	0.5	0.3	0.2
C	0.7	0.4	0.1
D	2.6	1.3	0.1
E	0.1	0	0
F	1.1	0.8	0.5
G	0.1	0.1	0
H1	3.1	2.5	2
H2	3.3	2.6	1.8

Table 9.10
Total phosphorus concentration in flowing water at a high water age location in mg/L as P (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.3	0.2	0.1
B	0.1	0	0
C	0.1	0.1	0.1
D	0.3	0.1	0
E	1.0	0.2	0
F	0.1	0	0
G	0.4	0.2	0
H1	0.7	0.4	0.1
H2	0.8	0.4	0

The use of dissociated ammonia by nitrifying bacteria as a nutrient is known as nitrification and is a concern in chloraminated systems. Nitrites and nitrates are the by-products of the nitrification process but can also be broken down by microorganisms for continued microbiological activity. In this project, Water Systems A, B, and C, having the same source water, measured similar concentrations of nitrates and nitrites in the water even though Water System A was the only chloraminated system as seen in Table 9.9. In Table 9.8, only Water System A had slightly higher ammonia concentrations than the other systems.

Several groundwater systems had higher concentrations of nitrates and nitrites than the other systems as seen in Table 9.9. Nitrates can be introduced to water systems as contaminants in the source water. Water Systems D, F, and H experienced the higher nitrate and nitrite compounds.

Phosphorus compounds (Table 9.10) are discussed in Chapter 8. Water Systems A, C, D, G, and H were adding phosphorus compounds to the system water. Water System E received phosphorus in its source water.

DISINFECTION

Factors that can counteract microbiological growth are lowered water age (Bremer et al. 2001) and disinfection (Connell 1996). The PRS Monitoring Stations exaggerate increased water age to magnify chemical and microbiological interactions with the water. The extreme condition puts disinfection to the test of controlling microbiological growth. Table 9.11 lists the total disinfection chemical arriving in the flowing system water at the PRS Monitoring Station. Table 9.12 lists the concentration of the disinfection chemical that is available to fight microorganisms. For any disinfection chemical, appropriate dosing must be set by studying biostability data. For chloraminated systems, the minimum dose is typically 1 mg/L total chlorine. For the free chlorine systems, anecdotally, a minimum disinfection concentration of 0.3 mg/L free chlorine is desired. Water Systems C and D averaged disinfection concentrations <0.3 mg/L

Table 9.11
Total chlorine concentration in flowing water at high water age location in mg/L (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	1.8	1.6	1.3
B	0.8	0.6	0.4
C	0.6	0.4	0.2
D	0.4	0.1	0
E	1.3	0.6	0
F	0.7	0.3	0
G	1.3	0.4	0
H1	1.0	0.6	0.3
H2	1.0	0.5	0

Table 9.12
Active disinfection concentration in flowing water at high water age location in mg/L (PRS monitoring station influent tap)

Water System	Active Disinfection	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	Monochloramine	1.7	1.5	1.3
B	Free Chlorine	0.7	0.5	0.3
C	Free Chlorine	0.4	0.2	0.1
D	Free Chlorine	0.3	0.1	0
E	Free Chlorine	1.2	0.6	0
F	Free Chlorine	0.7	0.3	0
G	Free Chlorine	1.1	0.4	0
H1	Free Chlorine	0.9	0.6	0.3
H2	Free Chlorine	0.9	0.4	0

ENVIRONMENTAL CONDITIONS

Microbiological life cycles can be affected by or can influence the water environment conditions. Increasing water temperature is typically conducive to increasing microbiological populations. The pH of the water can determine the effectiveness of a disinfection chemical as a disinfectant (Connell 1996). The pH of the water can also be decreased by microbiological activity (as in sulfide production) or increased (as in the use of entrained carbon dioxide as a source of carbon). The ORP of the water may indicate that disinfection, an oxidant, is plentiful and microorganisms have a low potential for growth. Or, a dropping ORP can indicate that microorganisms have outgrown the capabilities of the disinfection and have created a reducing environment.

CORRELATIONS

Trends in the water quality parameters related to biostability (ATP, dissolved organic carbon, ammonia, nitrite/nitrate, total phosphorus, total chlorine, and free chlorine/monochloramine) were compared to other water quality parameters in the system water and the test chamber lead and copper release. This was discussed in Chapter 6 and in Appendix A. In each water system, dissolved and sometimes particulate lead and copper release trended with either microbiological populations or microbiological nutrients or both.

SUMMARY OF OBSERVATIONS

The trending study -- correlation calculations along with the water quality parameter graph comparisons -- revealed complex relationships with lead and copper release. One major complexity is that many water quality parameters play a role in both chemical reactions and microbiological life cycles. It is difficult to discern which role they are participating in or if they are participating in both roles simultaneously.

For example, total phosphorus concentration can provide orthophosphate to create lead and copper phosphate corrosion barriers on pipe walls (particulate lead and copper outside of the system water flow). It can provide polyphosphate compounds which can hold lead and copper in the water (dissolved lead and copper in the system water). Or, the phosphorus can be used as food for microbiological growth with subsequent corrosion of piping material through several possible pathways (dissolved or particulate lead and copper in the system water or intertwined with pipe wall debris).

In addition, the water quality parameter may just be an artifact of a system operational event. The phosphorus concentration may be a characteristic of sloughing biofilms from pipe walls during a cleaning action that may coincide with lowered lead or copper.

A high ORP may indicate a highly oxidative water environment that lowers lead release by forming a highly insoluble form of lead oxide on pipe walls. And, a high ORP may indicate a highly oxidative water environment where microorganisms cannot survive and microbiologically influenced corrosion with subsequent lead or copper release cannot occur.

Similar contrasting lists can be developed for other water quality parameters such as nitrate, pH, and alkalinity.

Another aspect of the trending study is the focus it brings on nitrification in distribution systems. Water System A was the only chloraminated water system. Many water quality parameters, including some aspects of lead and copper release, appeared to be related to seasonal fluctuations of nitrification cycles with cycles of ammonia release, followed by an increase in microbiological population and dissolved organic carbon, and subsequent increases in nitrate and nitrite culminating in autumnal maximum concentrations. In water systems with naturally low levels of ammonia, the nitrification process appeared to occur to varying degrees, with repercussions with lead and copper release.

What is known from viewing these complexities is that microorganisms exist in the system water and live on the piping surfaces. The microorganisms and/or their nutrients and waste products coincide with the release of lead and copper and other metals in both dissolved and particulate forms. The water system nutrient concentrations, water age, and disinfection levels all determine the potential for microbiologically influenced corrosion to occur throughout the distribution system. These are the parameters that determine the biostability of the water, that is, the potential for microorganisms to grow excessively. The biostability parameters pervade a distribution system just as other water quality parameters, such as alkalinity and pH, do. Therefore, the biostability of water cannot be ignored as a systemic significant and intertwined factor in the control of lead and copper.

CHAPTER 10
FACTORS RELATED TO CHEMICAL SCALE FORMATION AND DISSOLUTION AND THEIR INFLUENCE ON METAL TRANSPORT IN WATER SYSTEMS

In this project, a number of metals were studied to determine how their dissolved and particulate forms trended with dissolved and particulate lead and copper release. As in Chapter 6 with lead and copper, other metals are presented here by showing:

- The concentrations of the total metals in flowing system water at a high water age location (the PRS Monitoring Station Influent Tap),
- The concentrations of the dissolved and particulate fractions of metals released from scales in the stagnating PRS Monitoring Station test chambers
- The metals' average and variation (expected concentration range) in the test chambers

Metals were organized in groups of commonality for discussion.

ADSORBING AND TRANSPORTING METALS

Aluminum, iron, and manganese have been found to be significant in distribution systems for adsorbing lead and copper and other metals, accumulating them in their scales, and then transporting the metals to consumers' taps when the scales crumble (Schock et al. 2014). These metals can be found to occur naturally in source water. They can also be components of water treatment chemicals. A third pathway into the drinking water is through corroding metal components in the water system; they are part of typical water system materials of construction.

Tables 10.1 to 10.3 display the concentrations of aluminum, iron, and manganese in the flowing system water where the water was sampled at the high water age location of the PRS Monitoring Station. Aluminum is higher in the Lake Michigan water systems compared to the groundwater systems; each of the Lake Michigan systems use an aluminum-based coagulant before filtration. Water System A (88 µg/L average) and Water System C (33 µg/L average) use aluminum sulfate as a coagulant. Water System B (13 µg/L average) uses polyaluminum hydroxychloride. Aluminum concentrations in the groundwater systems are from the source water and piping material contributions and average between 7 and 10 µg/L.

Iron in the system water at the Lake Michigan water systems was around 100 µg/L, the limit of detection at the laboratory. The groundwater systems, all of which had been found to have microbiologically influenced corrosion occurring in the wells, produced an iron concentration in the system that averaged as much as 350 µg/L. The upper expected range of concentrations in Water Systems D and G approached 1000 µg/L. Water System E had low iron concentrations because of a water system iron removal filter plus water softening in individual buildings which can also remove iron.

Manganese in the system water at the Lake Michigan water systems averaged around 2 µg/L. For the groundwater systems, the highest average manganese concentration was 150 µg/L which could reach an upper expected range of close to 300 µg/L.

Figures 10.1 to 10.6 show the tendency of aluminum, iron, and manganese to be either in dissolved or particulate form when released from pipe wall scale. Samples were taken from the stagnating water in the PRS Monitoring Station test chambers. Water Systems A and C, which used alum as a coagulant, had a specific pattern of aluminum concentration. Water System B, using the same source water, used a different coagulant which also includes aluminum. For groundwater systems, aluminum was not significant in the system water with the exception of Water System G. Water System G demonstrated a general presence of a variety of metals.

Table 10.1
Comparison of aluminum in flowing system water in µg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	160	88	13
B	22	13	3.3
C	47	33	18
D	9.4	8.9	8.4
E	16	11	6.2
F	8.6	8.2	7.8
G	7.8	7.4	7.0
H1	10	8.3	6.1
H2	8.5	8.0	7.5

Table 10.2
Comparison of iron in flowing system water in µg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	140	120	90
B	260	130	0
C	<100	<100	<100
D	1000	330	0
E	<100	<100	<100
F	350	190	40
G	870	350	0
H1	77	68	58
H2	95	71	47

Table 10.3
Comparison of manganese in flowing system water in µg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	4.5	3.1	1.7
B	6.1	1.9	0
C	<1.0	<1.0	<1.0
D	270	150	33
E	50	16	0.0
F	14	7.2	0.7
G	180	94	12
H1	3.5	1.8	0.1
H2	5.9	2.5	0

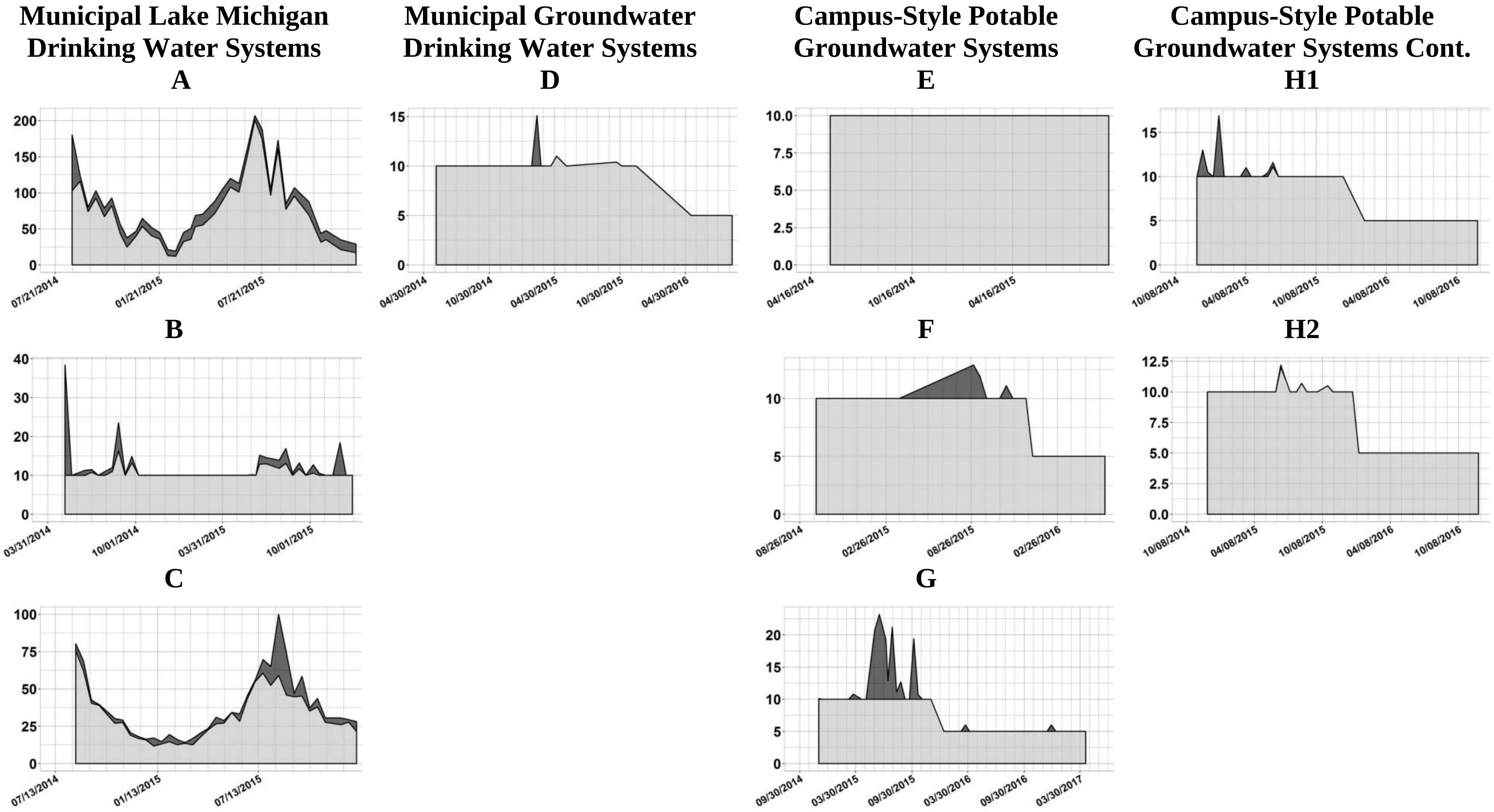


Figure 10.1 Aluminum released into PRS monitoring station lead test chamber stagnating water in µg/L

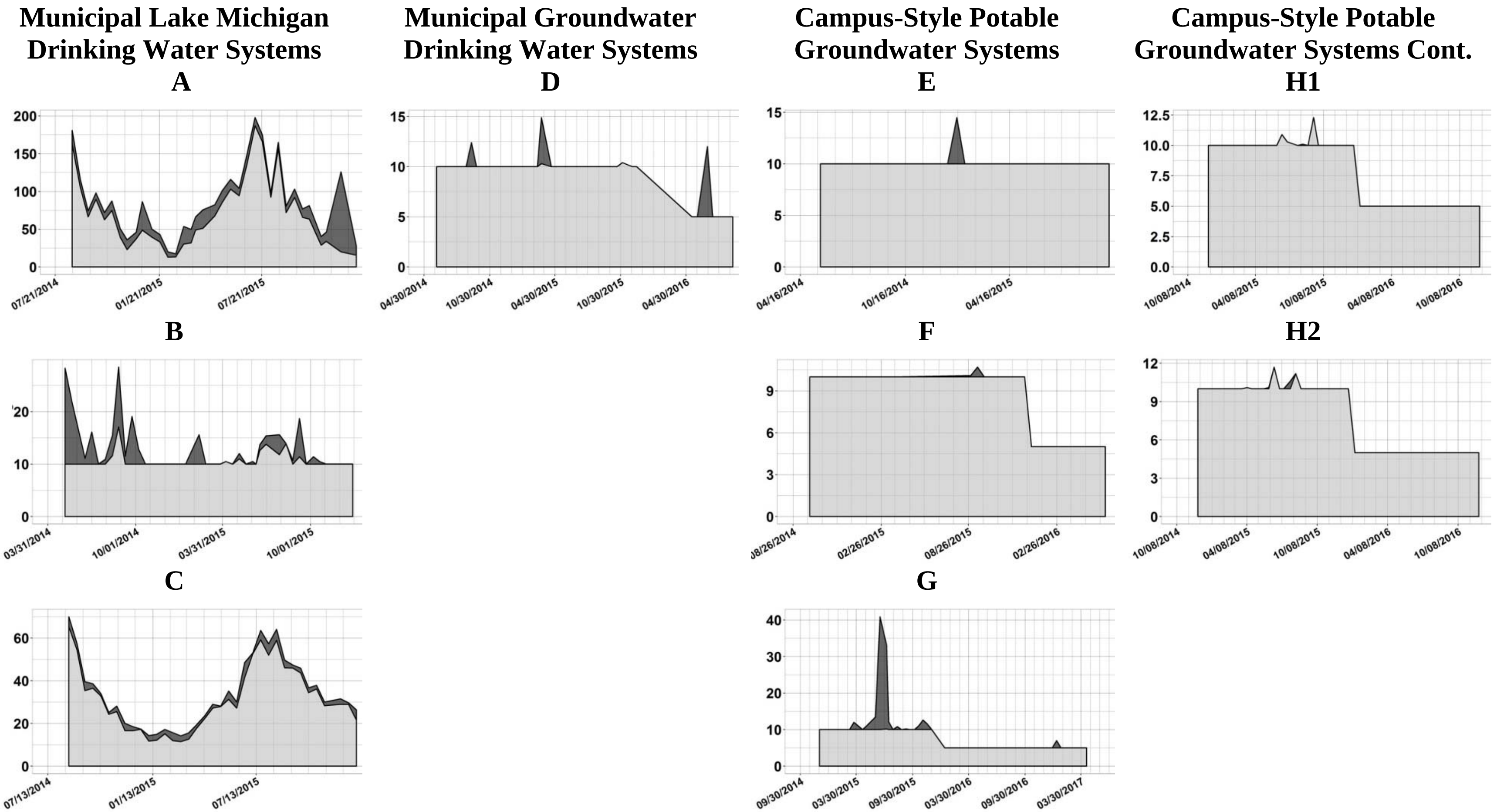
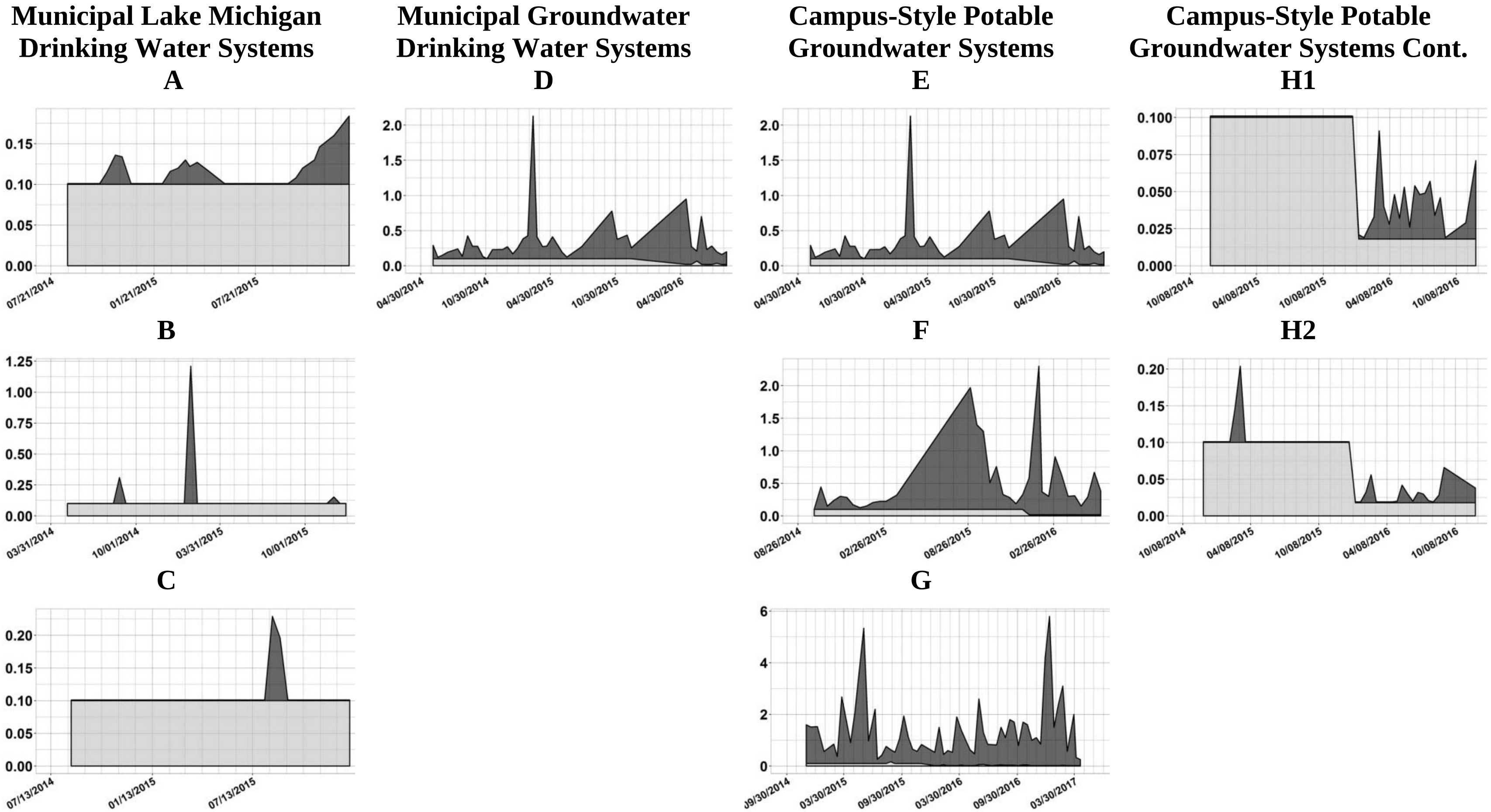


Figure 10.2 Aluminum released into PRS monitoring station copper test chamber stagnating water in µg/L



Municipal Lake Michigan Drinking Water Systems

Municipal Groundwater Drinking Water Systems

Campus-Style Potable Groundwater Systems

Campus-Style Potable Groundwater Systems Cont.

Figure 10.3 Iron released into PRS monitoring station lead test chamber stagnating water in mg/L

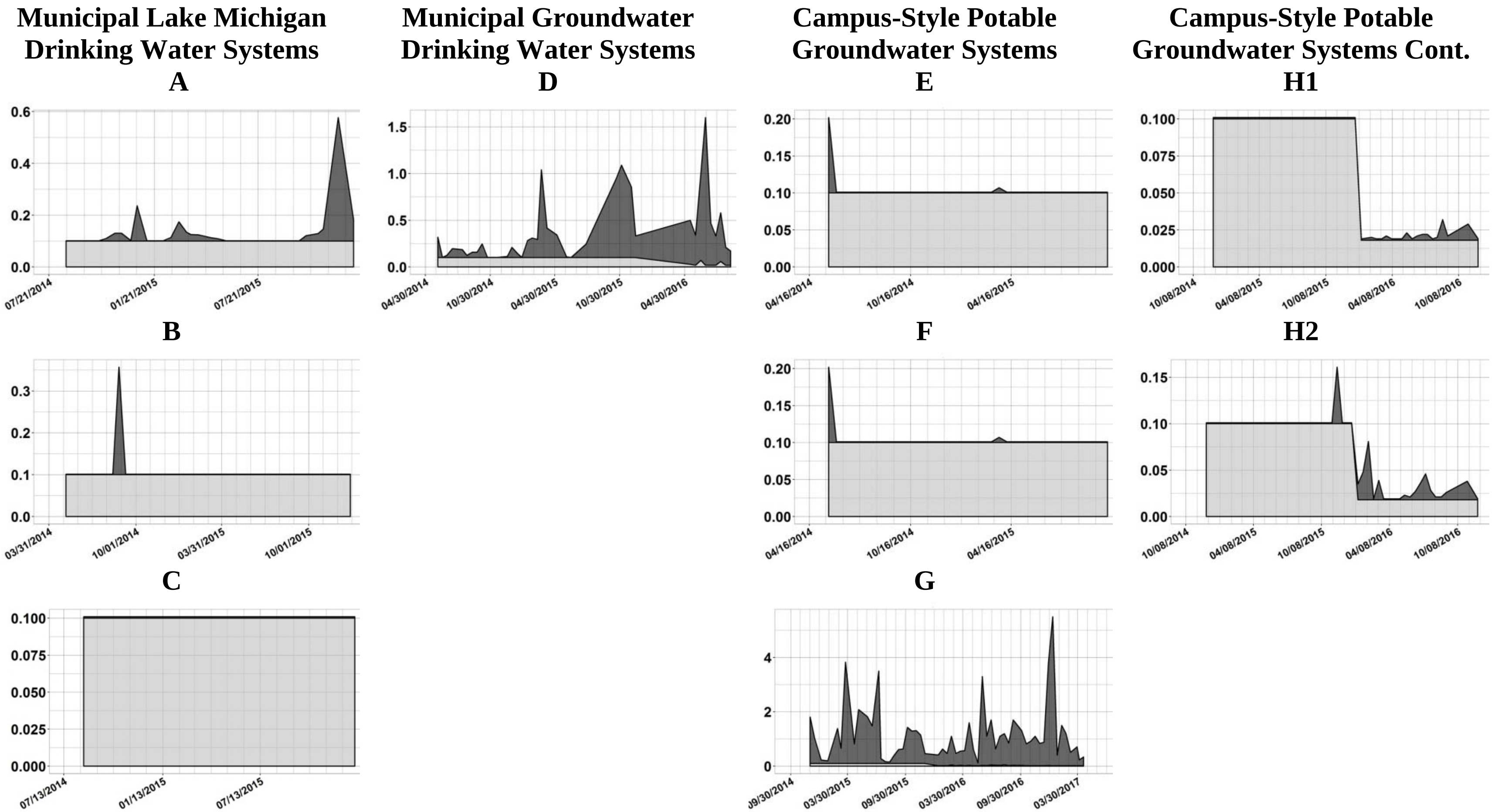
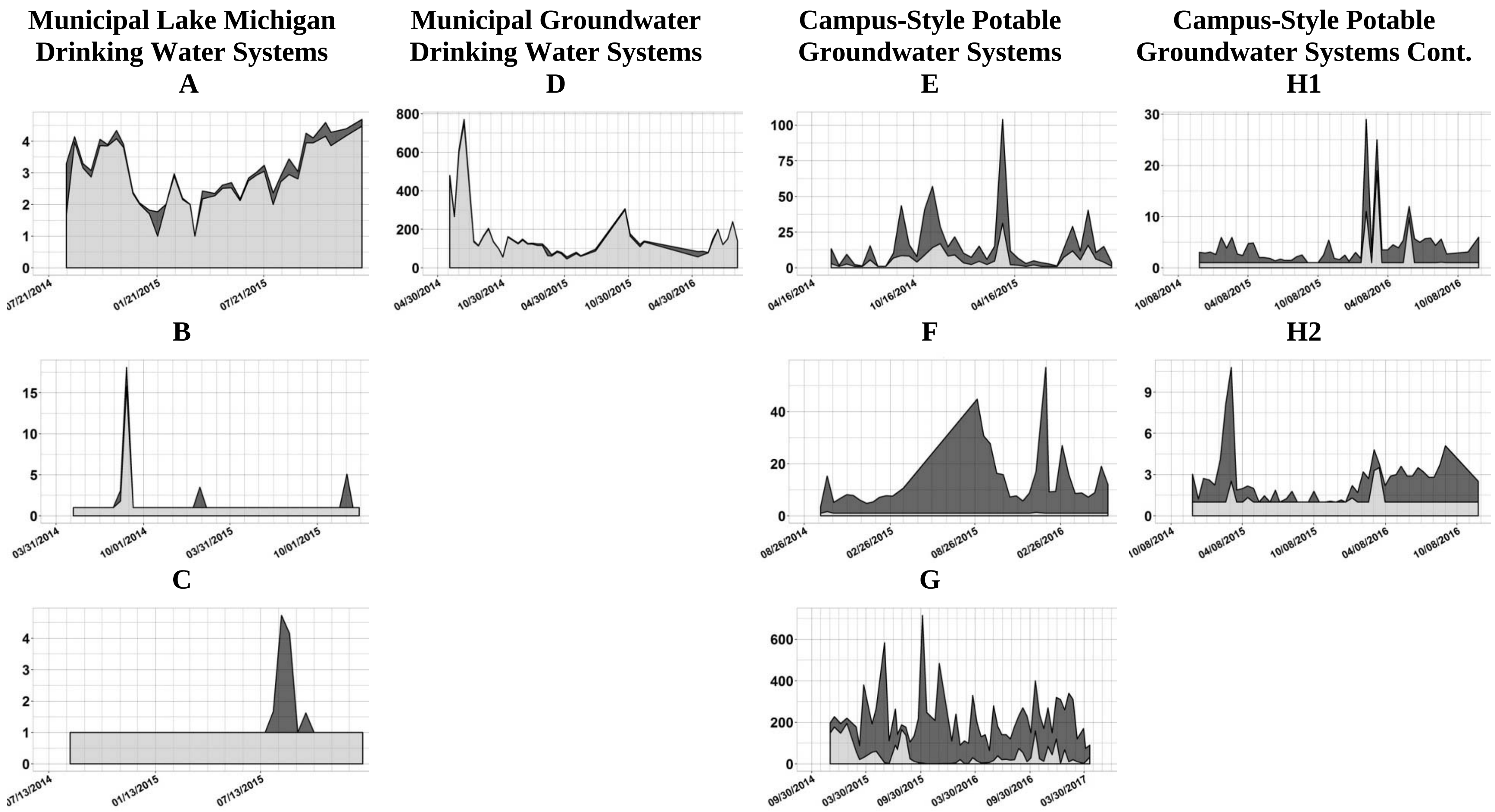


Figure 10.4 Iron released into PRS monitoring station copper test chamber stagnating water in mg/L



Municipal Lake Michigan Drinking Water Systems

Municipal Groundwater Drinking Water Systems

Campus-Style Potable Groundwater Systems

Campus-Style Potable Groundwater Systems Cont.

Figure 10.5 Manganese released into PRS monitoring station lead test chamber stagnating water in µg/L

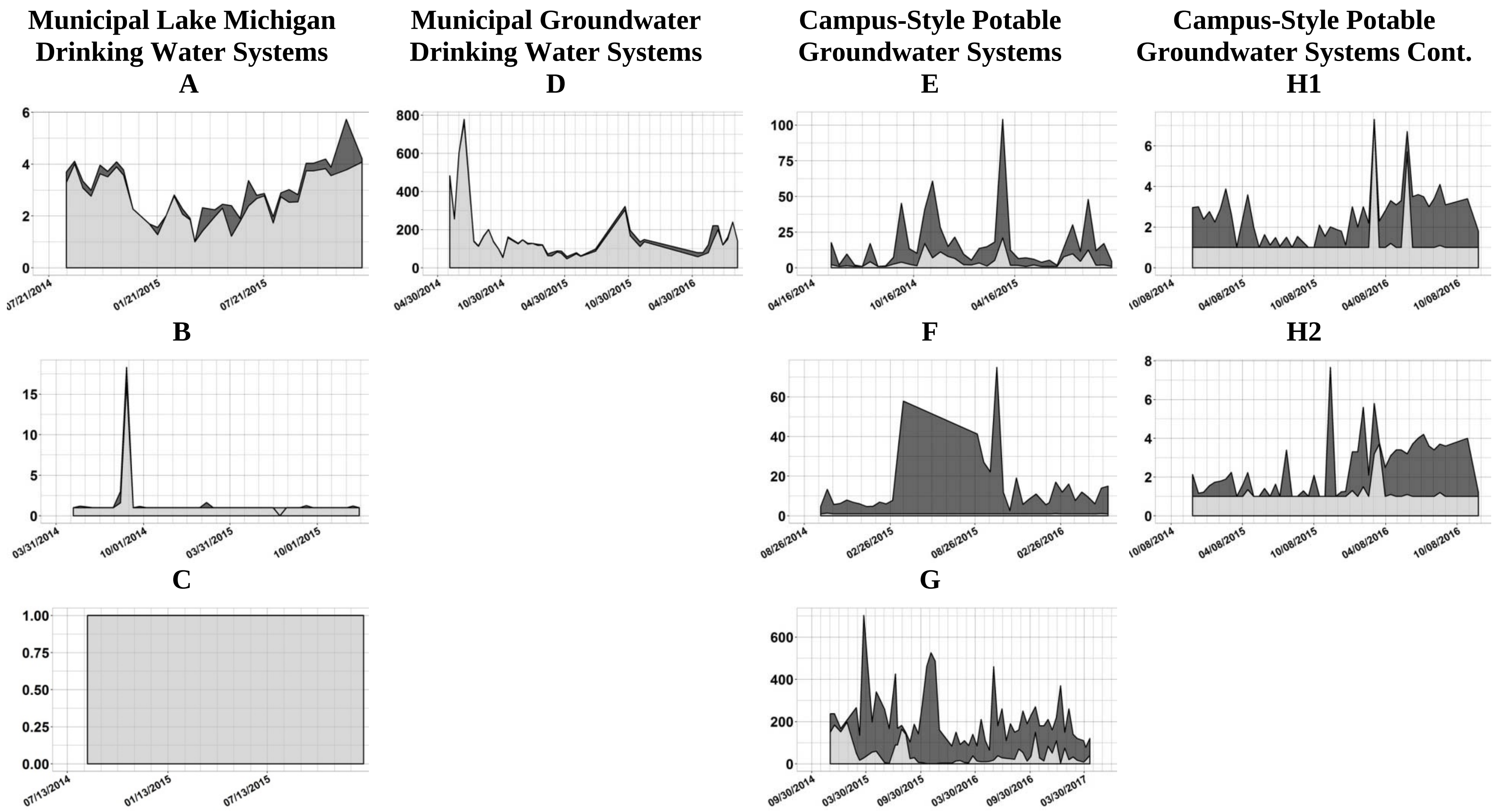


Figure 10.6 Manganese released into PRS monitoring station copper test chamber stagnating water in µg/L

For iron, the laboratory limit of detection was too high to see the variation of the iron at lower levels. For the water systems that were still monitoring when the laboratory was changed, such as Water System H, the variation of iron release can be seen at the lower limit of detection and used in correlations between water quality parameters. Iron release was the most dramatic in Water Systems D and G and sometimes F. Lake Michigan Water System A exhibited a high degree of particulate iron release compared to the other Lake Michigan systems. Particulate manganese was significant in the groundwater systems.

Tables 10.4 to 10.6 lists the average values of the metals in dissolved and particulate form found in the stagnating test chamber water and their typical variations.

PLUMBING RELATED METALS

Plumbing related metals that can be corroded and become dissolved or entrained in the system water were studied. Cadmium, chromium, cobalt, nickel, tin, and zinc were analyzed. They were not found to be significant except for the patterns of nickel and zinc.

Water system concentrations are shown in Tables 10.7 and 10.8. Released concentrations for nickel and zinc are shown in Figures 10.7 to 10.10. Statistics for the released metals are shown in Tables 10.9 and 10.10.

NATURAL HARDNESS RELATED MINERALS

Minerals related to water hardness and water softening were also studied (calcium, magnesium, barium, strontium, sodium, and potassium).

Calcium and magnesium are presented here. System water concentrations are shown in Tables 10.11 and 10.12. Released calcium and magnesium in the test chambers are shown in Figures 10.11 to 10.14. Tables 10.13 and 10.14 list the statistics for released calcium and magnesium.

From the tables and figures, it is seen that calcium and magnesium were mostly in dissolved form in all water systems. Alkalinity, pH, and temperature are major water quality parameters that control the formation of particulate calcium and magnesium. This was discussed in Chapter 7 regarding the calcium carbonate precipitation potential and the Langelier Index. Water systems cannot tolerate excessive precipitation of these minerals because of the potential for clogging piping, valves, and meters. In Water System E, the water was softened after it entered each building. The monitoring took place during a time that new softeners were being installed, so there were times that water was by-passing the softeners and hard water reached the PRS Monitoring Station.

OTHER SOURCE WATER METALS

Vanadium and arsenic were also studied. Water System G had previously had an issue with elevated arsenic in the groundwater. This problem was addressed when the wells were rehabilitated in association with this project. During monitoring, the average arsenic concentration in the flowing system water was measured at 5.8 µg/L. See Table 10.15 to compare Water System G to the other water systems.

Table 10.4
Aluminum released into PRS monitoring station test chamber stagnating water in µg/L

Copper Test Chamber: Particulate Aluminum

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	43	16	0
B	8.8	2.2	0
C	6.8	2.6	0
D	1.8	0.40	0
E	0.79	0.12	0
F	0.15	0.03	0
G	5.7	1.5	0
H1	0.02	0	0
H2	0.11	0.02	0

Copper Test Chamber: Dissolved Aluminum

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	134	70	6.4
B	13	11	8.5
C	45	31	18
D	9.6	9.0	8.5
E	10	10	10
F	8.8	8.3	7.9
G	7.6	7.3	7.0
H1	8.7	8.0	7.3
H2	8.8	8.1	7.3

Lead Test Chamber: Particulate Aluminum

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	26	13	0.59
B	6.7	1.5	0
C	19	5.4	0
D	0.99	0.15	0
E	0	0	0
F	0.87	0.18	0
G	5.3	1.3	0
H1	1.8	0.28	0
H2	0.03	0.01	0

Lead Test Chamber: Dissolved Aluminum

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	137	73	8.2
B	13	11	8.4
C	47	33	18
D	9.7	9.0	8.4
E	10	10	10
F	8.8	8.3	7.9
G	7.6	7.3	7.1
H1	8.1	8.0	7.8
H2	9.0	8.2	7.4

Table 10.5
Iron released into PRS monitoring station test chamber stagnating water in mg/L

Copper Test Chamber: Particulate Iron

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.14	0.03	0
B	0.04	0.01	0
C	0	0	0
D	0.85	0.29	0
E	0.01	0	0
F	1.2	0.35	0
G	3.0	1.0	0
H1	0.01	0	0
H2	0.03	0.01	0

Copper Test Chamber: Dissolved Iron

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.10	0.10	0.10
B	0.10	0.10	0.10
C	0.10	0.10	0.10
D	0.10	0.08	0.06
E	0.10	0.10	0.10
F	0.08	0.07	0.06
G	0.08	0.06	0.04
H1	0.07	0.07	0.06
H2	0.07	0.07	0.06

Lead Test Chamber: Particulate Iron

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.03	0.01	0
B	0.21	0.03	0
C	0.03	0.01	0
D	0.93	0.26	0
E	0.01	0	0
F	1.4	0.43	0
G	3.2	1.2	0
H1	0.03	0.01	0
H2	0.03	0.01	0

Lead Test Chamber: Dissolved Iron

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.10	0.10	0.10
B	0.10	0.10	0.10
C	0.10	0.10	0.10
D	0.10	0.08	0.07
E	0.10	0.10	0.10
F	0.08	0.07	0.06
G	0.10	0.06	0.03
H1	0.07	0.07	0.06
H2	0.07	0.07	0.06

Table 10.6
Manganese released into PRS monitoring station test chamber stagnating water in µg/L

Copper Test Chamber: Particulate Manganese

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	1.3	0.32	0
B	0.53	0.11	0
C	0	0	0
D	34	9.9	0
E	51	13	0
F	39	13	0
G	469	173	0
H1	3.2	1.3	0
H2	3.9	1.3	0

Copper Test Chamber: Dissolved Manganese

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	4.1	2.7	1.3
B	3.4	1.4	0
C	1.0	1.0	1.0
D	369	164	0
E	14	4.3	0
F	1.1	1.0	0.90
G	125	48	0
H1	2.5	1.2	0
H2	1.6	1.1	0.66

Lead Test Chamber: Particulate Manganese

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.71	0.22	0
B	1.4	0.24	0
C	0.89	0.23	0
D	21	6.8	0
E	43	11	0
F	34	12	0
G	478	173	0
H1	7.8	2.6	0
H2	3.6	1.4	0

Lead Test Chamber: Dissolved Manganese

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	4.3	2.8	1.4
B	3.3	1.4	0
C	1.0	1.0	1.0
D	360	160	0
E	18	5.7	0
F	1.2	1.0	0.86
G	130	46	0
H1	5.8	1.8	0
H2	1.7	1.1	0.61

Table 10.7
Comparison of nickel in flowing system water in µg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	<2.0	<2.0	<2.0
B	<2.0	<2.0	<2.0
C	<2.0	<2.0	<2.0
D	1.8	1.7	1.5
E	<2.0	<2.0	<2.0
F	1.6	1.5	1.3
G	4.0	2.5	0.9
H1	1.5	1.4	1.3
H2	12	3.0	0

Table 10.8
Comparison of zinc in flowing system water in µg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	<5.0	<5.0	<5.0
B	29	9.6	0
C	<5.0	<5.0	<5.0
D	5.6	5.2	4.7
E	32	12	0
F	17	8.0	0
G	38	15	0
H1	8.3	5.8	3.3
H2	12	6.9	2.0

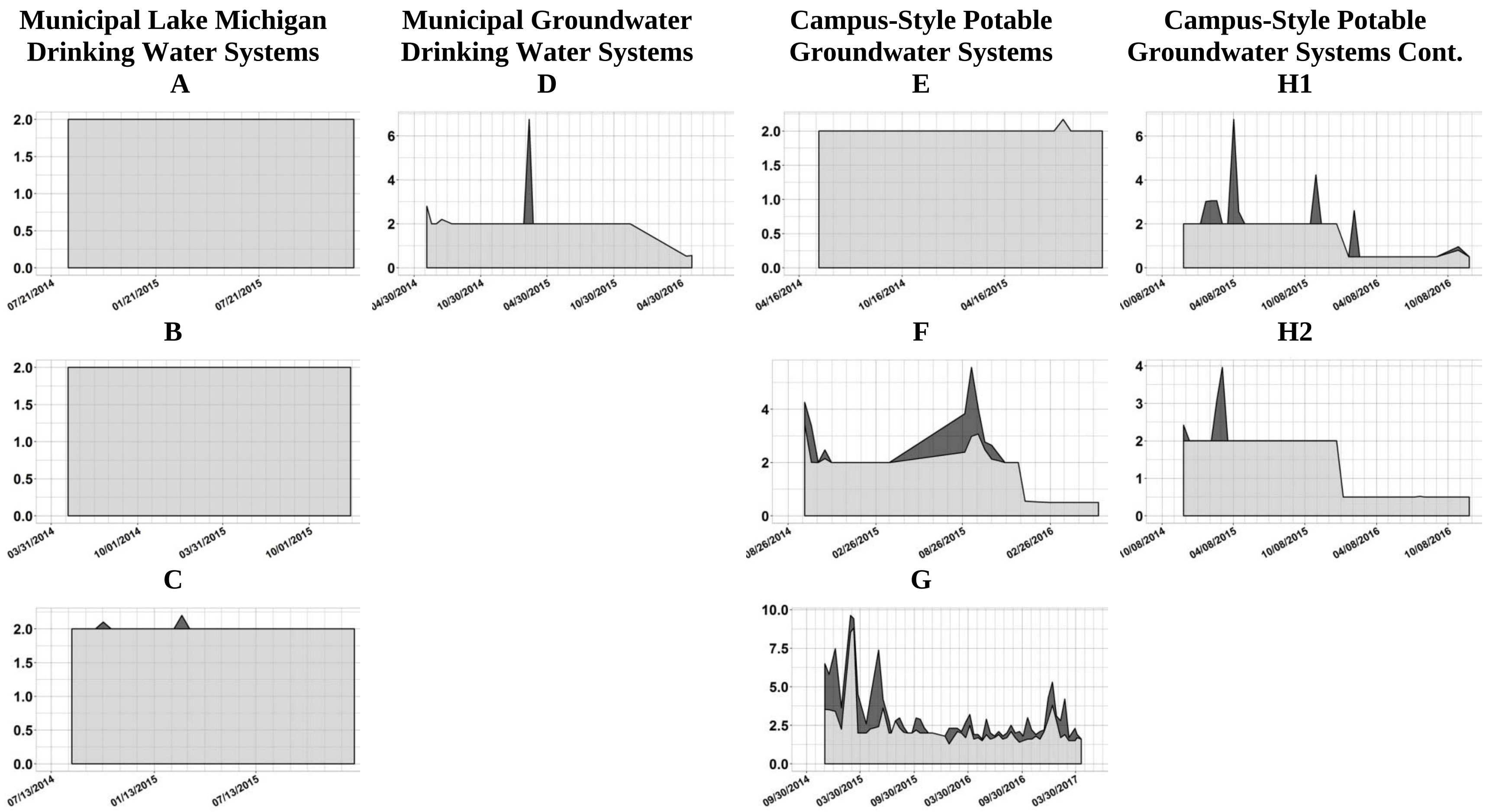


Figure 10.7 Nickel released into PRS monitoring station lead test chamber stagnating water in μg/L

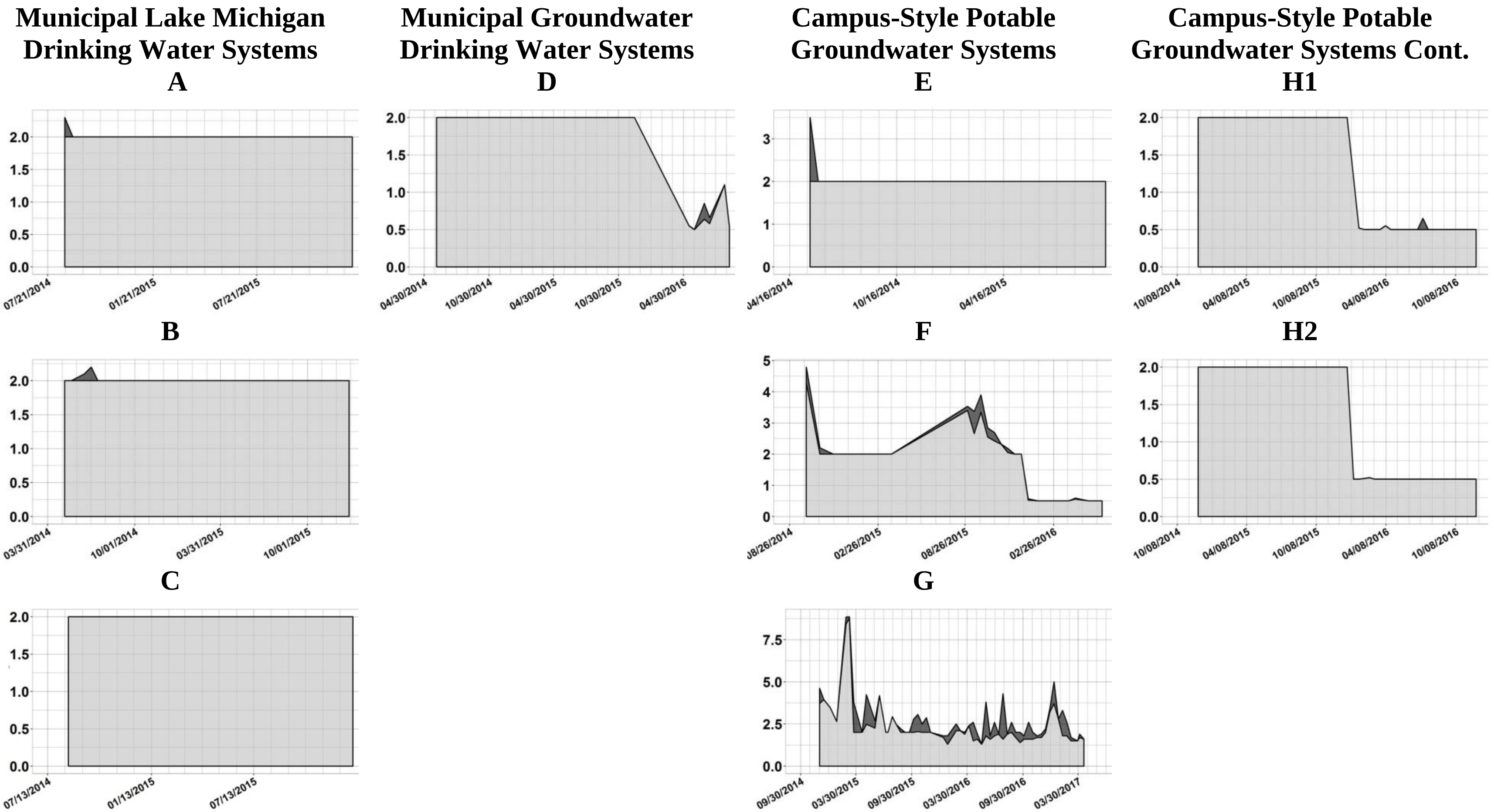


Figure 10.8 Nickel released into PRS monitoring station copper test chamber stagnating water in µg/L

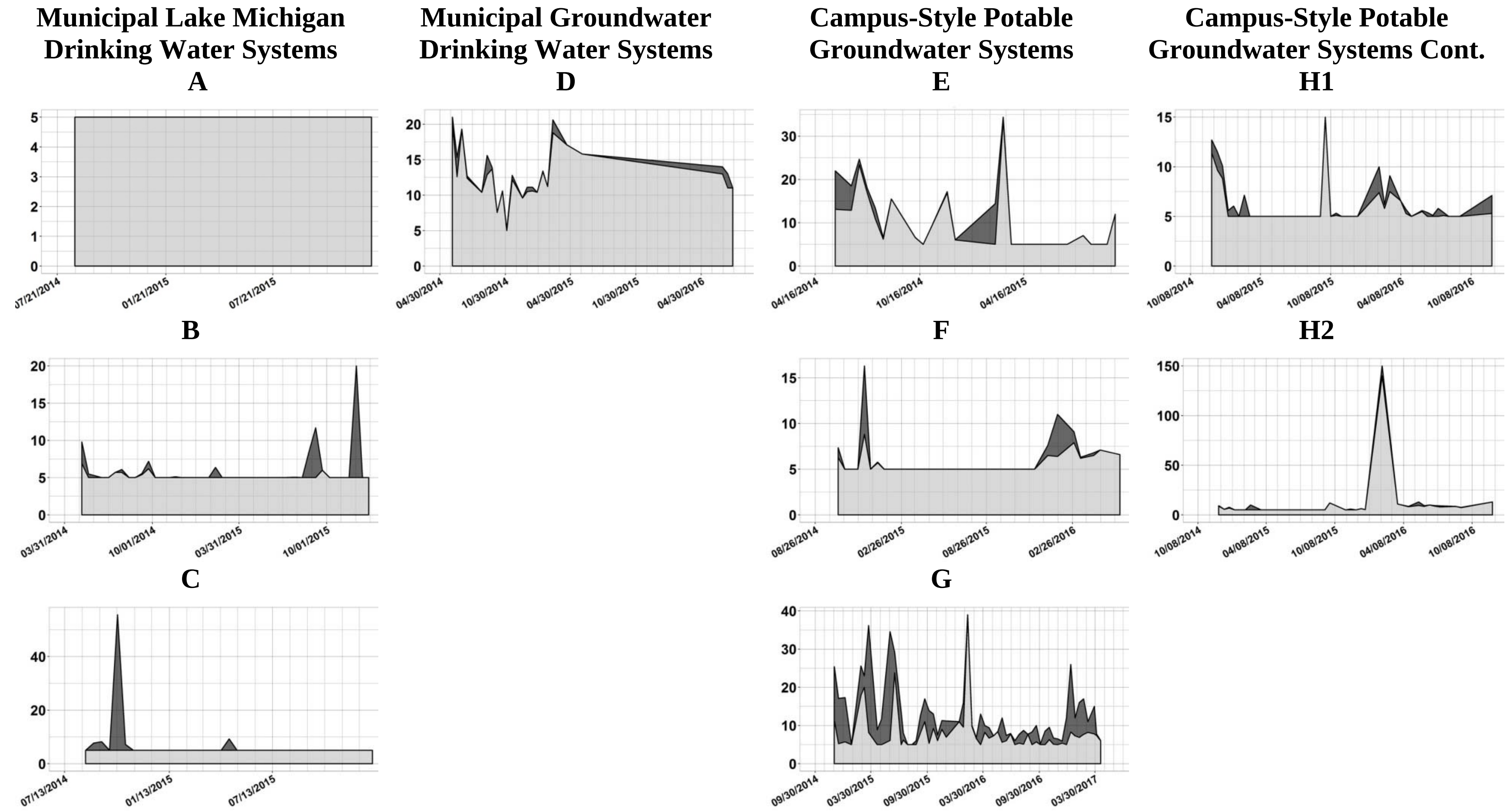


Figure 10.9 Zinc released into PRS monitoring station lead test chamber stagnating water in µg/L

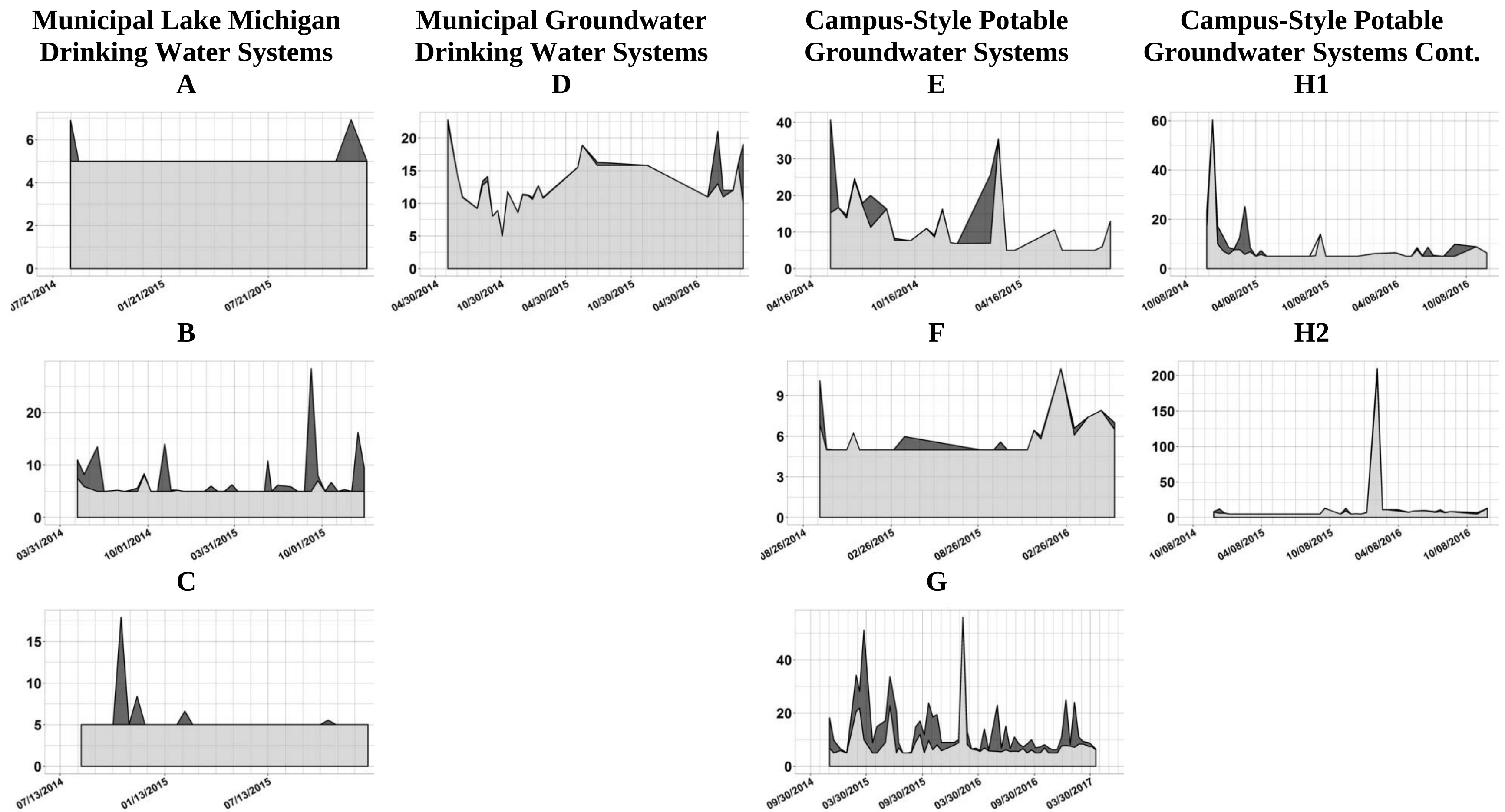


Figure 10.10 Zinc released into PRS monitoring station copper test chamber stagnating water in µg/L

Table 10.9
Nickel released into PRS monitoring station test chamber stagnating water in µg/L

Copper Test Chamber: Particulate Nickel			
Water System	**Highest Expected Concentration**	**Average Concentration**	**Lowest Expected Concentration**
A	0.03	0.01	0
B	0.03	0.01	0
C	0.00	0	0
D	0.02	0.01	0
E	0.16	0.04	0
F	0.31	0.10	0
G	2.2	0.44	0
H1	0.02	0	0
H2	0	0	0
Copper Test Chamber: Dissolved Nickel			
Water System	**Highest Expected Concentration**	**Average Concentration**	**Lowest Expected Concentration**
A	2.0	2.0	2.0
B	2.0	2.0	2.0
C	2.0	2.0	2.0
D	1.9	1.8	1.6
E	2.0	2.0	2.0
F	2.4	1.8	1.1
G	4.0	2.4	0.76
H1	1.4	1.4	1.4
H2	1.5	1.4	1.3
Lead Test Chamber: Particulate Nickel			
Water System	**Highest Expected Concentration**	**Average Concentration**	**Lowest Expected Concentration**
A	0	0	0
B	0	0	0
C	0.05	0.01	0
D	0.96	0.15	0
E	0	0	0
F	1.0	0.27	0
G	2.7	0.80	0
H1	1.5	0.27	0
H2	0.36	0.08	0
Lead Test Chamber: Dissolved Nickel			
Water System	**Highest Expected Concentration**	**Average Concentration**	**Lowest Expected Concentration**
A	2.0	2.0	2.0
B	2.0	2.0	2.0
C	2.0	2.0	2.0
D	2.2	1.9	1.7
E	2.0	2.0	2.0
F	2.2	1.7	1.2
G	3.9	2.3	0.76
H1	1.4	1.4	1.4
H2	1.6	1.5	1.4

Table 10.10
Zinc released into PRS monitoring station test chamber stagnating water in µg/L

Copper Test Chamber: Particulate Zinc

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.56	0.11	0
B	9.70	1.8	0
C	3.3	0.51	0
D	3.6	0.81	0
E	11	2.3	0
F	1.0	0.22	0
G	20	5.6	0
H1	8.4	1.6	0
H2	3.5	0.70	0

Copper Test Chamber: Dissolved Zinc

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	5.0	5.0	5.0
B	6.1	5.2	4.3
C	5.0	5.0	5.0
D	20	12	4.4
E	31	12	0
F	6.4	5.7	4.9
G	21	8.4	0
H1	19	7.7	0
H2	30	11	0

Lead Test Chamber: Particulate Zinc

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0	0	0
B	4.1	0.74	0
C	11	1.8	0
D	3.2	0.59	0
E	4.2	1.2	0
F	3.1	0.59	0
G	18	5.0	0
H1	1.5	0.41	0
H2	1.9	0.63	0

Lead Test Chamber: Dissolved Zinc

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	5.0	5.0	5.0
B	5.6	5.1	4.6
C	5.0	5.0	5.0
D	22	13	3.0
E	30	10	0
F	7.2	5.7	4.1
G	19	8.1	0
H1	8.3	5.8	3.3
H2	12	10	8.2

Table 10.11
Comparison of calcium in flowing system water in mg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	37	34	32
B	37	35	32
C	38	35	33
D	33	27	21
E	25	4.2	0
F	75	66	58
G	69	61	52
H1	92	82	72
H2	89	82	74

Table 10.12
Comparison of magnesium in flowing system water in mg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	13	12	11
B	13	12	11
C	13	12	11
D	8.4	5.7	3.1
E	24	4.2	0
F	41	36	32
G	33	29	26
H1	52	46	40
H2	51	46	41

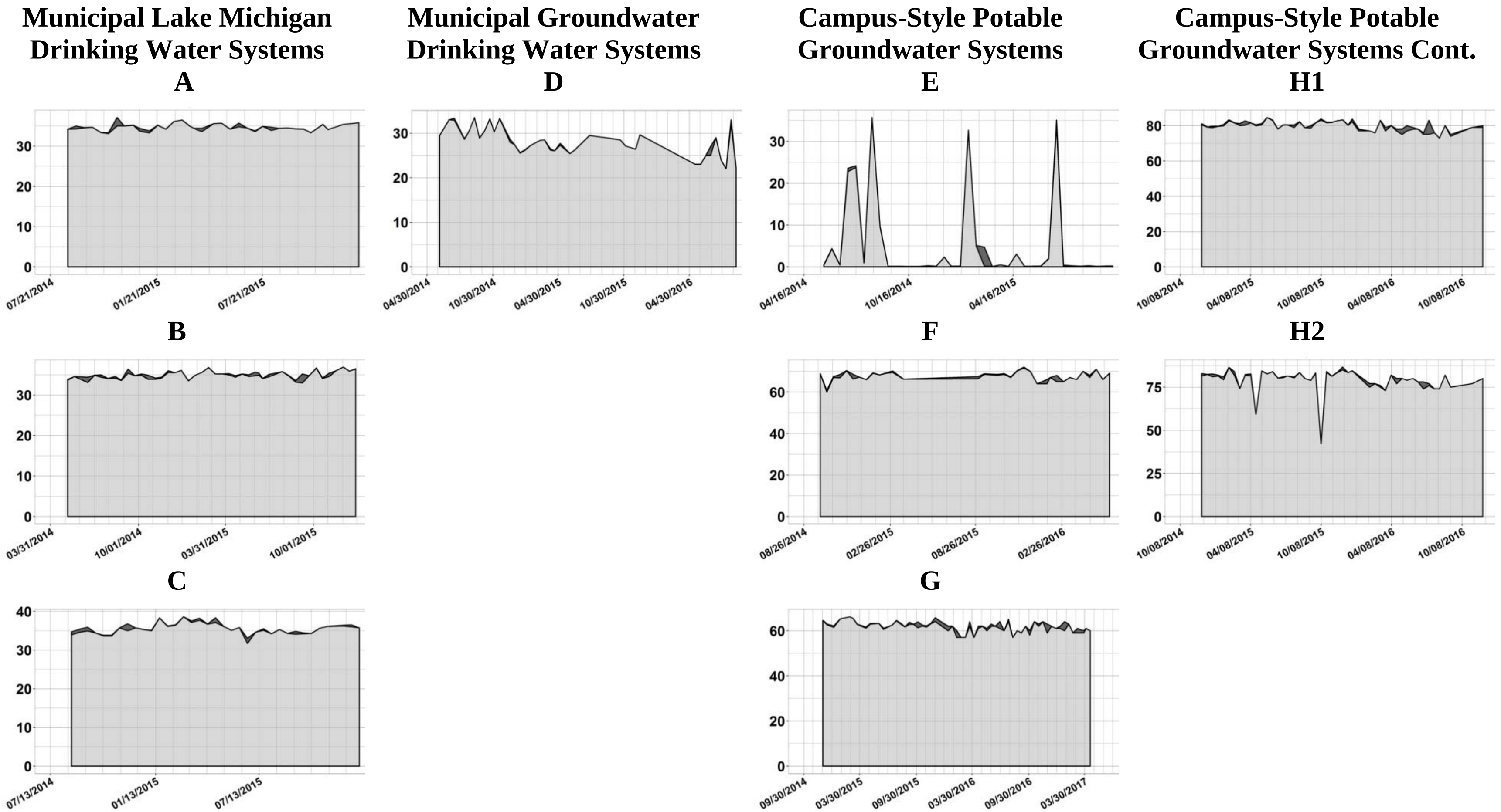


Figure 10.11 Calcium released into PRS monitoring station lead test chamber stagnating water in mg/L

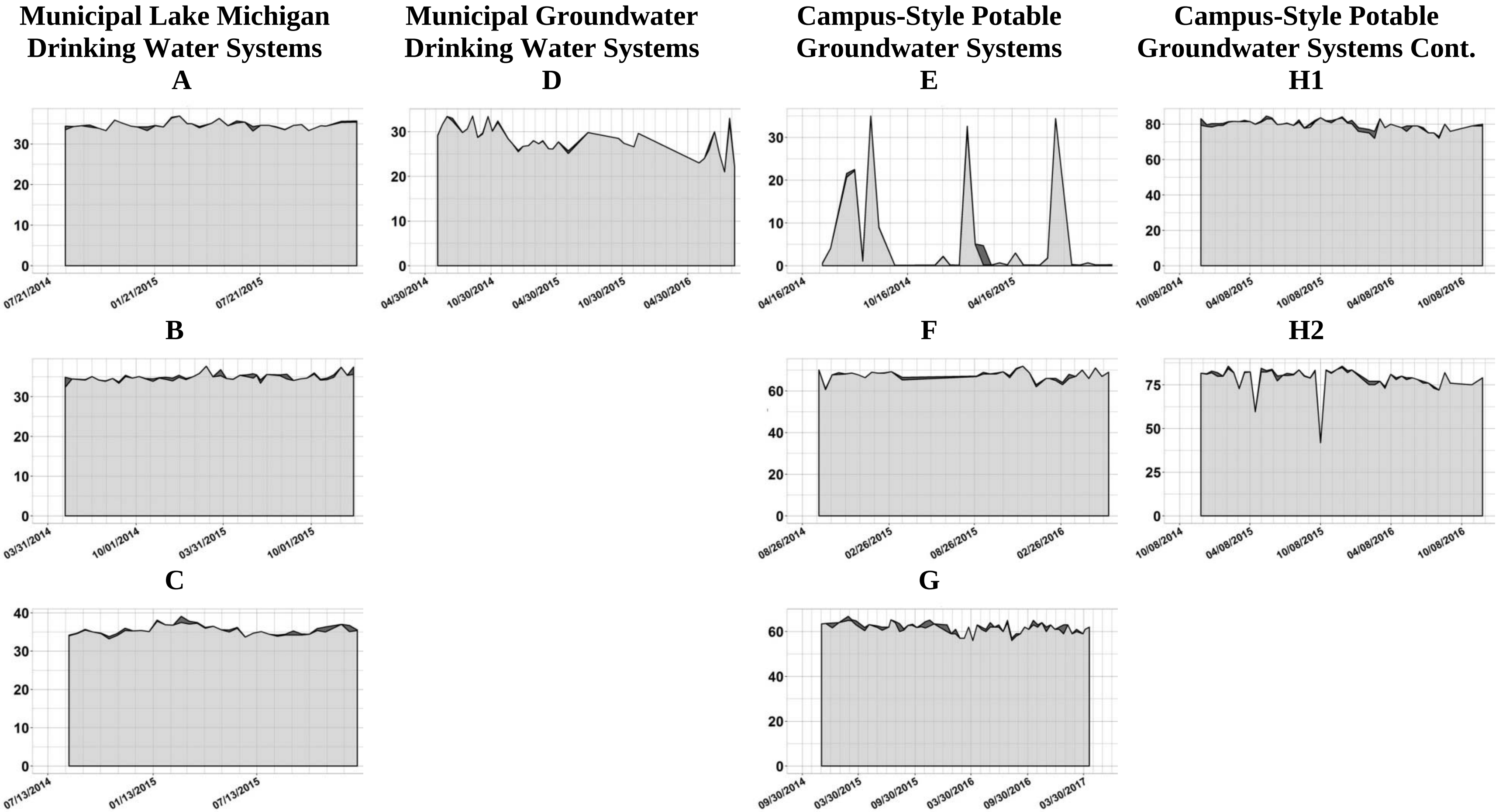


Figure 10.12 Calcium released into PRS monitoring station copper test chamber stagnating water in mg/L

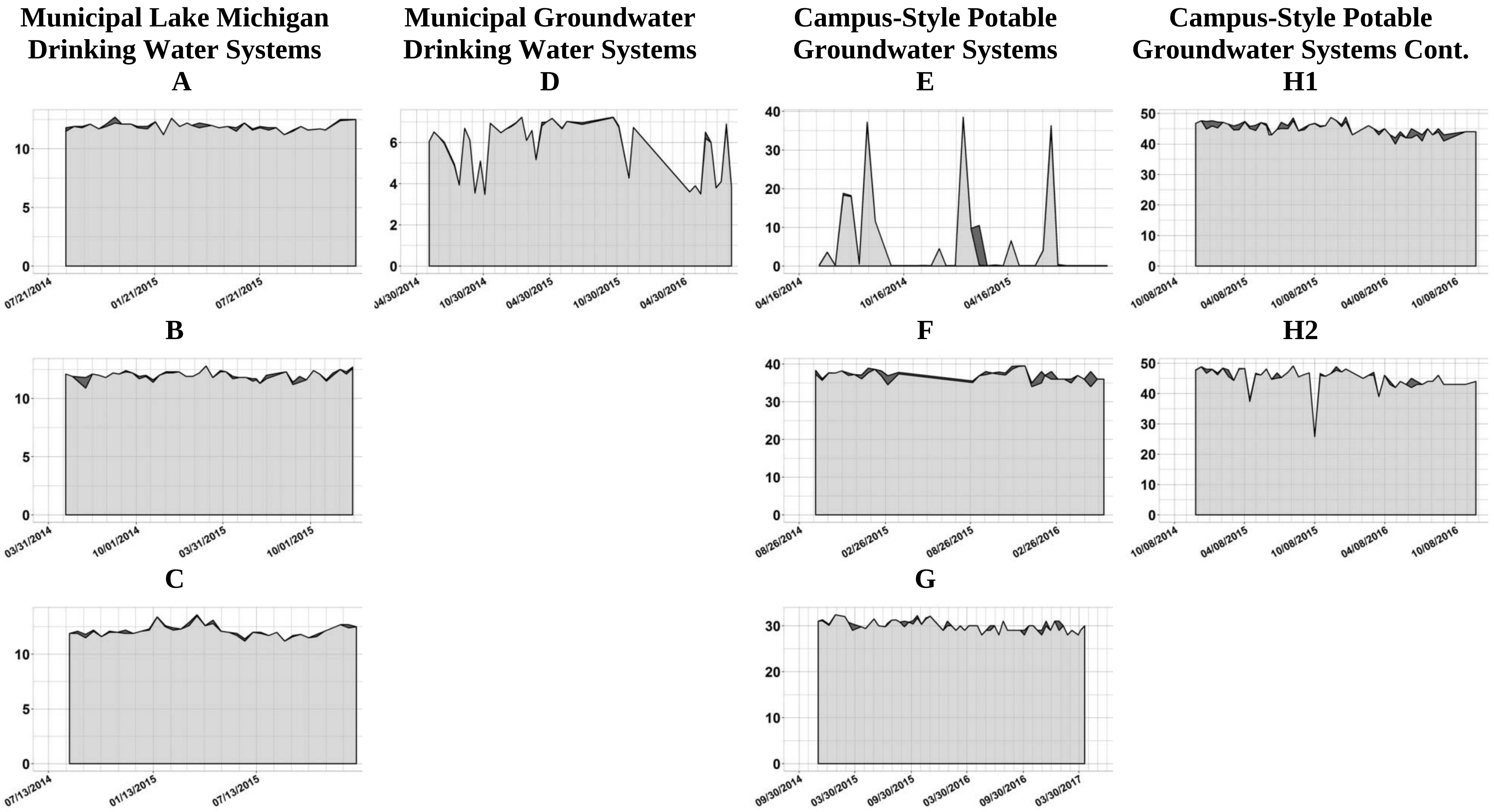
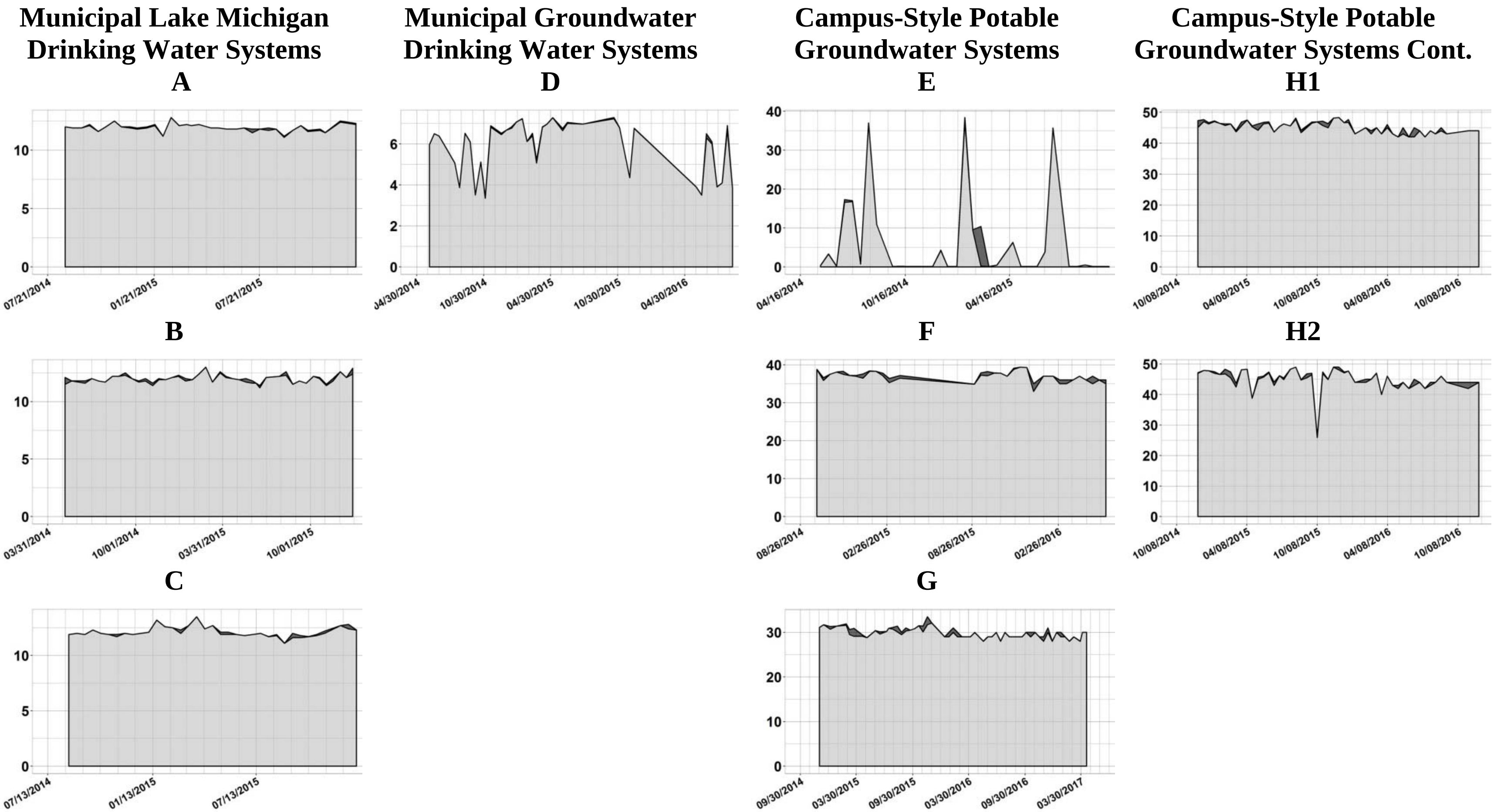


Figure 10.13 Magnesium released into PRS monitoring station lead test chamber stagnating water in mg/L


Municipal Lake Michigan Drinking Water Systems

Municipal Groundwater Drinking Water Systems

Campus-Style Potable Groundwater Systems

Campus-Style Potable Groundwater Systems Cont.

Figure 10.14 Magnesium released into PRS monitoring station copper test chamber stagnating water in mg/L

Table 10.13
Calcium released into PRS monitoring station test chamber stagnating water in mg/L

Copper Test Chamber: Particulate Calcium

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.81	0.15	0
B	1.5	0.34	0
C	1.4	0.32	0
D	0.73	0.12	0
E	1.5	0.25	0
F	1.5	0.31	0
G	3.7	0.85	0
H1	2.8	0.71	0
H2	2.6	0.55	0

Copper Test Chamber: Dissolved Calcium

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	37	35	32
B	37	35	32
C	37	35	33
D	35	28	21
E	27	5.8	0
F	74	67	61
G	67	61	56.
H1	84	7	74
H2	92	78	64

Lead Test Chamber: Particulate Calcium

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	1.2	0.20	0
B	1.5	0.30	0
C	1.4	0.29	0
D	0.80	0.13	0
E	1.2	0.23	0
F	2.5	0.46	0
G	3.3	0.65	0
H1	3.5	0.73	0
H2	2.7	0.49	0

Lead Test Chamber: Dissolved Calcium

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	37	35	32
B	37	35	32
C	38	35	33
D	35	28	21
E	25	4.9	0
F	74	67	61
G	67	61	56
H1	85	79	74
H2	93	79	64

Table 10.14
Magnesium released into PRS monitoring station test chamber stagnating water in mg/L

Copper Test Chamber: Particulate Magnesium

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.19	0.04	0
B	0.41	0.09	0
C	0.34	0.06	0
D	0.16	0.03	0
E	2.7	0.39	0
F	2.1	0.42	0
G	1.3	0.33	0
H1	2.3	0.46	0
H2	2.0	0.40	0

Copper Test Chamber: Dissolved Magnesium

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	13	12	11
B	13	12	11
C	13	12	11
D	8.8	5.8	2.9
E	28	5.8	0
F	40	37	34
G	32	30	28
H1	49	45	41
H2	53	45	37

Lead Test Chamber: Particulate Magnesium

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	0.40	0.08	0
B	0.47	0.09	0
C	0.47	0.09	0
D	0.14	0.03	0
E	2.4	0.39	0
F	3.3	0.67	0
G	1.0	0.19	0
H1	3.0	0.67	0
H2	1.9	0.31	0

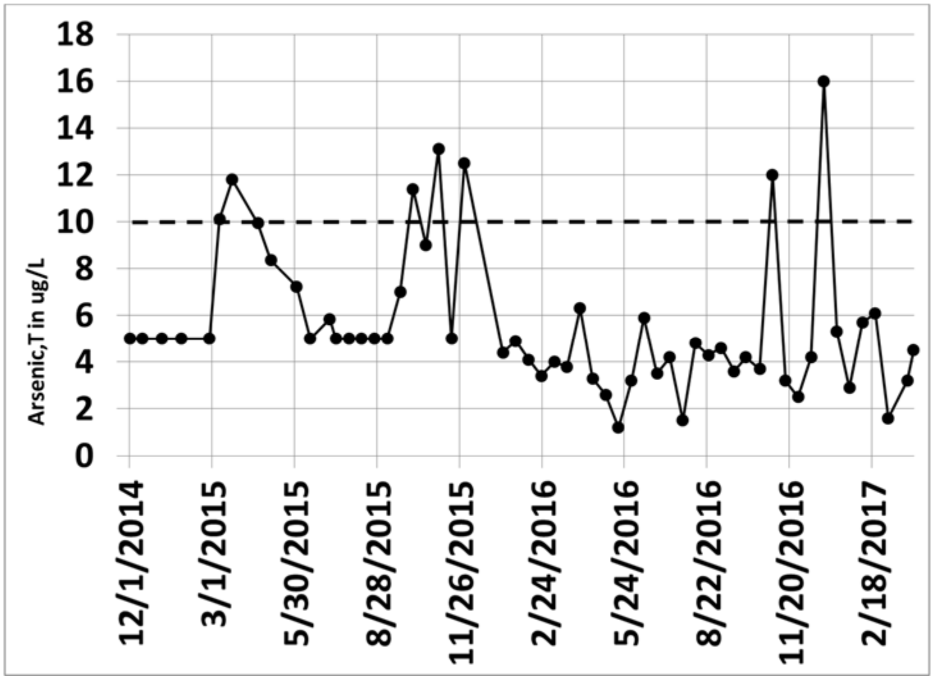
Lead Test Chamber: Dissolved Magnesium

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	13	12	11
B	13	12	11
C	13	12	11
D	8.8	5.8	2.7
E	28	5.4	0
F	40	37	33
G	33	30	27
H1	49	45	40
H2	52	45	37

Table 10.15
Total arsenic concentrations in flowing system water in µg/L taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
A	6.0	5.2	4.3
B	5.8	5.1	4.5
C	5.1	5.0	4.9
D	4.3	4.0	3.6
E	5.7	5.2	4.6
F	9.5	5.0	0.4
G	12	5.8	0
H1	4.6	3.3	2.1
H2	4.2	3.3	2.4

Arsenic concentration at a high water age location was measured over the source water maximum contaminant goal of 10 µg/L in about 10% of the system water samples (6 out of 56 samples). See Figure 10.15. The source water was in compliance with the maximum contaminant goal, but out in the distribution system, particulate arsenic released from scale above that limit.



The dashed line is the Maximum Contaminant Limit for arsenic in source water (10 µg/L).

Figure 10.15 Water System G: Arsenic released in flowing system water in µg/L taken at a high water age location (PRS monitoring station influent tap)

Table 10.16 lists the statistics for arsenic release into the stagnating water of the lead and copper test chambers. This shows that the release of arsenic in the distribution system tends to be in particulate form.

Table 10.16
Water System G: Arsenic released into PRS monitoring station test chamber stagnating water in µg/L

Site	Highest Expected Concentration	Average Concentration	Lowest Expected Concentration
Copper Test Chamber Particulate Arsenic	22	7.5	0
Copper Test Chamber Dissolved Arsenic	4.5	3.3	2.0
Lead Test Chamber Particulate Arsenic	21	7.7	0
Lead Test Chamber Dissolved Arsenic	3.8	3.3	2.7

TURBIDITY

System Water

Turbidity, representing particulates in the water, at the high water age locations in the systems are shown in Table 10.17. Water System D had the highest average system water turbidity.

Table 10.17
Turbidity in flowing system water in NTUs taken at a high water age location (PRS monitoring station influent tap)

Water System	Highest Expected	Average	Lowest Expected
A	1.0	0.7	0.30
B	0.6	0.2	0
C	0.3	0.1	0
D	8.3	2.9	0
E	1.4	0.6	0
F	1.2	0.6	0
G	1.7	0.9	0.10
H1	0.9	0.4	0
H2	1.0	0.4	0

Building Plumbing

For the four campus water systems where all buildings were accessible for monitoring, turbidity of the water was measured weekly at various locations as explained in Chapter 5. These were all water systems where microbiologically influenced corrosion had been found in the wells along with corroding metal components of the well. This appeared to have inoculated the rest of the plumbing system with the result that water mains and premise plumbing had significant quantities of pipe wall accumulations of chemical scales and biofilms. The measurement of turbidity tracked the release of these materials in the water systems' buildings.

In addition, efforts were made to break up and flush out the accumulations and clean up the water systems. Because of the quantity of accumulations, this had to be done slowly so as to not release material too fast and create a temporary water quality issue. The measurement of turbidity tracked the release of the material over time in order to alert water system personnel to any periods of high pipe wall debris release. Biofilm removing chemical dosage and flushing efforts were managed based on weekly building turbidity results.

The general turbidity patterns at each site were also studied. To compare turbidity between sites and systems, the Shewhart statistics were used. A summary table (Table 10.18) shows that hot water systems had the highest turbidities. This confirmed the findings of the initial investigations of each of these campuses where the highest microbiological populations and metals concentrations were measured in the hot water systems of these buildings. In addition, water from softeners in buildings was found to have high microbiological populations in the initial investigations. Softeners provide an environment of high water residence time and high resin surface area conducive to excessive microbiological growth.

Table 10.18
Summary table –average turbidity for each type of piping system in buildings in NTU

System	Water Entering Building	Far Cold Water Tap	Softener Outlet	Far Hot Water Tap
E	0.70	0.51	0.60	1.4
F	0.75	0.67	0.59	1.1
G	0.88	1.5	0.93	1.6
H	1.7 (actually deeper inside building than other "entry points")	0.62	no data	0.58

METAL PLATE CHEMICAL ANALYSIS

Many aspects of the metal plate scale analysis have already been discussed. The discussion is completed here with a look at aluminum, iron, and manganese in the scales (Tables 10.19 and 10.20).

Aluminum on lead plates was the highest in the scales of the three Lake Michigan water systems, Systems A, B, and C where aluminum-based coagulants are used. Water System A uses alum and displayed highly pronounced aluminum concentration pattern in the water and a high presence of aluminum in the lead plate scales. Water System B uses a polyaluminum hydroxychloride as a coagulant. There is no significant aluminum concentration in the water except for isolated peaks that may come from the lake or the coagulant but a significant presence on the lead plate scales. Water System C presents a third variation. Alum is used as in Water System A and there is a similar pronounced pattern of aluminum concentration. Yet, there is little presence of aluminum in the lead plate scales. Aluminum can also be found in the copper plate scales (Table 10.20) at the same or in lower amounts for the three systems. The groundwater systems do not have aluminum in their lead plate scales. Water Systems E and possibly F have some in their copper plate scales.

There is a very high presence of iron and manganese in Water System D lead and copper plate scales. The plates from Water System D were notable because they both were oddly colored, possibly from the presence of iron and manganese. In addition, phosphorus on both the lead and copper plates was "bound through adsorption onto amorphous iron oxide or hydroxide." These scales were unique.

Water System B would be expected to have lower iron and manganese because it is a lake water system. However, wells are used as a backup source of water. The wells are exercised routinely. The PRS Monitoring Station received some of this water especially during the issue of water stagnating in the influent line. Subsequently, iron and manganese built up on the lead plates. This is a reflection on the quality of the well water. In addition, Water System B had a harvested lead service line analyzed in 2013. The outer layer on the pipe was an iron/manganese hydroxide that could crumble and carry lead into the water.

Table 10.19
Extraneous elements on lead plates by x-ray fluorescence or energy dispersive spectroscopy by weight percent

Water System	Al	Fe	Mn
A	8.3	0.16	0.02
B	8.7	0.33	0.12
C	0.29	0	0.01
D-yellow area		0.80	0.15
D-blue area		1.8	0.39
D-hydrocerussite		1.4	0.28
D- Cerussite		1.9	0.18
D-Litharge		4.2	0.56
E			0.01
F		0.44	
G	PRS Monitoring Station still operating		
H		0.42	0.13

Table 10.20
Extraneous elements on copper plates by x-ray fluorescence or energy dispersive spectroscopy by weight percent

Water System	Al	Fe	Mn
A	5.2	0	0.01
B	0.23	0	0
C	0.47	0	0
D-lower P area		2.4	0.21
D-higher P area		12	0.37
E	0.35	<LOD	0.01
F	<LOD	0.66	
G	PRS Monitoring Station still operating		
H		0.38	0.22

LOD=Limit of Detection

CORRELATIONS

The following common trends were found between water quality parameters and the release of lead and copper in the test chambers:

Water System A showed a trend of influent turbidity with the release of particulate lead in the lead test chamber. Particulate iron was also measured in both test chambers and in the influent system water when influent turbidity was high. The turbidity was high in the system water when aluminum in the system water was low; this would correspond with the use of alum as a coagulant when the source water was the most turbid; this translates into the distribution system.

In Water System B, high turbidity in the system water corresponded with high microbiological population in the system water. Particulate iron, manganese, and aluminum release trended with particulate lead and copper release.

In Water System C, release of particulate iron, manganese, and aluminum trended together with particulate lead and copper.

For Water System D, metals concentrations were high in the system water and in the stagnating test chamber water. A variety of particulate metals tended to be measured releasing at the same time; likewise, a variety of dissolved metals tended to be measured releasing at the same time. When water system turbidity was high, high particulate metals were found in the test chambers; dissolved metals were found to be lower when particulate metals were higher. High turbidity occurred when microbiological populations were low.

In Water System E, particulate manganese trended with particulate lead and copper.

In Water System F, particulate lead was released in the lead test chamber at the same time as many other particulate metals.

Dissolved copper was released in the copper test chamber when dissolved barium, potassium, and sodium were high. This may imply that a certain well had these characteristics and dissolved copper released when that well's water was filling the water system.

With Water Systems G and H, release of particulate lead and copper trended with release of particulate iron and manganese and other metals. Release of dissolved lead and copper trended with the release of other dissolved metals as was seen in Water System D.

As shown in Appendix A, all water systems had particulate lead and copper trending with particulate iron, manganese, and/or aluminum in the water.

SUMMARY

A number of metals were studied in the water systems besides lead and copper. It was found that a variety of particulate metals tended to release together; a variety of dissolved metals tended to release together at other times. It could not be determined in this study if particulate iron, manganese, and aluminum, for example, caused the release of particulate lead and copper or if they were all merely co-trending parameters.

Various metals were intertwined in the scales on the metal surfaces. This implies that one cannot assume scale protective against corrosion will be deposited on clean metal surfaces. Instead, it can be assumed that such scales will be deposited on and within complex pipe wall accumulations.

In the correlation study, turbidity was sometimes representative of particulate metals in the water, sometimes representative of microorganisms in the water, and sometimes not correlative to other water quality parameters at all. Turbidity cannot be claimed to definitively represent particulate lead, particulate copper, or microbiological population. Perhaps the common light scattering analysis of turbidity is not sensitive enough to make these correlations. The precision of the turbidity analyses used in this project ranged from +/- 0.02 to 0.53 NTUs (See Table 5.8). Investigation of newer turbidity technology techniques, such as laser techniques, as a more sensitive water quality indicator should be performed.

However, if turbidity is high, it is by definition a measure of particulate matter in the water. The particulate matter can either come from water source particulates or pipe wall accumulations and it is undesirable to have this debris in the water. It is reasonable to assume that there is higher potential for water quality issues to be occurring, including the release of lead and copper to the water, with higher turbidity.

CHAPTER 11
OPERATIONS, MAINTENANCE, AND CLEANING OF WATER SYSTEMS AND THEIR INFLUENCE ON METAL RELEASE

The water systems participating in this project went through varying degrees of cleaning and phosphate dosing. The outcome of monitoring these activities have been scattered throughout Chapters 6 to 10. In this chapter, the story for each system's lead and copper release is continued with a focus on the effect of cleaning efforts and other system events.

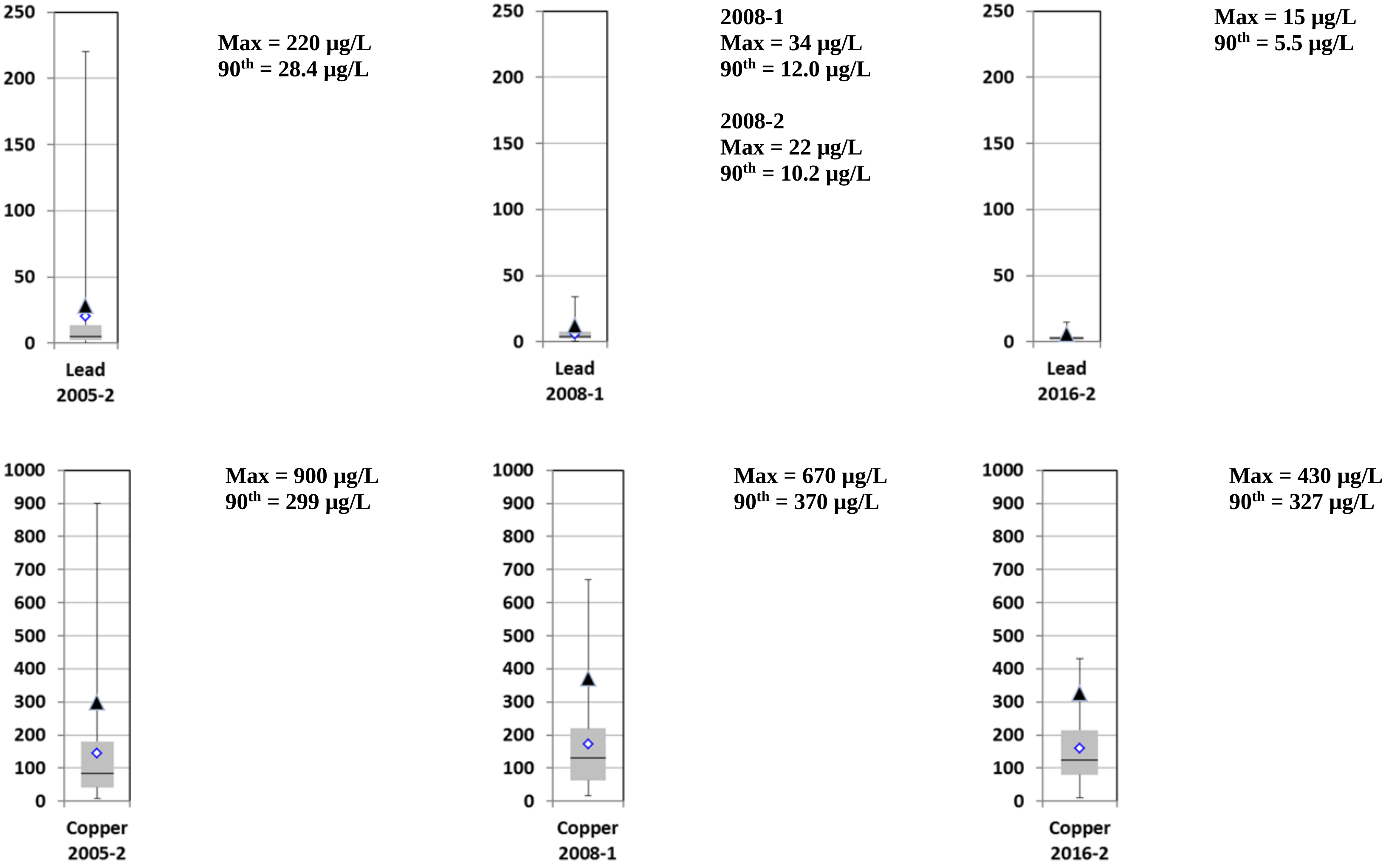
Each water system story began in Chapter 2 and was continued in Chapter 6. In this chapter, significant system events are summarized and the details of the dissolved and particulate lead and copper release trends are shown in a graph relating to cleaning efforts. Then, Lead and Copper Rule data before and after cleaning are shown in box and whisker plots (see Chapter 5). Note: All lead and copper concentration units on box and whisker plots are in µg/L. Refer to Tables 11.18 and 11.19 for a summary of Lead and Copper Rule maximum concentrations, 90th percentile concentrations, and cleaning activities for all water systems. Refer to Table 11.20 for a summary of all cleaning outcomes on lead and copper release in each water system.

CLEANING EFFORTS BY WATER SYSTEMS

Water System K

Water System K exceeded the lead Action Level in 2005. In a subsequent investigation, particulate lead and particulate manganese were found co-trending in residential water samples. Microbiological factors and chloride concentration were identified as factors regarding copper release. Manganese control and uni-directional flushing of water mains were recommended to remove legacy chemical scales and biofilms and to keep new accumulations from forming. Uni-directional flushing was first performed in the system in 2007. In 2008, the Lead and Copper Rule data showed a lower 90th percentile lead release below the Action Level. By 2016, the 90th percentile was 5.5 µg/L. See Figure 11.1. This research project was inspired by the Water System K success.

2007 Uni-directional flushing of water mains begins	**Uni-directional flushing of water mains performed most summers**



Max = 220 µg/L
90th = 28.4 µg/L

2008-1
Max = 34 µg/L
90th = 12.0 µg/L

2008-2
Max = 22 µg/L
90th = 10.2 µg/L

Max = 15 µg/L
90th = 5.5 µg/L

Max = 900 µg/L
90th = 299 µg/L

Max = 670 µg/L
90th = 370 µg/L

Max = 430 µg/L
90th = 327 µg/L

Figure 11.1 Water System K: Lead and Copper Rule data box and whisker plots

Water System A

Table 11.1
Water System A: Historical timeline significant to existing water quality

Date Range	Event
Before 2008	Had been adding 50/50 poly/orthophosphate blend for corrosion control
4/2008 - 9/2008	Offline chemical comparison study of phosphate products using PRS Monitoring Station
4/2008 - 9/2008	PRS Monitoring Station distribution system study of original water system where free chlorine disinfection and 50/50 poly/orthophosphate chemical were used
9/2008 - 11/2008	PRS Monitoring Station distribution system study of change to 10/90 poly/orthophosphate while still using free chlorine (see previous offline tests)
11/2008- 4/2009	PRS Monitoring Station distribution system study of change to chloramine disinfection
11/2009	PRS Monitoring Station study distribution system of steady states of water system after big changes and use for process control

Table 11.2
Water System A: Monitoring project timeline

ID	Date	Event
1	July 17, 2014	Started new PRS Monitoring Station project
2	March 02, 2015	Began feeding less alum for the year
3	January 04, 2016	Shutdown PRS Monitoring Station

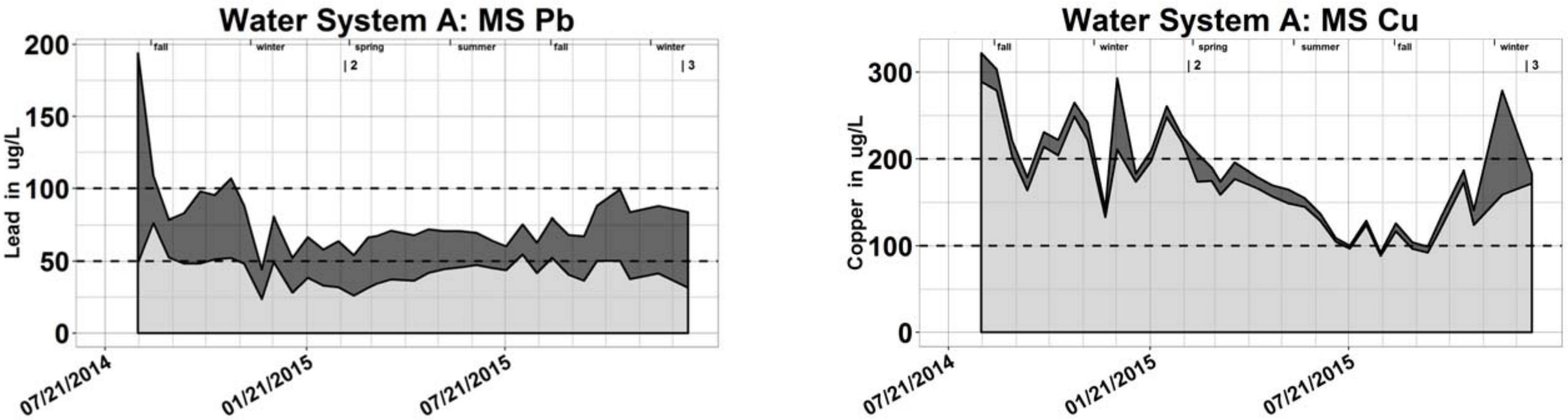


Figure 11.2 Water System A: Lead and copper release in PRS monitoring station test chambers

2008: Disinfection and phosphate chemicals changed

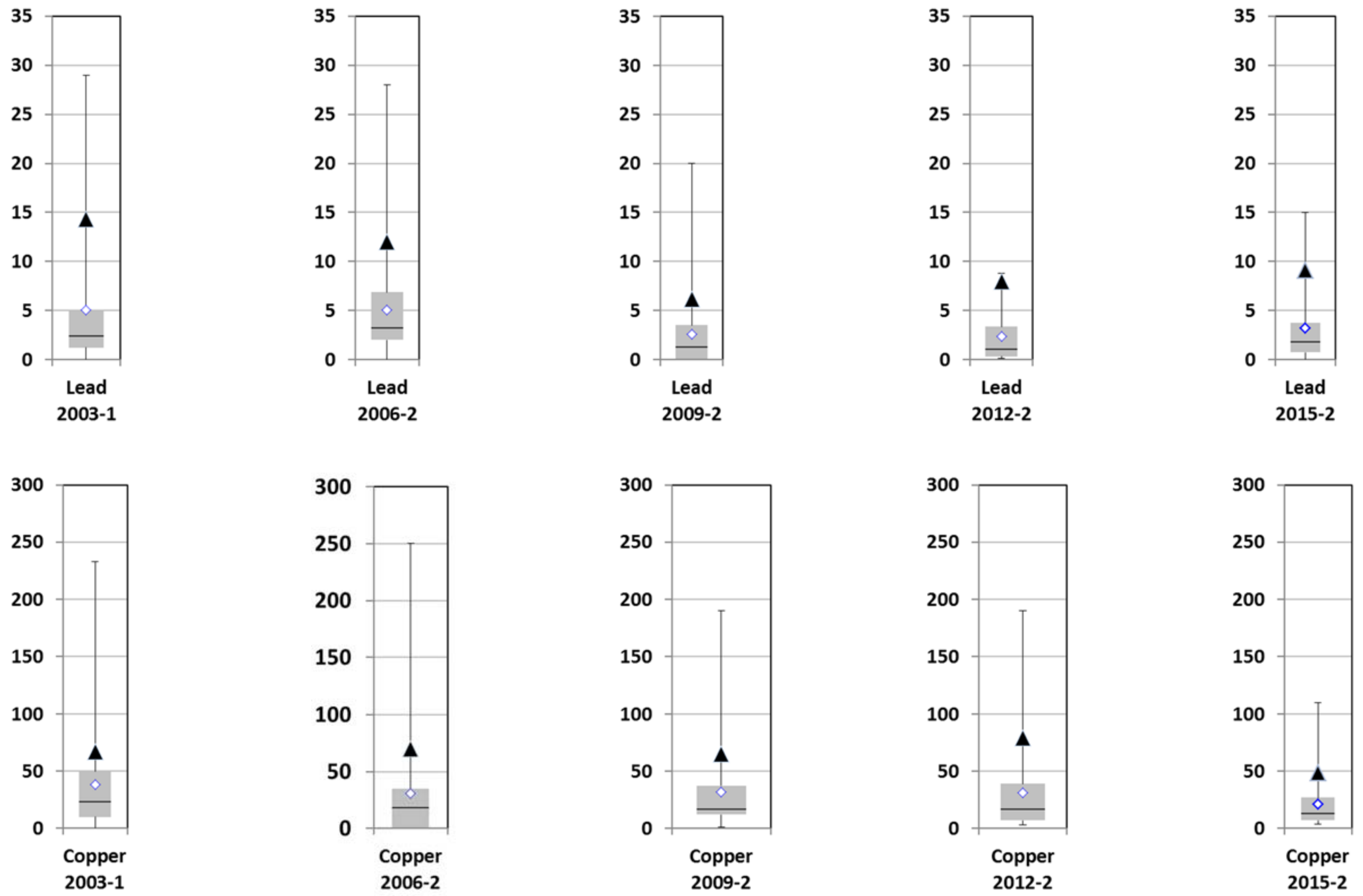


Figure 11.3 Water System A: Lead and Copper Rule data box and whisker plots

Water System A timelines of system changes and of monitoring project events are shown in Tables 11.1 and 11.2. Lead and copper release data are shown in Figures 11.2 and 11.3.

There were no significant cleaning events for Water System A during this project. The monitoring station data reflected the status quo of water quality since the 2008 disinfection and phosphate changes. The PRS Monitoring Station data showed particulate lead as a significant fraction of the total lead released in the water system. Nitrification patterns of lead and copper release were observed. Lead and Copper Rule data show a possible slow increase of the lead maximum and 90th percentile concentrations over time.

It is recommended that this water system consider the following actions to improve upon lead and copper control in the water systems:

- Plan for the removal of complete lead service lines.
- Make water main high velocity cleaning a priority. Without the pipe wall build-up of aluminum, iron, and manganese, the cyclic influences on lead and copper release become less severe. Clean water mains send less debris into building plumbing. With less accumulation in plumbing, it is possible that lead concentrations can be lowered by 50% by removing this material.
- Plan for the replacement of older and corroded water main to remove particulate iron from the water system.
- Consider optimization of alum use so that there is less excess build-up in the distribution system.
- Consider studying measures to lessen the degree of nitrification, such as boosting the total chlorine dosage and chlorine to ammonia ratio.
- Consider optimizing phosphate dosage as the current dosage has been found to be more than adequate to create a high presence of pyromorphite on pipe walls as shown in the lead plate scale analysis. Phosphate should only be adjusted incrementally and in tandem with the use of the distribution system monitoring station for feedback.

Water System B

Table 11.3
Water System B: Historical timeline significant to existing water quality

Date Range	Event
2000	Ozone on-line; begin to have trouble with copper pressure reducing valve components; now all are replaced with stainless steel
2005	2nd transmission line from lake to plant was built and in operation by June; treatment plant capacity was increased; a sodium hypochlorite system was installed to replace the use of gaseous chlorine
2011	Variable frequency drives on pumps added; some water system repair and construction performed; Lead and Copper Rule lead exceedance
2012	Lead service line harvested and chemical scales studied; Distribution system investigation also initiated

Table 11.4
Water System B: Monitoring project timeline

ID	Date	Event
1	March 31, 2014	Startup of PRS Monitoring Station
2	June 01, 2014	First round of uni-directional flushing begins; flushing near PRS Monitoring Station in August 2014
3	January 12, 2015	Main break one block east of monitoring station
4	June 01, 2015	Second round of uni-directional flushing begins
5	January 04, 2016	Shutdown of PRS Monitoring Station

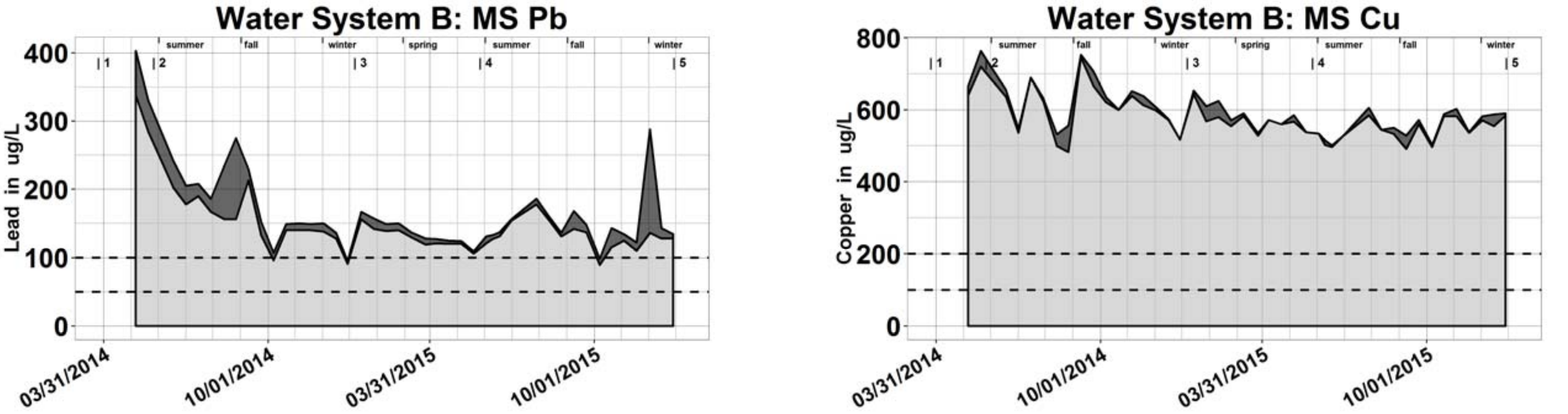
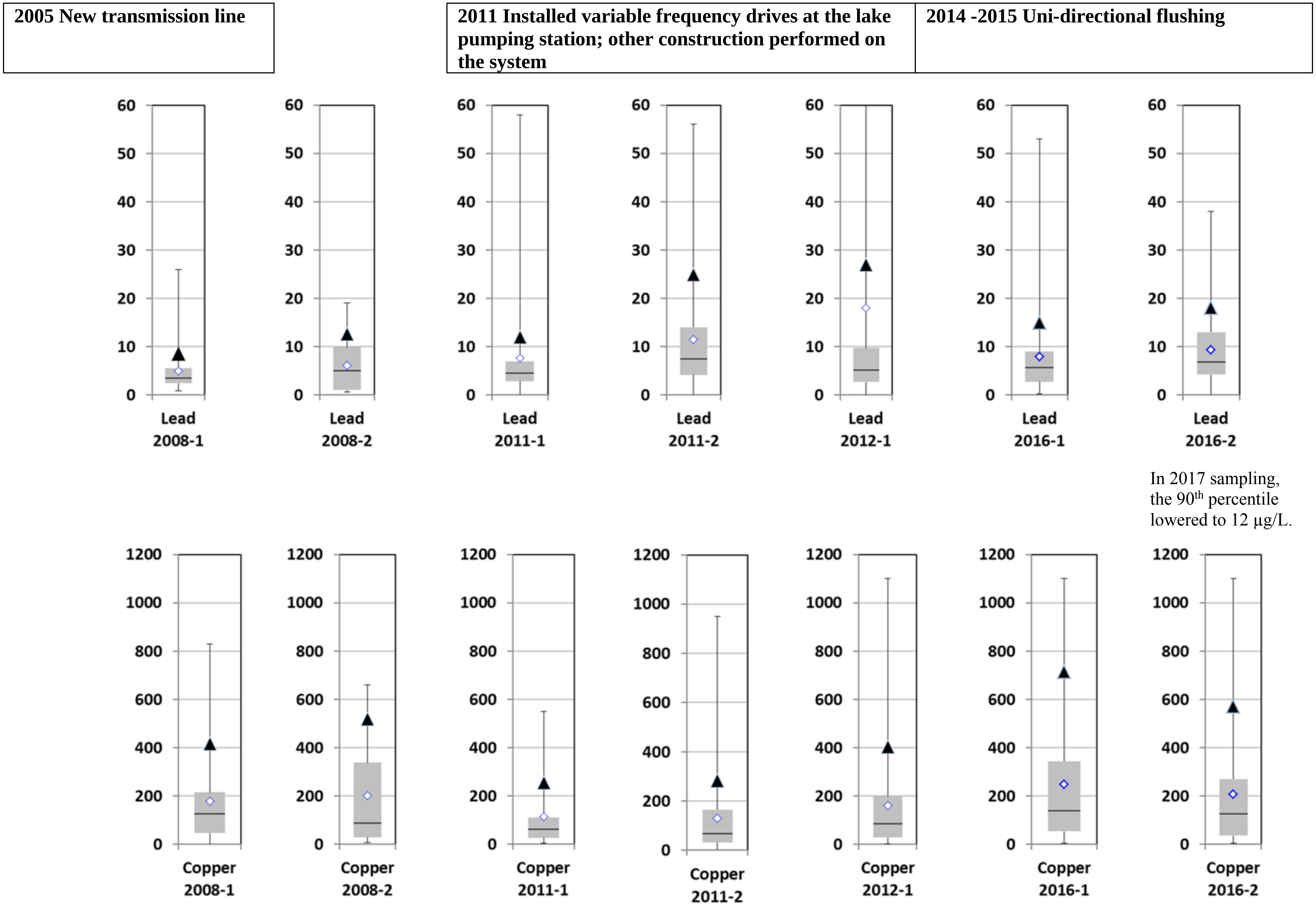


Figure 11.4 Water System B: Lead and copper release in PRS monitoring station test chambers


2005 New transmission line

2011 Installed variable frequency drives at the lake pumping station; other construction performed on the system

2014 -2015 Uni-directional flushing

In 2017 sampling, the 90th percentile lowered to 12 µg/L.

Figure 11.5 Water System B: Lead and Copper Rule data box and whisker plots

Water System B timelines of system changes and of monitoring project events are shown in Tables 11.3 and 11.4. Lead and copper release data are shown in Figures 11.4 and 11.5.

A relationship between legacy iron and manganese scales and particulate lead were identified with a study of harvested lead water service line scales. In addition, the PRS Monitoring Station data showed a relationship between particulate lead and aluminum scales.

Particulate and dissolved lead and copper release were also found to trend with microbiological factors of ammonia, dissolved organic carbon, and nitrate release – all related to nitrification cycles. An additional study by others traced the production of the three nutrients to biofilm formed in the lake water transmission lines, where residence time in the lines increased with the addition of the second transmission line in 2005. Two seasons of uni-directional flushing in 2014 and 2015 lowered the lead maximum and 90th percentile concentrations. However, flushing was not performed in the summer of 2016 and the 90th percentile lead concentration could not continue its decrease away from the Action Level. Instead, the 90th percentile lead concentration fluctuated just above the Action Level. With the completion of the biostability study as well as the monitoring station study, Water System B is on schedule to continue uni-directional flushing of water mains and in cleaning of the lake water transmission lines. After Lead and Copper Rule compliance sampling in 2017-1, Water System B was back in compliance with a 90th percentile lead concentration of 12 µg/L.

Stand-by wells also have the potential to become biologically unstable and to contribute particulate iron and manganese to the distribution system because of low usage.

Recommendations for this water system are:

- Plan for the removal of complete lead service lines and galvanized iron service lines.
- Continue to make water main high velocity cleaning a priority. Aluminum from coagulant and iron and manganese from intermittent use of groundwater that form the pipe wall debris must be routinely cleaned away. The scale is the precursor to transport of particulate lead and copper in premise plumbing. High velocity flushing also removes biofilms, the removal of which is essential to controlling a significant factor of lead and copper release in this water system.
- Plan for the replacement of older and corroded water main.
- Continue on the path to controlling the biostability of the transmission line water.
- Continue on the path to controlling the biostability of the water filter.
- Plan for investigation and routine maintenance of the stand-by wells for biostability.
- Consider incorporating the use of the wells in a more routine pumping/water blending program in order to achieve better biostability in the wells and to achieve more uniform chemical characteristics of system water.

Water System C

Table 11.5
Water System C: Historical timeline significant to existing water quality

Date Range	Event
1963	East Filter added
1999	Microfiltration system added
2011	Ran PRS Monitoring Station for the first time for year-long study

Table 11.6
Water System C: Monitoring project timeline

ID	Date	Event
1	July 13, 2014	Startup of PRS Monitoring Station
2	January 05, 2016	Shutdown of PRS Monitoring Station

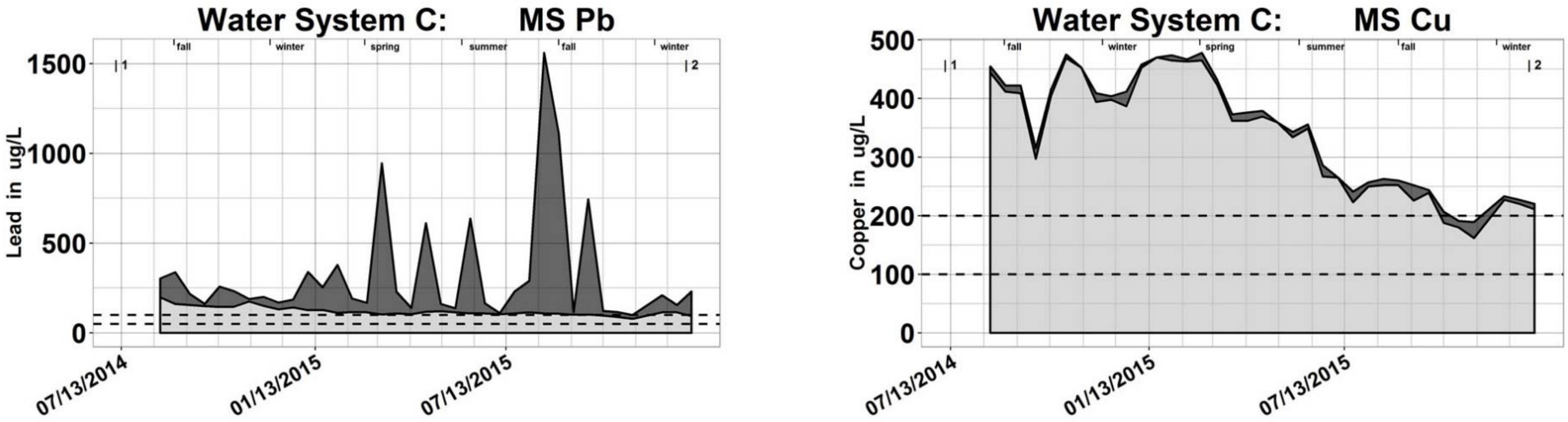


Figure 11.6 Water System C: Lead and copper release in PRS monitoring station test chambers

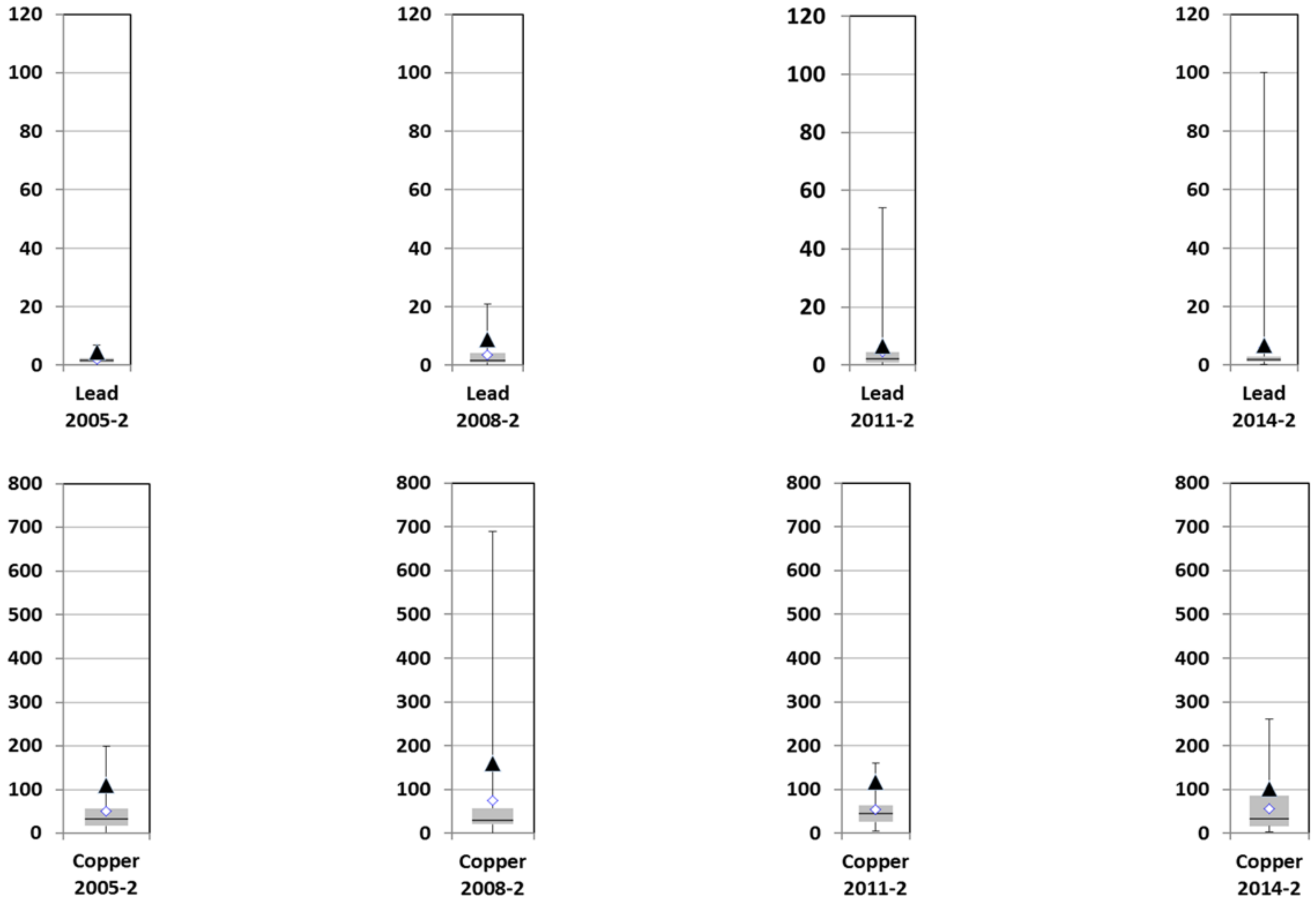


Figure 11.7 Water System C: Lead and Copper Rule data box and whisker plots

Water System C timelines of system changes and of monitoring project events are shown in Tables 11.5 and 11.6. Lead and copper release data are shown in Figures 11.6 and 11.7.

While Water System C has not been out of compliance with the Lead and Copper Rule, the PRS Monitoring Station data indicate a potential to develop biofilms and a potential for high release of particulate lead. Maximum lead concentrations in the Lead and Copper Rule sampling have been increasing over time. Trending analyses indicate that particulate aluminum in the water system may be a factor in the particulate lead release. Particulate lead may also trend with nitrite/nitrate concentration.

Cleaning of legacy chemical scales and biofilms would be beneficial.

Recommendations for Water System C are as follows:

- Plan for the removal of complete lead service lines.
- Make water main high velocity cleaning a priority. Without the pipe wall build-up of aluminum, iron, and biofilms, the influences on lead and copper release become less severe.
- Plan for the replacement of older and corroded water main. (Water System C is currently replacing mains installed from 1947 to 1966. This "spin-cast" pipe is the source of most main breaks).
- Investigate the possible influence of road salt on Lake Michigan water in the late winter/early spring. The influent chloride and possibly nitrate may be influencing particulate lead release and other water quality aspects.
- If there is a Lead and Copper Rule violation in the future, consider switching phosphate products to one with less or no polyphosphate included. For example, consider using a similar product to that of Water System A. The dose of orthophosphate could be increased without increasing the total phosphorus to the wastewater treatment plant. The current PO_4 concentration at the high water age location averaged 0.2 mg/L as PO_4. Using a 40% orthophosphate product, this is a concentration of 0.5 mg/L as PO_4 for total phosphorus. Using the 10/90 product that Water System A uses, the PO_4 dose could be increased to about 0.45 mg/L as PO_4, that is, the orthophosphate dose would be increased 2.25 times while maintaining the same total phosphorus load to the wastewater treatment plant. And, the polyphosphate fraction that can potentially hold metals in the water would essentially be eliminated.

Water System D

Table 11.7
Water System D: Historical timeline significant to existing water quality

Date Range	Event
1991	Two water systems, each consisting of 3 wells, were connected together
1995	A Vyredox system for iron and manganese control at Wells 3,4 and 5 was replaced with an ozone oxidation/pressure filtration system
6/1997	Lead and Copper levels found to be lower
Jan/Feb 2000	Filter media replaced
5/2004	Lead first exceeded the Lead and Copper Rule Action Level.
2006	Manganese found to be elevated in Well 2; polyphosphate feed adjusted to sequester its manganese which addressed customer complaints of discolored water; Well 2 use is minimized by designating it as the lag pump to Wells 1 or 6 lead
Apr/May 2006	Filter media replaced
5/2008	Temporary drop in lead and copper levels
12/2009	Copper first exceeded for Lead and Copper Rule
Jan 2011	Filter media replaced
Aug 2011	Lead and copper levels dropped below Action Level
Feb 2013	Filter media replaced
2012	Water quality investigation

Table 11.8
Water System D: Monitoring project timeline

ID	Date	Event
1	April 30, 2014	Startup of PRS Monitoring Station
2	May 01, 2014	Begin some modifications to water treatment plant
3	October 20, 2014	Well 5 out of service for rehabilitation; Flushed mains near PRS Monitoring Station on 10/7
4	November 14, 2014	Flushed mains near the PRS Monitoring Station
5	December 15, 2014	Well 5 back in service, Well 4 out of service for rehabilitation
6	March 20, 2015	2/26 Well 4 back in service; 3/3 Well 3 out of service; Well 3 back in service; 4/3 Lime feed has been removed and replaced by calcite tanks; New horizontal pressure filter arrived
7	August 25, 2015	High velocity flushing of water mains started
8	March 01, 2016	Optimization of treatment plant
9	June 01, 2016	Begin high velocity flushing of water mains
10	July 03, 2016	Finished high velocity flushing of water mains
11	September 20, 2016	Shutdown of PRS Monitoring Station
12	October 15, 2016	High velocity flushing of water mains

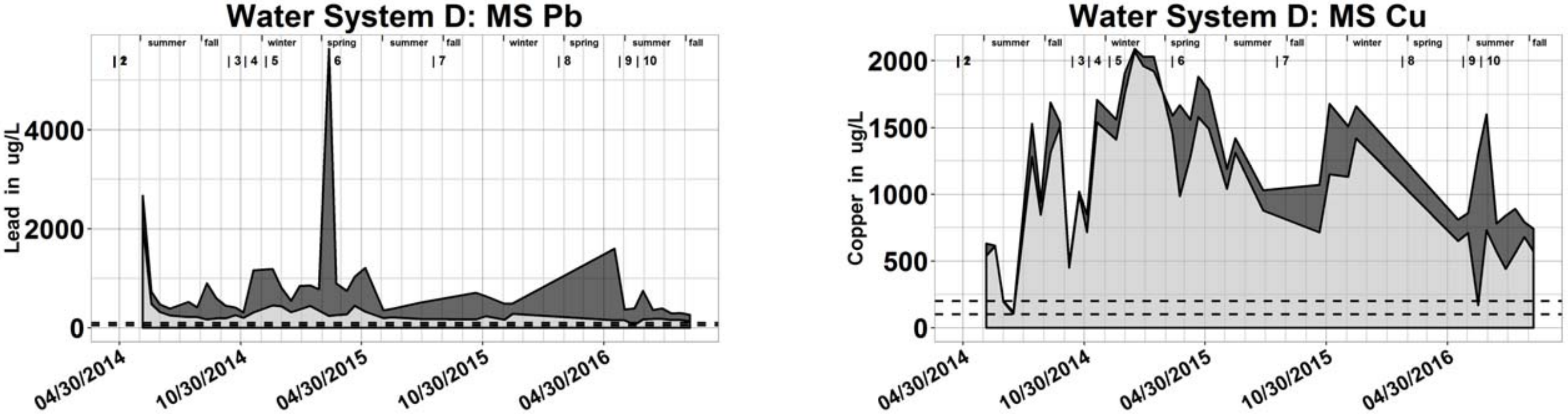
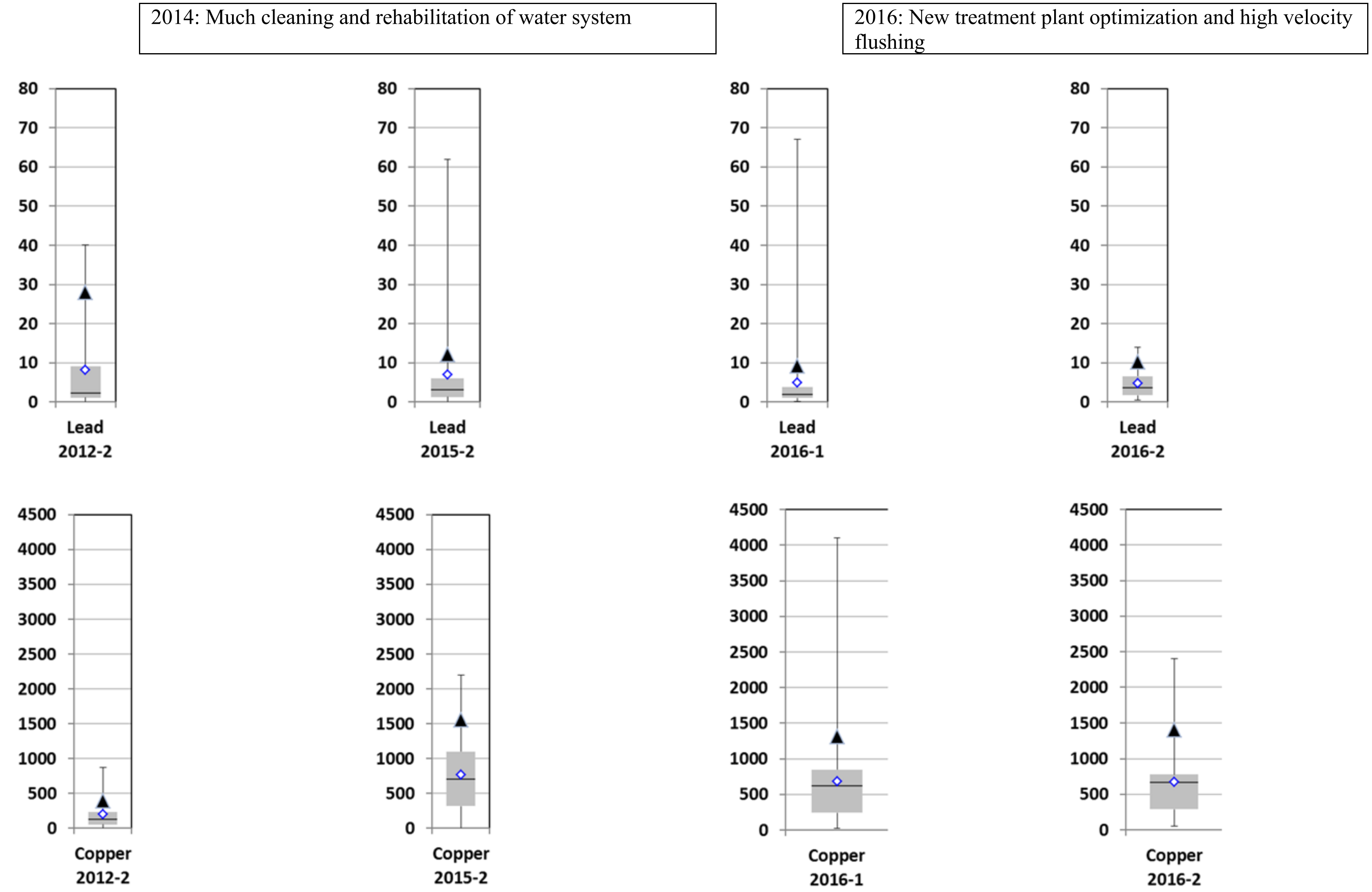


Figure 11.8 Water System D: Lead and copper release in PRS monitoring station test chambers


2014: Much cleaning and rehabilitation of water system

2016: New treatment plant optimization and high velocity flushing

Figure 11.9 Water System D: Lead and Copper Rule data box and whisker plots

Water System D timelines of system changes and of monitoring project events are shown in Tables 11.7 and 11.8. Lead and copper release data are shown in Figures 11.8 and 11.9.

With better biostability from a refurbished water treatment plant and high velocity flushing of water mains, Lead and Copper Rule data show lower lead maximum and 90th percentile concentrations and lower copper maximum concentrations. However, copper 90th percentile concentrations are elevated just above the Action Level. A high concentration of polyphosphate in the water is suspected of holding dissolved lead and copper concentrations elevated. In addition, the biostability of the water can still be improved through the water treatment plant. Finally, uni-directional flushing of water mains is necessary to continue removing legacy scales.

Recommendations for Water System D are:

- Continue with routine water main high velocity cleaning. Plan for the replacement of older and corroded water main.
- Polyphosphates should be removed from the water system but the only way that the polyphosphates can be removed is to install a second iron and manganese removal plant to treat the collective water of the three independent wells. Then, the phosphate-based additive can be changed to an orthophosphate product at both the existing treatment plant and the proposed treatment plant. Because there are not resources to add another treatment plant, a strategy is being devised where the treated water side of the river will no longer receive water from the independent wells. The phosphate product of the water leaving the treatment plant will be switched to a higher orthophosphate fraction, possibly 90 to 100% orthophosphate. Some water from the west side treatment plant will continue to flow to the water system on the other side of the river so that the pipe underneath the river will not contain stagnating water. The two water types with the two phosphate products will be mixed together as a continuous blend. The polyphosphate will be kept at a high enough level to continue to sequester the iron and manganese from the independent wells on the east side.
- There are 107 lead service lines in the system. Make plans to remove those lines properly and completely. Then, the water system would no longer be considered a critical lead service line system. That would allow the water system to modify the orthophosphate dosage. When the lead is out of the system along with the iron and manganese and old chemical scales, slowly wean the system off of the orthophosphate dose. This can be monitored and informed by using the PRS Monitoring Station once again. Brass plates, copper plates with lead solder, and iron or galvanized iron plates can be used in the monitoring station test chambers to determine if issues would arise with lead and copper release from those materials remaining in the water system after lead service line removal.
- Track ATP at wells and clean the wells when ATP exceeds 1000 ME/mL (or before).
- Continue with routine monitoring of treatment plant finished water and replace or clean treatment media with increases in iron, manganese, turbidity, ATP, and dissolved organic carbon.

Water System E

Table 11.9
Water System E: Historical timeline significant to existing water quality

Date Range	Event
1969	Surface water treatment of adjacent small lake
3/2005	Connection of piping from a new well house to existing water main made
3/29/2006	New well and iron removal plant placed into operation (iron removal filter media was not up to specifications)
2006	Dramatic increase in copper pipe leaks; were some routinely before but greatly increased
2006	Investigation with recommendations
2012	Investigation after more pinhole leaks
2013	Rehabilitation of iron removal filter media

Table 11.10
Water System E: Monitoring project timeline

ID	Date	Event
1	April 16, 2014	Start PRS Monitoring Station
2	May 26, 2014	Start Clearitas at 0.5 ppm; begin summer months of building softener replacement and plumbing modifications and flushing
3	June 16, 2014	Increase Clearitas to 1.0 ppm
4	July 28, 2014	Increase Clearitas to 1.5 ppm
5	October 27, 2014	Increase Clearitas to 2 ppm
6	February 02, 2015	Increase Clearitas to 3 ppm
7	June 11, 2015	Increase Clearitas to 4 ppm
8	October 05, 2015	Stop PRS Monitoring Station

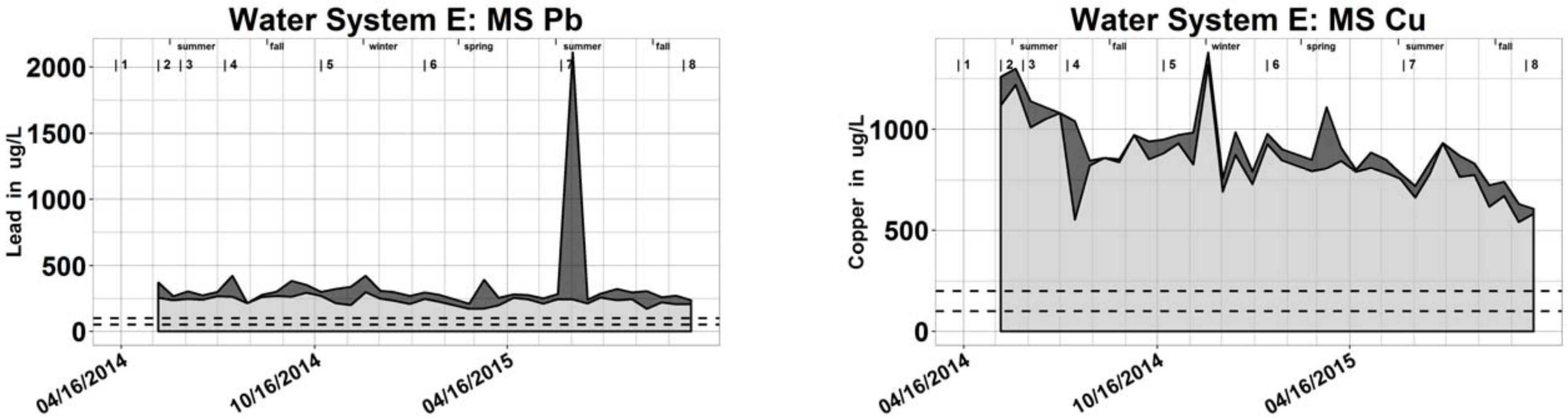


Figure 11.10 Water System E: Lead and copper release in PRS monitoring station test chambers

2014: Filter rehabilitation; system cleaning	September 2014: LCR sampling performed on sinks under renovation. Lead particulates released with turning of sink valves that had never been turned. Problem quickly remedied with line flushing.

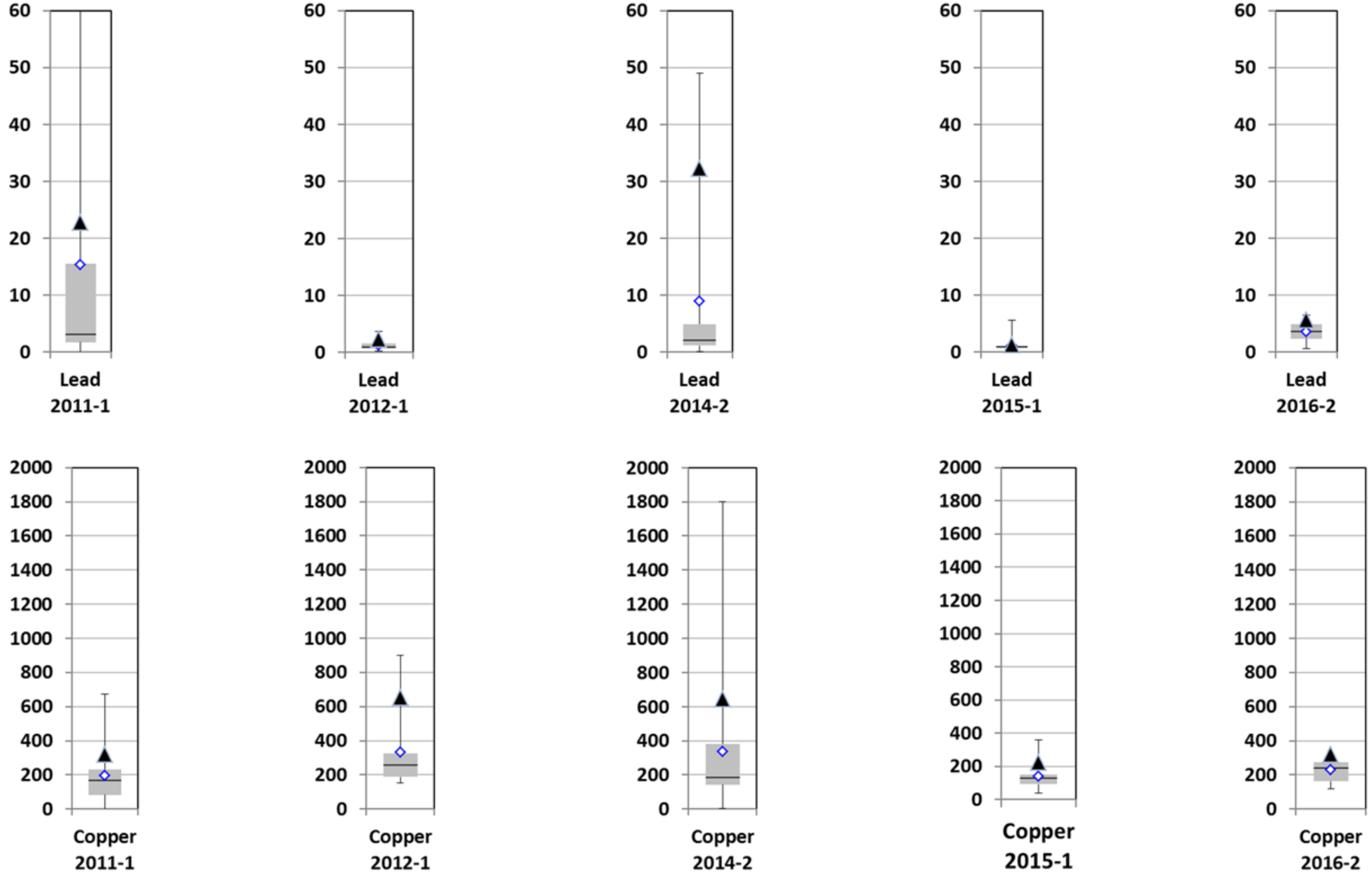


Figure 11.11 Water System E: Lead and Copper Rule data box and whisker plots

Water System E timelines of system changes and of monitoring project events are shown in Tables 11.9 and 11.10. Lead and copper release data are shown in Figures 11.10 and 11.11.

PRS Monitoring Station data showed that Water System E appears to be dependent on the water treatment filter performing with high iron and manganese removal and free of biofilms. It also appears to be dependent on the cleanliness of water softeners which, as newly installed, provided a barrier to issues developing in the water treatment filter. However, investigation of the old water softeners showed that the water softeners can turn into incubators of microorganisms with support of biofilm development and cause downstream microbiologically influenced corrosion, if they are not maintained.

The following actions were recommended to Water System E:

- Clean the main iron filter off-line to remove biofilms. The monitoring period ended and it took a year to gather the resources to clean the filter media and the wells. While customer satisfaction with the water had increased over the monitoring and rehabilitation period and pinhole leaks in copper piping had ceased, complaints of discolored water began to appear again waiting for the main iron filter to be cleaned.
- Routinely track turbidity and iron and manganese removal on the discharge of the iron filter and have the filter cleaned of biofilms when turbidity exceeds 1 NTU or less or iron or manganese levels increase.
- Track ATP at wells and clean them when ATP exceeds 1000 ME/mL or less.
- Routinely assess the dosing of the biofilm-removing chemical as to rate of debris removal and possible optimization of dosage
    - Monitor Total Coliform Rule sites for turbidity and free chlorine at the frequency of TCR sampling visits
    - Monitor entry points to buildings for turbidity and free chlorine once a week, especially if adjusting biofilm-removing chemical dosing
- Perform monthly blowdown of hot water tanks (about 3-minute blowdown or as determined by historical turbidity readings) and monthly turbidity readings
- Perform initial cleanup of water softeners as guided by ATP tests and then routine organic acid dosing approved for use with resins with regeneration at least every two weeks with ATP testing once or twice a year. Monthly ORP field tests are an easy way to track the cleanliness of the softener routinely.
- Continued routine flushing of building plumbing. In addition, a new air scouring technique is proving itself to be very effective in removing the legacy chemical scales and biofilms and would be useful in the campus buildings.
- Yearly, perform uni-directional flushing of water mains to turbidity <1 NTU with turbidity data for each flushing run. Higher biofilm-removing chemical levels in cleaning season should help with this.

Water System F

Table 11.11
Water System F: Historical timeline significant to existing water quality

Date Range	Event
2006	Well 4 constructed and placed online
2006	A 200,000-gallon reservoir added
After 2006	A high degree of plumbing equipment replacement reported, including copper piping and hot water heaters
2011	An increase in pinhole leaks in copper pipe
2011	Wells 3 and 4 serve the campus
2012	Health Services Unit building opened after a long construction period
	The building was found to have biofilms throughout the plumbing before occupancy with some pipe failure
2012	Water quality investigation of campus
4/2013	Investigation of wells
Winter 2014	Repair of Well 4 and rehab of Well 3

Table 11.12
Water System F: Monitoring project timeline

ID	Date	Event
1	August 26, 2014	Startup of PRS Monitoring Station
2	November 18, 2014	Water main break
3	March 24, 2015	Water main replacement begins; monitoring station continued but test chamber sampling on hold
4	August 01, 2015	Begin adding 0.5 ppm Clearitas

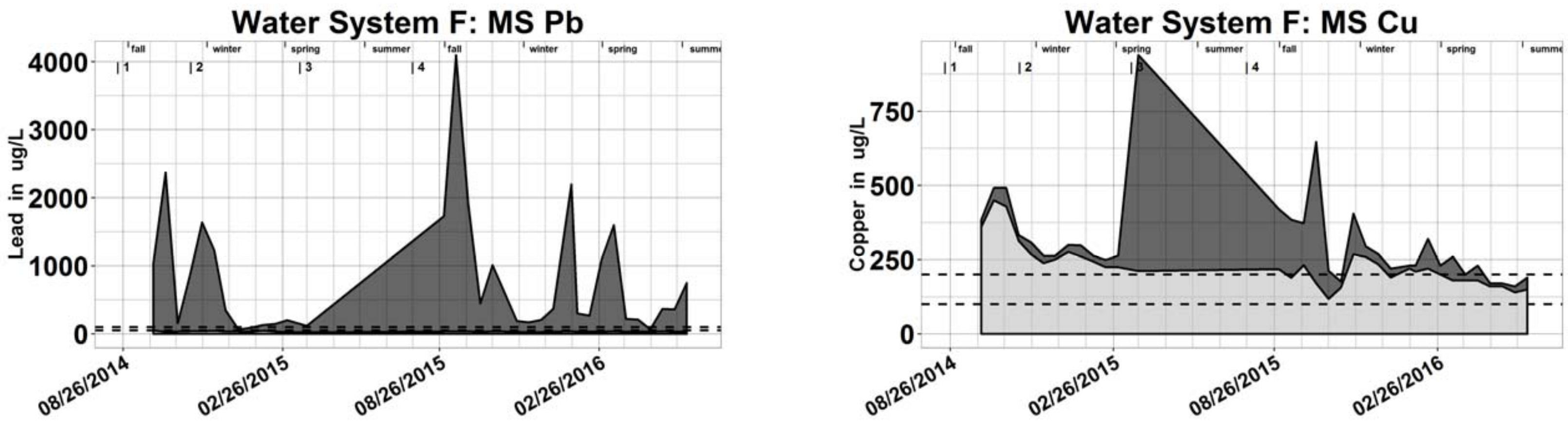


Figure 11.12 Water System F: Lead and copper release in PRS monitoring station test chambers

Data not shown here. Water System F has not been out of compliance with the Lead and Copper Rule. However, the system had a premise plumbing copper pipe pinhole leak issue.

Figure 11.13 Water System F: Lead and Copper Rule data

Water System F timelines of system changes and of monitoring project events are shown in Tables 11.11 and 11.12. Lead and copper release data are shown in Figures 11.12 and 11.13.

Well rehabilitation and the installation of new water mains appeared to lower microbiological populations in the water. The issue of particulate lead and copper release continued but damped out over time. Along with these improvements, the buildings were flushed and hot water tanks were blown down routinely. Pinhole leaks were no longer an issue on campus.

The following actions were recommended to Water System F:

- Track ATP at wells and clean them when ATP exceeds 1000 ME/mL or less.
- Routinely assess the dosing of the biofilm-removing chemical as to rate of debris removal and possible optimization of dosage
    - Monitor Total Coliform Rule sites for turbidity and free chlorine at the frequency of TCR sampling visits
    - Monitor entry points to buildings for turbidity and free chlorine once a week, especially if adjusting biofilm-removing chemical dosing
- Perform monthly blowdown of hot water tanks (about 3-minute blowdown or as determined by historical turbidity readings) and monthly turbidity readings
- Perform initial cleanup of water softeners as guided by ATP tests and then routine organic acid dosing approved for use with resins with regeneration at least every two weeks with ATP testing once or twice a year. Monthly ORP field tests are an easy way to track the cleanliness of the softener routinely.
- Continued routine flushing of building plumbing. In addition, a new air scouring technique is proving itself to be very effective in removing the legacy chemical scales and biofilms and would be useful in the campus buildings.
- Yearly, perform uni-directional flushing of water mains to turbidity <1 NTU with turbidity data for each flushing run. Higher biofilm-removing chemical levels in cleaning season should help with this.

Water System G

Table 11.13
Water System G: Historical timeline significant to existing water quality

Date Range	Event
2007	Well No. 4 drilled
2008	Exceeded Action Level for copper; phosphate dosing increased
2009	Re-sampling showed lower copper
2012	Exceeded Action Level for lead and copper
2013	Investigation performed on water system; plans made for cleaning and monitoring in water system
2013	Water system continued to be above Action Level for lead and copper
9/9/2013	Wells No. 3 and 4 out of service for partial rehabilitation
11/8/2013	Wells No. 3 and 4 back on-line with low quality water blocked
9/30/2014	Monitoring station installed in distribution system and monitoring/flushing plan put into action

Table 11.14
Water System G: Monitoring project timeline

ID	Date	Event
1	February 01, 2015	Wells No. 1 and 2 out of service for rehabilitation
2	March 05, 2015	Well No. 2 back on line; Well 1 abandoned; Well 4 out of service for rehabilitation on 3/9
3	April 01, 2015	Begin dosing biofilm removing chemical at 0.5 mg/L
4	June 01, 2015	Well No. 3 out of service for rehabilitation
5	August 01, 2015	Biofilm removing chemical dose increased to 0.1 mg/L
6	November 15, 2015	Building flushing frequency cut in half because of personnel shortage
7	December 01, 2015	Biofilm removing chemical dose increased to 2 mg/L. Phosphate dosage diluted to small percentage.
8	January 06, 2016	Well 3 put back in service on 12/22; Well 4 taken out of service on 12/28; Well 4 back in service on 1/4; On 1/6, Disruption of pipe scales from system-wide pressure gradient due to fire system inspection; immediate system flushing followed for control
9	February 04, 2016	Biofilm removing chemical dose turned off to let system scales settle down; increased flushing continued
10	March 02, 2016	Disruption to pipe scales after high disinfection dose
11	April 19, 2016	High velocity water main flushing attempted but water pressure loss occurred
12	May 16, 2016	Biofilm removing chemical is restarted at 0.5 mg/L; Reservoir was cleaned on 5/3; High velocity flushing of water mains is successful on 5/20
13	June 30, 2016	Lead and Copper Rule sampling is repeated and is below Action Level for lead and copper
14	September 20, 2016	Investigative Lead and Copper Rule sampling is performed and is below Action Level for lead and copper
15	October 20, 2016	High velocity flushing of water mains re-done
16	November 20, 2016	Lead and Copper Rule sampling is repeated

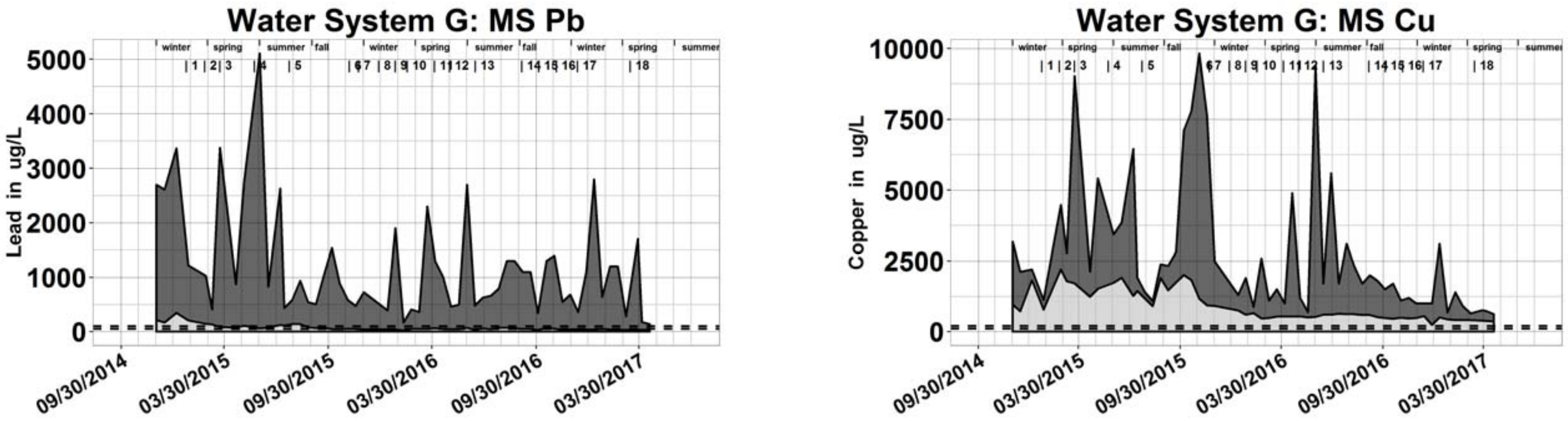


Figure 11.14 Water System G: Lead and copper release in PRS monitoring station test chambers

2014 well rehabilitation, reservoir cleaning, high velocity water main flushing, and building plumbing flushing and maintenance procedures.

2016 Three unrepresentative sample taps removed from Lead and Copper Rule sampling pool with regulators' approval.

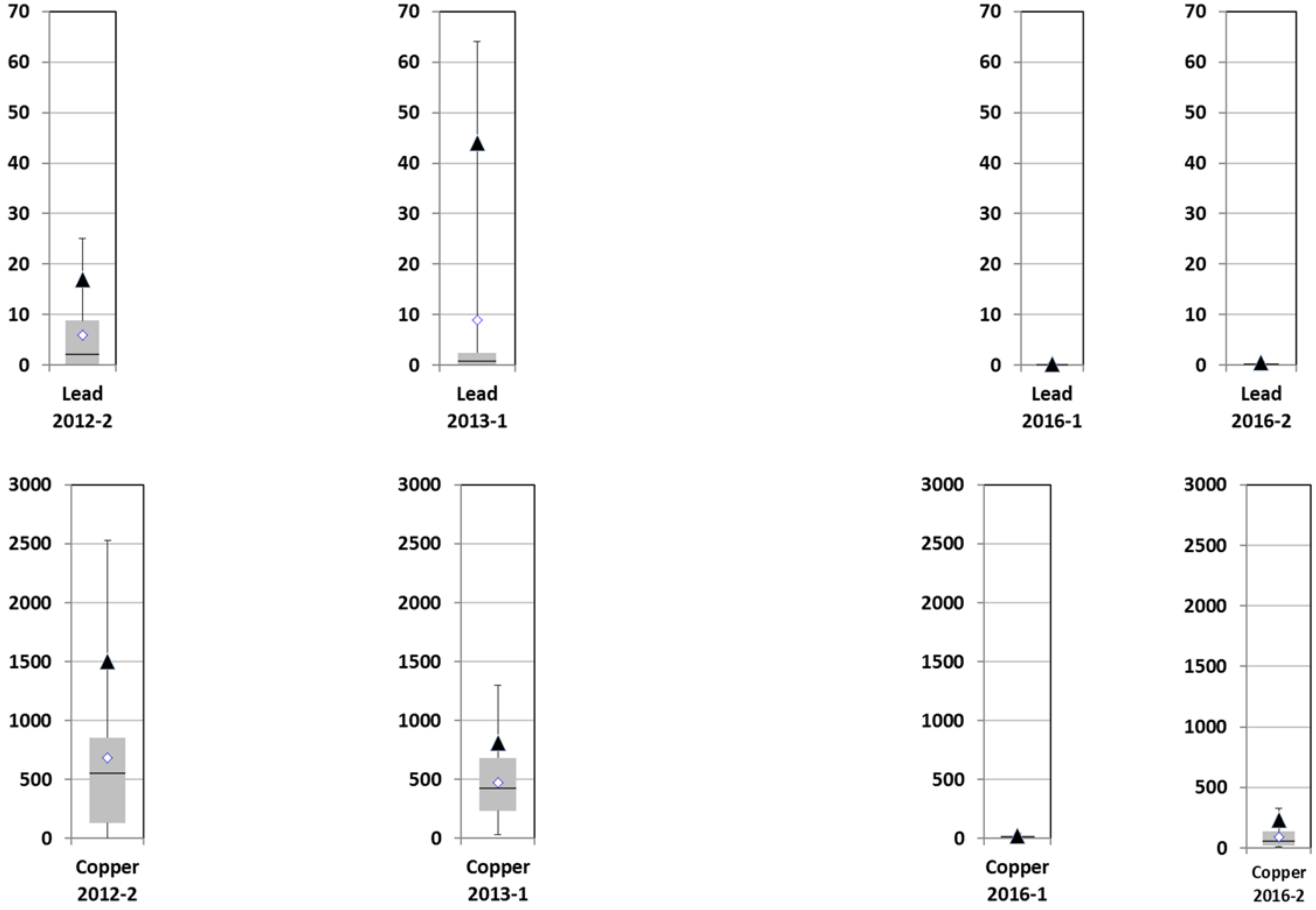


Figure 11.15 Water System G: Lead and Copper Rule data box and whisker plots

Table 11.15
Water System G: A comparison of 2013-1 Lead and Copper Rule data with and without unrepresentative sites

	Lead		**Copper**	
	All Sites	**Representative Sites Only**	**All Sites**	**Representative Sites Only**
Number of Sites	20	17	20	17
Maximum concentration	64	3.4	1300	1300
90th percentile concentration	44	2.6	812	818
Average concentration	9	0.93	473	534

Water System G timelines of system changes and of monitoring project events are shown in Tables 11.13 and 11.14. Lead and copper release data are shown in Figures 11.14 and 11.15.

There were three sites in the Lead and Copper Rule sampling pool that were not representative of water being consumed in the system. Regulators agreed that this was so. Ironically, if it were not for those three sites, the water system would be considered in compliance with drinking water regulations. The high degree of consumer complaints regarding discolored water would not have been acknowledged. The problem was a severe microbiological one initiating in the wells accompanied by high iron and manganese release from the wells. See Table 11.15 to compare data from all sampled Lead and Copper Rule sites versus data from only the sites that were representative of the consumers' water quality.

Recommendations for Water System G are:

- Track ATP at wells and clean them when ATP exceeds 1000 ME/mL or less.
- Routinely assess the dosing of the biofilm-removing chemical as to rate of debris removal and possible optimization of dosage
    - Monitor Total Coliform Rule sites for turbidity and free chlorine at the frequency of TCR sampling visits
    - Monitor entry points to buildings for turbidity and free chlorine once a week, especially if adjusting biofilm-removing chemical dosing
- Perform monthly blowdown of hot water tanks (about 3-minute blowdown or as determined by historical turbidity readings) and monthly turbidity readings
- Perform initial cleanup of water softeners as guided by ATP tests and then routine organic acid dosing approved for use with resins with regeneration at least every two weeks with ATP testing once or twice a year. Monthly ORP field tests are an easy way to track the cleanliness of the softener routinely.
- Continued routine flushing of building plumbing. In addition, a new air scouring technique is proving itself to be very effective in removing the legacy chemical scales and biofilms and would be useful in the campus buildings.
- Yearly, perform uni-directional flushing of water mains to turbidity <1 NTU with turbidity data for each flushing run. Higher biofilm-removing chemical levels in cleaning season should help with this.
- Phosphate addition has been eliminated. If a phosphate product must be used per regulations, eliminate the polyphosphate fraction, and only use orthophosphate.

Water System H

Table 11.16
Water System H: Historical timeline significant to existing water quality

Date Range	Event
2011	Out of compliance with LCR

Table 11.17
Water System H: Monitoring project timeline

ID	Date	Event
1	October 08, 2014	PRS Monitoring Station started
2	April 22, 2015	Clearitas started at 1 ppm
3	December 30, 2015	Clearitas increased to 2.5 ppm
4	May 16, 2016	Hydrants flushed
5	October 01, 2016	Water mains flushed again

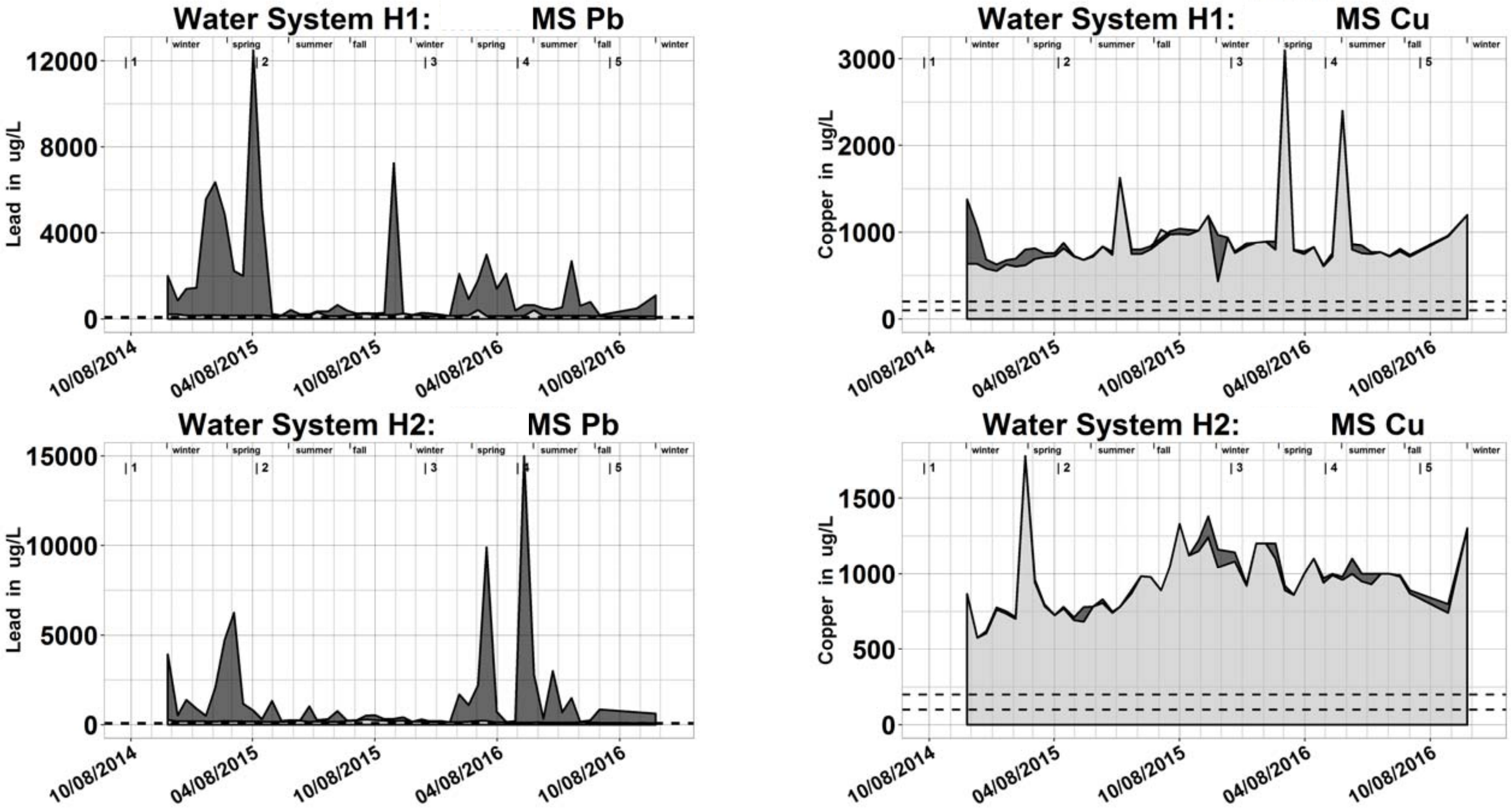


Figure 11.16 Water System H: Lead and copper release in PRS monitoring station test chambers

Water System H timelines of system changes and of monitoring project events are shown in Tables 11.16 and 11.17. Lead and copper release data are shown in Figures 11.16 and 11.17.

System cleaning has lowered the maximum lead and 90th percentile concentrations. However, copper concentrations have increased. The copper increase may be related to additional sampling sites with new copper piping installed. And, it may be related to the use of a high polyphosphate fraction product that holds metals in solution. And, it may be related to microbiological life cycles that influence corrosion of metals. The recommendations for Water System G apply to Water System H.

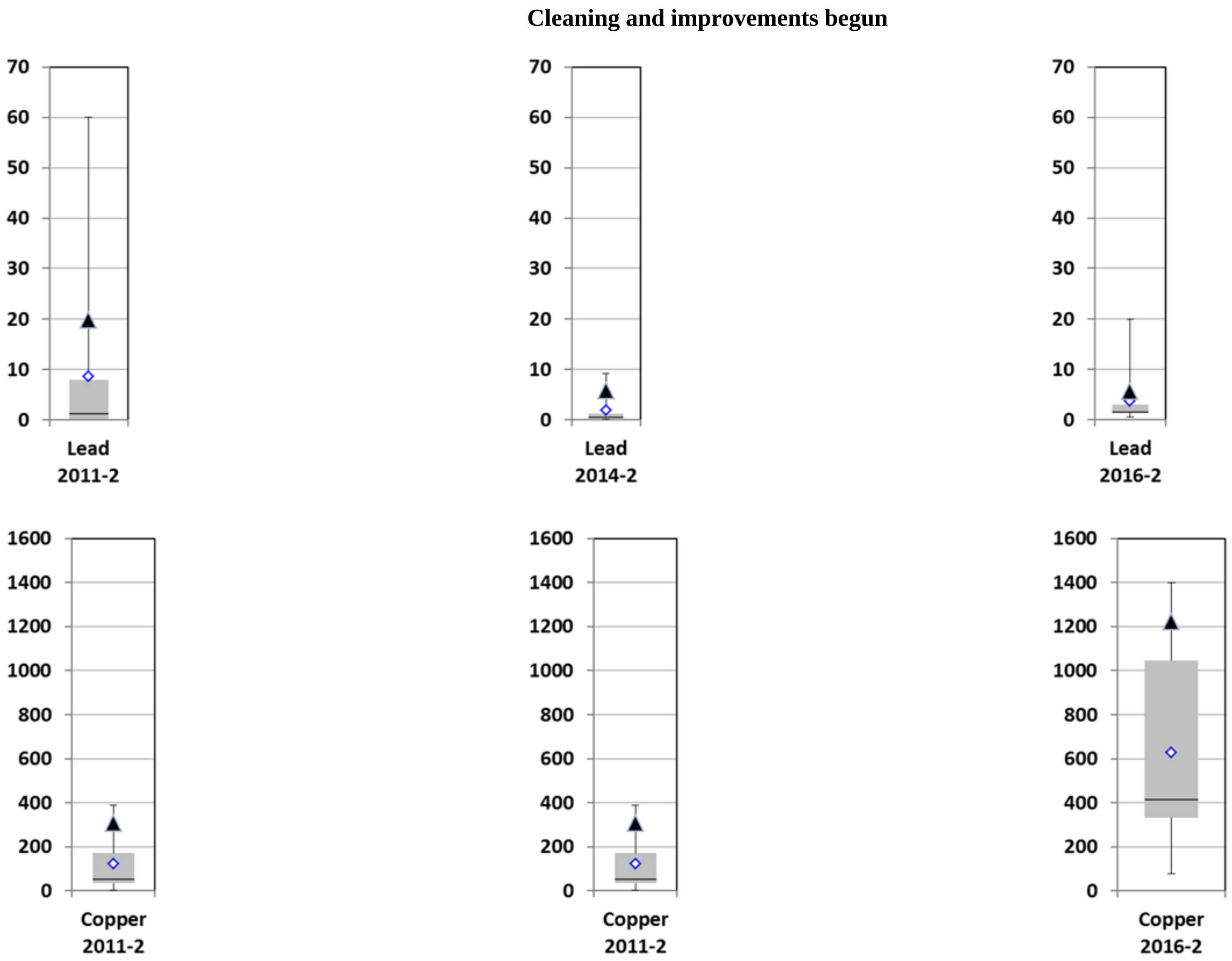


Figure 11.17 Water System H: Lead and Copper Rule data box and whisker plots

COMPARISON TO DISTRIBUTION SYSTEM DATA OF CHAPTER 4

In Chapter 4, disinfection concentrations and turbidity readings around some of the distribution systems were studied. These graphs are compared to patterns observed in the systems during the comprehensive study.

Water System A graphs of disinfection show that some locations experience a drop in disinfection level during the peak nitrification period in September, October, and November. Other sites appear to be immune to this. The PRS Monitoring Station data showed how nitrification affects lead and copper release in the water system. With this knowledge, the sites with and without nitrification patterns as identified from the disinfection graphs of Chapter 4 should be compared to see if there is something operational that could be done to minimize or stop nitrification during the warmer weather months at all sites.

The turbidity graphs offer the same opportunity to determine why there is great variation in turbidity at some sites in Water System A and not at others. Fifty percent of the lead that reaches consumers can be in particulate form as identified by the monitoring station data. Determining cleaning and operations routines that can lower the turbidity could protect consumers from sporadic contact with lead in the drinking water.

In Water System B, there were big variations in disinfection concentration at the distribution system sites. This should be investigated. Looking at the disinfection time series graphs, disinfection concentration made an improvement after the first summer of high velocity flushing and has stayed at this slightly higher level. In addition, there were very large variations in turbidity at some sites. Likewise, this should be investigated. This might be a result of the flushing program, but that should be determined and it should be checked that turbidity has returned to low values. Looking at turbidity time series graphs for the distribution system sites, there are sporadic turbidity peaks even outside of the cleaning season. Monitoring station data links high turbidity and low disinfection levels to a higher potential of lead and copper release with turbidity related to aluminum scale from coagulant use, iron and manganese scale from intermittent groundwater use, and a pattern of nitrification and biofilms that affect both dissolved and particulate lead and copper release.

In Water System C, chlorine concentrations and turbidity levels appear to be in good ranges. However, the lowest chlorine sites and the highest turbidity sites should still be investigated. Most important is investigating the sites with the greatest variations. Even though the turbidity is recorded as <1 NTU, why do the turbidity peaks occur? It could be operational or it could be related to sampling protocol. However, monitoring station data identify a high potential for particulate lead release. Lead and Copper Rule data identify an upward trend of lead release.

Water System I was in good control of disinfection levels and turbidity levels. Like every system, it would benefit by fine tuning that control in investigating sites of low disinfection and high turbidity and sites with high variations of parameters. The time series graphs show typical patterns in disinfection and turbidity that have been seen in PRS Monitoring Station studies where nitrification is occurring including Water System A in this project. Water System I is a chloraminated water system with a potential for nitrification similar to Water System A.

SUMMARY

In this project, it was desired to comprehensively monitor water systems before, during, and after water system cleaning efforts to capture any changes to lead and copper release in test chambers of a distribution system monitoring station. The timing of rehabilitation efforts and installation of the monitoring station did not always coordinate. In addition, some plans for cleaning efforts could not be carried out. Nevertheless, the comprehensive monitoring data provided many clues as to what shaped the water quality, including dissolved and particulate lead and copper release, in each water system. This system of monitoring provided the means to cautious empirical experimentation for water quality improvement in water systems and documentation of successful system operations.

Cleaning and biostability improvement efforts appeared to lower lead and copper concentrations overall in the project water systems. Results are summarized in Tables 11.18 to 11.20.

Cleaning efforts – flushing and the use of a biofilm-removing chemical – can potentially release pipe wall accumulations too quickly and temporarily create water quality issues in the distribution system. Even biostability efforts that cut off food supplies for microorganisms can cause a sloughing of biofilms and materials from pipe walls. For this reason, cleaning and biostability improvement efforts must be performed at a controlled pace and with a thoroughness that will minimize temporary disturbances of water quality. Monitoring of turbidity and disinfection concentration data history in the distribution system and throughout problematic buildings, if possible, can guide cleaning efforts.

Table 11.18
Lead and Copper Rule data: Lead

Water System	Year-Semester	90th Percentile	Maximum	Actions Taken
A	2006-2	12	28	
	2009-2	6.3	20	After change to orthophosphate from poly blend and chloramine
	2012-2	8.0	8.8	
	2015-2	9.1	15.0	
B	2012-1	27	490	
	2016-1	15	53	After two seasons of high velocity flushing
	2016-2	18	38	
	2017-1	12	41	
C	2005-2	4.5	6.9	
	2008-2	8.9	21	
	2011-2	6.7	54	
	2014-2	6.9	100	
D	2012-2	28	40	
	2015-2	12	62	After initial system improvements
	2016-1	9.1	67	After system improvements and high velocity flushing
	2016-2	10	14	
E (a pinhole leak system)	2011-1	23	160	
	2011-2	11	14	
	2012-1	2.3	3.7	
	2013-2	5.2	5.3	
	2014-2	32	49	Construction particulate release
	2015-1	1.3	5.6	After system improvements
	2015-2	6.3	7.8	
	2016-2	5.6	6.5	
F (a pinhole leak system)	2008-1	5.2	5.9	
	2011-2	2.9	4.7	
	2014-2	3.6	6.4	Begin system improvements
G	2008-2	4.1	11	
	2009-1	5.9	18	
	2009-2	1.6	3.7	
	2010-1	2.9	6.4	
	2010-2	1.2	2.1	
	2011-1	1.4	1.9	
	2011-2	5.1	14	
	2012-2	17	25	
	2013-1	44	64	
	2016-1	0.26	0.46	After system improvements but also different sites
	2016-2	0.56	0.68	
H	2011-2	20	60	
	2012-1	0.6	1.7	
	2012-2	0.2	0.7	
	2013-2	0.6	0.8	
	2014-2	5.8	9.2	
	2015-2	3.2	4.4	After system improvements
	2016-2	5.6	20	

Table 11.19
Lead and Copper Rule data: Copper

Water System	Year-Semester	90th Percentile	Maximum	Actions Taken
A	2006-2	70	250	
	2009-2	65	190	After change to orthophosphate from poly blend and chloramine
	2012-2	79	190	
	2015-2	48	110	
B	2012-1	400	1100	
	2016-1	710	1100	After two seasons of high velocity flushing
	2016-2	570	1100	
C	2005-2	110	200	
	2008-2	160	690	
	2011-2	118	130	
	2014-2	102	260	
D	2012-2	390	870	
	2015-2	1550	2200	After initial system improvements
	2016-1	1310	4100	After system improvements and high velocity flushing
	2016-2	1410	2400	
E (a pinhole leak system)	2011-1	320	670	
	2011-2	380	490	
	2012-1	652	900	
	2013-2	327	840	
	2014-2	642	1800	Construction particulate release
	2015-1	220	360	After system improvements
	2015-2	310	340	
	2016-2	320	320	
F (a pinhole leak system)	2008-1	240	270	
	2011-2	200	250	
	2014-2	260	260	Begin system improvements
G	2008-2	2030	2300	
	2009-1	1124	2100	
	2009-2	1600	1700	
	2010-1	1000	1100	
	2010-2	1300	1900	
	2011-1	1100	1200	
	2011-2	1700	4100	
	2012-2	1500	2500	
	2013-1	812	1300	
	2016-1	250	440	After system improvements but also different sites
	2016-2	230	330	
H	2011-2	300	390	
	2012-1	64	390	
	2012-2	63	110	
	2013-2	77	310	
	2014-2	140	170	
	2015-2	66	100	After system improvements
	2016-2	1200	1400	Changed sites to new copper

Table 11.20
Summary of cleaning and biostability improvement effort results

Water System	Cleaning and Biostability Improvement Efforts	Monitoring Station Data Results	Lead Compliance Data Results	Copper Compliance Data Results
K	After one cleaning season of water main high-velocity flushing	Not Applicable	90th percentile lowered to below Action Level; subsequent years lowered around 5 µg/L; maximum lowered	Lower maximum and slightly lower 90th percentile
A	No significant water system cleaning	Distinct nitrification patterns of lead and copper release; continuing high relative percentage of particulate lead release observed	Slow increase of maximum and 90th percentile over time	Relatively constant maximum and 90th percentile within some variation
B	Engineered high-velocity flushing program; later special biostability study that identified potential source of ammonia and acetate production in the water; only performed two years of the water main flushing program but should have continued the third year in order to further control biofilms and aluminum, iron, and manganese chemical scales	Lowering of dissolved lead; constant higher copper	Brought down maximum and 90th percentile lead.	Maximum has stayed constant; 90th percentile fluctuates slightly up and down.
C	None	Water forms low dissolved lead and dissolved copper and particulate copper with possibly seasonal variation; particulate lead release can be high.	Low 90th percentiles; maximums have increased over time	Low maximums and 90th percentiles
D	Well rehabilitation; water treatment plant renovation for iron, manganese, and organic carbon removal; high-velocity flushing of water mains. Suspect lead and copper solubility with polyphosphate product.	Lowered dissolved and particulate lead and copper	Greatly lowered max and 90th percentile	Lower maximum but higher 90th percentile

(continued)

Table 11.20 Continued

Water System	Cleaning and Biostability Improvement Efforts	Monitoring Station Data Results	Lead Compliance Data Results	Copper Compliance Data Results
E	Iron and manganese filter renovation; dosing of biofilm-removing chemical; installation of new all water softening in buildings; high-velocity flushing of water mains; *building maintenance package	Lowered particulate lead and copper and dissolved copper	Maximum and 90th percentile dependent on localized particulate release events the potential for which has been lowered.	Lowered maximum and 90th percentile
F	Well rehabilitation; water main replacement; dosing of biofilm-removing chemical; *building maintenance package	Dissolved lead already low; lowered dissolved copper and particulate lead and copper; pinhole leak epidemic ended	Not ever out of compliance with Lead and Copper Rule	Not ever out of compliance with Lead and Copper Rule
G	Well rehabilitation; dosing of biofilm-removing chemical; high-velocity flushing of water mains; service line flushing; *building maintenance package	Lowered dissolved lead, dissolved copper, and particulate copper. Particulate lead is lower but still quite variable.	Data similar to previous data with unrepresentative sites removed	Maximum and 90th percentiles have been lowered.
H	Well rehabilitation; dosing of biofilm-removing chemical; high-velocity flushing of water mains; *building maintenance package	Dissolved lead and particulate copper were already low. Lowered particulate lead. Dissolved copper higher.	Maximum and 90th lowered.	Maximum and 90th increased but not over Action Level.

*Building maintenance package includes routine flushing of building piping; routine hot water tank blowdown, routine softener cleaning with organic acid being instituted.

CHAPTER 12
PHOSPHORUS ENVIRONMENTAL IMPACT ANALYSES

In Wisconsin, where this project's participating water utilities were located, three administrative code chapters apply to controlling phosphorus discharges to the environment. Natural Resources (NR) 102.06 discusses setting water quality criteria for Wisconsin's waters.

NR 217 explains the setting of effluent limits for point sources. There are three types of effluent limits: water-quality based (the concentration that a natural body of water can receive without environmental damage), technology-based limits (the concentration that is technologically possible to achieve), and Total Maximum Daily Load (TMDL). A TMDL is the total mass of pollutant a body of water can receive without affecting its water quality. This limit can be used as a "budget" for a body of water where dischargers to the same body of water can trade or manage pollutant contributions as long as the budget is not exceeded.

NR 151 addresses runoff management (non-point sources) including nutrient management, such as for phosphorus. (WDNR 2012)

The phosphorus standards were published in the Wisconsin Administrative Code on December 1, 2010. Since that time, the Wisconsin Pollution Discharge Elimination System (WPDES) permits are being re-evaluated before renewal to determine if modification for more stringent phosphorus limits is needed. (WDOA and WDNR 2015)

Phosphorus removal at wastewater treatment facilities is achieved by means of chemical precipitation or biological treatment or a combination of both (Rodgers 2014). There are advantages and disadvantages to both technological means of phosphorus removal and a combination of the methods can minimize disadvantages (Tanyi 2006).

There are also other strategies available where a compliance deadline can be extended if progress toward meeting a discharge limit requires more time (variance), where adaptive management plans achieve water quality criteria for a body of water by balancing all point and non-point source discharges, or where point sources can trade discharge limits as practicable for each entity (WDNR 2012; WDOA and WDNR 2015).

In general, many wastewater treatment agencies are being required to meet increasingly stringent phosphorus criteria in their respective National Pollution Discharge Elimination System (NPDES) permits. Whatever the permitting mechanism, the result is a phosphorus discharge limit that is protective of the next downstream reach in the natural body of water that receives the discharge. Lower limits may force a wastewater treatment facility to implement a new technology to be deemed compliant. In this instance, a wastewater treatment facility would finance the capital expenditure but transfer the fiscal burden to the rate-paying public.

Tangible costs of phosphorus removal from wastewater include plant modifications that must be considered as phosphate loading increases, such as wastewater processing tank volume and solids storage volume (Tanyi 2006). In addition, annual operations costs include chemical addition, energy usage, solids processing, and solids disposal (Tanyi 2006). More sludge is produced by chemical treatment than by biological treatment requiring more solids storage, processing, and disposal and more chemicals being used (Tanyi 2006). However, more energy is used for the biological process and the anaerobic zone in wastewater processing tanks needs a larger volume than in chemical precipitation (Tanyi 2006). To attain very low discharge phosphorus levels, the chemical precipitation method must be used in addition to the biological removal method (B&V 2014).

Details of phosphorus concentrations and sources found in wastewater, environmental damage measured around the United States, regulations controlling phosphorus discharge from wastewater treatment plants, and removal methods can be found in summary documents available from the EPA and the American Water Works Association (EPA 2010, B&V 2014). This chapter uses findings from the summaries and other documents to calculate the effect of increasing dosages of phosphate in some of the participating water utilities of this project on their associated wastewater treatment facilities.

Information on current phosphorus loading at each wastewater treatment facility associated with this project's participating drinking water utilities was obtained by means of a survey and by direct communication with the facilities' managers. Key information included:

- Monthly influent wastewater flow for 2013, 2014, and 2015
- Monthly average influent phosphorus concentration for 2013, 2014, and 2015
- Monthly effluent wastewater flow for 2013, 2014, and 2015
- Monthly average effluent phosphorus concentration for 2013, 2014, and 2015
- Current and future phosphorus discharge limits
- List of municipal water systems that contribute to the wastewater flow

WASTEWATER TREATMENT FACILITY ASSOCIATED WITH WATER SYSTEMS A, I, AND J

The wastewater treatment facility associated with Water Systems A, I, and J consists of two separate plants. Calculations were performed for both plants, summed together as a facility total, and data averaged over the years 2013, 2014, and 2015. Table 12.1 shows the influent and effluent phosphorus loading.

Table 12.1
Total phosphorus loadings for wastewater treatment facility associated with Water Systems A, I, and J

Item Measured	Units	Average over 2013, 2014, 2015
Influent Flow	l/yr	250,000,000,000
Influent Phosphorus Mass	kg/yr	1,040,000
Effluent Flow	l/yr	264,000,000,000
Effluent Phosphorus Mass	kg/yr	104,000
Residuals Phosphorus Mass	kg/yr	941,000
Phosphorus Removal	%	90

In comparison to previous studies performed at the wastewater treatment facility, Table 12.1 results are reasonable. Previously, a residual phosphorus mass was calculated as 1,150 tons per year (1,043,262 kg/yr). An average phosphorus removal was calculated for 2004 to 2011 as 86.5% for one plant and 92.8% for the second plant with an average of the two of 89.6%.

The contribution of municipal drinking water to the wastewater flow and phosphorus loading is estimated in Table 12.2. Data for 2013, 2014, and 2015 were averaged for these calculations. Information on drinking water pumpage to distribution systems came from the Wisconsin Public Service Commission annual reports submitted by drinking water utilities. Phosphate dosing came from the Wisconsin Department of Natural Resources operations data submitted by drinking water utilities monthly and from phosphate concentrations measured in Water System A.

Regarding phosphate dosages in drinking water, drinking water utilities personnel refer to the dosages of orthophosphate in units of mg/L as PO_4. Even though some corrosion control products include a fraction of phosphate in the form of polyphosphate, it is only the orthophosphate fraction that participates in corrosion control. In addition, the field equipment used to measure the phosphate dosages only measures the orthophosphate fraction. Therefore, there can be more total phosphate in the water than just the stated or measured orthophosphate concentration. In order to translate a drinking water orthophosphate dosage into total phosphorus arriving at a wastewater treatment facility, the dosage as mg/L as PO_4 must first be divided by the ratio of molecular weights of PO_4 to P, which is 95/31=3.0645. Then the polyphosphate to orthophosphate ratio must be used to determine the total phosphorus in the water. For example, Water System J doses orthophosphate at 0.31 mg/L as PO_4 in the drinking water using a product where polyphosphate to orthophosphate is 60/40. The total phosphorus in the water is 0.31/ (3.0645 x 0.4) = 0.25 mg/L as P.

In Table 12.2, an estimate of phosphorus contribution was made for other municipalities outside of the municipalities in this study. It has been noted that typical phosphate dosages for drinking water systems range from 0.7 to 2 mg/L as PO_4 (0.22 to 0.65 mg/L as P) (Rodgers 2014). Anecdotally in Wisconsin, it is typical to see a dosage of around 0.3 mg/L as PO_4 (0.1 mg/L as P) and the use of a product where the poly/ortho ratio is 60/40. For the calculation in Table 12.2, a dosage of 0.3/(3.0645 x 0.4) = 0.25 mg/L as P was used. Water System I's dosage of 1.9 mg/L as PO_4 using phosphoric acid is atypical for Wisconsin.

The municipal contribution to the total phosphorus for this wastewater treatment facility was found to be 6%. A previous study at the wastewater treatment facility found the municipal contribution to be 22%, however, the phosphate dosing units were in mg/L as PO_4 but used in the calculation as P. Therefore, the previous finding is really 22%/3.0645 = 7.2%, closer to the calculations in this study. Other smaller variations in the results between the two studies are from using municipal drinking water flows and dosages from different years.

In comparison to studies at other wastewater facilities, one study found a range of municipal contributions of phosphorus to wastewater treatment facilities for ten water systems to range from 10 to 35% (B&V 2014). Cleveland, Ohio, calculations resulted in a current contribution of 10% but a regulatory increase of phosphate chemical would raise the contribution to 27% (Rodgers 2014).

Table 12.3 explores the effect of possible regulatory increases to the phosphate dose in drinking water on the wastewater treatment facility associated with this project's Water Systems I, J, and A. Guidance for corrosion control in 2016 was to use a dosage of 1 to 3 mg/L as PO_4 (0.3 to 1.0 mg/L as P) unless 3.5 mg/L as PO_4 (1.2 mg/L as P) is needed to control lead release from lead service lines, to control copper corrosion from new copper pipe, or if aluminum, iron, or manganese is present in the water (EPA 2016a). This is a guidance directive from EPA that could possibly become a regulatory directive in a revision of the Lead and Copper Rule.

Table 12.3 compares the phosphorus loading that will need to be addressed by the wastewater treatment facility if the municipal phosphorus loading is increased. The municipal loading of phosphorus would increase from 6% up to 20%. Note that the larger Water System I already uses a phosphate dosage of 1.9 mg/L as PO_4 (0.62 mg/L as P), so that phosphorus mass changes do not become significant at this wastewater treatment facility until that dose is exceeded by regulatory requirements. The wastewater treatment facility would be within the current and future phosphorus discharge limits through the highest drinking water phosphate dosage.

Table 12.2
Municipal phosphorus loadings for wastewater treatment facility associated with Water Systems A, I, and J

Item Measured	Units	Average over 2013, 2014, 2015	Source of Information
Influent Flow	l/yr	250,000,000,000	See Table 12.1
Inflow and Infiltration	l/yr	117,000,000,000	WWTF: 85 MGD for I/I
Remaining Wastewater Flow	l/yr	133,000,000,000	By subtraction
Flow from Water System I	l/yr	74,000,000,000	WPSC: drinking water flows WWTF: 35% of municipal flow is used for landscaping and cooling and does not enter the treatment plant
Flow from Water System J	l/yr	2,170,000,000	
Flow from Water System A	l/yr	2,740,000,000	
Other municipalities	l/yr	54,000,000,000	By subtraction
Phosphorus Dose from Water System I	mg/L as P	0.62	WDNR: Dose is 1.9 mg/L as PO_4 using a product with 100% of phosphorus as orthophosphate
Phosphorus Dose from Water System J	mg/L as P	0.25	WDNR: Dose is 0.31 mg/L as PO_4 using a product with 40% of phosphorus as orthophosphate and 60% as polyphosphate
Phosphorus Dose from Water System A	mg/L as P	0.25	WDNR: Dose is 0.69 mg/L as PO_4 using a product with 90% of phosphorus as orthophosphate and 10% as polyphosphate
Influent Phosphorus Load	kg/yr	1,040,000	See Table 12.1
Phosphorus Load from Water System I	kg/yr	45,900	Flow x Dose x 10^(-6)
Phosphorus Load from Water System J	kg/yr	550	
Phosphorus Load from Water System A	kg/yr	685	
Phosphorus Load from Other Municipalities	kg/yr	13,500	Assuming dose of 0.25 mg/L as P. See discussion in report.
Phosphorus Load from Other Sources	kg/yr	980,000	Subtraction of municipal load from influent load
Municipal Phosphorus Load	% of influent phosphorus load	6	

1.WWTF=wastewater treatment facility associated with Water Systems A, I, and J where a phosphorus study and flow studies have been performed in the past

2. WPSC= Wisconsin Public Service Commission; drinking water utilities submit annual reports on operations parameters and costs where flows to distribution systems were obtained for 2013, 2014, 2015. Flow used in calculations: flow quantity entering the distribution system minus non-revenue quantity for fire flows, flushing, etc. 65% of the calculated flow was used for this wastewater treatment facility based on facility estimates

3. WDNR= Wisconsin Department of Natural Resources operations data submitted by drinking water utilities monthly for 2013, 2014, 2015

Table 12.3

Municipal phosphorus loadings for wastewater treatment facility associated with Water Systems A, I, and J with increased drinking water phosphate dosages

Item Measured	Units	Current Phosphorus Dosing	Minimum of 1 mg/L as PO_4	Minimum of 3 mg/L as PO_4	Minimum of 3.5 mg/L as PO_4
Water System I	kg/yr	45,900	45,900	72,400	84,400
Water System J	kg/yr	550	1,770	5,310	6,200
Water System A	kg/yr	685	994	6,710	7,820
Other Municipalities	kg/yr	13,500	35,100	132,000	153,000
Other Phosphorus Sources	kg/yr	980,000	980,000	980,000	980,000
Total Influent Phosphorus Load	kg/yr	1,040,000	1,060,000	1,200,000	1,230,000
Municipal Phosphorus Load	% of influent phosphorus load	6	8	18	20
Residuals Phosphorus Mass (90% removal)	kg/yr	936,000	954,000	1,080,000	1,110,000
Effluent Phosphorus Mass (10% remains)	kg/yr	104,000	106,000	120,000	123,000
Effluent Phosphorus Concentration (264x10^9 L/yr)	mg/L	0.39	0.40	0.45	0.47
Current Phosphorus Discharge Limits	mg/L	0.66 minimum			
Future Phosphorus Limits	mg/L	0.66 minimum			
Increase of Phosphorus Removed	kg/yr	0	18,000	144,000	174,000
	lb/yr	0	39,700	318,000	384,000
Chemical Costs to Remove Increased Phosphorus	$/yr: $0.53/lb Fe x 2.2 lb Fe/lb P removed	$0	$46,300	$370,000	$447,000

1. See Table 12.2 for municipal wastewater flows and initial dosages.
2. Chemical costs were previously calculated by the wastewater treatment facility.

The cost of removing phosphorus from the wastewater was previously calculated by the associated wastewater treatment facility. It was found through operations data that 2.2 pounds of iron were required per each pound of phosphorus removed. This compares to findings of others that chemical precipitation dosages of 1.5 to 2.0 moles of a metal dose, such as iron, per mole phosphorus in the plant influent is typical for removing 80 to 98 percent of the phosphorus (EPA 2010). The phosphorus removed from the wastewater is 90% of the influent phosphorus for this wastewater treatment facility. The ratio of iron to phosphorus in moles can be converted to weight by means of pounds per pound-mole, where mole weights are 56 and 31, respectively. The mole ratio given above translates to (1.5 x 56) / 31 = 2.7 pounds iron for each pound influent phosphorus." Reaching lower limits with chemical precipitation requires a dose on the order of 6 to 7 moles of metal per mole influent phosphorus (EPA 2010).

It was also found at this wastewater treatment facility that it costs $0.53 per pound of iron. Those findings were used to calculate the additional chemical costs for the increased phosphorus loading associated with each regulatory dosage change. In Table 12.3, it is seen that additional chemical costs alone would rise to $447,000 per year for the maximum dosage of 3.5 mg/L as PO_4 (1.14 mg/L as P). Other costs would be incurred for sludge storage, processing, and disposal.

WASTEWATER TREATMENT FACILITY ASSOCIATED WITH WATER SYSTEM K

Similar calculations were performed for the wastewater treatment facility associated with Water System K as shown in Tables 12.4, 12.5, and 12.6. Only one municipal water system, Water System K, contributes to the wastewater influent. The drinking water pumpage into the distribution system was known from Wisconsin Public Service Commission annual reports. It is not known what percentage of municipal water enters the wastewater treatment facility, so calculations shown here assume 100% of the flow and give a conservative estimate of phosphorus impact.

The wastewater influent from sources other than the municipal flow was attributed to a high infiltration and inflow, especially from private property drainage which the wastewater manager identified as a significant contribution. Whey is also sent from a local cheese factory.

Water System K does not add phosphate to the drinking water, so the total phosphorus mass at the wastewater treatment plant is from non-municipal sources.

Table 12.6 shows the additional phosphorus loading if Water System K began dosing the drinking water with orthophosphate. Note that these calculations assume that an orthophosphate product would be used where there was no polyphosphate fraction. If a poly/ortho ratio of 50/50 product were used, the phosphate mass contributed from the drinking water would double from a maximum of 8.5% of influent phosphorus to 17%.

The greatest challenge at this facility is meeting the future phosphorus discharge limit of 0.075 mg/L as P, regardless of a drinking water phosphorus dose. The facility has recently begun operating a biological phosphorus removal system which has lowered the effluent phosphorus concentration to 0.17 mg/L as P. There is hope that the rest of the phosphorus removal obligation can be achieved by trading pollution credits with other sources in the watershed. This step will be determined as soon as the Total Maximum Daily Load has been determined by the regulatory agency.

Table 12.4
Total phosphorus loadings for wastewater treatment facility associated with Water System K

Item Measured	Units	Average over 2013, 2014, 2015
Influent Flow	l/yr	4,220,000,000
Influent Phosphorus Mass	kg/yr	28,400
Effluent Flow	l/yr	4,220,000,000
Effluent Phosphorus Mass	kg/yr	3,580
Residuals Phosphorus Mass	kg/yr	24,800
Phosphorus Removal	%	87

Table 12.5
Municipal phosphorus loadings for wastewater treatment facility associated with Water System K

Item Measured	Units	Average over 2013, 2014, 2015	Source of Information
Influent Flow	l/yr	4,220,000,000	See Table 12.4
Inflow and Infiltration + Cheese Factory	l/yr	1,900,000,000	By subtraction of Influent Flow – Municipal Flow
Flow from Water System K	l/yr	2,320,000,000	WPSC: drinking water flows Assumption: 100% of municipal flow enters the treatment plant
Phosphorus Dose from Water System K	mg/L as P	0	No phosphate dosing
Influent Phosphorus Load	kg/yr	28,400	See Table 12.4
Phosphorus Load from Water System K	kg/yr	0	Flow x Dose x 10^(-6)
Phosphorus Load from Other Sources	kg/yr	28,400	Subtraction of municipal load from influent load
Municipal Phosphorus Load	% of influent phosphorus load	0	

WPSC= Wisconsin Public Service Commission; drinking water utilities submit annual reports on operations parameters and costs where flows to distribution systems were obtained for 2013, 2014, 2015

Table 12.6
Municipal phosphorus loadings for wastewater treatment facility associated with Water System K with increased drinking water phosphate dosages

Item Measured	Units	Current Phosphorus Dosing	0.3 mg/L as PO_4	1 mg/L as PO_4	3 mg/L as PO_4	3.5 mg/L as PO_4
Water System K Phosphorus Load	kg/yr	0	227	755	2,270	2,640
Other Phosphorus Sources	kg/yr	28,400	28,400	28,400	28,400	28,400
Total Influent Phosphorus Load	kg/yr	28,400	28,600	29,100	30,700	31,000
Municipal Phosphorus Load	% of influent phosphorus load	0	0.8	3	7	8.5
Residuals Phosphorus Mass (87.3% removal)	kg/yr	24,800	25,000	25,400	26,800	27,100
Effluent Phosphorus Mass (12.7% remains)	kg/yr	3,600	3,600	3,700	3,900	3,900
Effluent Phosphorus Concentration (4.22x10^9 L/yr)	mg/L	0.85	0.86	0.88	0.92	0.93
Current Phosphorus Discharge Limits	mg/L	1				
Future Phosphorus Limits	mg/L	0.075				
Increase of Phosphorus Removed	kg/yr	0	200	600	2,000	2,300
	lb/yr	0	441	1,320	4,410	5,070
Chemical Costs to Remove Increased Phosphorus	$/yr: $0.53/lb Fe x 2.2 lb Fe/lb P removed	$0	$514	$1,540	$5,140	$5,910

1. See Table 12.5 for municipal wastewater flows and initial dosages.
2. Chemical costs were previously calculated by the wastewater treatment facility in Table 12.3.
3. These calculations assume that an orthophosphate product would be used where there was no polyphosphate fraction. If a poly/ortho ratio of 50/50 product were used, the phosphate mass contributed from the drinking water would double.

WASTEWATER TREATMENT FACILITY ASSOCIATED WITH WATER SYSTEM C

For Water System C, the wastewater phosphorus assessment results are shown in Tables 12.7 to 12.10. The drinking water phosphate chemical is about 3% of the total phosphorus load to the wastewater treatment plant. An increase to 3.5 mg/L as PO_4 in the drinking water would increase the phosphorus contribution to 36% using the current phosphate product.

If the current product is changed to one with no polyphosphate fraction, the phosphorus contribution would be 19% at the maximum dose of 3.5 mg/L as PO_4. This can be seen by comparing Tables 12.9 and 12.10. Another advantage of using an orthophosphate only product is that the wastewater effluent phosphorus concentration would not be pushed over the discharge limit. The effluent concentration would be 0.71 mg/L as P with the current poly/orthophosphate blend product; it would be 0.56 mg/L as P with an orthophosphate product. If the discharge limit is 0.66 mg/L as P, this would be a significant difference. A 100% orthophosphate product would also lower annual costs of phosphorus removal because there would be less total phosphorus in the water. At a dose of 3.5 mg/L as PO4 in the drinking water, additional chemical costs would drop from $89,700 with the current product to $32,400 with an orthophosphate product.

Table 12.7
Total phosphorus loadings for wastewater treatment facility associated with Water System C

Item Measured	Units	Average over 2013, 2014, 2015
Influent Flow	l/yr	29,300,000,000
Influent Phosphorus Mass	kg/yr	79,800
Effluent Flow	l/yr	29,300,000,000
Effluent Phosphorus Mass	kg/yr	13,700
Residuals Phosphorus Mass	kg/yr	66,200
Phosphorus Removal	%	83

WASTEWATER TREATMENT FACILITY ASSOCIATED WITH WATER SYSTEM B

For Water System B, the addition of phosphate to the drinking water would not push the wastewater discharge phosphorus concentration close to the limit as was estimated for Water System C. The addition would, however, impact annual costs and sludge handling. A phosphorus assessment for Water System B is seen in Tables 12.11 to 12.13.

WASTEWATER TREATMENT FACILITY ASSOCIATED WITH WATER SYSTEMS F AND G

Water Systems F and G are campus water systems. The water system, the buildings, and the wastewater treatment plant are owned by the same entity on each campus. Both water systems land-spread the wastewater and there are no phosphorus constraints in doing so. One land-spreading operation is adjacent to a stream. Even without constraints, the manager is concerned about phosphorus runoff to the stream.

Table 12.8
Municipal phosphorus loadings for wastewater treatment facility associated with Water System C

Item Measured	Units	Average over 2013, 2014, 2015	Source of Information
Influent Flow	l/yr	29,300,000,000	See Table 12.7
Inflow and Infiltration	l/yr	13,800,000,000	There are building perimeter drains tied to the sewer system.
Flow from Water System C	l/yr	15,500,000,000	WPSC: drinking water flows Assumption: 10% of municipal flow is used for landscaping and cooling and does not enter the treatment plant per manager
Phosphorus Dose from Water System C	mg/L as P	0.16	Dose is 0.13 to 0.2 mg/L as PO_4 using a product with 40% of phosphorus as orthophosphate and 60% as polyphosphate
Influent Phosphorus Load	kg/yr	79,800	See Table 12.7
Phosphorus Load from Water System C	kg/yr	2,500	Flow x Dose x 10^(-6)
Phosphorus Load from Other Sources	kg/yr	77,300	Subtraction of municipal load from influent load
Municipal Phosphorus Load	% of influent phosphorus load	3.1	

WPSC= Wisconsin Public Service Commission; drinking water utilities submit annual reports on operations parameters and costs where flows to distribution systems were obtained for 2013, 2014, 2015

Table 12.9
Municipal phosphorus loadings for wastewater treatment facility associated with Water System C with increased drinking water phosphate dosages using a poly/orthophosphate blend product

Item Measured	Units	Current Phosphorus Dosing	1 mg/L as PO_4	3 mg/L as PO_4	3.5 mg/L as PO_4
Water System C Phosphorus Load	kg/yr	2,500	12,700	38,000	44,400
Other Phosphorus Sources	kg/yr	77,300	77,300	77,300	77,300
Total Influent Phosphorus Load	kg/yr	79,800	90,000	115,000	122,000
Municipal Phosphorus Load	% of influent phosphorus load	3.1	14	33	36
Residuals Phosphorus Mass (82.8% removal)	kg/yr	66,100	74,500	95,200	101,000
Effluent Phosphorus Mass (17.2% remains)	kg/yr	13,700	15,500	19,800	21,000
Effluent Phosphorus Concentration (29.3x10^9 L/yr)	mg/L	0.47	0.53	0.68	0.71
Current and Future Discharge Limit	mg/L as P	assume 0.66 similar to WWTF for A, I, and J			
Increase of Phosphorus Removed	kg/yr	0	8,400	29,100	34,900
	lb/yr	0	18,500	64,200	76,900
Chemical Costs to Remove Increased Phosphorus	$/yr: $0.53/lb Fe x 2.2 lb Fe/lb P removed	$0	$21,600	$74,900	$89,700

1. See Table 12.5 for municipal wastewater flows and initial dosages.
2. Chemical costs were previously calculated by the wastewater treatment facility in Table 12.3.
3. These calculations assume that the current phosphate product with poly/orthophosphate ratio of 60/40 will continue to be used.

Table 12.10
Municipal phosphorus loadings for wastewater treatment facility associated with Water System C with increased drinking water phosphate dosages using an orthophosphate product

Item Measured	Units	Current Phosphorus Dosing	1 mg/L as PO_4	3 mg/L as PO_4	3.5 mg/L as PO_4
Water System C Phosphorus Load	kg/yr	2,500	5,070	15,200	17,700
Other Phosphorus Sources	kg/yr	77,300	77,300	77,300	77,300
Total Influent Phosphorus Load	kg/yr	79,800	82,300	92,500	95,000
Municipal Phosphorus Load	% of influent phosphorus load	3.1	6.1	16	19
Residuals Phosphorus Mass (82.8% removal)	kg/yr	66,100	68,200	76,600	78,700
Effluent Phosphorus Mass (17.2% remains)	kg/yr	13,700	14,200	15,900	16,400
Effluent Phosphorus Concentration (29.3x10^9 L/yr)	mg/L	0.47	0.48	0.54	0.56
Current and Future Discharge Limit	mg/L as P	assume 0.66 similar to WWTF for A, I, and J			
Increase of Phosphorus Removed	kg/yr	0	2,100	10,500	12,600
	lb/yr	0	4,630	23,100	27,800
Chemical Costs to Remove Increased Phosphorus	$/yr: $0.53/lb Fe x 2.2 lb Fe/lb P removed	$0	$5,400	$27,000	$32,400

1. See Table 12.5 for municipal wastewater flows and initial dosages.
2. Chemical costs were previously calculated by the wastewater treatment facility in Table 12.3.
3. These calculations assume that 100% orthophosphate is used.

Table 12.11
Total phosphorus loadings for wastewater treatment facility associated with Water System B

Item Measured	Units	Average over 2013, 2014, 2015
Influent Flow	l/yr	38,100,000,000
Influent Phosphorus Mass	kg/yr	179,000
Effluent Flow	l/yr	42,400,000,000
Effluent Phosphorus Mass	kg/yr	14,700
Residuals Phosphorus Mass	kg/yr	165,000
Phosphorus Removal	%	92

Table 12.12
Municipal phosphorus loadings for wastewater treatment facility associated with Water System B

Item Measured	Units	Average over 2013, 2014, 2015	Source of Information
Influent Flow	l/yr	38,100,000,000	See Table 12.4
Flow from Water System B	l/yr	22,700,000,000	WPSC: drinking water flows Assumption: 10% of municipal flow is used for landscaping and cooling and does not enter the treatment plant similar to Water System C assumption
Phosphorus Dose from Water System B	mg/L as P	0	No phosphate dosing
Influent Phosphorus Load	kg/yr	179,000	See Table 12.4
Phosphorus Load from Water System B	kg/yr	0	Flow x Dose x 10^(-6)
Phosphorus Load from Other Sources	kg/yr	179,000	Subtraction of municipal load from influent load
Municipal Phosphorus Load	% of influent phosphorus load	0	

WPSC= Wisconsin Public Service Commission; drinking water utilities submit annual reports on operations parameters and costs where flows to distribution systems were obtained for 2013, 2014, 2015

Table 12.13
Municipal phosphorus loadings for wastewater treatment facility associated with Water System B with increased drinking water phosphate dosages

Item Measured	Units	Current Phosphorus Dosing	1 mg/L as PO_4	3 mg/L as PO_4	3.5 mg/L as PO_4
Water System B Phosphorus Load	kg/yr	0	6,680	20,000	23,400
Other Phosphorus Sources	kg/yr	179,000	179,000	179,000	179,000
Total Influent Phosphorus Load	kg/yr	179,000	186,000	199,000	202,000
Municipal Phosphorus Load	% of influent phosphorus load	0	3.6	10	11.5
Residuals Phosphorus Mass (91.9% removal)	kg/yr	165,000	171,000	183,000	186,000
Effluent Phosphorus Mass (17.2% remains)	kg/yr	14,000	15,000	16,200	16,500
Effluent Phosphorus Concentration (42.4x10^9 L/yr)	mg/L	0.35	0.36	0.38	0.39
Current and Future Discharge Limit	mg/L as P	assume 0.66 similar to WWTF for A, I, and J			
Increase of Phosphorus Removed	kg/yr	0	6,220	18,500	21,600
	lb/yr	0	13,700	40,800	47,600
Chemical Costs to Remove Increased Phosphorus	\$/yr: \$0.53/lb Fe x 2.2 lb Fe/lb P removed	\$0	\$16,000	\$47,600	\$55,400

1. See Table 12.12 for municipal wastewater flows and initial dosages.
2. Chemical costs were previously calculated by the wastewater treatment facility in Table 12.3.
3. These calculations assume that 100% orthophosphate is used.

SUMMARY OF DRINKING WATER PHOSPHATE DOSING EFFECTS ON ASSOCIATED WASTEWATER TREATMENT FACILITIES

The impact that drinking water phosphate addition has on associated wastewater treatment facilities varies with many factors as demonstrated in this chapter – the drinking water pumpage versus the wastewater influent flow, the efficiency of the wastewater treatment facility's phosphorus removal, and the stringency of the phosphate discharge limit. A phosphorus assessment from the drinking water system through the wastewater treatment facility, similar to the one in this chapter, can be performed for individual water systems.

However, the cost analysis in this chapter only included the additional chemical costs needed to remove additional phosphorus from wastewater. More detailed costs of phosphorus removal can be calculated at the individual wastewater treatment facility to include increased tank volume installation costs, both for wastewater treatment tanks and sludge handling tanks, and additional annual costs of labor, energy, chemical usage, sludge storage, sludge processing, and sludge disposal. The costs could be studied over a set time period such as 30 years and a proper engineering economics calculation performed to establish a present worth cost of phosphorus removal to current and future limits. This present worth can be weighed against the present worth of lead and copper control strategies in the drinking water system.

It should be noted that using a phosphate-based corrosion control product with polyphosphate in it increases the total phosphorus loading to the wastewater treatment facility above the loading required to satisfy drinking water regulations. The additional phosphate from the polyphosphate fraction increases the cost of wastewater treatment plant phosphorus removal.

Phosphate-dosing is often miscommunicated because of confusion over units of measurement. Drinking water personnel often refer to dosing in terms of orthophosphate concentration in units of mg/L as PO4 while wastewater personnel refer to the total phosphorus concentration in units of mg/L as P. Specifically, wastewater agencies follow EPA method 365.1, Revision 2.0: Determination of Phosphorus by Semi-Automated Colorimetry (EPA 1993), for running samples of wastewater, surface water, and industrial waste.

Total phosphorus and orthophosphate concentrations must be converted to one unit or another for comparison, where mg/L as P is about one-third the concentration expressed as PO4. Also, only the orthophosphate fraction of the phosphorus addition into drinking water is typically measured and stated. The total phosphorus added into the drinking water must be stated with the inclusion of both the orthophosphate and the polyphosphate fractions.

In addition to tangible costs, the impact of the phosphorus discharged to the environment must be assessed. In the wastewater treatment facility calculations in this chapter, it was assumed that a percentage of the municipal flow does not enter the wastewater treatment facility; the remaining phosphorus-laden water is released directly into nature – mainly in the form of landscaping water and industrial non-contact cooling water discharge.

Non-contact cooling water is either discharged to a natural body of water through a pipe or it is allowed to infiltrate into the ground, especially in rural settings. The phosphorus discharge limits have created a dilemma for industries using non-contact cooling water as cooling water treatment may be required in the future. In some instances, industry is trying to negotiate sending all non-contact cooling water discharge to the wastewater treatment facilities to avoid costly upgrades, thus exacerbating the stress of removing phosphorus at the wastewater treatment facilities.

To assess the impact of a phosphorus discharge outside of a wastewater treatment facility and directly to a natural body of water, it is difficult to find appropriate indices of environmental and community impacts. In this case, the state regulatory agencies have already established such an index. That is, the phosphorus discharge limit set by state regulatory agency for the natural body of water that receives the wastewater, landscaping run-off, and industrial non-contact cooling water is a statement of environmental and community impacts; it is based on the sensitivity of the receiving body of water to additional phosphorus and the intended community use of the natural body of water.

The phosphorus assessment in this chapter provides the realization that lead and copper corrosion control strategies have impacts outside of the water system itself. This chapter provides a framework within which to calculate not only the environmental costs of phosphorus addition to drinking water, but to shed light on the socio-economic costs associated with removal and regulatory compliance.

The reality is that a drinking water utility is typically a separate agency from its receiving wastewater utility, both acting independently and unaware of the negative effects of their actions on their counterpart. The resultant outcome may unintentionally punish the rate-payers, who are customers of both agencies. This reinforces how crucial communications and joint research projects are between water and wastewater utilities.

CHAPTER 13
CONCLUSIONS

This project explored if lead or copper orthophosphate and carbonate compounds could continue to provide corrosion control in the presence of the various chemical and microbiological interactions actually occurring in water systems. A long list of water quality parameters was studied in relation to lead and copper release measured in special distribution system monitoring stations located in eight water systems. The stations allowed measurements in each system to be taken under similar conditions so that data could be compared over time and between systems. The conclusions from studying the parameters are organized into three general categories of factors that have been observed to shape water quality:

1. Uniform corrosion factors
2. Biostability factors
3. Chemical scale formation and dissolution factors

Conclusions continue in this section with various observations made from comprehensively studying the water systems.

UNIFORM CORROSION

The Lead and Copper Rule puts emphasis on uniform corrosion based on carbonate compound solubility as the reason that lead and copper are released into water. Two water quality factors, pH and alkalinity, are identified in the Rule as the controlling factors of lead and copper release in using this model. (Alkalinity is one expression of the carbonate concentration.)

In this project, eight water systems were evaluated for pH and alkalinity as well as many other water quality parameters, including routine lead and copper release data. No correlations were found between dissolved lead and copper release and pH and alkalinity (Chapter 7 and Appendix A). No correlations were found between the dissolved inorganic carbonate concentrations in the water and dissolved lead and copper release (Figures 7.4 and 7.6). Nor were correlations found between dissolved lead and copper release and the carbonate solubility models' predicted dissolved lead and copper release (Figures 7.3 and 7.5).

Insight as to why no patterns were seen between uniform corrosion parameters and actual lead and copper release comes from the chemical and microbiological analyses of the scales that formed on the metal plates in the monitoring station test chambers over the monitoring period (Tables 6.9, 6.10, 7.16, 7.17, 9.4, 9.5, 10.19, 10.20). There was not just one lead or copper carbonate compound found on the plates as idealized by the carbonate solubility models. Instead, there were mixtures of types of lead or copper carbonate compounds as well as lead or copper oxides. There were also other elements, such as iron, manganese, aluminum, phosphorus, and sulfur. In addition, there were thermodynamically unstable amorphous compounds observed on the plates, not just thermodynamically stable crystalline compounds assumed by the equilibrium-based carbonate solubility models. There were also chemical scales observed containing lead and copper that had the potential to crumble into the water and transport lead or copper as particulate matter, an aspect not considered in the carbonate solubility models. (From Chapter 6, it can be seen that particulate lead and particulate copper potentially can be quite a significant fraction of the total metals that can reach consumers.)

To add to this chemical complexity, there was the presence of a microbiological component in the metal surface accumulations (Chapter 9). Biofilms were quantified in the scales as well with data pertaining to degree of biofilm formation and degree that microorganisms were held in the biofilm versus in the water (Tables 9.4 and 9.5).

Given the lack of correlations to lead and copper release and the complex nature of the metal surface accumulations observed, the models of lead and copper carbonate solubility used by the Lead and Copper Rule to predict lead and copper release do not adequately represent the set of circumstances actually found in drinking water distribution systems.

This is not to say that lead and copper carbonate solubility concept should not be considered. Instead, this is an observation that carbonate solubility is only one of many factors that control the release of lead and copper in actual water distribution systems. The major water quality parameters of the carbonate concept, alkalinity and pH, must always be considered in an evaluation of lead and copper control along with two other groups of water quality parameters identified on the metal plates – parameters related to chemical scale formation and biostability of the water.

It is possible that each of these three general categories of lead and copper release factors (uniform corrosion, chemical scale formation, and biostability) may take on more or less significance in different time periods in a water system. For example, Figure 13.1 shows a typical lead release pattern from lead plates in a test chamber of a PRS Monitoring Station. When the clean metal plates are first put in contact with the system water in the test chambers, there is initially high metal release with a steep drop over time. This is most likely a time period when oxide and carbonate scales are developing on the metal surfaces by means of uniform corrosion mechanisms. Other chemical scales and biofilms are most likely forming but at a lower rate, making uniform corrosion the more significant factor in lead and copper release at that time.

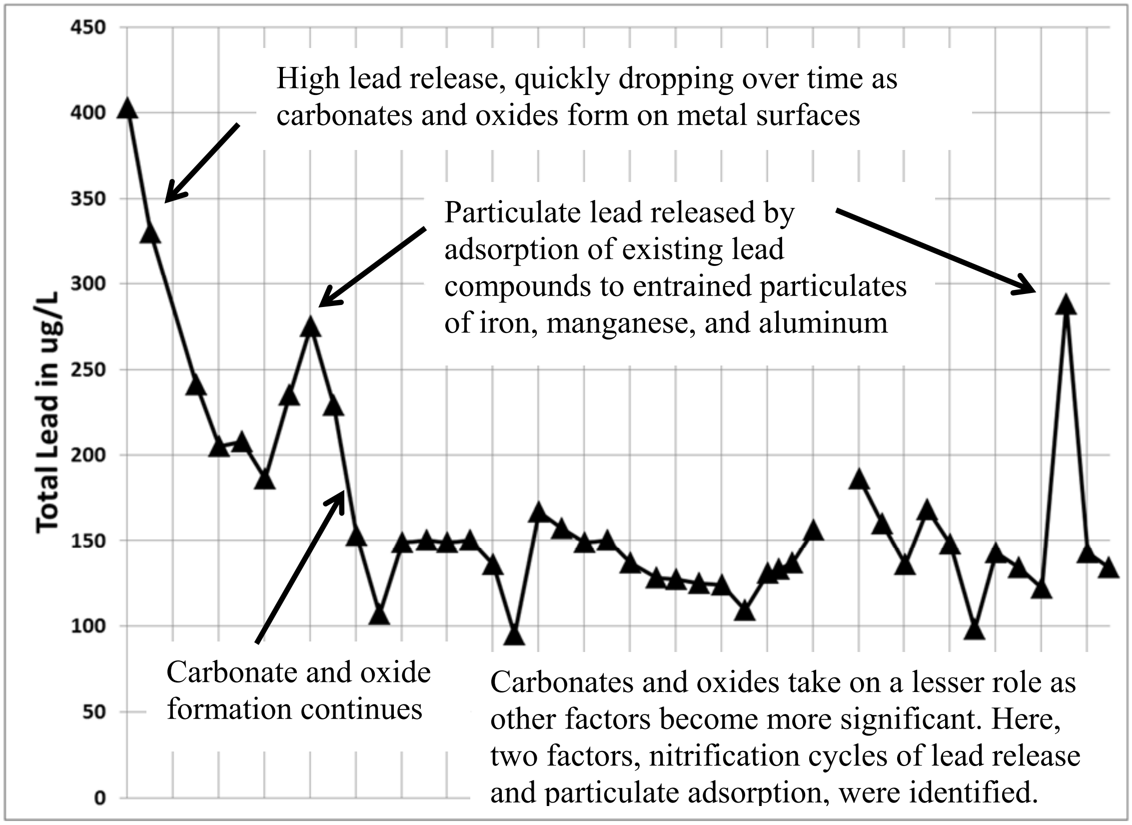


Figure 13.1 Example of lead release pattern over time from stagnating water in a lead test chamber

In Figure 13.1, during the period of carbonate and oxide formation, water main flushing occurred nearby sending iron, aluminum, and manganese particulates into the test chambers and creating an increase in released particulate lead, theoretically, by adsorption of lead carbonates and oxides to the entrained metal particulates. Therefore, a second significant factor of lead release, that is, adsorption of lead compounds by chemical scales, appears to have come into play in determining the total lead concentration in the water in addition to the uniform corrosion factor during that time period. The carbonate and oxide formation probably continued past that point as shown by a continued decrease in total lead concentration. Then, lead release fluctuated around a lower concentration range. Possible factors identified in this time period for release of lead were microbiological nitrification cycles and episodes of metal scale release from the water system. Therefore, no factor can be ignored in that it may take on more significance in release of lead and copper during other time periods.

Another aspect of the carbonate solubility models for uniform corrosion is that they ignore other compounds that can also control the uniform corrosion of metals. Oxides of lead and copper have already been mentioned as being present on the metal plates in this project (Tables 6.9 and 6.10 and Chapter 7). It is known that some oxides have lower solubility than other oxides (Lytle and Schock 2005). The ones with lower solubility provide better corrosion control. Those oxides form in a more oxidizing environment. To that end, oxidation/reduction potential was measured. In this project, oxidation/reduction potential did not show an inverse relationship with lead and copper release. However, two water systems were found to have traces of a highly insoluble lead oxide in their lead plate scales. Even though lead and copper oxide formation was not significant in this study, it must not be neglected when comprehensively studying lead and copper release into drinking water as every water system has its own combination of factors shaping its water quality.

Uniform corrosion by means of chloride and sulfate was explored in this project because of the high solubility of lead and copper chloride and sulfate compounds compared to the solubility of carbonates and oxides. Trends with the Larson-Skold Index, an index where the concentrations of chloride and sulfate are divided by the alkalinity were explored. A high index implies higher corrosion of lead and copper and higher dissolved lead and copper concentrations in the water. However, relationships found between the Larson-Skold Index and lead/copper were confounded with system operations factors in this project. This will be discussed under the section, "Development of Hypotheses and Conclusions from Water Quality Monitoring Data," in this chapter. The Chloride to Sulfate Mass Ratio, another index, was shown to be related to dissolved lead and copper release by means of an exponential function, staying relatively non-influential over a wide range of lead and copper concentrations and increasing in influence with the highest concentrations (Figures 7.12 and 7.14). This is possibly a statement on the higher solubility of chloride compounds versus sulfate compounds and, in this project, is not related to galvanic corrosion as it has been related in the literature (Nguyen et al. 2010; Nguyen et al. 2011). There were also no direct correlations identified between lead and copper release and chloride and sulfate concentrations in this project. Nevertheless, chloride and sulfate must not be neglected when comprehensively studying lead and copper release into drinking water as every water system has its own combination of factors shaping its water quality.

BIOSTABILITY

Biostability of water is the balance of factors that encourage the growth of microorganisms versus factors that discourage their growth. Factors that encourage their growth are nutrients (compounds of nitrogen, organic carbon, and phosphorus), long residence time, and low disinfection. These factors can be counteracted with limiting nutrients, lowering residence time/water age, and increasing disinfection.

The water systems studied in this project showed direct correlations of dissolved and/or particulate lead and copper release with biostability parameters and microbiological populations (Table 6.11, Table 6.12, Appendix A, and Chapter 9). For example, in Water Systems A and B dissolved lead release trended with nitrification patterns – a peak of ammonia release in the water system followed by a peak of organic carbon release with microbiological population increase. In addition, the nitrification pattern included a continuous increase in nitrite/nitrate concentration over warm weather months that trended with release of particulate lead and copper as well as dissolved copper into the autumn. But, nitrification was not the only microbiological activity seen in the water systems. Appendix A and Tables 6.11 and 6.12 show dissolved lead and dissolved copper release trending with microbiological population in most of the water systems. In some water systems, dissolved organic carbon appeared to dominate as a co-trending factor and in other water systems, ammonia, nitrate, and/or phosphorus appeared to dominate. In addition, all eight water systems had biofilms form on the test chamber metal plates and experienced increased microbiological populations in the test chambers (Tables 9.1 through 9.6). So, this project's data show that microorganisms and their biofilms were present in the test chambers and they were interrelated with lead and copper release.

But, the correlations of lead and copper release to biostability parameters and presence of an excessive population of microorganisms (> 500 microorganisms per mL per 40 CFR Part 141 Subpart H [Code of Federal Regulations 2010a]) do not prove that microbiologically influenced corrosion occurred. That was out of the scope of this project. In the scope was to explore the trending of lead and copper release with biostability parameters and microbiological populations. It can be theorized that microbiologically influenced corrosion was possible in these situations.

It is known that microorganisms can secrete acidic enzymes to attach to metal surfaces (Bremer et al. 2001) and that such localized acidity can corrode metal surfaces. With the prevalence of biofilms formed in the test chambers (Tables 9.1 through 9.6), corrosion from the surface acidity could have been possible.

It is also known that microorganisms can produce acidic waste products, such as hydrogen sulfide from sulfate-reducing bacteria, which forms a weak acid in water (Rittman and McCarty 2001; Madigan and Martinko 2006), another pathway to increased metal corrosion. Acidic waste products were not measured in this project. However, sulfur was found in the chemical scales of Water System B's metal plates. The analyst theorized that this could have been a remnant from sulfate-reducing bacteria. An independent biostability study of Water System B found sulfate-reducing bacteria to be a significant presence in pipe biofilm in the system.

Nitrifying microorganisms produce nitrates that can form highly soluble compounds of lead and copper and can possibly re-solubilize existing lead and copper films on metals surfaces. The production of nitrates within the nitrification process was measured in Water Systems A and B along with changes to lead and copper release in both dissolved and particulate forms. Study Water Systems A and B sparklines in Appendix A to see the trends.

Some microorganisms produce acetate (a form of dissolved organic carbon) which can also form soluble lead and copper compounds. This project's data showed a role that dissolved organic carbon played in the nitrification process. Water Systems A and B showed a peak of dissolved organic carbon occurring a few weeks after a peak of ammonia. Dissolved lead appeared to increase during the ammonia and carbon peaks. Dissolved copper began to increase as the dissolved lead and organic carbon diminished. As stated previously, in Water System B, an independent study of biostability was performed. It was found that the water has a tendency to form biofilms with microorganisms identified that produce nitrates and acetates (organic carbon). This matched the patterns measured at the PRS Monitoring Station where nitrate and organic carbon concentrations were related to dissolved lead and copper release.

It is also known that there are iron-oxidizing bacteria that use electrons from iron and other metals as their food source (Rittman and McCarty 2001; Madigan and Martinko 2006), yet another pathway by which metal can be oxidized by microorganisms in a water system. This was not observed in the PRS Monitoring Stations, but Water System F joined the project because of an epidemic of pinhole leaks in copper pipes. The initial investigation of the system and its remediation outside of this monitoring project studied microbiological populations and concentrations of nutrients in the water. Well and water main rehabilitation produced water that was improved in biostability. Pinhole leaks are no longer an issue in the water system. Pinholes created by microbiologically influenced corrosion are the result of bacteria utilizing electrons from adjacent metal for their metabolic pathways.

It can be theorized that these or other similar pathways are occurring in the presence of growing populations of microorganisms as found in the test chambers, especially when lead and copper release has been seen trending with microbiological nutrients, wastes, and populations.

From the above list of possible microbiological pathways that can affect metals corrosion, it can also be theorized that microbiological life cycles can produce both particulate metals and dissolved metals. Particulate metals can occur when electrons are utilized by microorganisms directly from metals, as described for iron-oxidizing bacteria, and oxidized metals in the form of solids are produced. Particulate metals can also result if biofilms experience a die-off in a changing water environment. With biofilms intertwined with chemical scales as observed on the metal plates, chemical scales can be broken up or metals adsorbed to biofilm material can be released to the water.

Dissolved metals can occur when acidic waste products are released into the water, lowering the general water pH. They can also occur when waste products, such as nitrates or acetates can form soluble compounds with lead or copper and can contribute to the uniform corrosion electrochemistry or re-solubilize lead and copper from previously formed uniform corrosion by-products.

Both dissolved and particulate lead and copper release were observed in this project in relation to microbiological populations and nutrients. Refer to Tables 6.11 and 6.12 and Appendix A.

The concept of biostability also leads to the realization that microbiologically influenced corrosion is systemic in a distribution system. A colony of microorganisms in a biofilm may be localized but microbiological nutrients, microbiological waste products, and microorganisms themselves can be measured throughout a distribution system. For example, from Chapter 9, it is seen that the biostability parameters of ammonia, nitrite/nitrate, dissolved organic carbon, microbiological population, and disinfection concentration were measured at a high water age location of the water systems. In this way, the potential for microbiological life cycles with resultant metals corrosion pervades a distribution system.

CHEMICAL SCALE FORMATION AND DISSOLUTION

A variety of metals were tracked along with lead and copper release. Particulate metals often appeared together in the system water as did dissolved metals. Particulate metals often released together in the stagnating water of the test chambers as did dissolved metals. Lead and copper followed the trends of other metals. In this project, it was difficult to discern if metals in the system water influent to the test chambers caused the release of lead and copper in the test chambers or if lead and copper release was a response to other conditions that caused the other metals to release as well. Nevertheless, Tables 6.11 and 6.12 and Appendix A show that particulate lead and copper release was typically accompanied by the presence of particulate iron, manganese, and/or aluminum.

In addition, various metals were intertwined in the scales on the surfaces of the test chamber metal plates (Tables 10.19 and 10.20). This implies that one cannot assume that carbonate or orthophosphate scale protective against corrosion will be deposited uniformly on metal surfaces. Instead, it can be assumed that such scales will be deposited on and within complex pipe wall accumulations.

DIFFERENTIATION OF TOTAL LEAD AND COPPER INTO DISSOLVED AND PARTICULATE FORMS

Besides observations in the three general categories of factors that can affect lead and copper release, several additional aspects of lead and copper release in a water distribution system were demonstrated by this study. First of all, lead and copper must be studied by differentiating dissolved lead and copper from particulate lead and copper. Each form of the metals is influenced by different factors and can only be controlled by knowing those factors. Refer to Tables 6.11 and 6.12 to view the various factors that co-trended with each form of lead and copper.

DEVELOPMENT OF HYPOTHESES AND CONCLUSIONS FROM WATER QUALITY MONITORING DATA

One must be very careful in drawing conclusions regarding cause and effect. The Spearman rank correlations and sparkline time series graphs used in this study only show that two parameters are trending together or trending in opposite directions. No causality should be assumed but only used in hypotheses for further empirical testing. Predictions of future water system behavior based on the hypotheses must match measured observations of outcomes, otherwise theories must be changed. This is empirical science; it is a common industrial process control technique (Wheeler and Chambers 1992).

One must also be careful in interpreting the reason that a water quality parameter might be influencing lead and copper release. There are many water quality parameters that can play a role in more than one category of lead and copper release factors. ORP, total phosphorus, pH, nitrate, and alkalinity, for example, can all be involved in purely chemical interactions or can be involved in microbiological mechanisms. For example, dissolved copper trended inversely with pH in Water System A. This could mean that a higher pH suppressed copper release as theorized in the carbonate solubility model in a chemical role. But, pH change was found to be occurring in context of a microbiological nitrification process. Dissolved lead increased in concentration during the same time. It was more likely that dissolved copper release and dissolved lead release were influenced by multiple nitrification factors and not solely a function of pH as idealized in the carbonate solubility model.

In addition, a water quality parameter might be the outcome of a water system operational change. For example, in Water System D, dissolved lead trended inversely with alkalinity. However, alkalinity was representative of which water source was entering the PRS Monitoring Station. One water source had high dissolved organic carbon and high polyphosphate concentrations while the alternate source had higher alkalinity but lower dissolved organic carbon and polyphosphate concentrations. Direct trends between dissolved lead and dissolved organic carbon and polyphosphate concentrations were seen. It cannot be said necessarily that it was the high alkalinity that caused the lower dissolved lead release.

On a final note, deceptive relationships can be uncovered in correlating water quality parameters. In Water System A, alum dosing, used as a coagulant in source water treatment, expressed itself as an increase in sulfate concentration in the distribution system water. But, instead of dissolved lead, it was particulate lead release that trended with the Larson-Skold Index, a sulfate and chloride-based index. This was unexpected and theoretically occurred because increased turbidity and particulate iron concentrations trended with increased particulate lead release at the same time. The trend between particulate lead release and turbidity/particulate iron follow the current understanding that particulate iron and other particulate metals represented by turbidity can adsorb and transport lead. See Figure 13.2 for a schematic of the events described in this example. In another case, water softening added chloride to the water. Dissolved lead release trended oppositely to the Larson-Skold Index instead of with the Index as was expected. It appeared that newly installed clean water softeners were acting as a barrier to system water contaminants, especially regarding factors that lower the biostability of the water, resulting in decreased dissolved lead release. See Figure 13.3 for a schematic of events in that water system. In both of these cases, the lead release appears to have been influenced by other factors and not necessarily the chloride and sulfate concentrations or the Larson-Skold Index.

These examples show that care must be taken in formulating conclusions merely from common assumptions regarding the role of specific water quality parameters.

REGULATORY COMPLIANCE DILEMMAS

Another aspect demonstrated by this project was that Lead and Copper Rule compliance does not necessarily represent a water system free of significant lead and copper release. Residential profile sampling in Chapter 3 showed the possibility of higher lead and copper levels after the first one liter sample even in water systems dosing orthophosphate. Water Systems E, F, G, H, and C demonstrated the potential for discrete random metals releases which may or may not be captured in the Lead and Copper Rule compliance sampling. Water System F had never been out of compliance with the Lead and Copper Rule and yet experienced a system-wide epidemic of pinhole leaks in copper pipes with the potential for high particulate lead and copper release. Water System G had experienced a great number of customer complaints of discolored water over the years but would not have been out of compliance with the Lead and Copper Rule for lead if it were not for erroneously including three non-representative sampling sites in the compliance sampling pool.

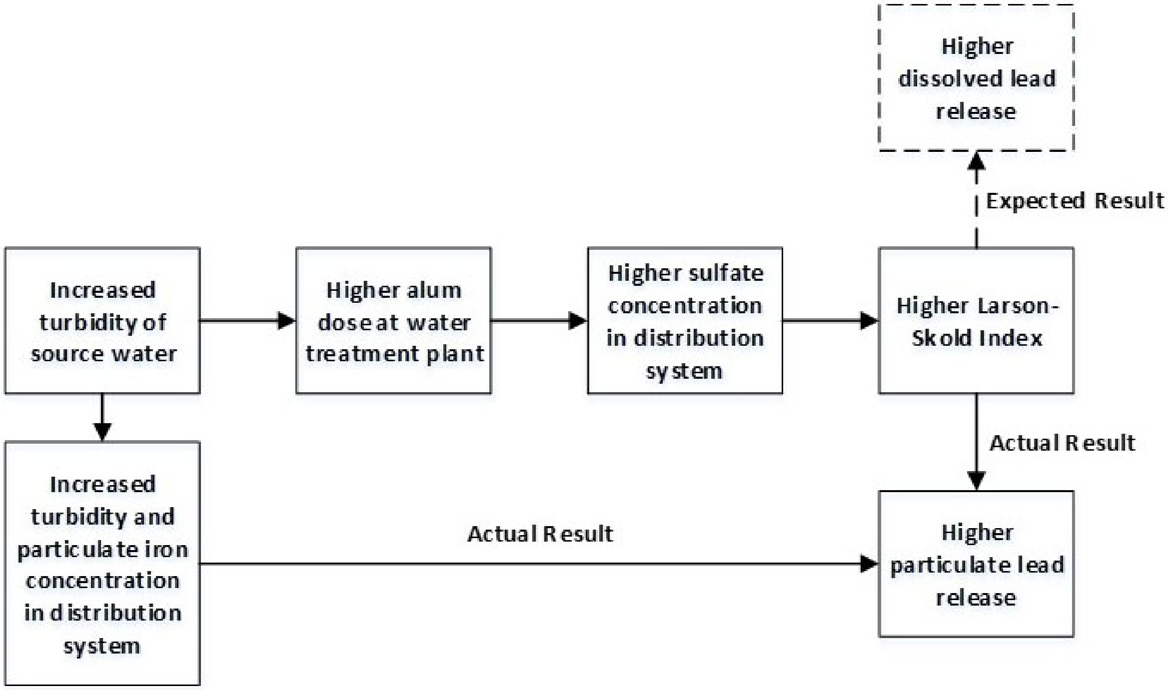


Figure 13.2 Water System A events involving sulfate and the Larson-Skold Index

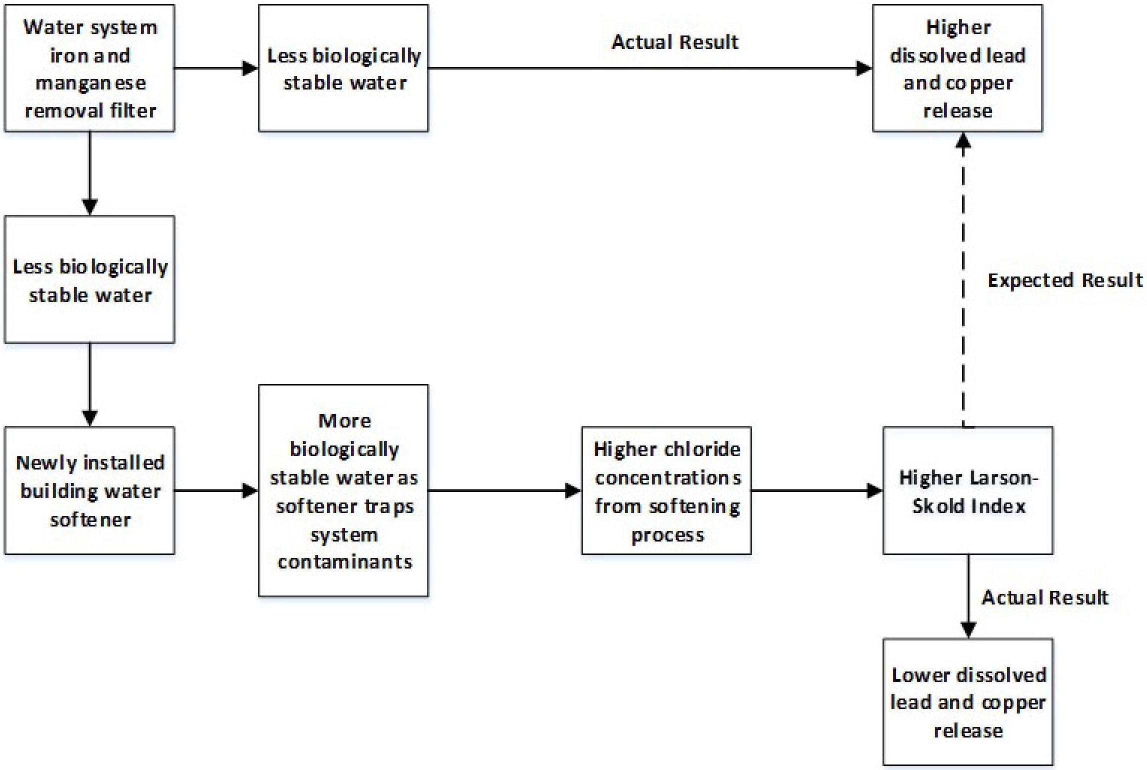


Figure 13.3 Water System E events involving chloride and the Larson-Skold Index

SURROGATE MONITORING FOR LEAD AND COPPER RELEASE

The monitoring data in this project identified three field tests that were good surrogates for tracking the potential for lead and copper release in a water system. However, they are not excellent surrogates because the lower precision of the field tests may have rendered the data less sensitive to correlation with other water quality parameters. In general, it can be said that oxidation/reduction potential (ORP) increases as disinfection concentration, an oxidant, is increased. Increased disinfection concentration has the potential to limit microbial growth and often is seen trending oppositely to microbial growth in the monitoring data. Therefore, ORP and disinfection concentration as monitored parameters can indicate the ability to control the growth of microorganisms and to prevent biofilm formation in a water system, thereby lowering the potential for corrosion of metals through microbiological life cycle pathways.

In the water quality parameter correlation study, turbidity was sometimes representative of particulate metals in the water, sometimes representative of microorganisms in the water, and sometimes not correlative to other water quality parameters at all. Turbidity cannot be claimed to definitively represent particulate lead, particulate copper, or microbiological population. Perhaps the common light scattering analysis of turbidity is not sensitive enough to make these correlations. Investigation of newer turbidity technology techniques, such as laser techniques, as a more sensitive water quality indicator should be performed.

However, if turbidity is high, it is by definition a measure of particulate matter in the water. The particulate matter can either come from source water particulates or pipe wall accumulations. It is reasonable to assume that turbidity represents:

- Possible entrainment of lead and copper-adsorbing metal particulates (iron, manganese, and aluminum)
- Possible entrainment of lead and copper particulates
- Possible entrainment of microbiological materials – microorganisms and biofilm materials

In Chapter 4 and Chapter 11, it was demonstrated how graphs of disinfection concentration and turbidity over time at routinely-visited monitoring sites, such as the Total Coliform Rule distribution system compliance sampling sites, can pinpoint locations and time periods with potentially degraded water quality, that is, lower disinfection concentrations and higher turbidities, than other sites and time periods. This can lead to an assessment of specific operational events in order to improve those water quality parameters and lower the potential for water quality issues. In this project, graphs of disinfection concentration and of turbidity displayed patterns of nitrification in two chloraminated systems, Water Systems A and I. They also showed results of high velocity flushing of water mains in Water System B. Therefore, these indicators of water system cleanliness and biostability – disinfection concentration, ORP, and turbidity – can be an economical means of tracking the water quality status in a water system, including the possible release of lead and copper.

THE EFFECTS OF DISTRIBUTION SYSTEM CLEANING

This study occurred over cleaning and rehabilitation activities carried out by many of the water systems. The timing of rehabilitation efforts and installation of the monitoring station did not always coordinate. In addition, some plans for cleaning efforts could not be carried out. Project schedules and budgets ended before efforts were completed. Nevertheless, each water system experienced its own insights and successes. These are summarized in Table 11.20. In general, removal of chemical scales and biofilms from pipe walls and efforts to improve the biostability of the water resulted in lowered lead and copper releases as seen in PRS Monitoring Station test chamber data and Lead and Copper Rule compliance sampling data. Several of the water systems had not completed all of the initial efforts required to bring the system into overall control but were heading in that direction. After legacy scales and biofilms can be cleaned from a water system, routine maintenance for cleaning and biostability is required. This is “water system hygiene” that must be a continuing part of water system operations.

All water systems were in compliance with the Lead and Copper Rule by the end of the monitoring phase of this project with two exceptions. Water System B lead and Water System D copper 90th percentile concentrations were just above the Action Levels but predicted to move below the Action Level by the next sampling round after additional efforts. Water System B did subsequently achieve Lead and Copper Rule compliance with a 90th percentile lead concentration of 12 µg/L. Water System D was in the process of lowering the polyphosphate levels and continuing to clean water mains and maintain organic carbon removal at the new treatment plant in order to further lower copper levels. Water System D achieved Lead and Copper Rule compliance for copper in October 2017. With all the participating water systems continuing the water system hygiene activities as part of routine operations, improvements to lower lead and copper release continue in those systems.

PRS Monitoring Station test chamber data continued to show spikes of particulate lead or copper release even at the end of this monitoring project, but were typically reduced in magnitude and/or occurrence. One must keep in mind that the test chambers did not undergo the scouring that the system piping did. This was intentional because it was desired to eventually study scale composition on the test chamber metal plate surfaces. The slower damping out of particulate metal releases in the test chamber versus the actual pipes was expected.

Each water system defined lead and copper release trends and associated those trends with other water quality parameters and system operations as working theories of metals release. Focus on these trends is now ongoing in daily operations and not only being addressed every three years as is done with Lead and Copper Rule compliance.

Each water system is now focused on small changes in lead and copper release and routinely working on improvements instead of being triggered by the Action Levels of the Lead and Copper Rule in order to make improvements.

As each water system makes improvements for lowering lead and copper release, they also lower their potential for other water quality issues such as Total Coliform Rule and Disinfection By-Products Rule compliance as well as secondary water quality standards such as iron and manganese release by removing materials from the water systems associated with these regulatory compliance issues.

THE ROLE OF ORTHOPHOSPHATE IN CORROSION CONTROL OF METALS

The theory behind orthophosphate's effectiveness at corrosion control is based on its ability to inhibit the release of dissolved lead from piping material. But, what effect does the orthophosphate have on suppressing release of lead particulates from existing pipe wall scales? What effect does orthophosphate have on suppressing release of dissolved lead in the presence of high chloride, nitrate, or acetate concentrations? What effect does orthophosphate have on the same aspects with copper piping and copper release? These questions have not been definitively answered in this study. However, with the monitoring data from this study, these various factors are now called into question and suspected of interfering with the idealized function of orthophosphate in inhibiting uniform corrosion of metal.

With this study of the effect of orthophosphate on controlling lead and copper release in actual water systems, there was no clear picture that the chemical renders a water system safe from lead release to consumers. Both Water System A and Water System I, using the relatively higher doses of orthophosphate in comparison to the other systems, had residences with lead levels above the 15 µg/L Action Level of the Lead and Copper Rule found during profile sampling. In Water System A, the higher lead reaching the consumer's tap was in particulate form and not the dissolved form that orthophosphate has been found to address. However, it cannot be known in this study if orthophosphate dampened the release of particulate lead or not.

There were also no common trends that tied orthophosphate dosage to the lowering of lead or copper release in the five phosphate-dosing water systems that also operated a distribution system monitoring station.

With the higher dosing water systems that also operated a distribution system monitoring station (Water Systems A, D, and H), lead and copper release differed greatly in average concentration and in variation of concentrations. Water System A had the lowest lead and copper release of the three water systems. It was the one system that had a very low polyphosphate concentration in its corrosion control product. However, there were other differences as well that confound the ability to draw conclusions: Water System A is a surface water system using chloramine disinfection with one distribution system entry point delivering water undergoing a constant treatment process where water characteristics are able to be kept within a narrow range. Water Systems D and H, using a higher concentration of polyphosphate, are groundwater systems using chlorine disinfection with multiple distribution system entry points delivering water with characteristics more variable as delivered by a well at any point in time. With all these factors, it cannot be claimed that orthophosphate was definitively responsible for the lower lead and copper release in Water System A.

The study of the scales formed on monitoring station test chamber metal plates brought up other questions about the effectiveness of phosphate-dosing. Plates from four of the water systems that used a phosphate-based corrosion control chemical were studied. Water System A exhibited the formation of the desired protective lead phosphate compound as the most prominent peak in the x-ray diffraction analysis (Table 8.6). Nevertheless, the water had the propensity to release the same quantity of particulate lead as it did dissolved lead, where dissolved lead is controlled by orthophosphate. Water System C had a presence of the desired protective lead phosphate compound at one-third the most dominant x-ray diffraction peak. However, the focus of Water System C's propensity to release lead was on the high particulate release of lead and not its low dissolved lead release. Water Systems D and H showed no presence of the desired protective lead phosphate in their metal plate scales.

Besides looking for phosphate minerals on the plates, the element, phosphorus, was measured. Phosphorus was found at almost 10% by weight in Water System A's lead scales and almost 5% by weight in the copper scales. In Water System C, the phosphorus was found at almost 1% but not found in the copper scales. A significant presence of phosphorus was found in Water System D's lead and copper scales but was found to be bound into an amorphous carbon and iron-laden mass. No significant phosphorus was found on the lead and copper scales of Water System H.

In addition, all scales that were studied showed that other metals, such as iron, manganese, and aluminum, can be a significant presence in the scales as well.

These observations lead to the theory that orthophosphate is not necessarily able to form a uniform barrier over lead or copper surfaces in mature water systems. Instead, it is woven into a web of scales with many other metals and biofilms and many times is not adequately present even when regulatory-approved corrosion control dosing is occurring.

This does not mean that orthophosphate is not a viable tool for corrosion control. It should always be considered in the comprehensive approach to corrosion control but placed within proper context. It should never be assumed that its use is applicable to all water systems. It should never be assumed that its use provides a guaranteed protection from exposure to lead or copper for consumers.

POLYPHOSPHATE VERSUS ORTHOPHOSPHATE

As described in Chapter 1, drinking water systems have a long history of phosphate-based chemical usage. The original products were polyphosphates known for their ability to hold (sequester) metals in water. They were used for pulling solid calcium, iron, and manganese accumulations from well components, water filters, water main walls, and plumbing fixtures and holding them in the water to be flushed out of the water system or consumed.

In addition, some polyphosphate applications were for iron and, later, lead corrosion control. Early on, it was not realized that polyphosphate could break into orthophosphate ions. It was not realized that orthophosphate ions could form insoluble compounds with metals that would possibly create corrosion-inhibiting barriers on metal surfaces. Instead, it was thought that polyphosphate molecules could provide corrosion inhibition itself. Confusion arose as some testing scenarios with polyphosphate successfully lowered metals concentrations in water and other scenarios increased the metals concentrations, most likely dependent on the degree of polyphosphate reversion to orthophosphate. Refer to Chapter 1.

The confusion continues to current times even after reports of the inadequacy of polyphosphate to inhibit corrosion and why (Holm and Schock 1991; AwwaRF and DVGW 1996; Cantor et al. 2000; EPA 2016a). These reports also warn of the possibility of polyphosphates increasing lead and copper concentrations in the water, pulling lead and copper compounds into the water and holding them there just like calcium, iron, and manganese compounds. Many water systems continue to use a polyphosphate/orthophosphate blended product as a corrosion control agent. In this project, polyphosphate fractions ranged from 10 to 100% (Table 8.1). For Water Systems C, D, and G in this project, total phosphorus trended with dissolved lead and copper release. These data may reflect a relationship between polyphosphate's sequestering abilities, or it may be related to sloughing of phosphorus-laden chemical scales or biofilm material from pipe walls.

As another consideration, when polyphosphates are incorporated in corrosion control chemicals, the orthophosphate concentration is a fraction of the total phosphorus concentration. The orthophosphate fraction may be providing metals corrosion control. The polyphosphate fraction may be inert or may be holding metals in solution, but it is not providing metals corrosion control. This means that the polyphosphate has increased the total phosphorus loading to the wastewater treatment facility and the environment without providing the drinking water system the benefit of lead or copper corrosion control. Refer to Chapter 12.

THE ENVIRONMENTAL IMPACT OF PHOSPHATE CHEMICALS

Details of the effect of total phosphorus on wastewater treatment facilities and the environment were explored in Chapter 12. This exercise of calculating the impact of phosphate-based corrosion control chemicals on associated wastewater treatment plants emphasized that lead and copper corrosion control strategies have impacts outside of the water system itself.

The impact that drinking water phosphate addition has on associated wastewater treatment facilities varies with many factors – the drinking water pumpage versus the wastewater influent flow, the efficiency of the wastewater treatment facility's phosphorus removal, and the stringency of the phosphate discharge limit.

A cost analysis should include more than the additional chemical costs needed to remove additional phosphorus from wastewater as was performed in Chapter 12. More detailed costs of phosphorus removal can be calculated at the individual wastewater treatment facility to include increased tank volume installation costs, both for wastewater treatment tanks and sludge handling tanks, and additional annual costs of labor, energy, chemical usage, sludge storage, sludge processing, and sludge disposal. The costs could be studied over a set time period such as 30 years and a proper engineering economics calculation performed to establish a present worth cost of phosphorus removal to current and future limits. This present worth can be weighed against the present worth of lead and copper control strategies in the drinking water system.

As mentioned previously, it should be noted that using a phosphate-based corrosion control product with polyphosphate in it, increases the phosphorus loading to the wastewater treatment facility above the loading required to satisfy drinking water regulations.

In addition to tangible costs, the impact of the additional phosphorus discharged to the environment can be assessed for an individual location. Typically, it is difficult to find appropriate indices of environmental and community impacts. In this case, the state regulatory agencies have already established such an index. That is, the phosphorus discharge limit set by state regulatory agency for the natural body of water that receives the wastewater, the landscaping run-off, and the industrial non-contact cooling water is a statement of environmental and community impacts; it is based on the sensitivity of the body of water to additional phosphorus and the intended community use of the water.

COMPARISON BETWEEN THE LEAD AND COPPER RULE PERSPECTIVE AND THE COMPREHENSIVE PERSPECTIVE OF LEAD AND COPPER CORROSION CONTROL

The Lead and Copper Rule focuses on pH/alkalinity adjustment and orthophosphate addition for control of lead and copper corrosion. According to the current EPA guidance manual (EPA 2016a) for lead and copper control, Water Systems A, B, and C should raise the pH or add orthophosphate for corrosion control. But, even Water System A with a seemingly appropriate dose of orthophosphate could not prevent particulate lead from reaching consumers. Raising the pH of the water for Water System A, would aid the effectiveness of the chloramine disinfection (Connell 1996) but possibly take the water system out of the most effective range for orthophosphate addition. In addition, an increase in pH in Water Systems B and C could render free chlorine disinfection less effective (Connell 1996). Both systems may have been experiencing some forms of microbiologically influenced corrosion and raising the pH would not be helpful in fighting microbiological growth.

For the groundwater systems in this study, the EPA guidance advises them to add blended phosphates or remove iron and manganese and add orthophosphate. This would ignore the issue of microbiologically influenced corrosion that actually occurred in the wells of the water systems of this project and was attributed to the production of iron and manganese. In addition, the water systems except for E and F had been adding blended phosphates and problems were increasing. Water System G specifically increased the blended phosphate dosing several times in order to comply with the Lead and Copper Rule to no avail because the issues in the wells were overlooked. Water Systems C, D, and G were found to have increasing dissolved lead and copper release with increasing phosphorus possibly because of the polyphosphate fraction in the corrosion control products.

This project has used a more comprehensive strategy than the idealized perspective upon which the Lead and Copper Rule is based to understand the nuances of individual water systems. The comprehensive perspective describes water entering distribution system piping as a very complex solution of naturally-occurring chemicals and microorganisms as well as added treatment chemicals. Drinking water comes to the system from nature where it has been in contact with soil, rocks, and air. Chemicals from those media dissolve into the water or become entrained as particulate matter. Microorganisms, which are everywhere in our environment, are also transferred to the water along with nutrients for their growth. Water treatment, when performed, does not necessarily remove all of the chemical and microbiological components in the water and additional chemicals may also be added for treatment.

When inside of distribution system piping – not only the water mains, but also the service lines and the premise plumbing – water is subjected to even more complexity. There are various accumulations of chemical scales and biofilms that have built up over years with which the water comes in contact. Coming out of the piping is drinking water that has been transformed by its interaction with the pipe wall debris. This is the process by which distribution system water quality is shaped. See Figure 13.4.

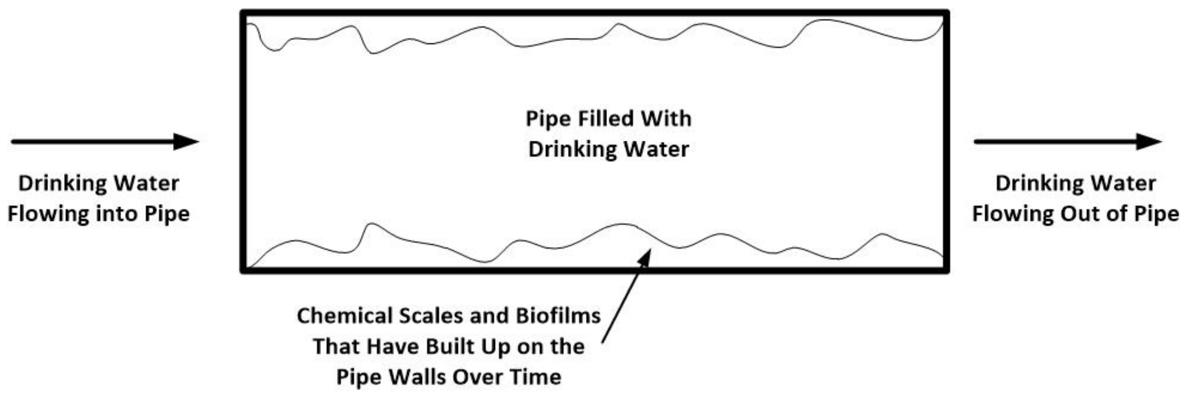
Figure 13.5 shows the many combinations of interactions that can occur inside the piping – chemistry in water, microbiology in water, chemistry in pipe wall accumulations, microbiology in pipe wall accumulations, chemistry between the water and the pipe wall accumulations, microbiological interactions between water and pipe wall accumulations, chemical and microbiological interactions in water, chemical and microbiological interactions in pipe wall accumulations, chemical and microbiological interactions between water and pipe wall accumulations. Physical disturbances in the system, such as water velocity, pressure gradients, and vibrations can also add to this complexity. The point is that there are no scientific formulae that can describe this complexity; the final water quality cannot be predicted.

The final water quality can include quite a number of disagreeable and harmful qualities, some of which are addressed by primary and secondary drinking water regulations – discolored water, water with odor, release of lead or copper, release of iron or manganese or other metals, presence of pathogenic microorganisms (*E. coli, Legionella*), formation of disinfection by-products – and some which are not addressed, such as excessive growth of non-pathogenic microorganisms. Refer to Figure 13.4.

The point of this comprehensive perspective is that all of the water quality outcomes – both good and bad – are all related. They are manifestations of the same phenomena, the interactions of the complex solution of water coming in contact with the complex pipe wall accumulations of chemical scales and biofilms.

In the comprehensive perspective, the remedy for bad water quality, including lead and copper release, is to physically remove the pipe wall accumulations as would be practicable. In addition, the water must be controlled to prevent excessive growth of all microorganisms (not just pathogenic ones) and their biofilm formation. That is, the water must be made "biologically stable."

The drinking water regulations for distribution system water quality issues treat each issue separately. For the Lead and Copper Rule, the water solution entering the pipe is a solution of carbonate ions (Figure 13.6). The pipe wall accumulations are hypothesized as only containing carbonates of lead or copper – no other chemicals or microorganisms. The quantity of lead or copper dissolved in the water is dependent on the solubility of the lead or copper carbonate compounds formed. The more soluble the compound, the more lead or copper is dissolved in the water. From the regulatory perspective, lead and copper control is a matter of finessing the pH and/or alkalinity of the water to produce a more insoluble compound of lead and copper carbonates. Alternatively, orthophosphate can be added to form highly insoluble compounds of lead and copper phosphates. Substitute the word, orthophosphate in Figure 13.6 for the word, carbonate.



Pipe influent drinking water composition:
    compounds of organic carbon, nitrogen, phosphorus, carbonate, hydroxide, hydrogen, oxygen, carbon dioxide, sulfate, chloride, iron, manganese, and many other metals and microorganisms, etc.

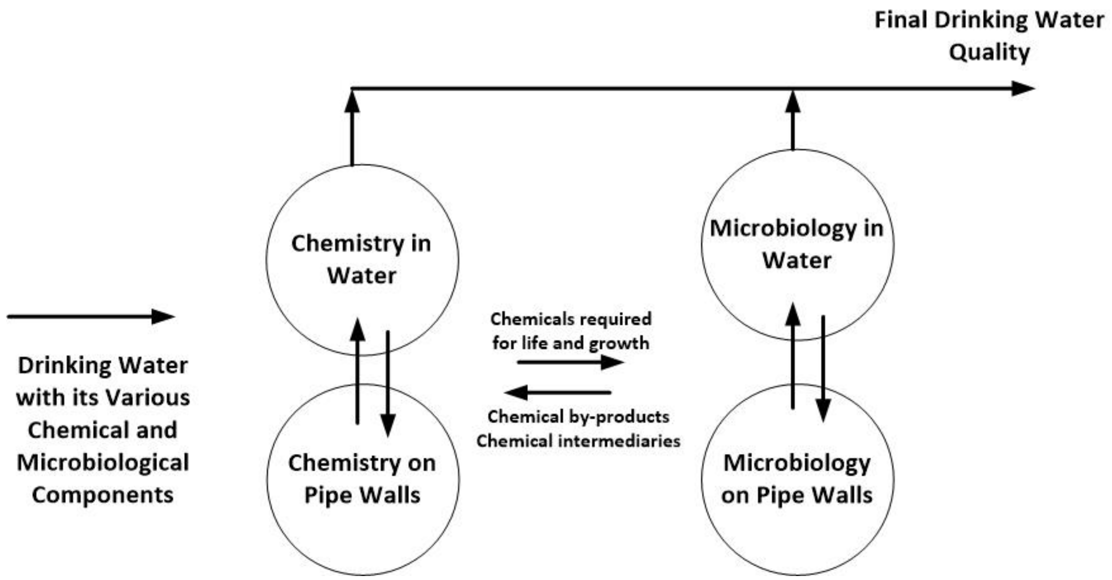
Water inside pipe: See Figure 13.5

Pipe wall accumulations:
    chemical scales of a variety of solids (including carbonates, oxides, iron, manganese, aluminum, phosphorus, sulfur) and biofilms

Pipe discharge possible drinking water quality characteristics:
    lead, copper, iron, and other metal release in both dissolved and particulate form; discolored water; water with odor; presence of pathogenic microorganisms like E. Coli and Legionella; excessive growth of non-pathogenic microorganisms; formation of disinfection by-products, etc.

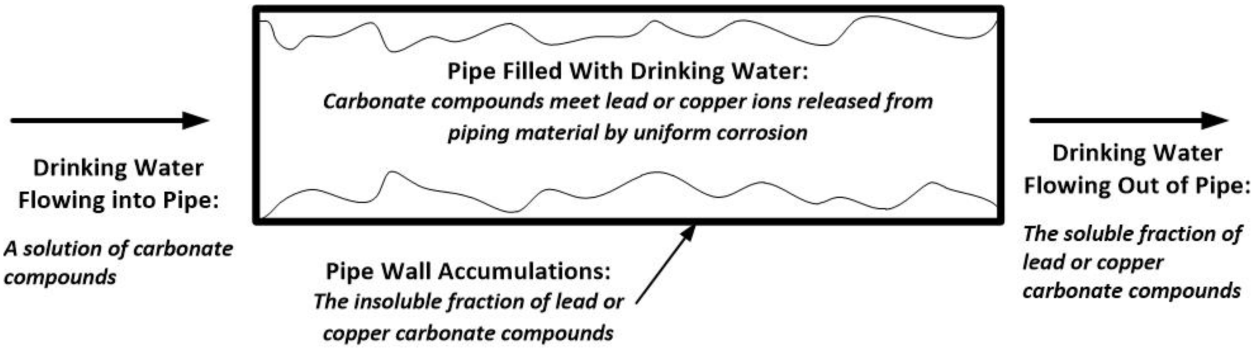
Source: Courtesy of Process Research Solutions, LLC of Madison, WI.

Figure 13.4 The comprehensive perspective of lead and copper release and overall distribution system water quality



Source: Courtesy of Process Research Solutions, LLC of Madison, WI.

Figure 13.5 The complexity of the water and pipe wall accumulation interactions



Compare this figure to Figure 13.4.

Source: Courtesy of Process Research Solutions, LLC of Madison, WI.

Figure 13.6 The regulatory perspective of lead and copper release

The comprehensive perspective was developed over many years of experience in investigating water distribution systems. Just after the Lead and Copper Rule was passed, conflicts arose between aspects of the Rule with observations and data gathered from actual water systems (Verburg 2016; Cantor et al. 2000). Issues regarding the transport of lead by existing pipe wall scale arose in investigations after that (Cantor 2006; Schock et al. 2014). Then came investigations that glimpsed into the reality of microbiological participation in shaping the distribution system water quality (Cantor et al. 2003b; Cantor et al. 2006). These experiences led to the development of tools to study a comprehensive list of water quality parameters, to obtain information from the distribution system in a consistent and comparable way, and to understand what the data were implying (Cantor et al. 2000; Cantor et al. 2003a; Cantor 2008; Cantor 2009; Cantor and Cantor 2009; Cantor 2010; Cantor 2011; Cantor et al. 2012). The tools enabled the gathering of more data where more nuances of distribution system water quality could be uncovered. In 2014, a presentation (Cantor 2014) comparing actual distribution system data to Lead and Copper Rule predictions of lead and copper release summarized these experiences.

There is confirmation of many aspects of the comprehensive perspective in the literature. The Lead and Copper Rule and its uniform corrosion model only include dissolved lead and copper release and not particulate lead and copper. But, chemical scales have been acknowledged as a complexity that shapes lead and copper release in the distribution system (Schock et al. 2014; EPA 2016a). Chemical scales, such as iron, manganese, and aluminum, can adsorb lead and copper, accumulate them, and release them as significant particulate concentrations when the coarse scales crumble. Existing chemical scales also can prevent the lead or copper carbonate, oxide, or phosphate solids from forming a uniform, non-porous barrier on pipe walls (DeSantis and Schock 2014). Nevertheless, the finessing of pH and alkalinity or the addition of orthophosphate continues to be the first step as Lead and Copper Rule guidance (EPA 2016a), ignoring the acknowledged interference of chemical scales.

Oxides of lead have been acknowledged and the presence of a more insoluble form of lead oxide has been acknowledged as contributing to lead control in water systems (Lytle and Schock 2005). Chlorides and sulfates have been acknowledged as creating more soluble lead and copper compounds, helping to perpetuate the corrosion of the pipe walls (Larson and Skold 1958; Nguyen et al. 2010; Nguyen et al. 2011).

The role of microorganisms in shaping the water quality continues to be a topic of misunderstanding. The viewpoint of many drinking water researchers and practitioners appears to assume that corrosion occurs first as caused solely by chemical factors and this creates debris where the microorganisms take up residence. This is exemplified in a study of biostability where corrosion rate was studied as a factor contributing to the formation of biofilms instead of formation of biofilms contributing to the corrosion rate; causality was not proven, it was assumed (LeChevallier et al. 2015). In an article on iron pipe corrosion, "a diverse microbiological community (sic) can be found in the scale" is stated (Burlingame et al. 2006). The article describes the complete corrosion process as chemical only with the corrosion debris merely providing a structure to which microorganisms attach. Both of these articles imply an assumption that microorganisms have no role in the corrosion process. Practitioners in other fields have a broader understanding of microbiologically influenced corrosion and the complex ways that a "consortia" of microorganisms in biofilms can interact (Peabody 2001).

Other common misunderstandings about microbiologically influenced corrosion have been addressed in the "Biostability" section of this chapter. In summary, this project has demonstrated that:

- Microbiologically influenced corrosion is the outcome of many pathways of microbiological life cycles including formation of acidic biofilms, production of acidic waste products, production of waste products that form highly soluble compounds with existing lead and copper compounds on pipe walls, and use of electrons from metals as a food source by metals-oxidizing bacteria.
- Microbiologically influenced corrosion is a systemic issue in a water system and not necessarily a localized issue because microbiological nutrients, waste products, and microorganisms themselves can be measured throughout a water system.
- Microbiologically influenced corrosion can produce both particulate and dissolved lead and copper release because of the various life cycle pathways that can either release insoluble oxidized metals or can re-solubilize existing solid metal compounds.

ORTHOPHOSPHATE ADDITION OR PH ADJUSTMENT VERSUS WATER SYSTEM HYGIENE

Orthophosphate addition and pH/alkalinity adjustment as dictated by the Lead and Copper Rule are relatively straightforward to install and operate. Water system hygiene – cleaning of infrastructure and achieving biostability of water – as a means of lead and copper corrosion control is an involved process. This section considers if this more complicated route should be taken.

First, this study demonstrated that orthophosphate and pH/alkalinity adjustment are not necessarily providing the protection that is assumed. This has been summarized previously in this chapter.

But, there appears to be many successful applications of pH/alkalinity adjustment and of orthophosphate dosing in lowering lead and copper concentrations in water systems around the United States. This could be for any of several reasons, as demonstrated in this project:

- The pH/alkalinity adjustment or orthophosphate dosing is effective in specific water systems.
- Or, the influencing water quality parameters can play a role in both chemical and microbiological interactions and the true reason that adjustment of the specific water

quality parameters is effective for lowering lead and copper release has not been identified.

- Or, other water system operations, such as carrying out a high velocity flushing program or reduction in system residence time or better elimination of nutrients or filter cleaning, are occurring simultaneously to the presumed corrosion control strategy and are actually the real influencing factors on corrosion control.
- Or, follow up sampling of the outcome of the corrosion control strategy is inadequate and not representative of the actual effectiveness.

In summary, it is difficult to uncover the true influencing factors on lead and copper release. A comprehensive list of water quality parameters must be tracked and they must cover at least the three general categories of metals corrosion influencing factors: uniform corrosion by several types of chemistries, biostability of water, and formation and dissolution of chemical scales. It is an ongoing empirical process of testing hypotheses to determine lead and copper release controlling factors. If there has not been a comprehensive approach performed, there is no proof that the pH/alkalinity adjustment or orthophosphate dosing is the actual controlling factor. The other factors and inter-relationships have not been ruled out. Refer to the section, "Development of Hypotheses and Conclusions from Water Quality Monitoring Data," in this chapter for examples of how assumptions of cause and effect might not be justified.

There is concern that the time it takes to clean a water system and achieve biologically stable water is too long a time for consumers to wait for protection from lead and copper release. However, this project demonstrated that maximum concentrations of lead and copper and the frequency of release can be controlled at least over one cleaning season and even more progress can be made within the time frame that the Lead and Copper Rule lays out for the installation of corrosion control. The Lead and Copper Rule uses the time frame of five years, listed in Table 13.1, to move from a compliance exceedance to confirmed protection.

Table 13.1
Lead and Copper Rule time frame for compliance

Action	Time Frame in Months
A water system conducts regulatory Lead and Copper Rule monitoring and exceeds the Action Level for lead or copper	
Complete a corrosion control study	18
Regulators designate optimized corrosion control from study	6
Corrosion control technique is installed	24
Follow-up monitoring for two consecutive six-month periods	12
Total time to confirmation of protections against lead and copper release	60 months = 5 years

Water System K achieved compliance within one year of exceeding the lead action level by means of high velocity flushing, manganese control before the entry point, and actions toward biostability in maintenance of wells. It has been ten years and the water system has continually improved so that the 90th percentile concentration for lead is currently around 5 µg/L.

After two seasons of high velocity flushing, Water System B had greatly lower maximum lead concentrations and a 90th percentile concentration hovering around the Action Level but lower than before flushing as shown in Table 13.2.

Table 13.2
Water System B Lead and Copper Rule lead data in µg/L

Sampling Year – Period	90th Percentile Concentration	Maximum Concentration
2012-1	27	490
2016-1	15	53
2016-2	18	38
2017-1	12	41

Water System B also performed a biostability study and pinpointed the epicenter of the system's sudden change to bio-instability – the installation of a second large water transmission line that added days of residence time to the water. By the end of the fourth cleaning season since non-compliance, they will have progressed farther as can be seen in Table 13.2 for the sampling period, 2017-1. Water Systems D, E, F, G, and H, all have similar stories of progress made in one cleaning season and on their way to even lower lead and copper release.

The comprehensive approach of achieving a clean water system and biologically stable water is also a pro-active approach that can and should be instituted into water system routine operations even without a Lead and Copper Rule exceedance. It lowers the potential for any of the water distribution water quality issues to occur, not just lead and copper release.

This water system hygiene activity is an approach with which pH/alkalinity adjustment or orthophosphate addition can be performed simultaneously as a situation might require. In a water system practicing system hygiene, any intended passivating scale formation could more uniformly develop on metal surfaces and be more effective without the interference of the other scales and biofilms.

SUMMARY

This report challenged common understandings of lead and copper corrosion control. However, it does not advise discarding the traditional understandings and use of pH and alkalinity adjustments or orthophosphate dosing. Instead, these are to be used as tools in a much larger tool box. They must always be considered in a comprehensive approach to lead and copper control and water quality improvement.

These findings do suggest that one should not initially define a water system as corrosive to lead or copper based solely on pH and alkalinity. The carbonate solubility model cannot be used as an indicator of water corrosivity. This project has demonstrated that the idealized models for lead and copper release do not adequately represent the set of circumstances actually found in drinking water distribution systems. A water system must be evaluated comprehensively in order to theorize the most likely factors influencing dissolved lead, particulate lead, dissolved copper, and particulate copper release.

These findings also suggest that dosing of orthophosphate is not guaranteed to protect consumers from lead and copper release. Consumer protection can only be assessed with a comprehensive investigation as demonstrated in this study.

Water quality is shaped by the cleanliness of the water pipes and the biostability of the water in mature water systems. Water systems need to adopt a standard of practice of removing accumulations of chemical scales and biofilms from pipe walls routinely and a standard of practice of routinely tracking and improving the biostability of the water through water system components. The basis of water quality control, including lead and copper control, should be this new focus on water system hygiene.

CHAPTER 14
RECOMMENDATIONS

The Lead and Copper Rule is relatively straightforward to carry out. The comprehensive perspective of water quality is not. How can practitioners who have a multitude of water system operational demands and budget constraints control lead and copper release by applying the comprehensive perspective? The following is a list of recommendations:

ROUTINELY IMPROVE INFRASTRUCTURE

Recommendations listed here for infrastructure improvement are standard activities in drinking water systems. Historically, however, many of these activities have been relegated to the bottom of the annual budget because of other pressing needs. This report points out that it is the state of the infrastructure that is shaping the water quality in the system. Putting infrastructure improvement first can replace the need for corrosion control chemical addition and its perpetual annual costs and more comprehensively address the influencing factors on metals release in a water system.

Develop a Plan to Remove Lead and Galvanized Iron Service Lines

Discussion regarding a new version of the Lead and Copper Rule has emphasized removing lead from water systems, specifically the remaining lead service lines (EPA 2016b). This should be a top priority for water systems.

However, there are water systems out of compliance with the Lead and Copper Rule that do not have lead service lines. So, removal of lines is an important step but it should not exempt a water system from taking the other steps listed here.

In addition, galvanized iron piping has also been found to either aid in holding and transporting lead or in contributing lead to the water directly (McFadden et al. 2011). If service lines are made of galvanized iron pipe, they also should be removed.

Develop a Water Main Replacement Program

Some water mains have too large a quantity of accumulations to clean or are prone to breakage and should be replaced. Most water system operations include a list of water mains requiring replacement.

Develop and Carry out Routine Uni-Directional Flushing of Water Mains

High velocity flushing programs should be prepared, preferably using a hydraulic model of the water system. Flushing should be performed for each flushing run until the turbidity of the water is brought down to <1 NTU so that contaminants are less likely to remain entrained in the water when released from pipe wall accumulations. Turbidity before and after each flushing run should be recorded as well as recording the time to reach the final turbidity. Data such as these items aid in optimizing flushing efforts for the next flushing season.

Use Chemical Cleaning Aids, When Applicable, and Use Them Cautiously

Chemical cleaning aids, such as a biofilm-removing chemical like the Clearitas® product that was used in four water systems in this project, can be used in on-line continuous dosing but with caution in order to prevent too fast a release of existing pipe wall debris. Chemicals should be used initially at low doses to keep the release of pipe wall debris manageable. Frequent flushing of water system components should be performed along with the chemical addition. Monitoring of turbidity in the system being cleaned should be performed frequently to gauge the degree that pipe wall debris is released. The dosage can be increased slowly as long as there are no water quality disruptions from fast pipe wall release.

The cleaning chemicals help to soften pipe wall debris for faster removal. Typically, scouring is also required to completely remove pipe wall debris especially biofilms. Scouring can come from high-velocity turbulent water flow, from rough objects pushed through the pipeline (pigging), or from other methods of creating abrasive action along the pipe wall.

Clean Other Water System Components

Other water systems components, such as tanks, reservoirs, and filters, must also be cleaned at a routine interval, especially when biostability parameter monitoring indicates a cleaning is necessary. These components can typically be taken off-line and cleaned with high concentrations of cleaning chemicals, such as the Clearitas® product used in this project, and scouring.

ADOPT AN ONGOING BIOSTABILITY IMPROVEMENT PROGRAM

To achieve biostability in a water system, nutrients in the water (organic carbon, ammonia, nitrite/nitrate, total phosphorus) must be controlled, residence time of water in the system must be minimized, and disinfection must be adequately dosed into the water. Water system components – such as source water, wells, large transmission lines, water treatment filters, and storage tanks – can become incubators of microorganisms and producers of microbiological nutrients and waste products that subsequently can corrode metals throughout a water system. An understanding of how the microbiological world is intertwined with the chemical world must be adopted for water system operation.

Perform biostability tracking and improvement in source water, wells, filters, storage tanks, and critical distribution system sites as water quality parameters for lead and copper control. Parameters to evaluate are active disinfection, ammonia nitrogen, nitrite, nitrate, total phosphorus, and dissolved organic carbon concentrations. Additionally, the ATP analysis should be used routinely to track the microbiological populations. The ATP analysis measures all microorganisms present (except viruses) and gives a more comprehensive measurement than older tests, such as the heterotrophic plate count measuring only heterotrophic bacteria, did. The complete microbiological population, not just the pathogens, must be acknowledged as playing a role in shaping water quality.

Drinking water system standards of practice should include the understanding that microbiological populations in flowing and stagnating water should be under 500 microbial equivalents per milliliter. More importance should be placed on keeping dissolved organic carbon levels below 0.5 mg/L, a typical limit of detection in laboratories. Nitrification can occur in water systems, even those not adding chloramines, and should be controlled as was seen in Water System B. Other sources of nitrogen, organic carbon, and phosphorus compounds must be controlled.

Source water should be re-evaluated using the biostability parameters. More stringent treatment goals may be necessary in order to prevent biologically unstable water from entering a distribution system.

The biostability concept is especially important to monitor around water treatment filters. Filters host a high residence time for water to the advantage of microbiological growth. Filter media with its high surface area is excellent for biofilm attachment. If filters become biologically unstable, they can inoculate the downstream water system with high microbiological populations, nutrients, and waste products.

For groundwater systems, drinking water system standards of practice should be more stringent on the routine biostability testing of wells, routine cleaning to keep metals and biostability parameters in check, and more comprehensive inspections when cleaning does not solve identified issues.

Water storage tanks and large capacity pipelines should be included in a biostability monitoring program. Residence time in these structures is a major consideration in achieving biologically stable water.

MAINTAIN AN ONGOING CORROSION CONTROL STUDY

Water systems are directed to prepare a corrosion control study when the Action Levels for lead or copper have been exceeded. It is best to keep ongoing documentation to determine the status of water quality over time and to investigate issues at the time that they arise.

Change the Perspective and Directives of the Lead and Copper Rule

This study has shown that the Lead and Copper Rule directives for lead and copper control are too simplistic. The Lead and Copper Rule should start water systems first on a path toward cleanliness and biostability and then make an ultimate decision as to whether orthophosphate or pH/alkalinity adjustment is required or not. If a water system is out of compliance with the Lead and Copper Rule, much progress can be made using existing data, more involved distribution system monitoring, and performing initial cleaning efforts within of Lead and Copper Rule time frames for achieving compliance. If a water system is not out of compliance with the Lead and Copper Rule, the path toward cleanliness and biostability should nevertheless be started and continued as a proactive measure to maintain and improve water quality.

The directives regarding lead and copper release dependent on pH and alkalinity need to be re-evaluated. There are too many aspects missing from that simplistic model when applied to actual water systems. The corrosivity of water should not be defined by pH and alkalinity alone and especially not from predictions from the idealized carbonate solubility models and published graphs. These statements do not negate the importance of the roles of pH and alkalinity in shaping water quality. Their roles in a given system must be included in a comprehensive corrosion investigation but must be determined empirically.

Likewise, orthophosphate should not be assumed to be generally applicable to all water systems for corrosion control without a comprehensive evaluation of a specific water system.

Keep an Updated Desktop Study and Timeline

A desktop study should look very much like the beginning of this report. Before monitoring in the distribution systems, existing information was gathered to understand the components and possible nuances of each water system. Chapter 2 lists information to be gathered to understand a water system's configuration.

In addition, the use of existing Lead and Copper Rule data can be instrumental in pinpointing periods of time where system operations might have changed in the water system to cause a change in lead or copper release. See Chapter 2.

Finally, insight from studying the Lead and Copper Rule data can be combined with other historical events in the water system's operation for a water system timeline. The timeline should be continued as operational and system changes are made. The timeline aids in evaluating possible reasons for water quality and regulatory compliance issues. See Chapter 2.

Perform a Routine Distribution System Water Quality Indicator Study and Take Action Immediately as Informed by Data

Chapter 4 describes how to use existing distribution system sampling sites, such as those selected for Total Coliform Rule compliance, as an inexpensive but highly informative distribution system water quality monitoring program. The common field tests of disinfection concentration and turbidity are indicators of the cleanliness and biostability of a water system. Tracking these parameters over time at critical flowing water sampling sites around the distribution system can identify times and locations of compromised water quality, including lead and copper release. The timeline, discussed in the previous paragraphs, can aid in identifying operational events that may have impacted those locations.

Weekly, monthly, or quarterly evaluation of such graphs with action taken immediately where indicated on the graphs can prevent small water quality issues from becoming larger.

Study the Water Quality of Problematic Buildings

Buildings or a subset of the buildings with the highest lead or copper release as identified in Lead and Copper Rule compliance sampling or with other water quality issues should be studied in more detail. Profile sampling as was described in Chapter 3 can be a thorough investigation for lead and copper release in cold water piping when combined with other water quality parameters described in Chapter 5.

If Possible, Routinely Gauge Lead and Copper Release

The indicator variables of turbidity and disinfection concentration are inexpensive and easy to work with as described above, but sometimes it is important to directly track the release of lead and copper and their relationship to many other water quality parameters. A comprehensive study of distribution system water quality can be carried out as described in this report. This is helpful for understanding how corrosion control strategies and operational changes are affecting the distribution system water quality. Chapters 5 to 11 of this report describe such a study. The use of a controlled distribution system monitoring station, such as a pipe loop apparatus, a PRS Monitoring Station, or a fully accessible building, is necessary in these comprehensive studies with monitoring performed frequently over time.

Consider Using Orthophosphate for Corrosion Control in Specific Cases

Many small and medium-sized water systems can make progress in controlling lead and copper release within one cleaning season. Water System K is an example of coming into compliance with the Lead and Copper Rule after one season. The eight water systems in this study are also examples of making significant progress on lead and copper control after one season of cleaning and within the Lead and Copper Rule compliance timeline.

However, if improvement is not being seen as the water system is cleaned, orthophosphate dosing could be considered. Offline testing and then a partial system test should be done to determine if the orthophosphate lowers the potential for consumer exposure to both dissolved and particulate lead and copper and if there are no negative side effects to dosing.

Larger water systems cannot be cleaned as quickly as smaller systems. It is possible that orthophosphate can lower the lead and copper release in a system while it is undergoing initial water system hygiene activities.

In no case should complete consumer protection be assumed with the use of orthophosphate or any other corrosion control chemical adjustment scheme. Cleaning, pipe replacement, and biostability efforts should continue with high priority.

Water systems that were not employing methods to ensure a clean system but now are may consider revisiting their corrosion control strategy. If their previous strategy included use of orthophosphate then testing should be conducted to evaluate if the current orthophosphate dose is appropriate. Testing may confirm that lowering their orthophosphate dose, now that they have a cleaner system, is appropriate.

The orthophosphate dosage should never be abruptly stopped as that would disrupt existing pipe wall scales where orthophosphate is providing structural support. Instead, the dosage should be lowered slowly and monitored for lead and copper release trends by comprehensive testing using a distribution system monitoring station or other pipe loop-style apparatus. That is, no water quality change should be done quickly or blindly. This report describes the tools and methods that can be used in order to make a data-informing water quality change.

If there is concern over lead release from metal alloys such as brass, offline PRS Monitoring Station or pipe loop tests can be run using brass plates or pipes to determine the response of brass to water without orthophosphate dosing.

If a decision is made to use orthophosphate, polyphosphates in the corrosion chemical product should be avoided. Polyphosphates have the potential to hold lead and copper in solution instead of decreasing their concentrations. In addition, the total phosphorus sent to the wastewater treatment plant is higher in meeting orthophosphate dosage goals when an additional fraction of the corrosion control product includes polyphosphate than if the product included only orthophosphate.

An additional consideration for using orthophosphate for corrosion control is to use a dose sufficient to form the desired protective scales on the metal surfaces. Water System A was successful in forming protective scales at a dose averaging 0.6 mg/L as PO4. Literature on phosphate dosing suggests an initial dose of 3.0 to 3.5 mg/L as PO4 with a maintenance dose of 1 mg/L as PO4 (EPA 2016a). In the other water systems using lower orthophosphate dosages, little to no phosphorus was found on the metal surface scales. That is, if orthophosphate dosing is to occur, then the dose must be sufficient in order to develop the desired scales.

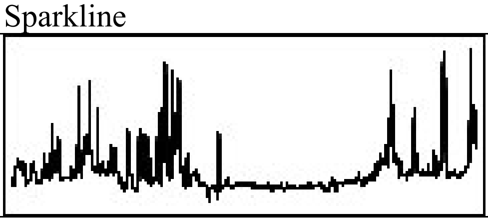
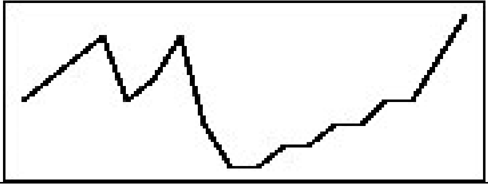
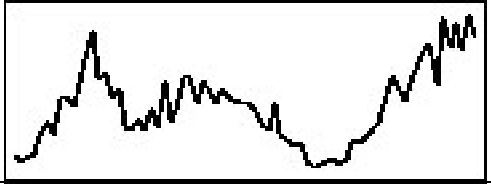
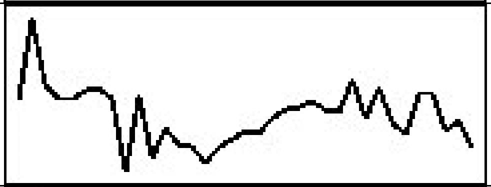
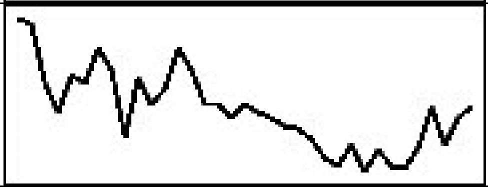
Perform an Environmental Impact Analysis of Phosphorus before Selecting Orthophosphate for Corrosion Control

If contemplating using a phosphate-based corrosion control chemical, begin a dialogue with the associated wastewater treatment facility personnel. Chapter 12 lists steps to evaluating the impact of the corrosion control strategy on meeting phosphorus discharge limits.

A portion of phosphate-dosed water also runs directly into natural bodies of water when used for outdoor purposes or industrial cooling water purposes. Consider the impact of the phosphate on the receiving body of water, especially using the phosphorus discharge limits determined by regulatory agencies.

APPENDIX A
CORRELATIONS

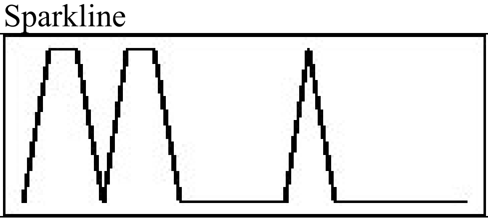
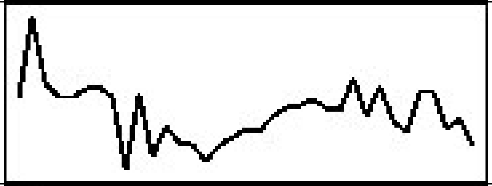
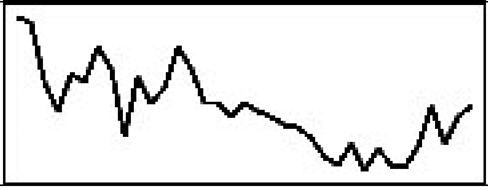
WATER SYSTEM A

Parameter	Sparkline	
Alum Dosing		in flowing water influent to the monitoring station
Aluminum		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Turbidity		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

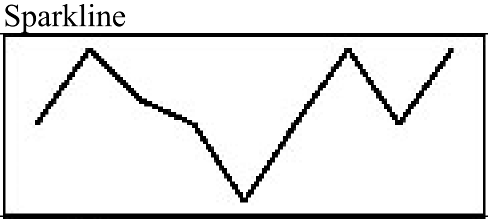
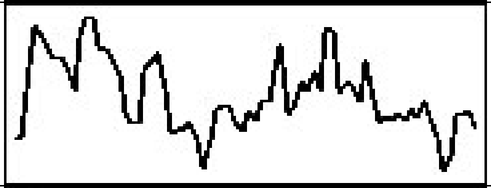
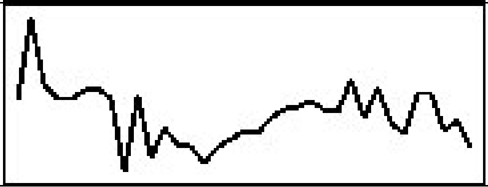
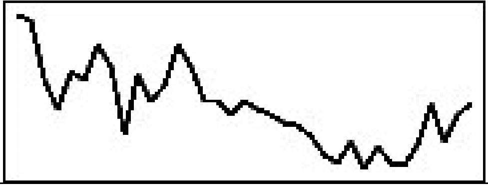
Alum (aluminum sulfate) was dosed the most in the colder months. Sulfate concentration in the water followed the alum dosing trend. Aluminum appeared to be stored on the pipe wall and was released mostly in dissolved form during the summer when alum dosing was at its lowest. The aluminum trend was inverse to the sulfate trend.

pH trended oppositely to alum dosing as alum lowered the pH of the water. Turbidity in the distribution system followed the alum dosing trend. Turbidity and pH trended inversely.

Dissolved lead peaked in the summer when pH was high and turbidity and alum dosing were low. Dissolved copper followed an opposite trend from dissolved lead in the summer. Dissolved copper trended with dissolved lead earlier in the year suggesting that different forces were at work in the colder months than in the warmer months.

Parameter	Sparkline	
Alkalinity		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

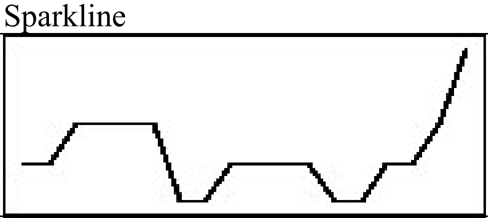
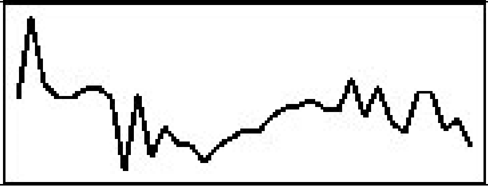
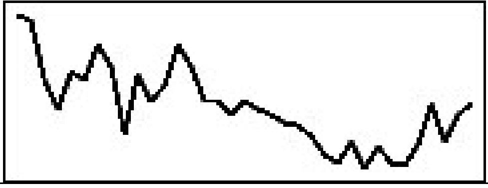
Dissolved lead and dissolved copper did not trend with alkalinity. Dissolved lead trended with pH in the summer but this relationship appeared to be related to alum dosing or some other factor influencing both dissolved lead release and pH. Dissolved copper trended oppositely with pH in the summer.

Parameter	Sparkline	
Total Phosphorus		in flowing water influent to the monitoring station
Ortho-phosphate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

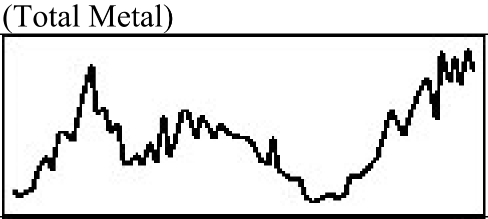
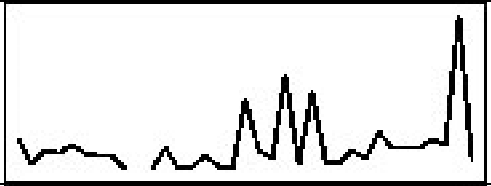
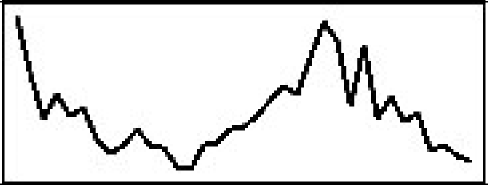
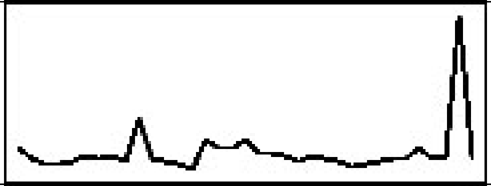
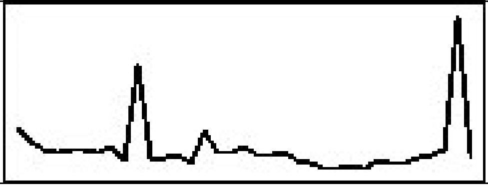
Dissolved lead increased with orthophosphate most likely because of other factors and not because of a cause and effect relationship between orthophosphate and dissolved lead. It is possible for phosphorus to be released from accumulations on pipe walls either as inorganic compounds or as incorporated into biological materials. Perhaps a pipe wall release would create this relationship between dissolved lead and orthophosphate.

Total phosphorus continued to increase at the end of the monitoring period (autumn) while orthophosphate decreased. It is possible that some orthophosphate was incorporated into biological materials at that time utilizing the phosphorus as organically-bound instead of as orthophosphate.

Copper was lowered as orthophosphate increased, but this also does not imply cause and effect, especially when observing the other complicated summer patterns.

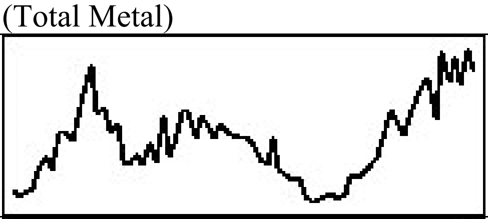
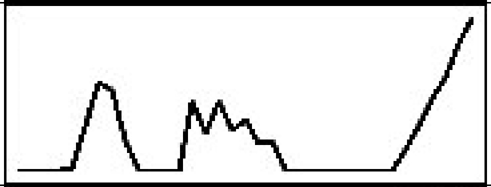
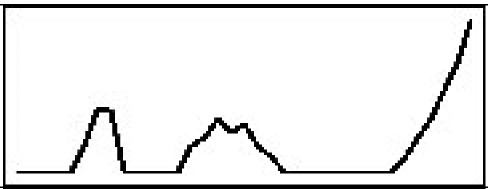
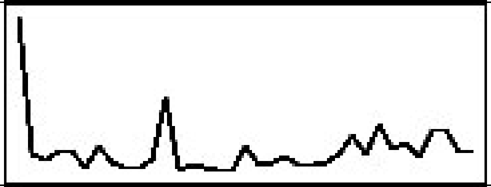
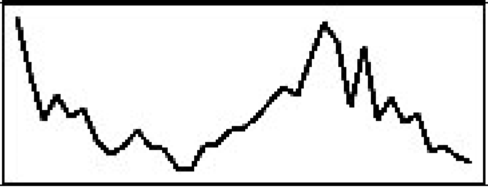
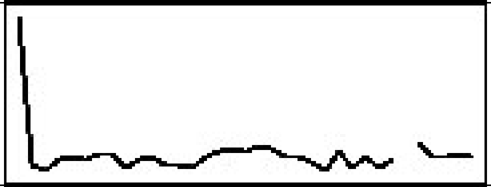
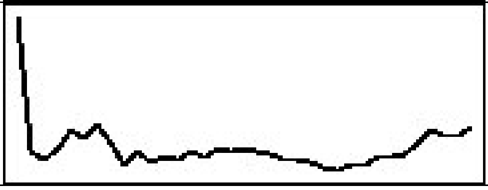
Parameter	Sparkline	
Chloride		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

Chloride and sulfate increased as the temperature warmed and continued into the fall. Dissolved copper began an increase in mid-summer and then followed parameters such as chloride and sulfate in the fall.

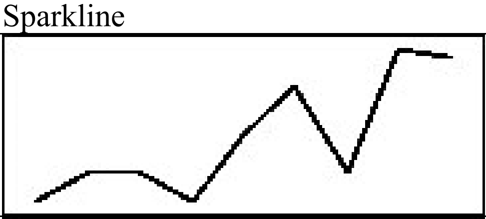
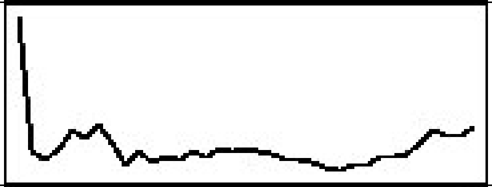
Parameter	Influent Flowing Water (Total Metal)	Copper Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum		
Copper		

System water total iron followed the turbidity trend where the largest increase was at the end of the monitoring period in the fall. System water total manganese increased in the fall with turbidity and iron. System water aluminum (which was mostly in dissolved form) followed the dissolved lead release pattern seen previously while manganese, also mostly dissolved, somewhat followed the dissolved copper release trend.

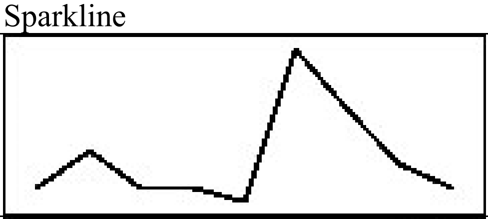
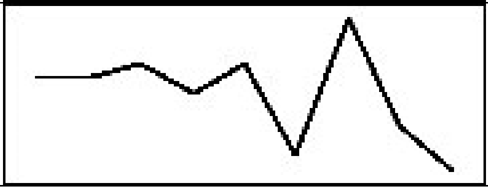
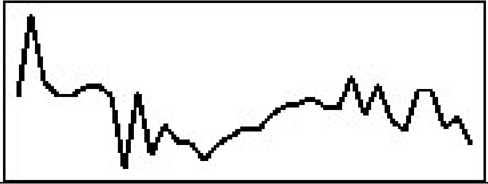
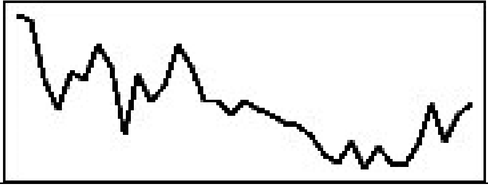
Particulate copper was co-released with particulate iron, manganese, and aluminum in the copper test chamber.

Parameter	Influent Flowing Water (Total Metal)	Lead Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum		
Lead		

Particulate lead was co-released with particulate aluminum and manganese in the lead test chamber.

Parameter	Sparkline	
Nitrite/ Nitrate		in flowing water influent to the monitoring station
Particulate Lead		in stagnating lead test chamber water
Particulate Copper		in stagnating copper test chamber water

Nitrite/nitrate began an upward climb as the temperature warmed. Particulate lead and copper release increased in fall along with nitrite/nitrate.

Parameter	Sparkline	
Ammonia		in flowing water influent to the monitoring station
Nitrite/ Nitrate		in flowing water influent to the monitoring station
Dissolved Organic Carbon		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

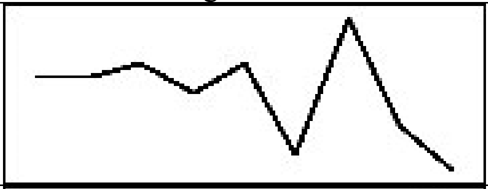
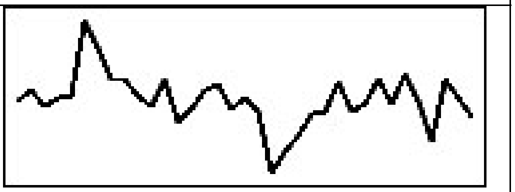
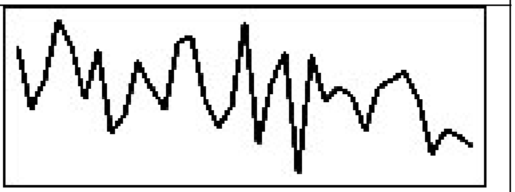
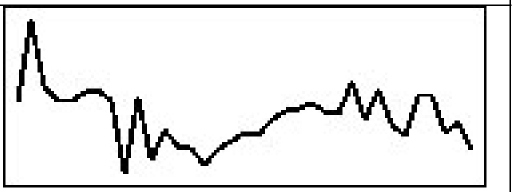
As the temperature warmed, the chloramine disinfection released free ammonia. This became food for microorganisms and the nitrification process began as ammonia was transformed into nitrite and nitrate by microorganisms. Nitrite/nitrate had a steady increase with variability into the fall while ammonia had a peak in the summer.

Just after the ammonia peak, dissolved organic carbon peaked. Dissolved organic carbon trended oppositely to nitrite/nitrate.

Dissolved lead release appeared to peak in the summer over the ammonia and dissolved organic carbon peaks while dissolved copper release followed an opposite trend.

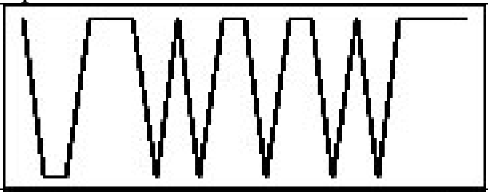
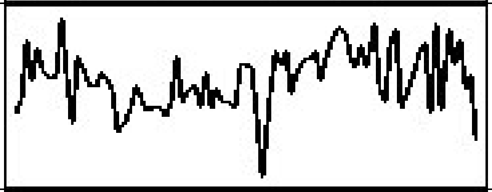
Dissolved copper and nitrite/nitrate increased into fall.

Given these distinct nitrification patterns, the patterns associated with alum dosing previously discussed can be theorized to be another effect of nitrification. Even the release of particulate lead, copper, and other metals as nitrite/nitrate increased in the fall could possibly be an effect of nitrification.

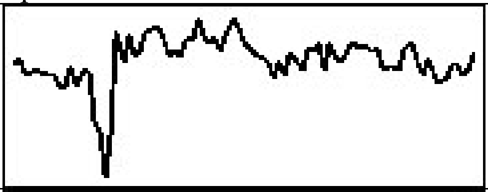
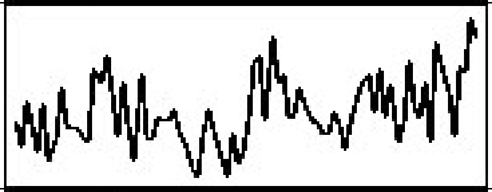
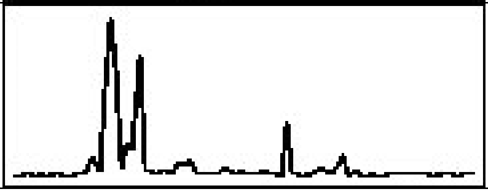
Parameter	Influent Flowing Water	Test Chamber Stagnating Water
Dissolved Organic Carbon		
Microbiological Population		 Lead Test Chamber
		 Copper Test Chamber
Disinfection		
Dissolved Lead		 Lead Test Chamber
Dissolved Copper		 Copper Test Chamber

No clear trends were seen between dissolved organic carbon, microbiological population, disinfection concentration, and dissolved lead and copper release.

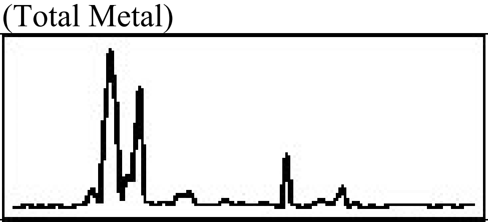
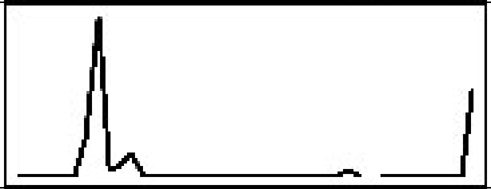
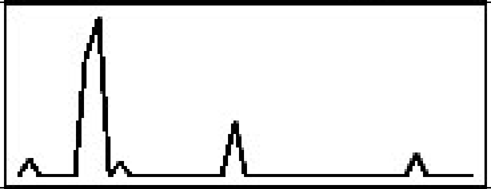
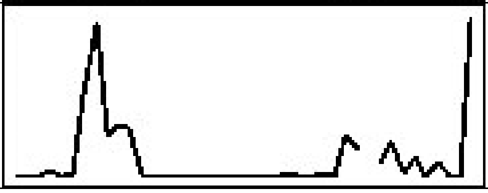
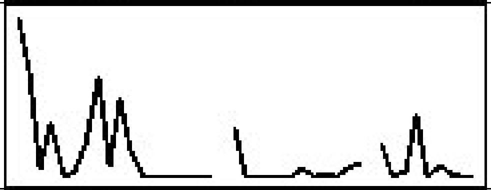
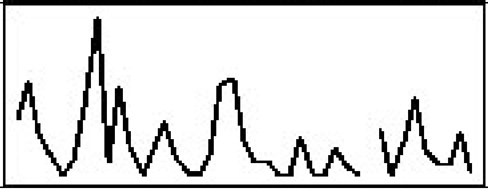
WATER SYSTEM B

Parameter	Sparkline	
Alkalinity		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

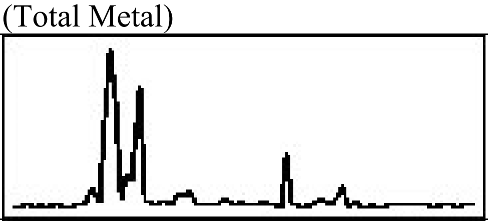
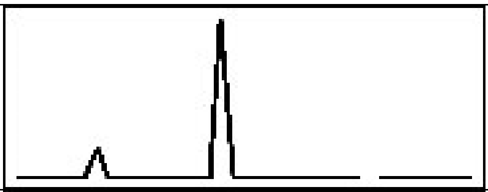
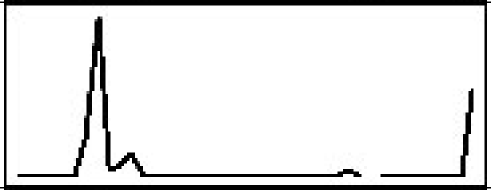
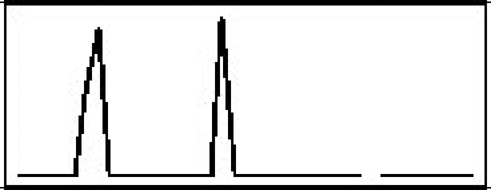
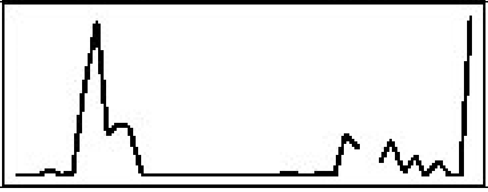
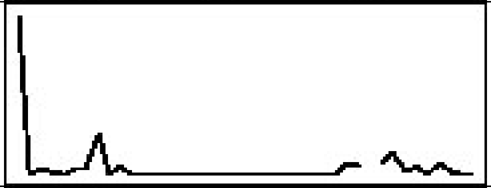
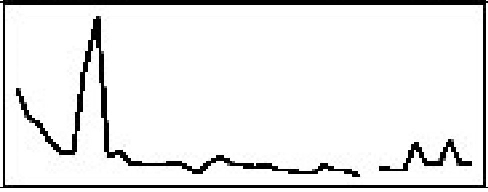
No correlations were seen between pH and alkalinity and dissolved lead and copper release. Dissolved lead and copper release trended together.

Parameter	Sparkline	
Oxidation/ reduction potential		in flowing water influent to the monitoring station
Conductivity		in flowing water influent to the monitoring station
Turbidity		in flowing water influent to the monitoring station

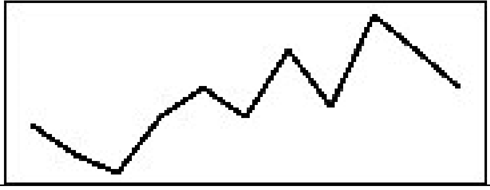
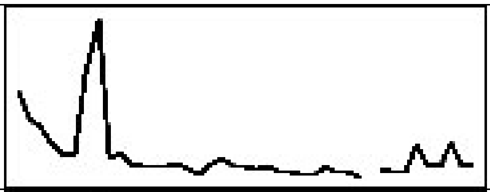
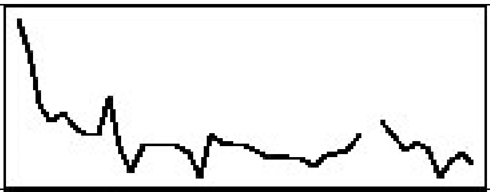
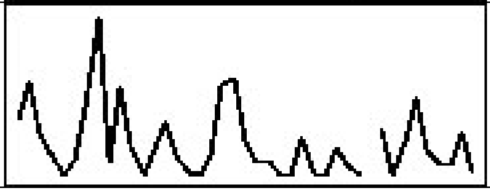
There was water main flushing in the first August of the monitoring program near the monitoring station. The lowest ORP was seen in the system water accompanied by an increase in both conductivity and turbidity. Conductivity continued to increase over time.

Parameter	Influent Flowing Water (Total Metal)	Copper Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum		
Copper		

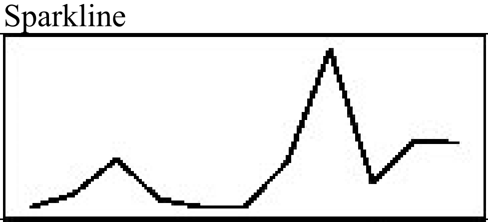
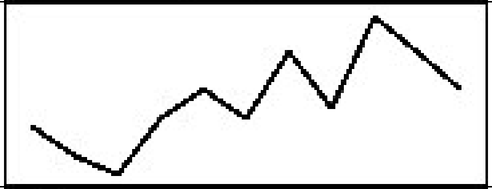
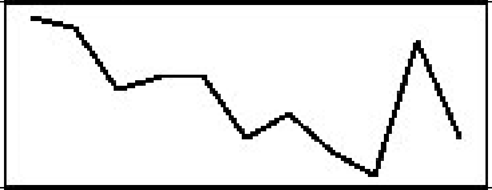
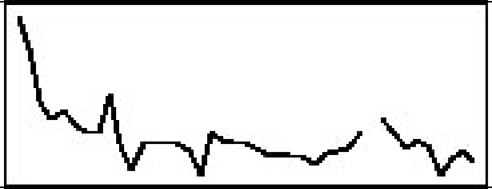
The August water main flushing event appeared to have increased turbidity, iron, manganese, and aluminum in the system water. The effect was seen in the copper test chamber release of all four metals. In general, particulate copper release trended with particulate aluminum, manganese, and possibly iron release.

Parameter	Influent Flowing Water (Total Metal)	Lead Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum		
Lead		

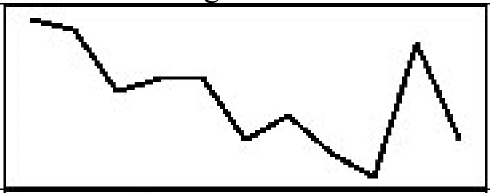
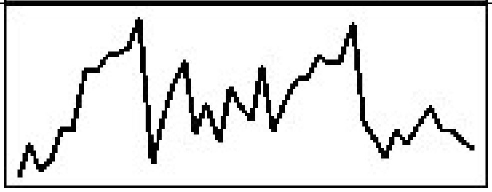
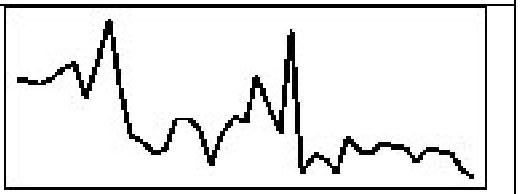
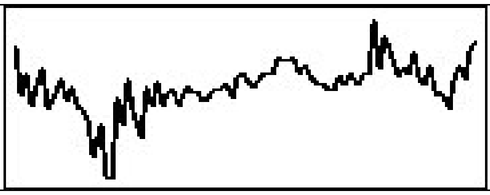
In general, particulate lead release trended with particulate aluminum release. Particulate iron and manganese trended together and possibly with particulate lead.

Parameter	Sparkline	
Nitrite/ Nitrate		in flowing water influent to the monitoring station
	Particulate Metal	Dissolved Metal
Lead in lead test chamber stagnating water		
Copper in copper test chamber stagnating water		

Particulate lead and copper releases were not trending with the increase of nitrite/nitrate to the degree that was seen in Water System A. They were trending in an opposite direction with a small increase in the fall. Dissolved lead and particulate lead trended together. Dissolved copper and particulate copper trended together. All of the metal forms decreased over all.

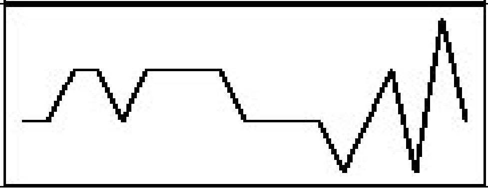
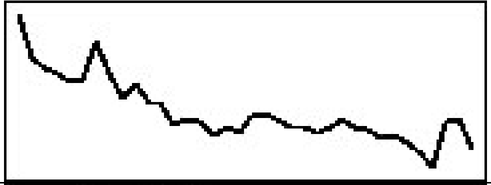
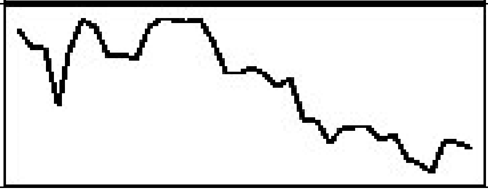
Parameter	Sparkline	
Ammonia		in flowing water influent to the monitoring station
Nitrite/ Nitrate		in flowing water influent to the monitoring station
Dissolved Organic Carbon		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

The nutrient graphs of Water System B look like those of Water System A where nitrification was occurring. Ammonia increased in the water system to a summertime peak. Dissolved organic carbon peaked just after the ammonia. Dissolved organic carbon appeared opposite in trend to nitrite/nitrate. Dissolved lead release, even though decreasing in general as the water system was cleaned, experienced an increase and then a decrease over the ammonia and dissolved organic carbon patterns. Dissolved copper release did this also but appeared to continue an upward climb with nitrite/nitrate whereas dissolved lead release continued downward. This was also similar to Water System A.

Parameter	Influent Flowing Water	Test Chamber Stagnating Water
Dissolved Organic Carbon		
Microbiological Population		 Lead Test Chamber
		 Copper Test Chamber
Disinfection		
Dissolved Lead		 Lead Test Chamber
Dissolved Copper		 Copper Test Chamber

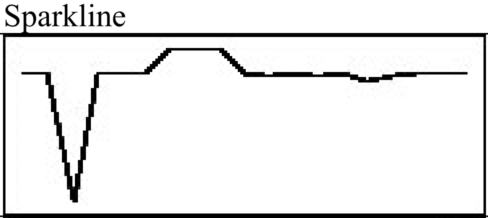
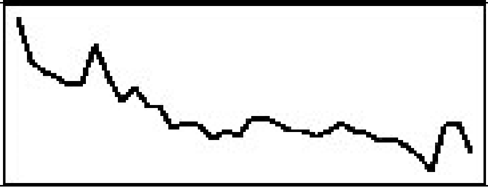
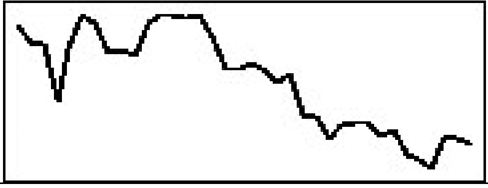
Disinfection appeared to follow an opposite trend to microbiological population. Dissolved lead and copper release appeared to follow microbiological populations in their respective test chambers.

WATER SYSTEM C

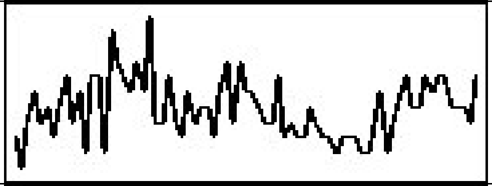
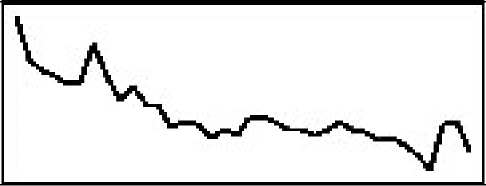
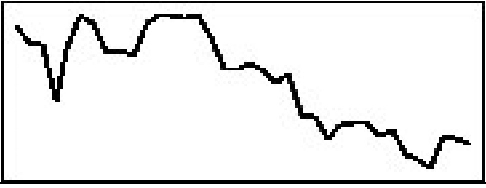
Parameter	Sparkline	
Aluminum		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Turbidity		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

Water System C used alum for coagulation like Water System A. A similar release of dissolved aluminum was seen in the summer similar to Water System A. The sulfate in the water was similar to A except that there was greater variation in the summer. Dissolved copper trended inversely with dissolved aluminum.

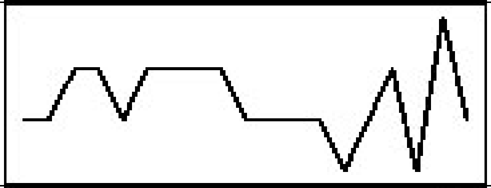
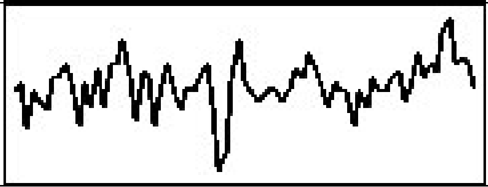
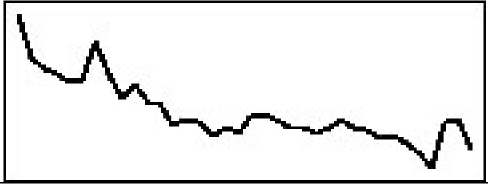
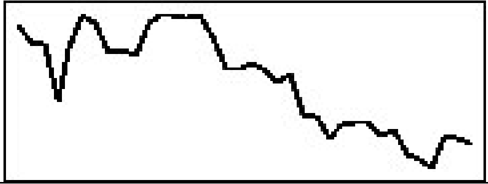
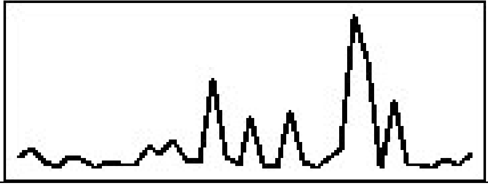
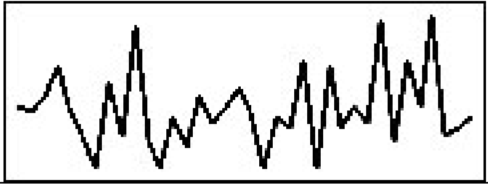
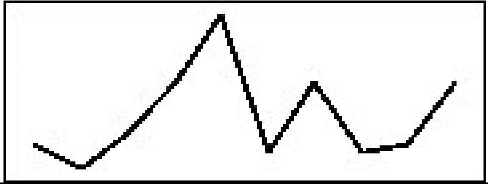
Dissolved lead and copper trended with each other and not opposite each other like in Water System A in the summer.

Parameter	Sparkline	
Alkalinity		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

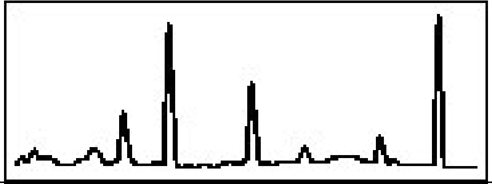
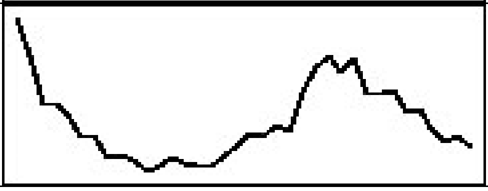
There appeared to be no similar trends between dissolved lead and copper release and alkalinity and pH.

Parameter	Sparkline	
Total Phosphorus		in flowing water influent to the monitoring station
Ortho-phosphate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

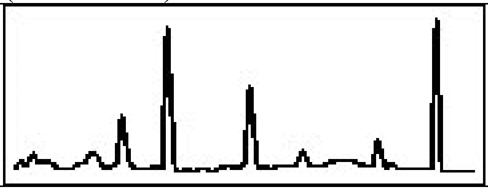
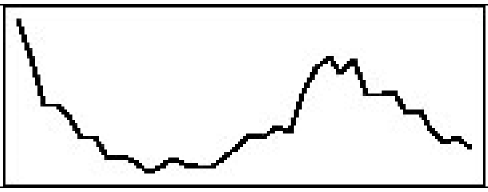
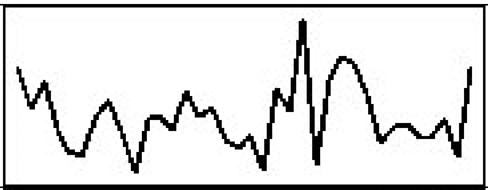
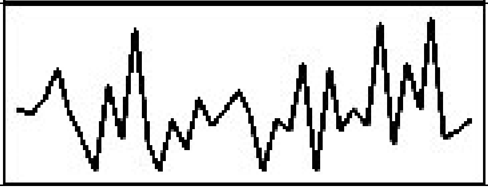
There was a possible common trend between total phosphorus/orthophosphate and dissolved lead and copper release. They all reached a minimum but phosphorus did so before the dissolved metals did.

Parameter	Sparkline	
Chloride		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water
Particulate Lead		in stagnating lead test chamber water
Particulate Copper		in stagnating copper test chamber water
Nitrite/ nitrate		in flowing water influent to the monitoring station

There was a jump in chloride in the late winter. The pH dropped when chloride was at its highest concentration. Nitrite/nitrate peaked just before the chloride peak. It is suspected that the late winter behavior may be related to runoff from roads with winter road salt into the lake and affecting the water quality far out about a mile at the water intake structures. Particulate lead release increased at that time but it may be coincidence because it continued to spike long after the chloride and nitrate event.

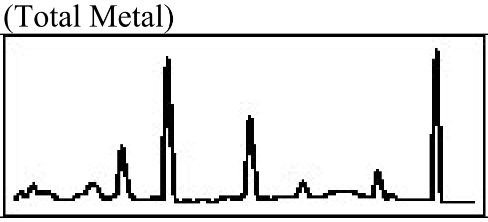
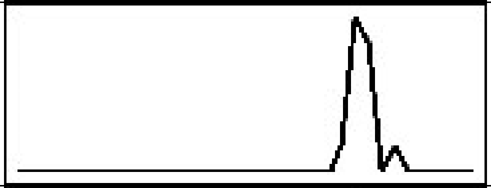
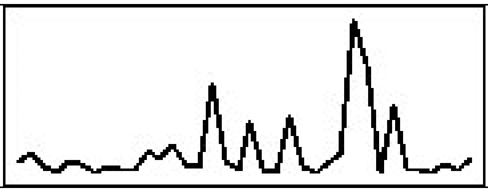
Parameter	Sparkline	
Oxidation/ reduction potential		in flowing water influent to the monitoring station
Conductivity		in flowing water influent to the monitoring station
Turbidity		in flowing water influent to the monitoring station
Aluminum		in flowing water influent to the monitoring station

ORP and conductivity appear to trend together. Dissolved aluminum released in the system water appeared to trend opposite to ORP and conductivity. This is confusing since conductivity is an indication of dissolved solids in the water.

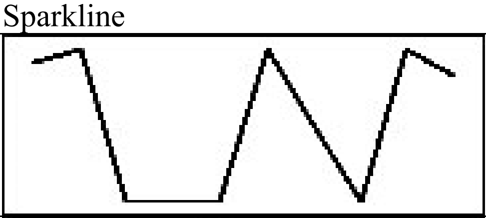
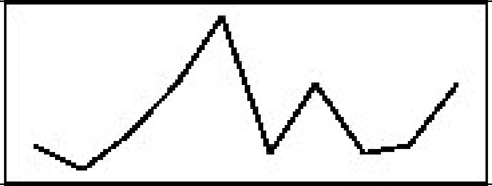
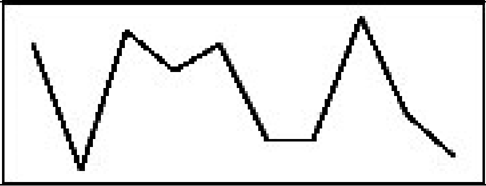
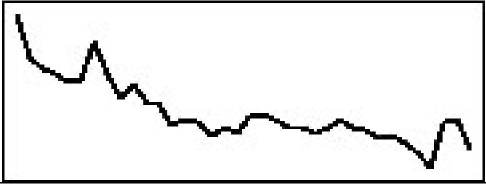
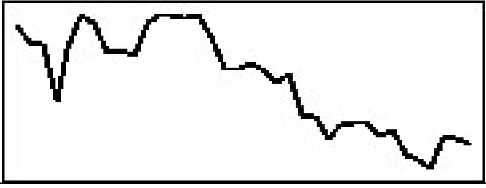
Parameter	Influent Flowing Water (Total Metal)	Copper Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron	below detection limit	below detection limit
Manganese	below detection limit	below detection limit
Aluminum		
Copper		

Turbidity of the system water showed high spikes of particulates over time. However, the particulates could not be defined; iron and manganese were below detection limit and only total aluminum was measured above the detection limit.

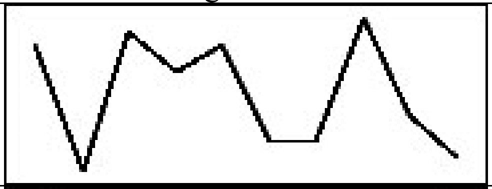
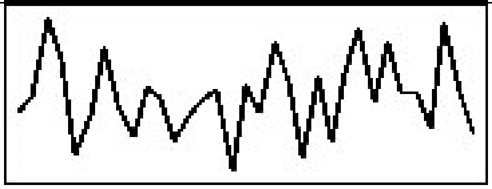
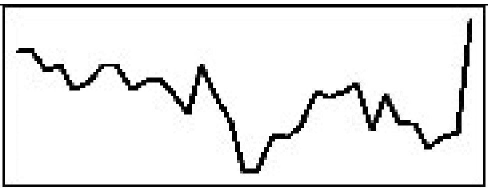
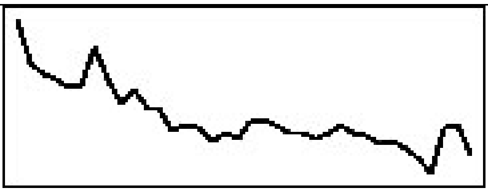
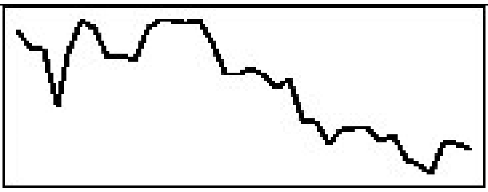
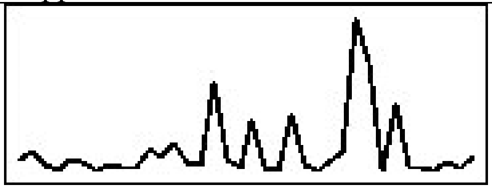
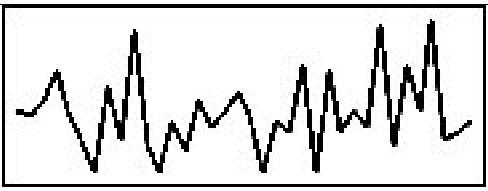
In the copper test chamber, particulate copper and particulate aluminum released together.

Parameter	Influent Flowing Water (Total Metal)	Lead Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron	below detection limit	
Manganese	below detection limit	
Aluminum		
Lead		

In the lead test chamber, particulate lead and particulate aluminum released together. Toward the end of the monitoring period, particulate iron and manganese were measured as above detection limit in the events. The limit of detection for iron may have been too high to reveal more correlated trends. The manganese limit of detection was satisfactory but manganese was at very low levels in the water system.

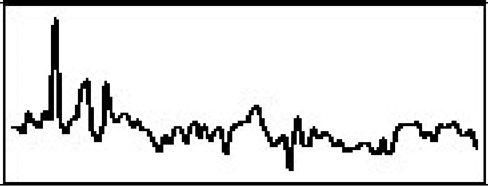
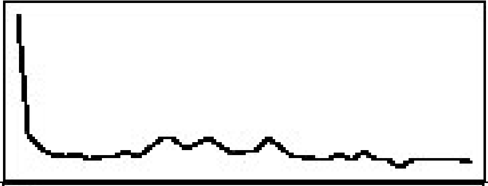
Parameter	Sparkline	
Ammonia		in flowing water influent to the monitoring station
Nitrite/ Nitrate		in flowing water influent to the monitoring station
Dissolved Organic Carbon		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

The nitrification pattern was not observed in Water System C.

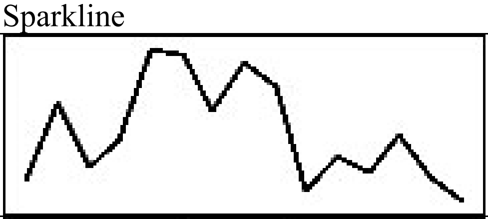
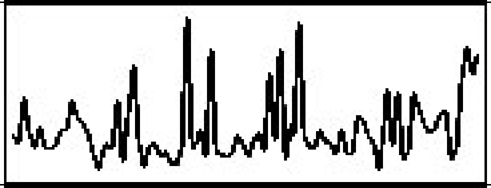
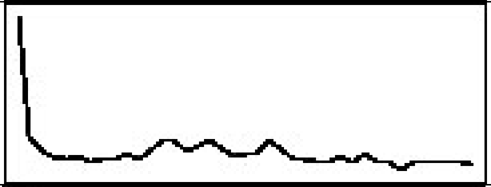
Parameter	Influent Flowing Water	Test Chamber Stagnating Water
Dissolved Organic Carbon		
Microbio-logical Population		 Lead Test Chamber
		 Copper Test Chamber
Disinfection		
Dissolved Lead		 Lead Test Chamber
Dissolved Copper		 Copper Test Chamber
Particulate Lead		 Lead Test Chamber
Particulate Copper		 Copper Test Chamber

There were possibly similar trends between microbiological populations and lead and copper release, especially copper release in particulate form.

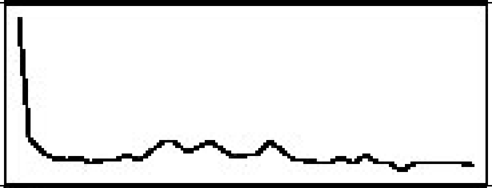
WATER SYSTEM D

Parameter	Sparkline	
Alkalinity		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
		Repeat of dissolved lead graph but without initial high value
Dissolved Copper		in stagnating copper test chamber water

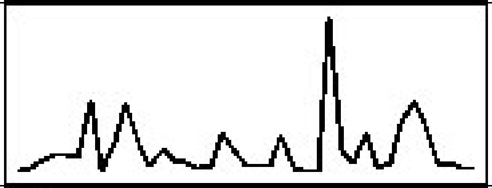
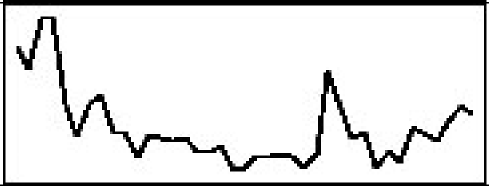
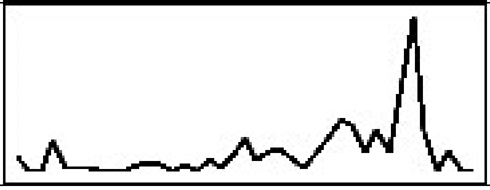
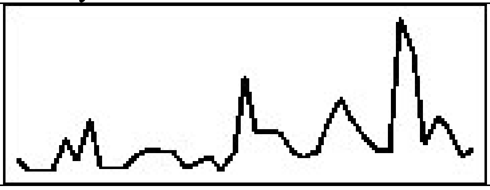
Alkalinity trended inversely to dissolved lead and copper release. This may have been a function of which wells were providing water to the monitoring station at the time of sampling. Note that dissolved lead and dissolved copper show similar release patterns after the initial high dissolved lead value is hidden.

Parameter	Sparkline	
Total Phosphorus		in flowing water influent to the monitoring station
Ortho-phosphate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
		Repeat of dissolved lead graph but without initial high value
Dissolved Copper		in stagnating copper test chamber water

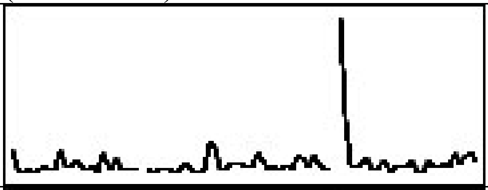
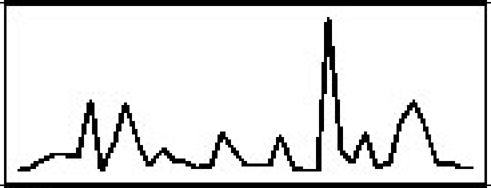
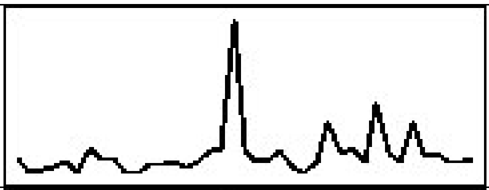
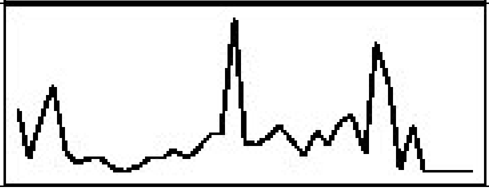
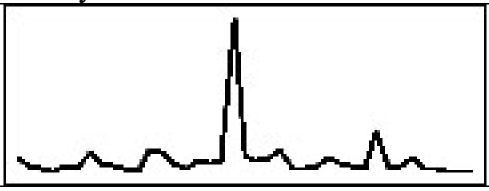
Dissolved copper and lead release appeared to trend with total phosphorus. This is theorized to occur from the presence of polyphosphate in the water holding the metals in the water. It could also be a microbiological phenomenon where total phosphorus is being released from pipe walls in organically-bound compounds. This could be a factor affecting metal solubility or there could be a third factor that influenced both parameters.

Parameter	Sparkline	
Chloride		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
		Repeat of dissolved lead graph but without initial high value
Dissolved Copper		in stagnating copper test chamber water

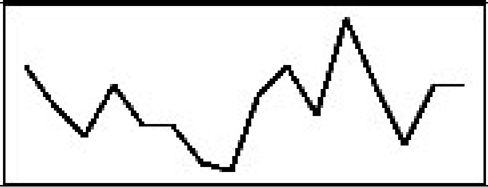
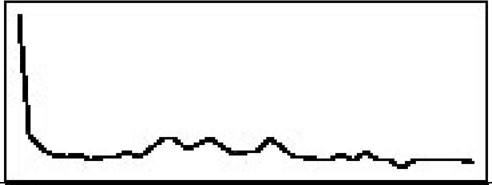
Chloride and sulfate appeared to trend together however they did not appear to be related to dissolved lead or copper release.

Parameter	Influent Flowing Water (Total Metal)	Copper Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum	Below detection limit	Mostly below detection limit
Copper		

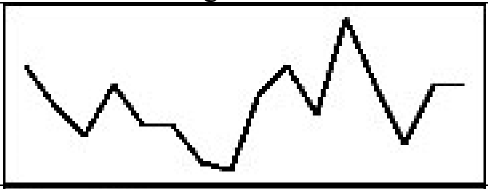
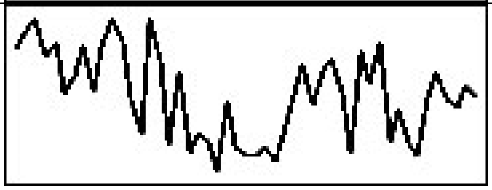
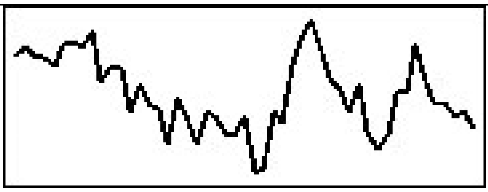
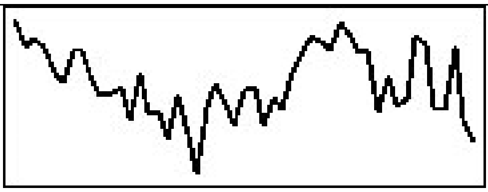
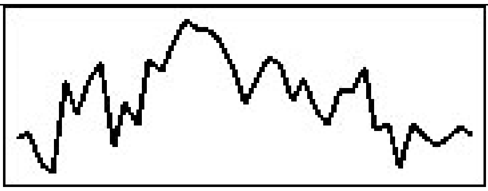
Particulate copper released with particulate iron and manganese. Iron and manganese and possibly turbidity trended together in the system water.

Parameter	Influent Flowing Water (Total Metal)	Lead Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum	Below detection limit	Mostly below detection limit
Lead		

Particulate lead released with particulate iron and manganese. Iron and manganese and possibly turbidity trended together in the system water. Note that particulate lead and copper release were similar in trends.

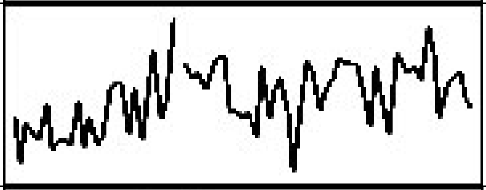
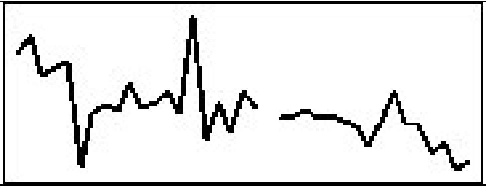
Parameter	Sparkline	
Ammonia		in flowing water influent to the monitoring station
Nitrite/ Nitrate		in flowing water influent to the monitoring station
Dissolved Organic Carbon		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
		Repeat of dissolved lead graph but without initial high value
Dissolved Copper		in stagnating copper test chamber water

Unlike nitrification patterns seen in Water Systems A and B, ammonia and nitrate trended together. Dissolved organic carbon appeared to trend opposite to nitrate as seen in the other water systems. Dissolved copper and lead release trended somewhat with the ammonia and nitrate patterns. Previously, it was shown that they possibly trended with phosphorus released from pipe wall accumulations.

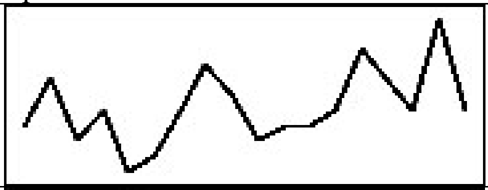
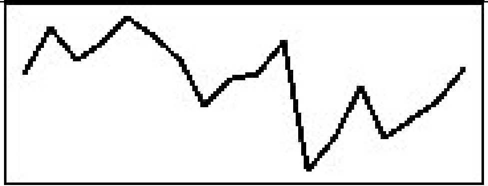
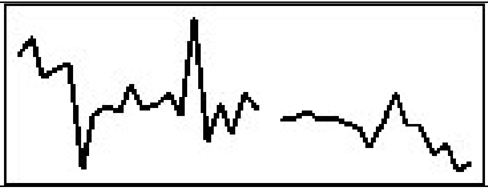
Parameter	Influent Flowing Water	Test Chamber Stagnating Water
Dissolved Organic Carbon		
Microbio-logical Population		 Lead Test Chamber
		 Copper Test Chamber
Dissolved Lead		 Lead Test Chamber
Dissolved Copper		 Copper Test Chamber

Dissolved organic carbon trended with the microbiological population. Dissolved lead and copper were trending oppositely to microbiological population.

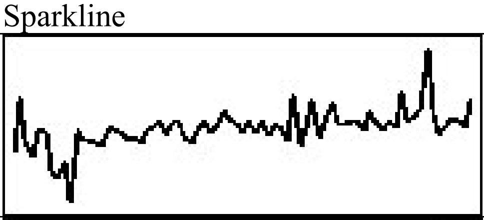
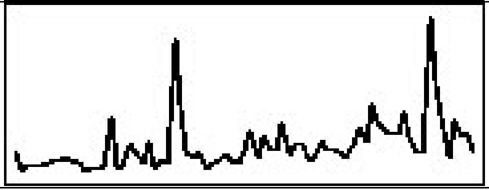
WATER SYSTEM E

Parameter	Sparkline	
Alkalinity		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

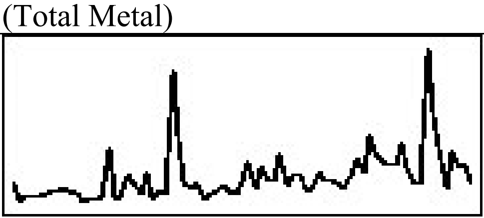
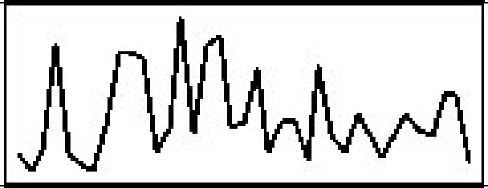
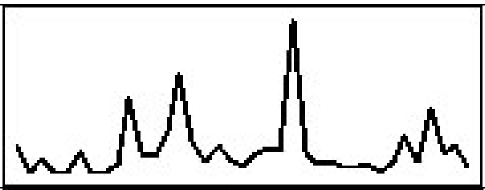
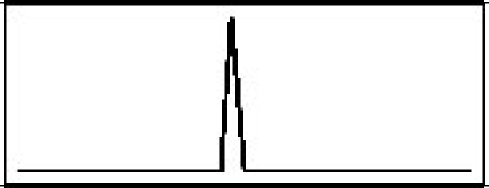
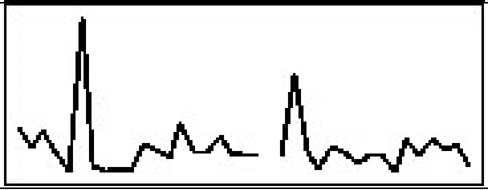
There were no common trends between alkalinity and pH and dissolved lead and copper release. Dissolved lead release was similar to dissolved copper release. Both decrease during the later monitoring period.

Parameter	Sparkline	
Chloride		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

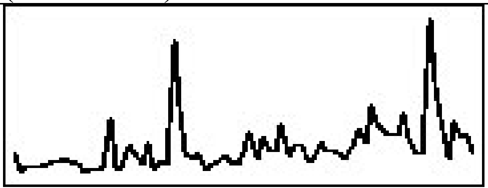
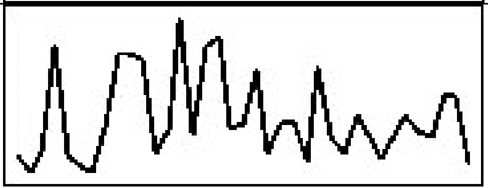
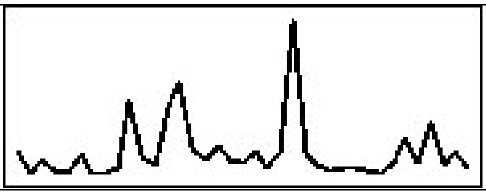
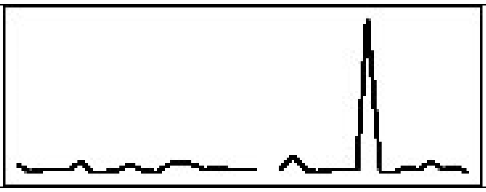
Chloride increased as sulfate decreased along with dissolved lead and copper release. The increasing chloride was from the use of new water softeners. It is theorized that the softeners kept out chemical and microbiological components of the system water from reaching the monitoring station.

Parameter	Sparkline	
Conductivity		in flowing water influent to the monitoring station
Turbidity		in flowing water influent to the monitoring station

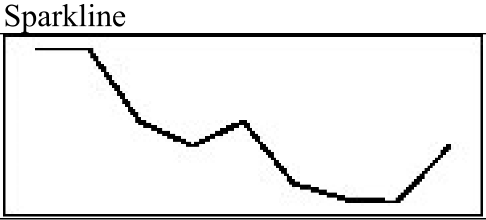
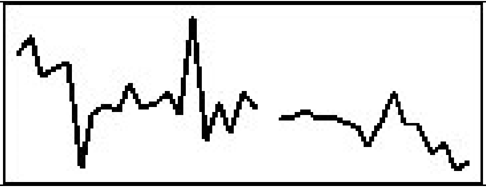
Both conductivity and turbidity of the system water increased over time. It was seen that the system water filter was producing more turbid water over time.

Parameter	Influent Flowing Water (Total Metal)	Copper Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		Mostly below detection limit
Manganese		
Aluminum		
Copper		

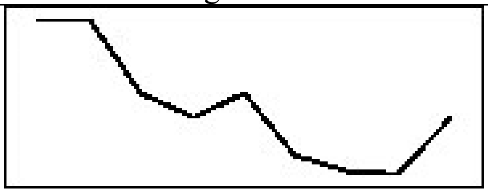
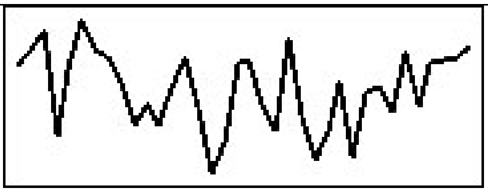
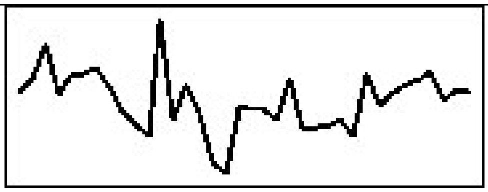
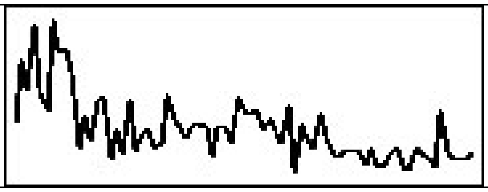
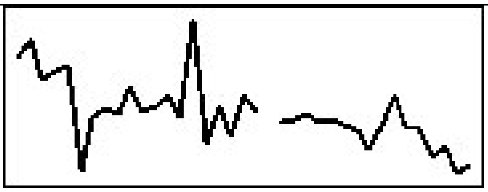
Manganese was a main component in the system water in both dissolved and particulate form. Particulate copper released with particulate manganese in the copper test chamber.

Parameter	Influent Flowing Water (Total Metal)	Lead Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		mostly below detection limit
Manganese		
Aluminum		Below detection limit
Lead		

Particulate lead released with particulate manganese in the lead test chamber.

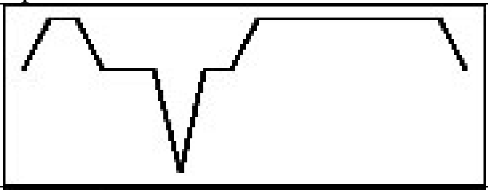
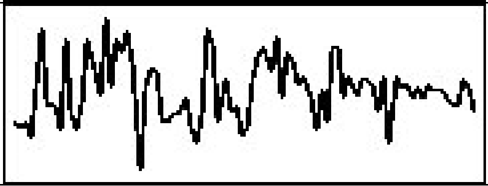
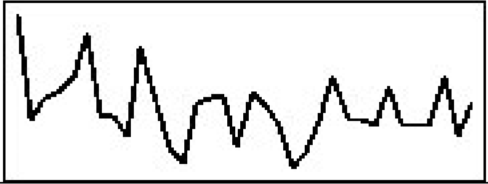
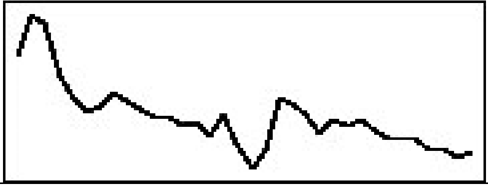
Parameter	Sparkline	
Dissolved Organic Carbon		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

Dissolved organic carbon decreased over time as did dissolved lead and copper.

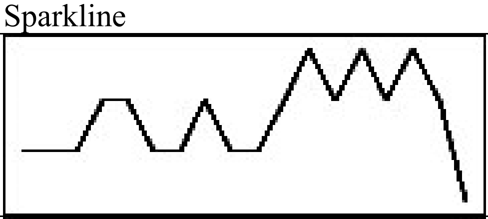
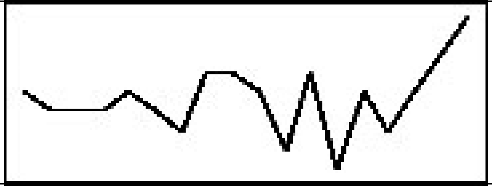
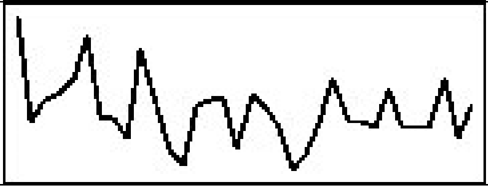
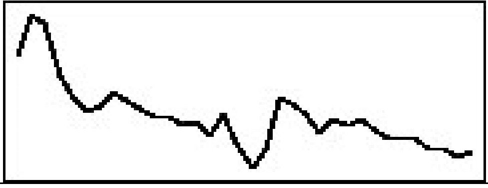
Parameter	Influent Flowing Water	Test Chamber Stagnating Water
Dissolved Organic Carbon		
Microbio-logical Population		 Lead Test Chamber
		 Copper Test Chamber
Disinfection		
Dissolved Lead		 Lead Test Chamber
Dissolved Copper		 Copper Test Chamber

Dissolved organic carbon did not trend with microbiological population. Populations were increasing in the test chambers by the end of the monitoring period. Disinfection in the system water was dropping. Dissolved lead and copper dropped over time.

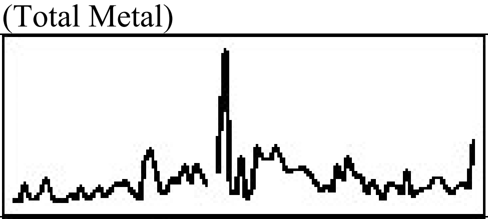
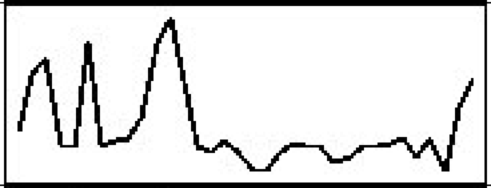
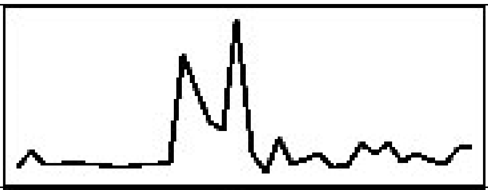
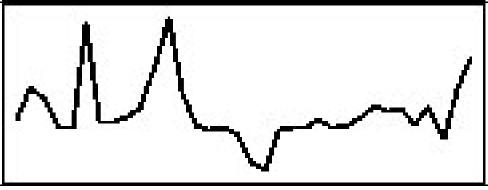
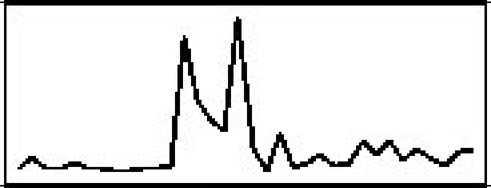
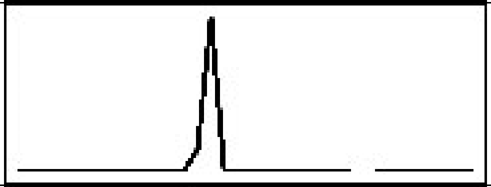
WATER SYSTEM F

Parameter	Sparkline	
Alkalinity		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

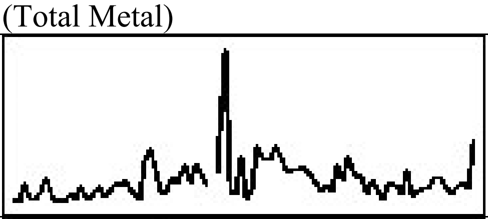
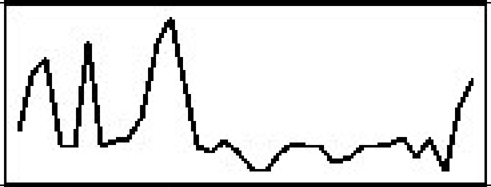
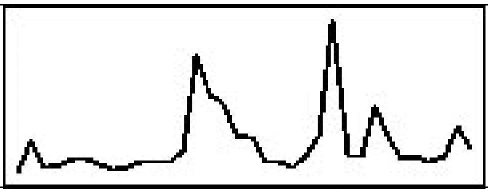
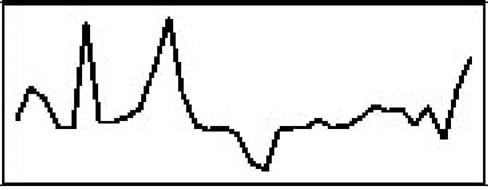
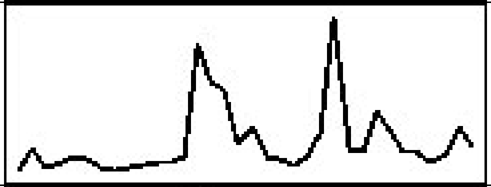
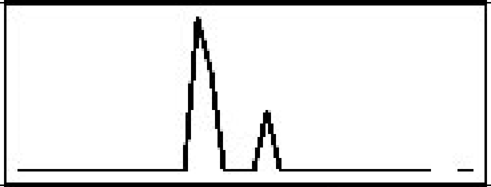
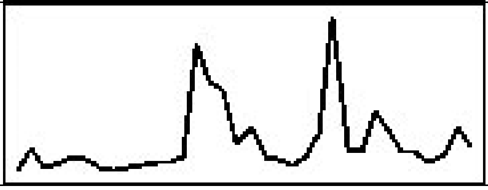
There were no common trends between alkalinity, pH, and dissolved lead and copper release.

Parameter	Sparkline	
Chloride		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

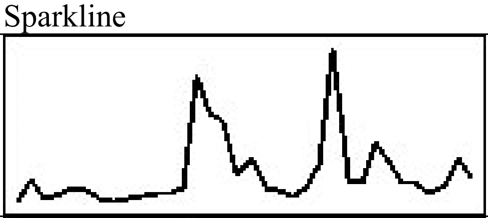
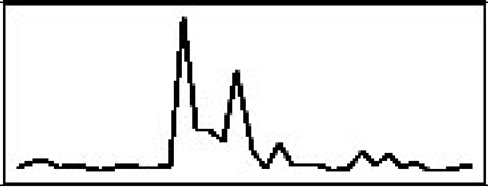
There were no common trends between chloride, sulfate and dissolved lead and copper release.

Parameter	Influent Flowing Water (Total Metal)	Copper Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum	Below detection limit	
Copper		

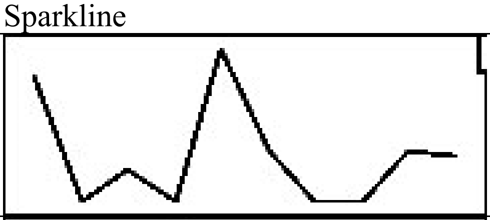
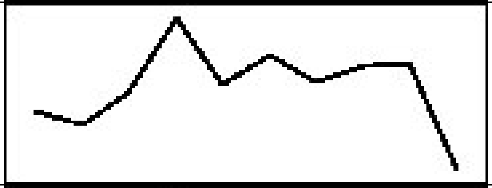
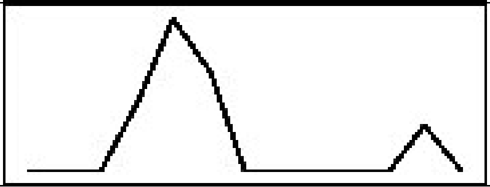
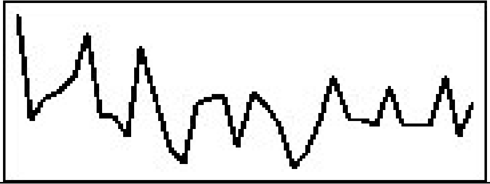
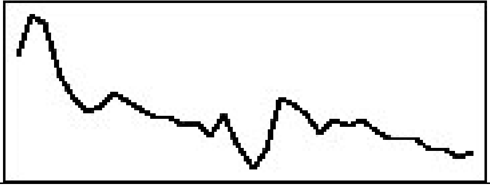
Iron and manganese trended with each other in the system water. Particulate copper released with particulate iron, manganese, and aluminum in the copper test chamber.

Parameter	Influent Flowing Water (Total Metal)	Lead Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum	Below detection limit	
Lead		

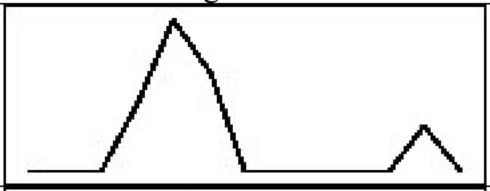
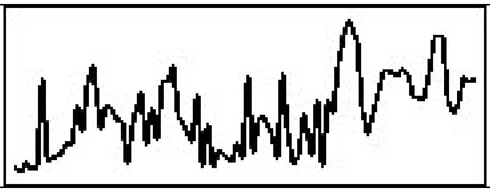
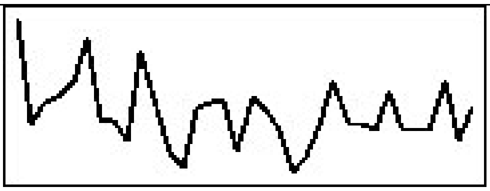
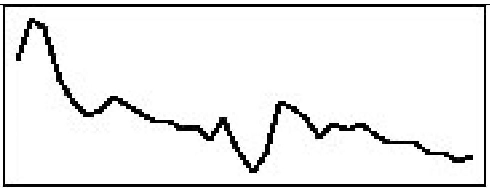
Particulate lead released with particulate iron, manganese, and aluminum in the lead test chamber.

Parameter	Sparkline	
Particulate Lead		in stagnating lead test chamber water
Particulate Copper		in stagnating copper test chamber water

Particulate lead and copper release trended in a similar pattern.

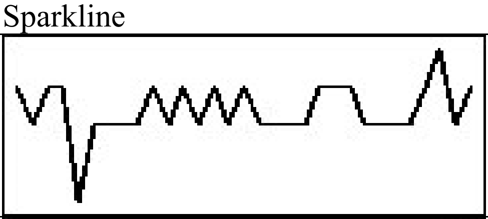
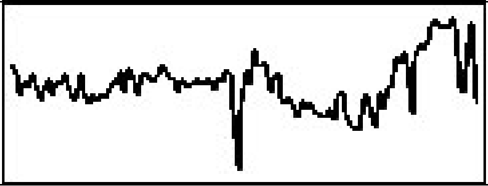
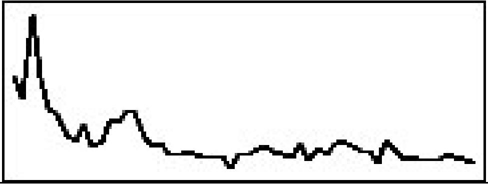
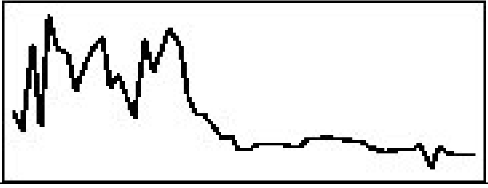
Parameter	Sparkline	
Ammonia		in flowing water influent to the monitoring station
Nitrite/ Nitrate		in flowing water influent to the monitoring station
Dissolved Organic Carbon		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

There were no common patterns between the nutrients and the dissolved lead and copper release.

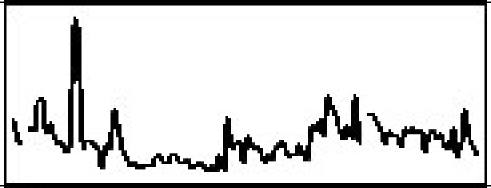
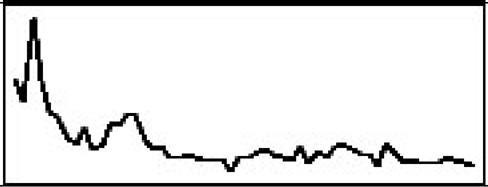
Parameter	Influent Flowing Water	Test Chamber Stagnating Water
Dissolved Organic Carbon		
Microbiological Population		 Lead Test Chamber
		 Copper Test Chamber
Disinfection		
Dissolved Lead		 Lead Test Chamber
Dissolved Copper		 Copper Test Chamber

Dissolved copper release trended with microbiological population. Dissolved lead release somewhat trended with microbiological population. Disinfection increased as population decreased.

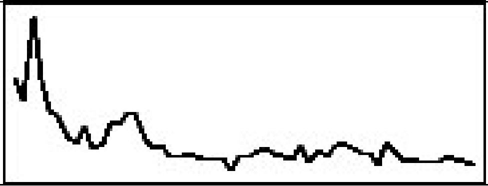
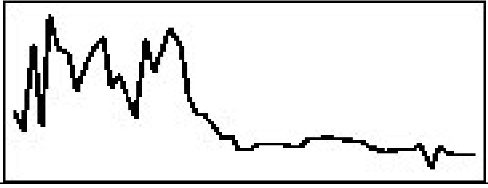
WATER SYSTEM G

Parameter	Sparkline	
Alkalinity		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

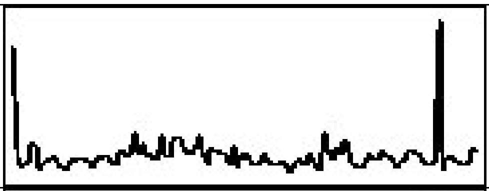
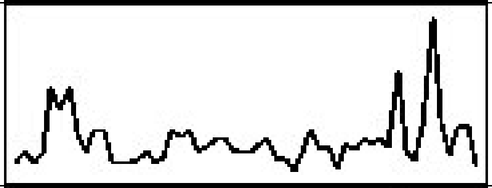
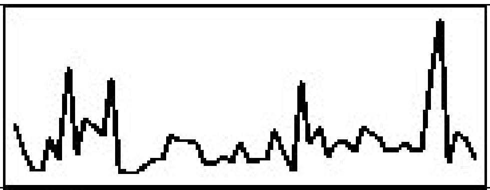
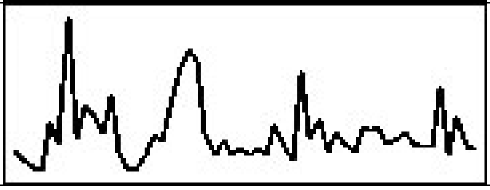
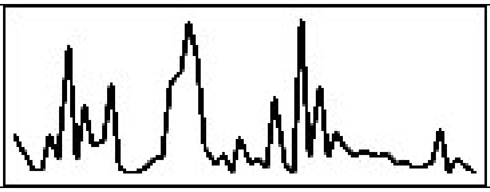
There were no common patterns between alkalinity, pH, and dissolved lead and copper release. Dissolved lead release was similar to dissolved copper except that copper stayed higher for longer and then dropped to a lower value and continued to decrease along with lead.

Parameter	Sparkline	
Total Phosphorus		in flowing water influent to the monitoring station
Ortho-phosphate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

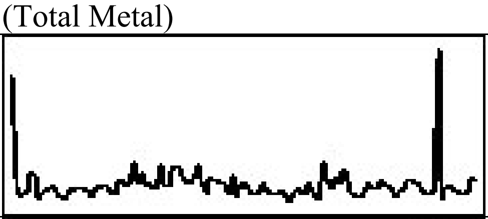
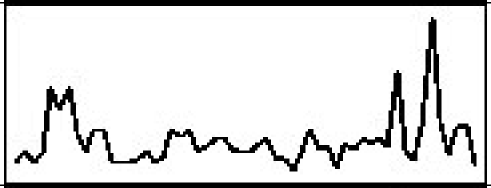
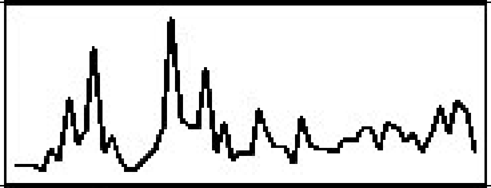
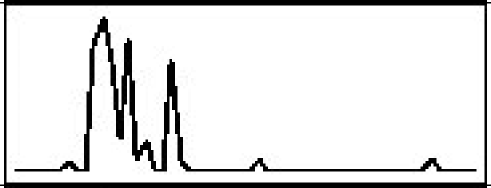
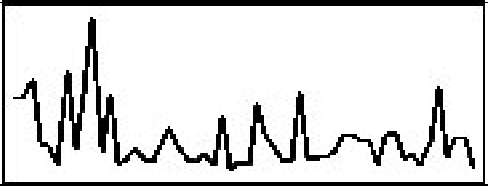
Dissolved copper was possibly related to total phosphorus in that both stayed high at first and then dropped greatly.

Parameter	Sparkline	
Chloride		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

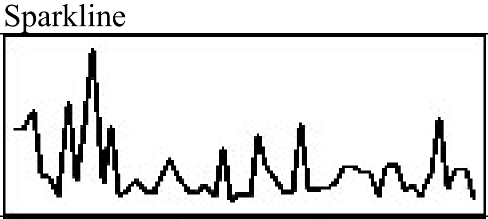
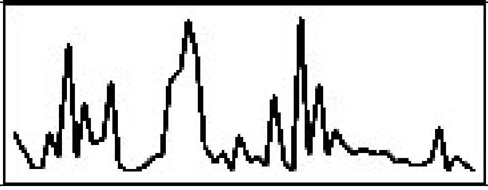
Chloride and sulfate appeared to be somewhat related but did not trend with dissolved lead and copper release.

Parameter	Influent Flowing Water (Total Metal)	Copper Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum	Below detection limit	Below detection limit
Copper		

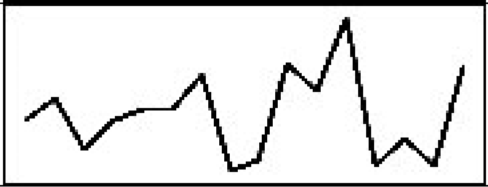
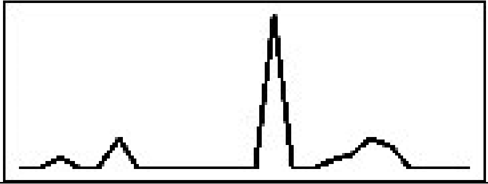
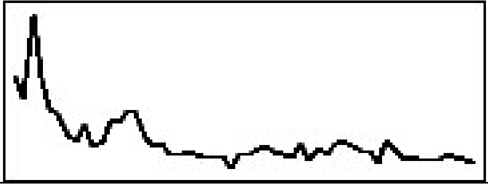
Particulate copper released with particulate iron and manganese in the copper test chamber. Iron and manganese trended together in the system water.

Parameter	Influent Flowing Water (Total Metal)	Lead Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum	Below detection limit	
Lead		

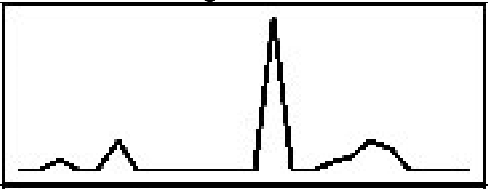
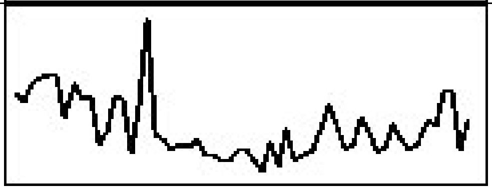
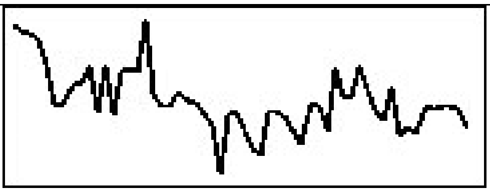
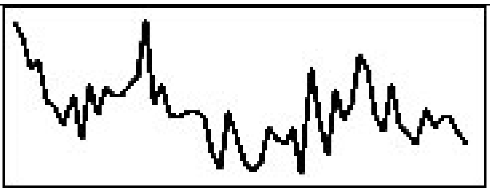
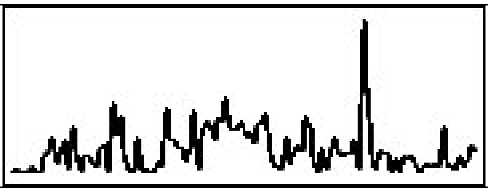
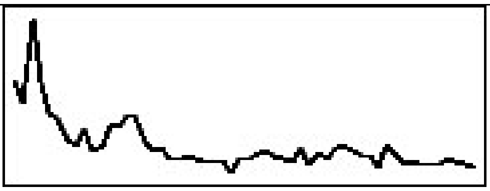
Particulate lead was released with particulate iron and manganese in the lead test chamber. Particulate aluminum followed a different pattern and was also very low. Iron and manganese trended together in the system water.

Parameter	Sparkline	
Particulate Lead		in stagnating lead test chamber water
Particulate Copper		in stagnating copper test chamber water

Particulate lead and copper were similar in release patterns.

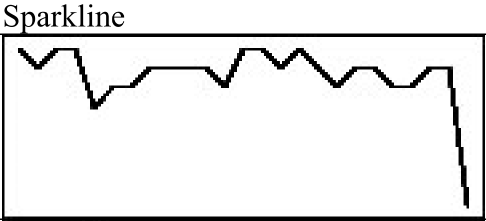
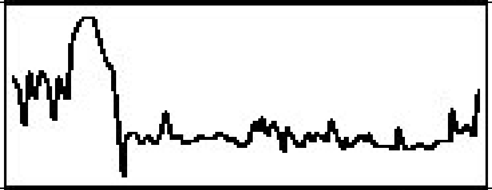
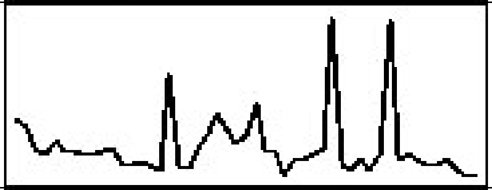
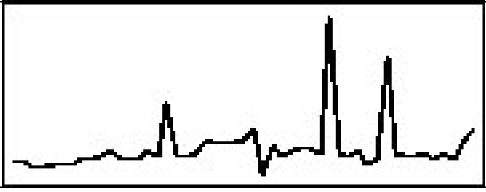
Parameter	Sparkline	
Ammonia		in flowing water influent to the monitoring station
Nitrite/ Nitrate		in flowing water influent to the monitoring station
Dissolved Organic Carbon		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

No common patterns were seen with nutrients and dissolved lead and copper release.

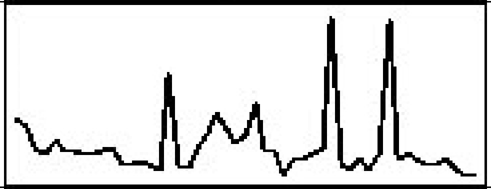
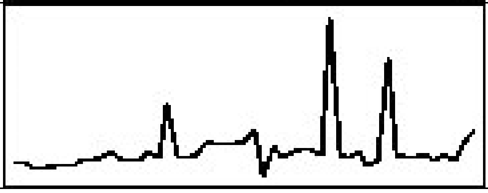
Parameter	Influent Flowing Water	Test Chamber Stagnating Water
Dissolved Organic Carbon		
Microbiological Population		 Lead Test Chamber
		 Copper Test Chamber
Disinfection		
Dissolved Lead		 Lead Test Chamber
Dissolved Copper		 Copper Test Chamber

There was correlation between microbiological population and dissolved lead and copper release in that the population started high and dropped to a lower general level. The microbiological population showed a second small increase later in monitoring period. Dissolved lead and copper release slightly increased at the same time.

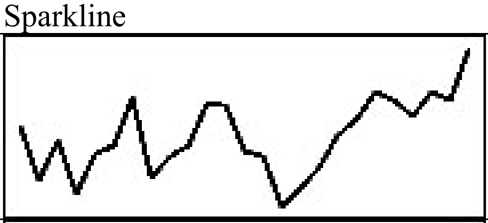
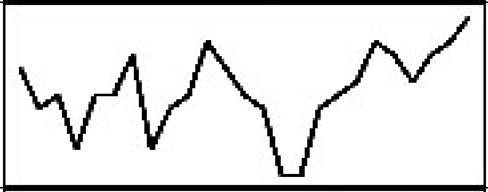
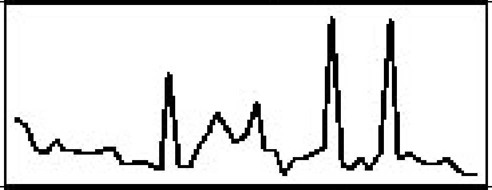
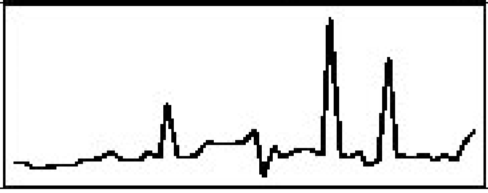
WATER SYSTEM H1

Parameter	Sparkline	
Alkalinity		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

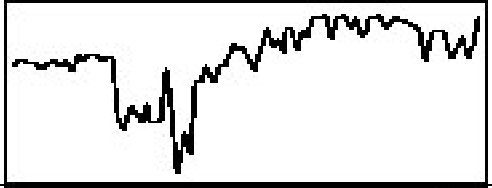
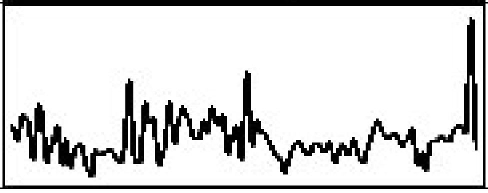
There were no common trends between alkalinity, pH, and dissolved lead and copper release. Dissolved lead release was similar to dissolved copper release.

Parameter	Sparkline	
Total Phosphorus		in flowing water influent to the monitoring station
Ortho-phosphate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

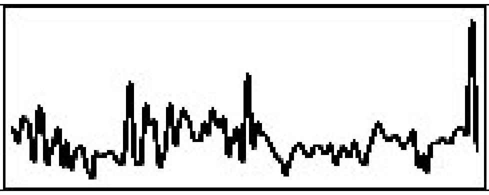
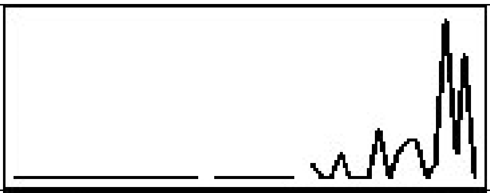
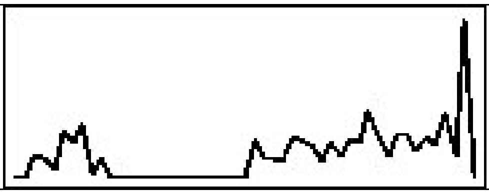
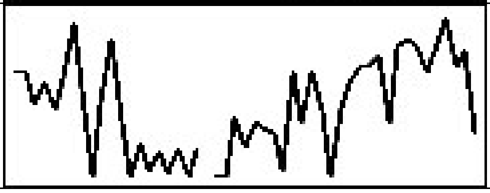
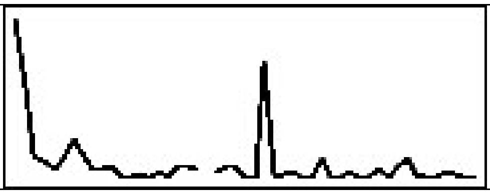
There were no common trends between total phosphorus/orthophosphate and dissolved lead and copper release.

Parameter	Sparkline	
Chloride		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

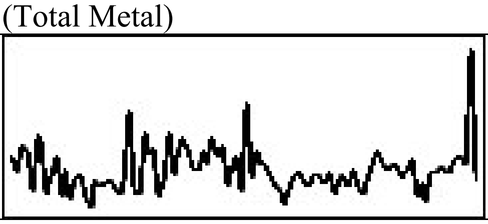
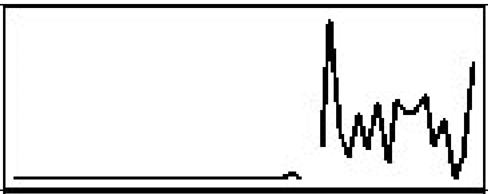
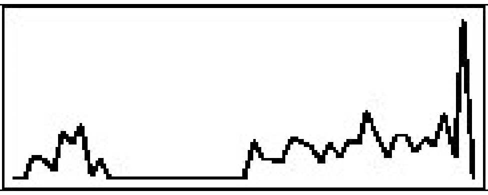
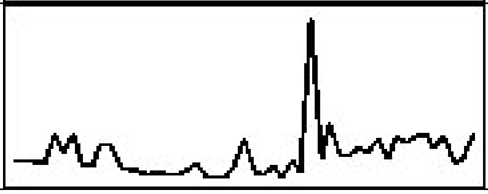
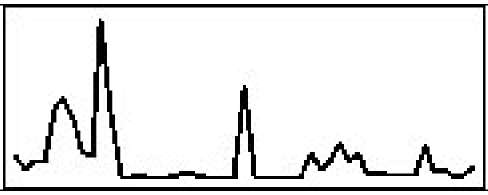
Chloride and sulfate trended together. They did not appear to trend with dissolved lead and copper release.

Parameter	Sparkline	
Oxidation/ reduction potential		in flowing water influent to the monitoring station
Conductivity		in flowing water influent to the monitoring station
Turbidity		in flowing water influent to the monitoring station

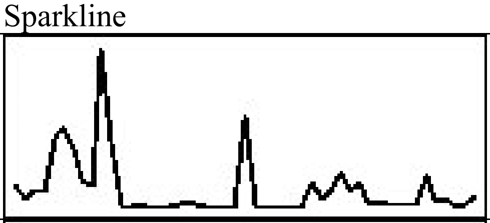
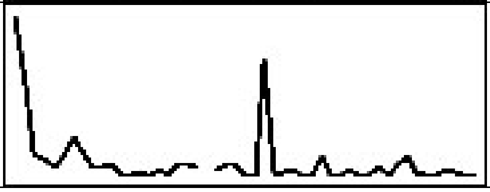
No common trends could be seen between ORP, conductivity, and turbidity.

Parameter	Influent Flowing Water (Total Metal)	Copper Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron	Near detection limit	
Manganese		
Aluminum	Near detection limit	Near detection limit
Copper		

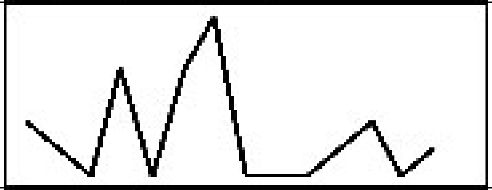
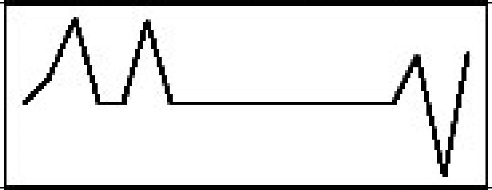
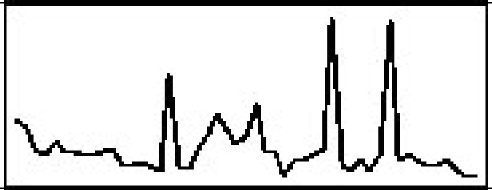
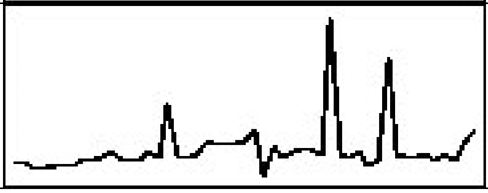
Trends could not be determined between particulate iron and manganese and particulate copper release.

Parameter	Influent Flowing Water (Total Metal)	Lead Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron	Near detection limit	
Manganese		
Aluminum	Near detection limit	Near detection limit
Lead		

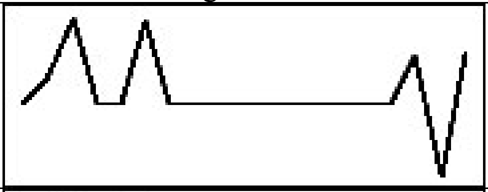
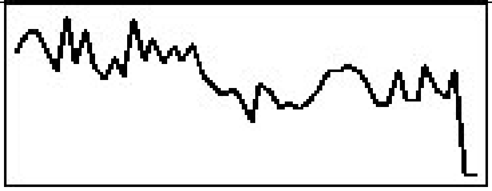
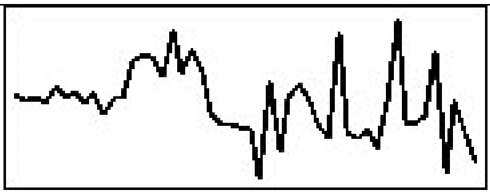
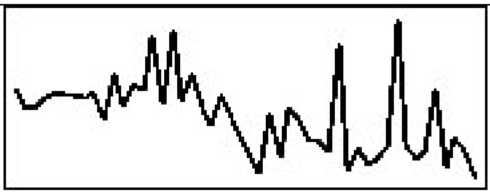
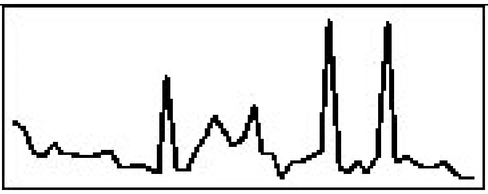
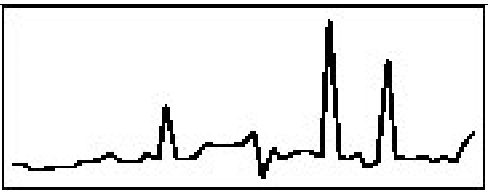
There were possible trends between particulate lead release and particulate iron and manganese.

Parameter	Sparkline	
Particulate Lead		in stagnating lead test chamber water
Particulate Copper		in stagnating copper test chamber water

Particulate lead release appeared to be similar to particulate copper release.

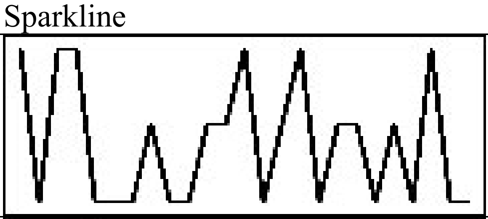
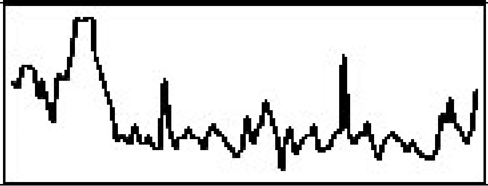
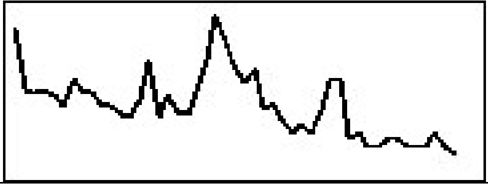
Parameter	Sparkline	
Ammonia		in flowing water influent to the monitoring station
Nitrite/ Nitrate		in flowing water influent to the monitoring station
Dissolved Organic Carbon		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

Nitrite/nitrate trended oppositely to dissolved organic carbon. The nutrients did not appear to trend with dissolved lead and dissolved copper release.

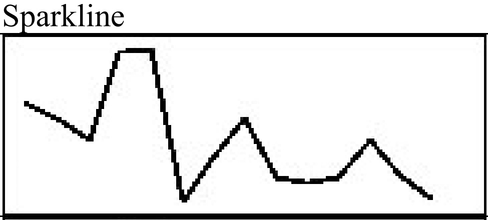
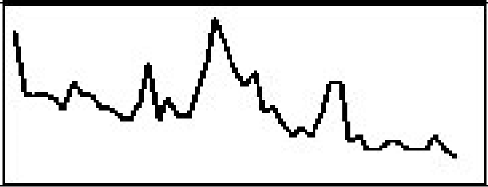
Parameter	Influent Flowing Water	Test Chamber Stagnating Water
Dissolved Organic Carbon		
Microbio-logical Population		 Lead Test Chamber
		 Copper Test Chamber
Disinfection		
Dissolved Lead		 Lead Test Chamber
Dissolved Copper		 Copper Test Chamber

Dissolved lead and dissolved copper release trended with microbiological populations in their test chambers. Disinfection increased as microbiological population dropped.

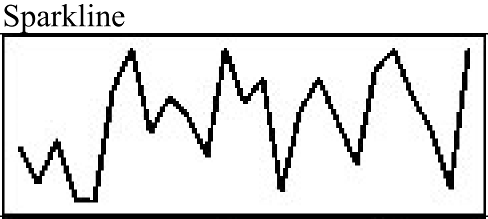
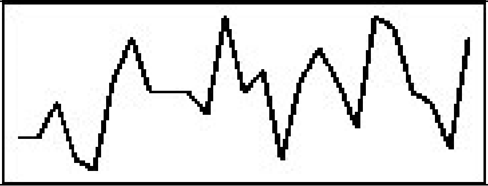
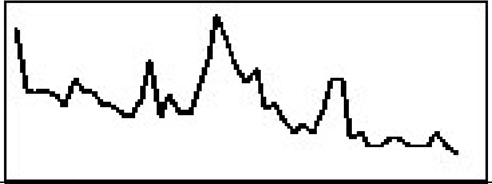
WATER SYSTEM H2

Parameter	Sparkline	
Alkalinity		in flowing water influent to the monitoring station
pH		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

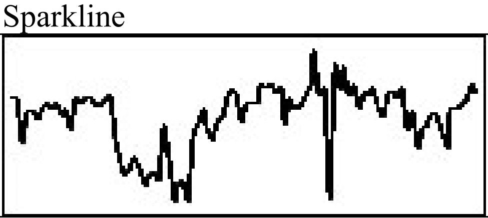
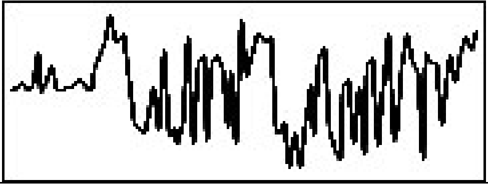
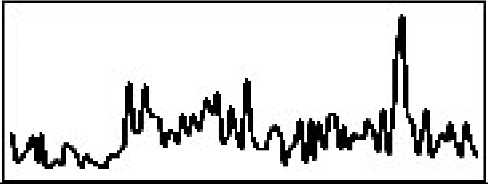
There were no common trends between alkalinity and pH and dissolved lead and dissolved copper release.

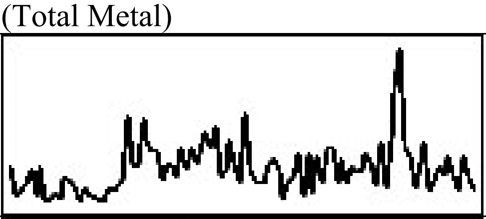
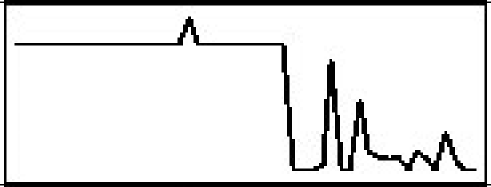
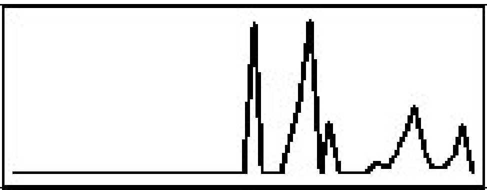
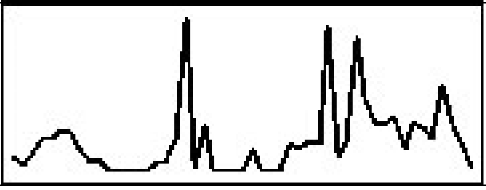
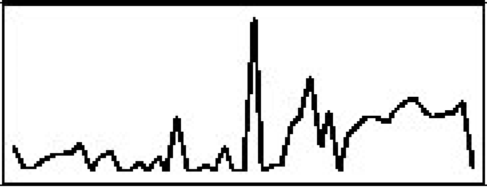
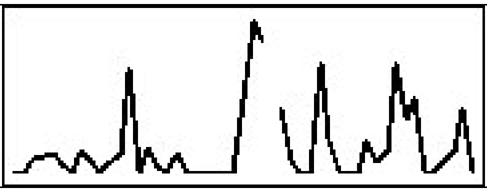
Parameter	Sparkline	
Total Phosphorus		in flowing water influent to the monitoring station
Ortho-phosphate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

Dissolved copper and especially dissolved lead release trended inversely to orthophosphate.

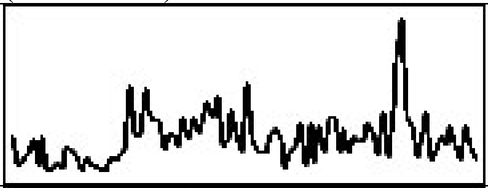
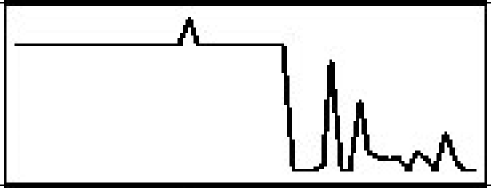
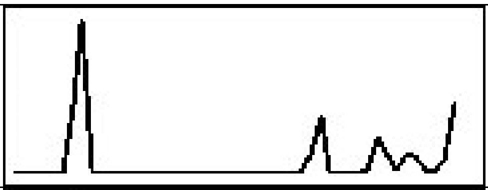
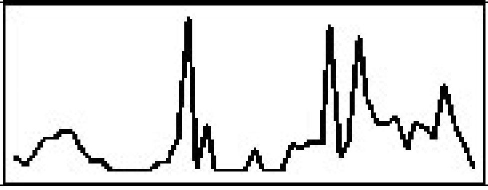
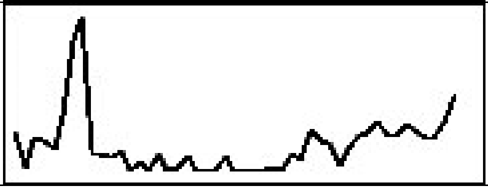
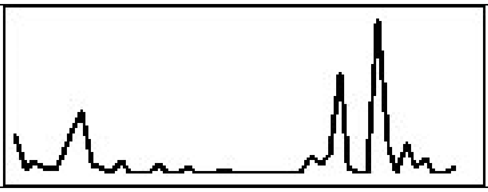
Parameter	Sparkline	
Chloride		in flowing water influent to the monitoring station
Sulfate		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

Chloride and sulfate trended together but were not related to dissolved lead and copper release.

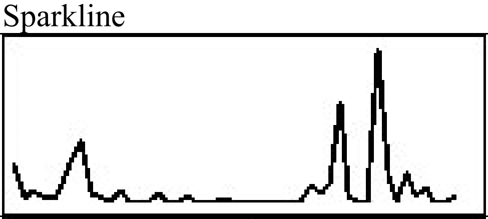
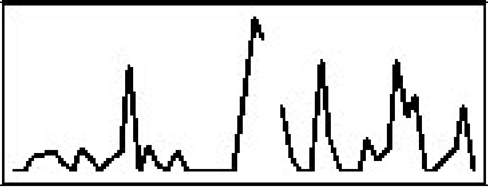
Parameter	Sparkline	
Oxidation/ reduction potential		in flowing water influent to the monitoring station
Conductivity		in flowing water influent to the monitoring station
Turbidity		in flowing water influent to the monitoring station

Parameter	Influent Flowing Water (Total Metal)	Copper Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum	Near detection limit	
Copper		

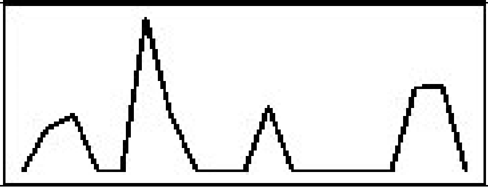
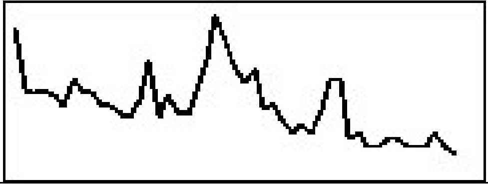
Particulate copper trended with particulate iron and manganese release.

Parameter	Influent Flowing Water (Total Metal)	Lead Test Chamber Stagnating Water (Particulate Metal)
Turbidity		
Iron		
Manganese		
Aluminum	Near detection limit	
Lead		

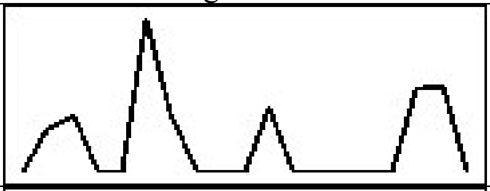
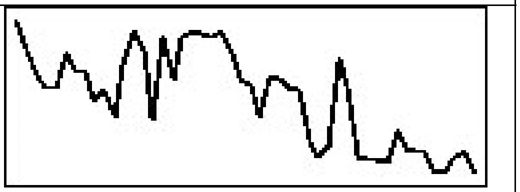
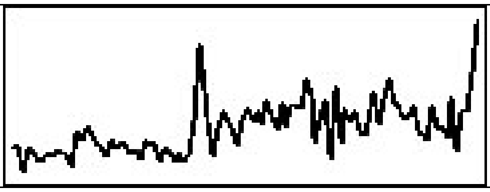
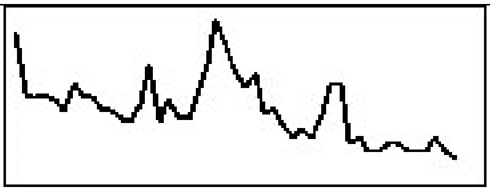
Particulate lead trended with particulate iron and manganese release.

Parameter	Sparkline	
Particulate Lead		in stagnating lead test chamber water
Particulate Copper		in stagnating copper test chamber water

Particulate lead and copper release were somewhat similar

Parameter	Sparkline	
Ammonia		in flowing water influent to the monitoring station
Nitrite/ Nitrate		in flowing water influent to the monitoring station
Dissolved Organic Carbon		in flowing water influent to the monitoring station
Dissolved Lead		in stagnating lead test chamber water
Dissolved Copper		in stagnating copper test chamber water

Dissolved lead and copper release did not trend with nutrients.

Parameter	Influent Flowing Water	Test Chamber Stagnating Water
Dissolved Organic Carbon		
Microbiological Population		 Lead Test Chamber
		 Copper Test Chamber
Disinfection		
Dissolved Lead		 Lead Test Chamber
Dissolved Copper		 Copper Test Chamber

Dissolved lead release trended with microbiological populations in the lead test chamber.

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ABBREVIATIONS

ATP	Adenosine triphosphate
CSMR	Chloride to sulfate mass ratio
DOC	Dissolved organic carbon
EPA	U.S. Environmental Protection Agency
LCL	Lower control limit
LCR	Lead and Copper Rule
LOD	Limit of detection
NPDES	National Pollution Discharge Elimination System
ORP	Oxidation Reduction Potential
PRS	Process Research Solutions
TCR	Total Coliform Rule
TMDL	Total Maximum Daily Load
UCL	Upper control limit
WDNR	Wisconsin Department of Natural Resources
WPDES	Wisconsin Pollution Discharge Elimination System
WPSC	Wisconsin Public Service Commission
WWTF	Wastewater treatment facility