COMMERCIAL BUILDING WATER QUALITY: DETECTING CHEMICAL AND MICROBIAL CHANGES, THEIR CAUSES, AND EVALUATING REMEDIAL ACTIONS

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ABSTRACT

In the U.S, more than 5.6 million commercial buildings are in operation and some include offices, schools, and childcare centers. These large buildings have complex indoor plumbing and often drinking water chemical and microbiological safety hazards can go undocumented. Generally, the larger the building's square footage, the greater number of building occupants potentially exposed to the drinking water and greater amount and complexity of indoor cold and hot water piping and appurtenances. Because commercial buildings routinely undergo periods of low to no water use (e.g., holidays, weekends) cold and hot water can stagnate in the plumbing. This stagnation can allow for chemical and biological drinking water quality safety to deteriorate. This thesis work was designed to examine water safety challenges in school, childcare center, and office buildings to address existing knowledge-gaps.

The study described in Chapter 1 was conducted to better understand the risks of elevated copper levels at U.S. schools and childcare centers. Study goals were to: (1) understand occurrences of copper in school and childcare center drinking water systems, (2) review acute and chronic health impacts associated with the ingestion of copper contaminated water, and (3) examine the effectiveness of remedial actions to address copper in drinking water. Of the more than 130,000 schools and 856,000 childcare centers in the U.S., only about 1.7% of all those facilities had copper drinking water testing data recorded in a federal Safe Drinking Water database since the database was created in 1992. Of these facilities that were designated public water systems, about 13% (2,332) had reported a copper drinking water exceedance. Over a period of 30 years, very few studies have been conducted to document copper levels in schools and childcare centers. Available studies reported widely different sampling protocols and remedial actions. Flushing copper contaminated water from plumbing was the most evaluated remedial action, but flushing sometimes needed to be repeated indefinitely because copper exceeded safe limits within hours after flushing stopped. In-building water treatment with ion exchange systems and orthophosphate corrosion inhibitor addition have been used. At present, there is limited data from testing for copper in schools and childcare centers as well as studies to aid building managers in identifying and remediating copper occurrences.

The study described in Chapter 2 was designed to better understand chemical and microbiological quality in a green office building due to weekend stagnation events (~60 hours per

event). Specific goals were (1) to investigate characterize disinfectant, pH, as well as heavy metal and microbial contaminant levels at the building point-of-entry and fixtures throughout the building, (2) understand how water quality varied spatially and by fixture use frequency, and (3) investigate the effectiveness of remedial actions on removing the water quality problems identified. As-built plumbing drawings were used to create a sampling plan and flushing plan. The total chlorine concentration decreased during stagnation ($p < 0.05$) and was highest at the building entry point (max 0.8 mg/L), and lower throughout the building (max 0.28 mg/L). Total cell counts were greater on Mondays compared to Fridays ($p < 0.05$). *Legionella* spp. was highest at the fixture with zero water use recorded during the study. Copper and lead levels throughout the building increase over the weekend ($p < 0.05$). Copper exceeded the U.S. federal health-based drinking water limit (1.3 mg/L) at 4 of the 12 tested locations. These locations all branched off the same riser. Manual fixture flushing temporarily reduced copper levels, but copper rebounded quickly prompting the need to flush fixtures every 19 hours. Results showed that drinking water testing should be required for building water systems before occupancy permits are issued, and after an extended stagnation period to understand worst case conditions. Testing should include disinfectant level, copper, lead, and legionella.

This thesis research found that a general lack of water testing data for existing office, school, and childcare center buildings inhibited a wider understanding of water safety risks. It is recommended that building officials adopt water testing as a requirement for building occupancy certificates. Testing should also be conducted periodically during the life of the buildings especially after unusually long stagnation periods (e.g., shutdowns or holiday breaks), and in buildings where children or other sensitive populations (e.g., elderly or people with underlying conditions) are occupants. Testing should include disinfectant level, copper, lead, and legionella at the point of entry and multiple locations throughout the building, depending on fixture use and building occupants. Without water testing, occupants may continue to be exposed to water that does not meet federal safe drinking water limits and go undetected. If contamination is found, building managers should review the flushing plan and potentially consider point of use water treatment to address short- and long-term water safety problems.

1. COPPER IN SCHOOL AND CHILDCARE CENTER DRINKING WATER: A REVIEW OF THE HEALTH EFFECTS, CHEMISTRY, OCCURRENCE AND REMEDIATION

1.1 Abstract

The study described in Chapter 1 was conducted to better understand the risks of elevated copper levels at U.S. schools and childcare centers. Study goals were to: (1) understand occurrences of copper in school and childcare center drinking water systems, (2) review acute and chronic health impacts associated with the ingestion of copper contaminated water, and (3) examine the effectiveness of remedial actions to address copper in drinking water. Of the more than 130,000 schools and 856,000 childcare centers in the U.S., only about 1.7% of those facilities had copper drinking water testing data in a federal Safe Drinking Water database created in 1992. Of the facilities designated public water systems, about 13% (2,332 of 6,419) had reported a copper drinking water exceedance. Over a period of 30 years, very few studies have been conducted to document copper levels in schools and childcare centers. Available studies reported widely different sampling protocols and remedial actions. Flushing copper contaminated water from plumbing was the most evaluated remedial action, but was not found to be reliable because copper quickly rebounded when flushing stopped. In-building water treatment with ion exchange systems and orthophosphate corrosion inhibitor addition have been used. At present, there is limited data from testing for copper in schools and childcare centers as well as studies to aid building managers in identifying and remediating copper occurrences.

1.2 Introduction

Hydration is critical to child development, and children are fundamentally dependent on safe drinking water for cognitive and physical health. More susceptible to dehydration than adults, children depend on adults for hydration (Bar-Or et. al., 1980). The greater skin surface area to body mass ratio of children, in comparison to adults, allows for greater water loss through their skin (Bar-Or, 1989; D'Anci et. al., 2006). Mild dehydration can affect the cognitive development of a child, such as decreased visual attention and short-term memory (D'Anci et. al., 2006;

Edmonds and Jeffes, 2009; Edmunds and Burfurd, 2009; Benton and Burgess, 2009). For these reasons drinking water access to children is critical.

To help ensure proper hydration for children, the U.S. Department of Agriculture implemented the National School Lunch Program (NSLP) in 2011, which required participating schools to provide water at mealtime (section 9. [42 U.S. code § 1758] (USDA, 2011). In 2016, the Child and Adult Care Food Program (CACFP) was added to NSLP to require childcare centers to supply access to water throughout the day (section 17. [42 U.S. code § 1766]) (USDA, 1996). These programs do not have requirements for water testing before allowing access. Methods of access include "water pitchers and cups on lunch tables, a water fountain or a faucet that allows students to fill their own bottles or cups with drinking water" (USDA, 2011). Regulated under the Safe Drinking Water Act (SDWA), the U.S. Environmental Protection Agency (USEPA) reported drinking water for approximately 8,000 U.S. school and childcare centers is provided by a public water system (PWS) that is owned by the school or childcare center (i.e., onsite water source such as drinking water well and serve more than 25 people) (USEPA, 2010; NCES, 2016). All other school and childcare centers, approximately 98,000 and 500,000 respectively, receive their drinking water from a PWS served by a community water system. For schools and childcare centers that do not own their own PWS, testing school drinking water inside the building, before the building is occupied and during the life of the building, is not common (USDA, 2011).

The limited number of schools and childcare centers that own their PWS (i.e., they are supplied an independent well) must follow the federal lead and copper rule (LCR) requirements initially published in 1991 and revised in 2021, 30 years later. The regulation 40 CFR (Code of Federal Regulation) part 141 - National Primary Drinking Water Regulations subpart I (40 CFR §§ 141.80-141.86) is dedicated to the control of lead and copper (USEPA, 1991; USEPA, 2021). Schools and childcare centers that own their own PWS are categorized as non-transient or non-community. As of the last revision, schools must initially sample every 6 months, once the law is fully in action in 2024. Sampling consists of a first-draw sample after 6 hours of stagnation (not overnight or weekend stagnation), with a 1 L wide mouth bottle for copper. Sampling requirements will vary slightly based on service line and distribution system pipe material, size of population served and access to sampling locations. The number of sampling locations is based on the population size and which locations are representative of the plumbing and should avoid point of use (POU) or point of entry (POE) treatment devices (USEPA, 2021). The school will follow a

reduced (annual, triennial or every nine years) monitoring timeline, based population size, water quality, and risk of exceedances after the initial two consecutive 6 month periods if they qualify. Qualifying PWSs, for reduced monitoring, have optimal water quality (based on a range determined during the initial 6-month sampling for that specific PWS), and no lead or copper exceedances. If copper or lead exceedances are found, corrosion control treatment or source water treatment may need to be implemented followed by consecutive sampling. Though, unlike lead, copper does not require public education (i.e., notifying the patrons of the building of the exceedances). Also, if lead is the only persistent issue, copper sampling may be reduced in frequency in comparison to lead.

Copper leached from copper-containing plumbing materials can pose acute and chronic health-related concerns. The federal health-based, maximum contaminant level goal (MCLG) for copper in drinking water is 1.3 mg/L, which is called an action level (AL) under the lead and copper rule.[12-15] This threshold is based on acute health effects reported in Wylie (1957) that include abominable pain, gastrointestinal illness. The 1.3 mg/L AL was determined by taking the lowest copper concentration reported by Wylie (5.3 mg/L). The sample was taken from a cocktail in a copper tumbler, that had been sitting in the refrigerator for about two hours. The 5.3 mg/L concentration was then divided by an uncertainty factor of 2 to achieve a maximum contamination level (MCL) of 2.65 mg per 2 L (Knobeloch et. al., 1994; Fitzgerald, 1998). A metallic or bitter taste can be detected from 1 to 5 mg/L (WHO, 2004; USEPA 1979; Pizzaro et. al., 2001; Dietrich et. al., 2004; Health Canada 2019). Also, when copper concentrations are higher the water may turn blue/green in color, depending on the particulate size of the copper by-product deposited in the water. Concentrations between 3 to 10 mg/L can cause the change in color (Barceloux and Barceloux, 1999; Edwards et. al., 2000)

The overall goal of this review was to better understand the current knowledge associated with copper in school drinking water and supply recommendations for schools and childcare centers seeking to identify and address copper contamination in their buildings. Specific aims were to examine: (1) the existence of copper in school and childcare center drinking water, (2) review acute and chronic health impacts associated with the ingestion of copper contaminated water, (3) summarize copper school drinking water occurrence studies, and (4) examine the effectiveness of remedial actions to address copper in drinking water.

1.3 Methods

The authors reviewed the peer-reviewed and grey literature, federal and state government resources, as well as reports produced by the *U.S. National Academies of Science Engineering and Mathematics*. Keywords used during the search included copper, school, copper corrosion, drinking water, and copper health. Databases used were primarily Web of Science and Google Scholar. Very few water testing studies were found for U.S. schools, so the literature search was expanded to other countries where studies were found, including Canada and Saudi Arabia. U.S. federal and state regulations, as well as school water sampling results were found on available local and state government websites and were analyzed. Other efforts involved identifying published media reports regarding school water sampling results and industry POU and POE water treatment device literature.

1.4 Results and Discussion

1.4.1 Sources and Factors Applicable to Copper Occurrences in Schools

Copper in drinking water can originate from well materials, piping, tubing, tanks, and valves (Lytle and Schock, 2000; Barn et. al., 2014; Ra et. al., 2020) and can even be added to control other contaminants such as *legionella* in hot water systems (Liu et. al., 1994; Mietzner et. al., 1997; Stout et. al., 1998; Stout and Yu, 203; Springston and Yocavitch, 2017). Even when plastic piping is used, copper can leach from brass valves and fixtures (Sarver and Edwards, 2011; Huang et. al., 2019). Copper is susceptible to uniform and non-uniform (pitting) corrosion. As a result, "scale" made up of copper minerals and potentially other constituents can form on the inside wall of the pipe (Ferguson et. al., 1996; MWH, 2005). This scale can be a source of particulate copper in the case of hydraulic sheering and other disturbances. Copper can also dissolve into the water from scale due to changes in environmental conditions (Merkel et. al., 2002; Calle et. al., 2007).

In oxic and disinfected drinking waters, Cu^{2+} [Cu(II)] mineralogy and chemistry largely controls copper release into the water (Ferguson et. al., 1996; MWH 2005). The relationship between Cu(II) solubility in tap water and important water quality parameters such as pH and dissolved inorganic carbon (DIC) are well established (Schock et. al., 1995a; Schock et. al., 1995b; Ferguson et. al., 1996). For example, Cu(II) solubility decreases with increasing pH, and DIC

complexes in new plumbing have been found to dominate copper speciation above pH 6.5, resulting in increased Cu(II) solubility with increasing DIC (Schock et. al., 1995a) (Figure 1a). Temperature also has an important role in copper solubility and water quality (Boulay and Edwards, 2001; Rushing and Edwards, 2004).

The prediction of copper levels in tap water is complicated by the reported aging phenomena of copper minerals. Over time (years to decades), passivating films on copper pipes build and change, and as a result, associated Cu(II) solubility decreases (Schock et. al., 1995a; Lagos et. al., 2001; Edwards et. al., 2002; Turek et. al., 2011). The cupric hydroxide model provides a conceptual understanding of copper solubility changes as Cu(II) solids age in water (Schock et. al., 1995a). The model proposes that Cu(II) solubility-controlling solids on the surface of copper plumbing "age" from a relatively soluble copper solid to an insoluble one. The aging process of copper most likely involves the re-crystallization and dehydration of relatively soluble copper hydroxide, $Cu(OH)_2$, or possibly georgeite (Lytle et. al., 2019), $Cu_2(CO_3)(OH)_2 \cdot 6H_2O$, into less soluble tenorite, CuO, and the slow formation of malachite, Cu_2CO_3OH, in pH ranges below the general stability boundary of tenorite (Figure 1b). Given the importance of plumbing age on copper levels at the consumer's tap and water quality impact on Cu(II) solubility, worst case copper levels can be anticipated in relatively new homes and buildings plumbed with copper plumbing, particularly in elevated DIC and/or lower pH waters in the absence of phosphate corrosion control treatment.

Exactly how the copper aging process, corresponding solubility transformation, water quality and frequency of use all relate in total scale formation is not well understood but scale formation can progress over years to decades. The presence of sulfate, bicarbonate, and orthophosphate can cause immediate changes to the type of solid present in water systems that hold cupric hydroxide or cupric ion solids, which leads to short term reductions in cuprosolvency. For example, at lower pH values, adding orthophosphate rapidly decreases Cu(II) solubility. However, at high pH and over long periods of time, orthophosphate could stabilize higher levels of copper than would naturally occur (Schock et. al., 1995a; Schock and Sandvig, 2009). One such project found that orthophosphate and polyphosphate treatment helped to reduce soluble copper on long time scales (Edwards et. al., 2002). The study also further confirmed that at certain pH values and DIC levels, orthophosphate interferes with the formation of other copper minerals that typically control solubility on the long term; however, short term decreases in copper

concentrations following orthophosphate treatment were also observed in some cases, illustrating the complications involved in making copper phosphate solubility predictions. These possible effects should be considered when trying to reduce the release of copper corrosion by-products from building plumbing.

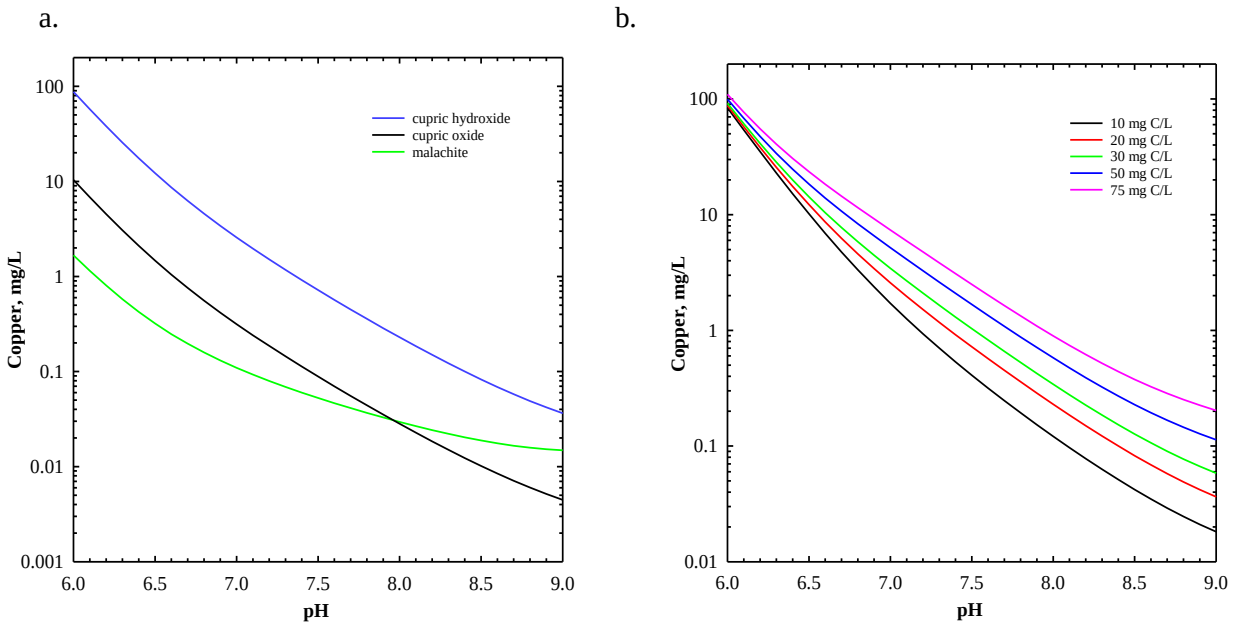

Figure 1.1. The impact of (a) "age" on Cu(II) mineralogy and solubility with pH (20 mg C/L DIC, I= 10 mM), and (b) pH and DIC on the solubility of "new" plumbing (assuming cupric hydroxide as the solubility-controlling solid, I = 10mM). Theoretical simulations were performed using R programming language based on previous work (Schock & Lytle, 1995) and fundamental chemistry principles. Thermodynamic equilibrium model inputs were selected from past work: cupric hydroxide (Schindler, et al., 1965), cupric oxide (Schindler, et al., 1965) and malachite (Symes & Kester, 1984).

1.4.2 High Levels of Copper Can Cause Acute and Chronic Health Impacts

In recent years, attention has re-emerged on the health effects associated with exposure to metals, particularly lead through drinking water exposure. While the health impacts of lead are well recognized and studied, impacts of copper ingestion are recognized but considered less of a concern. Yet, the increased information on violations of the copper standard in water, particularly for children, refocuses the question of copper's health implications.

Copper is an essential nutrient, but high intake of soluble copper salts is associated with gastrointestinal illness and liver toxicity in some susceptible individuals (Wylie, 1957). Humans can digest copper through food but not inorganic dissolved salts via drinking water. When the

intake of copper increases, the body's ability for absorption decreases. Both the intestinal tract and the liver are involved in copper metabolism and storage (Turnlund et. al., 1989; Olivares et al., 2002). There are, however, some susceptible individuals that have a genetic condition that prevents the body from regulating excess copper and thus can develop a syndrome known at Wilson's disease which causes cirrhosis of the liver. The gene associated with this disease is found throughout the human race around the globe at a frequency of 0.3 to 0.7% (Uauy et. al., 2008)

Copper intake for dietary purposes has been estimated at between 0.45 to 1.2 mg for infants to adults (Pennington et. al., 1989). This is often referred to as a dose of mg/kg of weight of the average individual per day. It was in the 1950s that the toxicity of copper associated with gastrointestinal illness, the most common symptom, was noted via an accidental ingestion (15 adult individuals) which was acute and immediate (copper doses were estimated to be of 5.3 to 32 mg) (Wylie, 1957; Hopper and Adams, 1958). As mentioned previously, this report was used by the USEPA to produce a "safe" level of 1.3 mg/L or a level where no observed adverse health effects were noted (NOAEL), achieved by using a 2-fold safety factor and assuming 2 L of water consumed per day (USEPA, 1991; Donohue, 1997). Taylor et. al. (2019) reviewed the health implications of copper ingestion, and some key findings are summarized in Table 1.1.

Table 1.1. Some Health Impacts of Exposure to Copper Via Ingestion

Health impact shown with a single dose	Symptoms	Minimum levels	Population
Acute toxicity, accidental and experimental ingestion	Nausea most common (75%), others include diarrhea, vomiting (food or blood); Stomach pain; Black, "tarry" stools; Headache; Difficulty breathing; An irregular heartbeat.	2.65 mg/L to 4 mg/L: lowest-observed-adverse-effects level (LOAEL) 2 mg/L: no-observed-adverse-effects level (NOAEL)	Human adults
Liver failure Neurotoxicity	Liver malfunction Dementia and anxiety	Toxic accumulation even at low levels, diagnosed at 8 to 50 years of age.	Wilson's disease patients
Reproductive effects	Toxicity occurred at doses that also caused maternal toxicity.	381 mg/L: NOAEL	Rats
Developmental	Maternal toxicity, reduced food intake, abortion, death	6 mg/kg body weight/day: NOAEL	Rabbits
Neurologic	Deficiency or excess of copper vaguely associated with neurodegenerative Alzheimers disease (oxidative damage related to copper and other metal ions)	Drinking <0.01, 2, 4, or 6 mg/day in water for 2 months no effect found.	(n=48 men; 49 women)
Mutagenic, carcinogenic	No evidence of such impact	-	-

1.4.2.1 Waterborne Disease Outbreaks Associated with Copper Reported to the CDC

The U.S. Center for Disease Control (CDC) has published waterborne disease outbreaks from drinking water from 1971 to 2014 (CDC, 2014). The authors found waterborne disease outbreaks in the U.S. associated with the consumption of drinking water containing copper. The number of illnesses reported ranged from a single individual at a home to as many as 74 cases associated with restaurants. Generically, it is often stated in the records that "outbreaks were similar, occurred after highly corrosive water entered the pipes, addressed by addressing corrosive water". For some restaurant and school outbreaks excess copper was released from copper pipes due to back siphonage of CO_2 and carbonated water from soda machines. In 1993, 43 illnesses were identified at a hotel associated with "corrosive" water. New homes and renovated homes with

copper piping were associated with 27 cases over two months, supporting what is known about new homes being susceptible to copper exposure through drinking water via new copper pipes. In 1997, a release of sulfuric acid at a water plant into the water distribution system caused copper release.

Unfortunately, outbreak records contain very little data on what happened and over what time frame (e.g., days). In the 1997 to 1998 surveillance reporting of drinking waterborne diseases the CDC described, a decreased amount of reporting's from previous years (CDC, 1998). The decreased in reporting were attributed to (1) most copper disease outbreaks from drinking water occur in a private home, affecting a small number of people, not making it apparent to public health officials, (2) chemical exposure through drinking water is difficult to identify and associate with a non-specific chemical, (3) these waterborne disease outbreak database is not commonly known or referenced and (4) chemical poisonings may be difficult for physicians to diagnose. Interestingly, since 2005 there have been no reports of copper-related waterborne outbreaks, which could be due to the reasons listed above.

There were outbreaks documented in schools, but the information available was limited. For example, the surveillance report published in 2001, only included a brief description of the waterborne outbreak. Noting consumers mentioned the water was bluish in color, and then symptoms occurred quickly following consumption. No quantitative evidence was given. The outbreak was thought to be caused by an improperly installed anti-scaling device (CDC, 2001). The sparse information over approximately 40 years, makes it difficult to find copper related waterborne disease outbreaks reported in the U.S.

1.4.2.2 Waterborne Disease Outbreaks Reported in Literature

As reported in Knobeloch et. al. (1994), a few studies reported acute illnesses due to the ingestion of copper contaminated drinking water. Copper levels ranged from 0.22 to 1.1 mg/L (notably under the AL) in new and renovated homes in Sweden where three children were ill. Diarrhea was chronic and exposure was associated with low weight (Stenhammer, 1979). In Vermont, U.S., a new house had levels between 2.8 and 7.8 mg/L, which was associated with residents having recurring vomiting and abdominal pain (Spitlany et. al., 1984). Copper concentrations greater than 1 mg/L, in a study that took place in Sweden, were associated with children with vomiting, diarrhea, colic and constipation (Pettersson and Kjellman, 1989). In

Wisconsin, copper and unexplained diarrhea was investigated where it was found that copper levels exceeding 3 mg/L (ranging from 0.09 to 12 mg/L) were likely a common cause of these health impacts (Knobeloch et. al., 1994).

The acute illness caused by copper toxicity has a rapid onset, so it may be reasonable for public health professionals, in particular school nurses, to be educated about impacts of copper drinking water exposure. This would allow for water samples to be collected as a rapid response to concerns. This is a responsive act, that would be useful in identifying whether copper in drinking water was related. Efforts should be focused on preventing copper toxicity by monitoring water systems. Schools that are designated as public water systems with multiple exceedances of the copper action level should be on alert in regard to the problems that could exist for the students. Schools that experience low occupancy or water use (e.g., during breaks, repairs, or shutdowns), should be aware that such conditions could aggravate copper release to the drinking water.

1.4.3 A Knowledge Gap: Occurrences in School Drinking Water

1.4.3.1 Peer-Reviewed Studies

When the authors searched the Web of Science Database for the keywords “lead”, “school”, “drinking”, and “water,” 219 entries were found. When the keyword lead was changed to copper only 32 results were available, only approximately 14% of the total number of results when “lead” was used. Only 12% (4/32) of the results were school case studies associated with copper exposure. When “schools” was replaced with “childcare centers” no results were returned associated with “copper” but returned two for “lead.” Two other results returned for “lead” when “daycare” was substituted for “childcare centers.” Switching “childcare centers” to daycares did not return any results for “copper.” Peer-reviewed studies which investigated and reported copper concentrations in school and childcare drinking water systems have been sparsely published over a period of just about 30 years since the lead and copper rule has been published. Peer-reviewed studies were found for schools in the U.S. (Murphy, 1993; Ra et. al., 2020), Canadian (Barn et. al., 2014; Dore et. al., 2018) and Saudi Arabia (Al-Saleh, 1996). The two U.S. school studies were 27 years apart. Also, in the U.S, one study with a childcare center has been peer-reviewed (Grace et. al., 2012). Another childcare center study was completed in Sweden, but was not translatable (Berg, 1987).

A 1993 study examined copper in 50 schools in New Jersey, USA (Murphy, 1993). Two water fountains per school were sampled monthly after two total stagnation periods, (1) 8 hours overnight and (2) 3 to 5 hours following a 10 minute flush after the first draw sample. The median first draw levels of copper went from 0.26 pre-flush to 0.068 mg/L after the 10 minute flush. By lunch time (3 to 5 hours after the first draw), the median copper level had rebounded. Murphy (1993) concluded that school building water systems should be flushed every 2 to 3 hours and for 5 to 10 minutes to reduce copper levels. Although, it is not clear why the 5 minute minimum was chosen, since the study looked at 10 minute flushes only. Study limitations include the lack of description of type of plumbing materials, volume of water to each fixture, fixture use frequency, and sampling location in relation to the POE.

In Saudi Arabia, drinking water testing was conducted at 32 primary schools (Al- Saleh et. al., 1996). Most of the school buildings were rented households. Two high use drinking water fountains were tested at 27 schools and one water fountain was available to test at five schools for a total of 59 water samples. The copper concentrations found had a range of 2.19 to 106.69 μg/L. Of the elevated samples, using the European Economic Community elevated copper guideline of 100 μg/L, the average copper level was 105.32 ± 1.94 μg/L. No remedial actions were discussed.

Two studies that summarize water testing and remedial actions at numerous schools in Canada are the most extensive to date. From May 2012 to June 2012, water sampling was conducted in 11 schools at a total of 130 locations (Dore et. al., 2018). The majority of service lines were lead; therefore, copper was assumed to originate from building plumbing components. For larger buildings without corrosion control the first draw concentration ranged from 141 to 619 μg/L compared to smaller buildings with corrosion control (13.7 to 63.5 μg/L) and without corrosion control (73.5 to 415 μg/L). Different fixture types, sampling protocols, and building sizes were considered. The investigators reported that concentrations differed between fixtures in the same building (up to 202-fold) and varied (up to 39-fold) at the same tap depending on sampling protocol and the abundance of particulate copper. The maximum copper level reported in the study was 1,566 μg/L, which was discovered at a water fountain. A 30 second flush decreased the copper level by 59% from the first draw sample but elevated levels (above California Public Health Goal [300 μg/L] used by the author) persisted after flushing.

Four schools in Canada also underwent testing in 2014 (Barn 2014). This study analyzed both elementary and secondary schools because “water intake differs by age.” The most frequently

tested school had nine fixtures sampled with pre- and post- flushing samples collected. Fixtures sampled were water fountains, kitchen sinks, and breakroom sinks. Water samples from the water main at the most studied school revealed that the elevated levels of copper were originating from building plumbing. The mean pre-flush copper level in one elementary school was 4.9 mg/L and was reduced to 2.0 mg/L after a 5 minute flush. At a secondary school, the mean pre flush level was 3.2 mg/L and after a 5 minute flush the mean level was 4.3 mg/L. The degree of stagnation before the first-draw sample was taken is unknown. Ten minutes of flushing was recommended to reduce copper levels below the aesthetic Drinking Water Guidelines (DWG), which is 1 mg/L (Health Canada, 2019). The remedial actions suggested to resolve elevated copper levels were: (1) adjusting pH to a less corrosive value, (2) adding corrosion inhibitors; (3) removing lead and copper containing plumbing; (4) implementing a flushing protocol and highly stagnated fixtures, (5) limiting use to only cold water use; (6) restricting use at outlets where there are elevated levels, (7) installing point of use filters, and (8) providing alternated sources of water such as water bottles.

The most recent case study was conducted at a 7-year-old school in Indiana, U.S. in 2018. Test results were interpreted considering building design, sampling, and remediation implications (Ra et. al., 2020). School-wide water contamination was discovered during summer break and continued after students and staff returned in the fall. Water fountains, kitchen sinks, as well as bathroom and laboratory sinks were sampled. Copper levels entering the school from the public water supplier were negligible, but a statistically significant relationship was found between copper concentration and the length of copper pipe between the building entry point and the sampling location. During the summer water outlets further into the building often saw copper exceed 1.3 mg/L (27/54 samples). The maximum copper concentration reported was 2.72 mg/L at a cold-water fixture. Once fall classes began, 37% of cold water taps still exceeded the 1.3 mg/L and the average cold water copper level decreased. The school-wide mean cold-water level during the summer (1.4 mg/L) decreased to 0.66 mg/L when returning in the fall. Interestingly, hot water sampled at the same location for the purposes of another study rarely exceeded 1.3 mg/L (2/54 samples). Flushing water at faucets did not consistently reduce copper concentration, and sometimes copper levels were greater after flushing. The drinking water delivered to the school throughout the study had high DIC levels.

An investigation of a childcare center with reported copper levels above the AL located on Wright-Patterson Air Force Base (WPAFB) in Ohio was reported (Grace, et. al., 2012). The study

took place between October of 2005 and January of 2006 and investigated the effectiveness of orthophosphate as corrosion control in a new building with elevated copper levels associated with high alkalinity water. Additional studies investigating the role stagnation on copper levels in the distribution system were conducted in September 2006. To understand the copper levels of the distribution system before adding orthophosphate, samples were collected biweekly between October and December 2005 at five sampling locations in the building. These sampling locations were strategically decided to try to create a complete profile of the building distribution system, with fixtures at varying distances from the point of entry. The following sampling protocol was implemented: First, the tap was flushed for 3 minutes and then a 250 mL sampled was collected. Next, the water sat stagnant for 12 hours before another 250 mL sample was taken. The sampling before orthophosphate was added revealed that every copper sampled after the 12 hour stagnation was above the AL ranging from 1.4 to 2.4 mg/L. The samples (17) taken after the initial 3 minute flush had copper levels ranging from 0.1 to 2.0 mg/L, with four flushed samples (4/17) having levels above the AL. Orthophosphate was added to the system in January 2006 and copper levels remained above 1.3 mg/L at most locations until March 2006. The stagnation study done in September 2006 revealed that copper concentrations increased the most in the initial 10 hours of stagnation, although the copper levels still increased beyond the 10 hours. In one example, a sample taken after 12 hours of stagnation was 0.8 mg/L and increased to 1.4 mg/L in the following 60 hours, after a total of 72 hours of stagnation. These results highlight the importance of sampling protocol and proper duration of stagnation, as the copper levels continued to increase above the AL after the required 12 hours of stagnation before sampling as also seen in Dore et. al. (2018).

Copper problems in schools and childcare centers have been reported globally, yet the amount of peer-review literature is scarce on the issue. Sampling protocols to determine the copper issues were all different and some of the studies revealed examples of copper problems that could go unnoticed if the building is not properly sampled. When copper levels were found, only one investigator supported flushing for remediation (Murphy, 1993), and follow-up investigations revealed copper rebounded rapidly negating the benefits of flushing or prompted increased copper levels. Most studies provide evidence that flushing is not a reliable method for reducing children's exposure to copper contaminated water in schools (Barn et. al., 2014, Dore et. al., 2018; Ra et. al., 2020) and childcare centers (Grace et. al., 2012). Effective alternative methods to flushing

identified include ion exchange POU treatments and corrosion inhibitor addition (Grace et. al., 2012; Dore et. al., 2018).

1.4.3.2 Government Reported Copper Testing Results

For the limited number of schools and childcare centers who have their own water source or treat water received from a neighboring water system, they may be considered a PWS (depending on population served) and are required to comply with the LCR. Since 1992, 17,653 unique PWSs have been entered into the Safe Drinking Water Information System (SDWIS) and Federal Data Warehouse (Pennino et. al., 2017) as schools and childcare centers. Based on PWS name, it was estimated that schools and childcare centers constituted 12,193 and 5,460 of the systems, respectively. Since 1992, a total of 6,419 AL exceedances have been reported by 2,332 different schools and childcare centers (13.2% of all schools and childcares). Considering only schools and not childcare centers, 5,108 AL exceedances associated with 1,831 schools (15% of all schools in the database) were reported, since 1992.

Separately from PWS requirements, some school districts and state governments have decided to voluntarily test for copper in drinking water (Table 2), often as part of concurrent lead testing programs and because common analytical approaches for lead can be easily adapted to monitor for copper in the same water sample. For example, the Detroit Department of Education, the Massachusetts Department of Environmental Protection, and Maryland's Carroll County Public School system tested for copper in school and childcare centers starting 2016. Alexandria County Public Schools in Virginia began testing for copper in 2019. Table 2 provides a summary of the copper problems found in these schools based upon their voluntary testing efforts. The variety in the presentation of copper issues supports studies that claim water quality varies by regional and geographic location, building and pipe age, and level of education (Patel et. al., 2013; Alexander and Lewis, 2014; Hood et. al., 2014).

Table 1.2. Schools with reported copper levels exceeding the 1.3 mg/L action level based on voluntary testing efforts

State/Year	# of Schools	# of Schools with Copper Levels Above USEPA AL	Remedial Actions	Reference
Detroit, Michigan/ 2016	133	11	• Adding DiHydro Corrosion Control. • Water fountains with onsite filtration systems.	Detroit Department of Health (2016)
Massachusetts/ 2016	~2,000	Schools-344 Childcare Facilities- 7	• Remove fixtures from use. • Flush for 1 minute. • Use cold water only.	MassDEP (2016)
Carrol County Public Schools, Maryland/ 2016	40	4	• Signs were placed on the faucets still in use saying "Not for Drinking/Not for Potable Use." • Fixtures are to be replaced.	CCPS (2016)
Alexandria County Public Schools, Virginia/ 2019&2020	25	Winter 2020- 6 Winter 2019- 9	• Remove the fixture from utility. • Flush the lines (time unknown) and replace aerators. • Retest, and if the issues persist, replace the fixtures or pipes.	ACPS (2020)

In Massachusetts, U.S. approximately 2,000 schools and childcare facilities have participated in copper water testing, of which 2,302 out of the 84,153 fixtures (e.g. water fountains, kitchen sinks, and classroom sinks) tested were either greater than or equal to the 1.3 mg/L AL (maximum 53.2 mg/L at kitchen faucet). These results correspond to approximately 344 schools and 7 childcare centers with copper levels above 1.3 mg/L. The remedial actions implemented included flushing each tap for 1 minute before use, posting 'Do Not Use' signs on fixtures, and only using cold water taps (MassDEP, 2016).

In Michigan, U.S., Detroit's Health Department supported copper testing at schools and childcare centers in 2016. For each of the 133 participating schools, 3 water samples were drawn, including high use water fountains and kitchen faucets. Of the schools, 11 found copper at more than 1.3 mg/L (maximum 15.5 mg/L at a kitchen faucet). As a remedy, Detroit Public Schools

installed ion exchange systems at water fountains and added DiHydro™ corrosion control to the main water system for a few school districts (Detroit Health Department, 2016).

In Maryland, U.S., Carroll County Public Schools participated in testing in late fall 2016 (November-December). Across 40 schools, the maximum level of copper, 10.2 mg/L, was found for a kitchen sink. The fixtures dedicated for drinking water were taken off line, whereas fixtures associated with non-potable water (e.g., primarily water for cleaning) are still in use. Signs were placed on the faucets still in use saying, "Not for Drinking/Not for Potable Use." All fixtures that exceeded any AL were placed on a list for replacement, with drinking water fixtures designated as a priority. After the fixtures are replaced there will secondary testing (CCPS, 2016). As of January 2017, it was reported for 16 of the schools with copper exceedances, the "failed" fixtures removed and replaced (Chapelle, 2017). It is unclear if any of the replaced fixtures had both copper and lead AL exceedances or just an exceedance with one metal.

School water quality test results were reported by the Alexandria County Public Schools in Virginia. In the winter of 2019, 25 schools, childcare centers and academic buildings participated, and 9 organizations had buildings in exceedance of 1.3 mg/L. The maximum copper level reported was 7.73 mg/L at a sink. In the winter of 2020, 6 of the same buildings underwent an additional round of testing, and 3 buildings had copper levels in exceedance of 1.3 mg/L (with a maximum of 11.4 mg/L at a sink). The remedial actions implemented by the school district included: (1) removing the fixtures from use; (2) flushing the lines (time unknown); and (3) replacing aerators. After each remedial action, fixtures were to be retested. If remedial actions like flushing and replacing aerators did not lower copper levels, then the entire fixture was replaced. Finally, if the problem persisted after fixture replacement, it was recommended for the pipes to be replaced (ACPS, 2019).

1.4.4 Beliefs and Perceptions about Copper in Drinking Water with Limited Data

There are divergent data sets as it pertains to school and childcare center water safety. Optimistic studies in the U.S. show 92.6% of middle and 90.4% of high school students believe the drinking water supplied was "clean or very clean." and only 11% of participants across the U.S. in another study believed that water is unsafe in schools (Hood et. al., 2014; Long, 2016). Some other studies are not as positive. Another 2014 U.S. study found 40% of participants did not believe water fountains at school were "clean and safe" and a study in California showed stakeholders

have expressed concerns about drinking water quality in schools and expressed confusion over policy (Patel et. al., 2010; Onufrak et. al., 2014).

Challenges for managing copper contamination in school and childcare centers are likely because of mixed public beliefs of school water quality and access, confusion about what organization handles testing school drinking water, different plumbing codes, and persistent questions over sampling protocol (e.g., how to collect samples, appropriate stagnation periods, how often, and at what locations). According to a 2014 U.S. study, 86.4% of elementary schoolers, 87.4% of middle schoolers and 89.4% of high schoolers were enrolled in schools that "met drinking water requirements" (Hood et. al., 2014). This result is inconsistent with a 2019 study where only 46.5% of schools surveyed in the U.S. flush after stagnation periods, 45.8% do routine testing for lead, and only 25.6% report giving training to custodial and maintenance staff on school drinking water quality (Cradock et. al., 2019). Of the 92% of schools that were serviced by a PWS, only 38.3% communicated results to school faculty and staff, 22.7% communicated results to students' families and only 15.8% shared results with students (Cradock et. al., 2019). A 2016 study in Massachusetts found that only 59% of the Massachusetts schools surveyed met state plumbing codes (Kenney et. al., 2016). Districts that adopt plumbing codes that do not require a ratio of less than or equal to 100 water fountains per one student are more likely to have less accessible drinking water for students (Onufrak et. al., 2014). Though, drinking water is obtained from multiple locations in school buildings besides water fountains (e.g. cafeterias, outdoor spigots and bathroom faucets by sporting groups). Evidence suggests work is needed to determine the degree beliefs relate to the actual state of school plumbing and water safety.

1.4.5 Strategies to Consistently Reduce Copper Levels in Existing Building Water Systems

To reduce the risk of children being exposed to copper contaminated water, a series of approaches have been reported in the literature, though their practicality has gone largely unexplored. When elevated copper levels were found in several school districts, the fixtures were shut down and some were replaced (Massachusetts Department Environmental Protection (MassDEP, 2016; Carrol County Public Schools [CCPS], 2016, Alexandria County Public Schools [ACPS], 2016). Flushing the contaminated water from the plumbing and replacing it with fresh water has been recommended by some (Murphy, 1993). Water treatment device installation (e.g., ion exchange, which is important to note is not activated carbon does not work for copper removal)

or corrosion control measures (i.e., corrosion control agent, chemical addition, ion exchange, and filters) has also been mentioned (Dore et. al., 2018).

Limited data exists to validate their effectiveness, economic consequences, and length of benefit of copper drinking water reduction actions. Building water outlet flushing was the most often mentioned remedial approach (USEPA, 1991, Murphy 1993; Grace et. al. 2012; Barn et. al, 2014; MassDEP, 2016; Dore et. al., 2018; Ra et. al., 2020; ACPS, 2020). The intent of flushing in a school would be primarily to remove copper particulate material and accelerate copper pipe scale age. Multiple studies reported that flushing outlets at a copper piped school did not consistently reduce copper levels at the water outlets, and sometimes copper levels increased in response to flushing (Grace et. al., 2012; Barn et. al, 2014; Dore et. al., 2018; Ra et. al., 2020). Copper was attributed to pipes and fittings throughout the building and the hypothesis that copper contamination was found throughout the entire building water system, not just at select locations. Further, the time needed to completely flush out the water from a large building can take multiple hours (Ra et. al., 2020), and then copper levels can rapidly rebound in as little as 30 minutes therefore requiring additional flushing (Dore et. al., 2018). Flushing approaches also differ based on the building design and volume of water within the distribution system from service line to the furthest tap. The oldest study found was conducted in New Jersey schools in the 1990s and suggested flushing fixtures for 5 to 10 minutes every 2 to 3 hours, with 5 minutes maybe being insufficient for some fixtures (Murphy, 1993). As mentioned, more recent peer-reviewed evidence indicates flushing should not be relied upon to remediate copper contamination. Flushing a school or childcare center is also not trivial and there are limited personnel available. Many persons and hours may be needed per building depending on the plumbing design, and rate of copper rebound to levels above 1.3 mg/L may render the flushing activity meaningless (Patel et. al., 2010; Dore et. al., 2014; Hood et. al., 2014, Ra et. al., 2020). Apart from copper, flushing can have other benefits (Proctor et. al., 2020; MEGLE, 2020; Rhoads et. al., 2020; USEPA, 2020; WADOM, 2020).

The use of POE and POU water treatment technologies have been successfully applied to reduce copper levels in schools, specifically ion exchange and reverse osmosis processes, but are not capable of addressing all copper problems. Importantly, POE and POU treatment processes require validation that they are working and proper maintenance to ensure they continue to perform as desired. As noted in California, the use of POU devices can be costly to schools (Patel et. al., 2010). At present, commercial building water treatment device manufacturers pursue NSF

International certification, which conducts commercial device testing against NSF International device performance criteria. Some commercial devices pertaining to copper removal from drinking water, including ion exchange systems, are associated with NSF International Standard 53 and 58 certifications. The NSF International Standard 53 requires a copper reduction from 3 mg/L to below 1.3 mg/L (NSFI/ANSI, 2015). Table 3 summarizes the testing conditions; the filters undergo a 16-hour testing period, where water containing "3,000 ppb copper" is pushed through the device to determine if the device reduces levels below "1,300 ppb". The product must be tested at the highest and constant flow rate. Notably, under real-world conditions multiple metal ions may be present such as lead, dissolved and particulate copper, and dissolved or particulate organic matter, all of which may influence device performance. In some situations, these contaminants can compete for ion exchange adsorption sites and foul filtration surfaces. Water alkalinity, pH, hardness, temperature and turbidity levels in real buildings can also differ from those which the devices are challenged against. For reverse osmosis treatment, the NSF International Standard 58 certification focuses on total dissolved solids (TDS) reduction, not copper. NSF International Standard 58 does not purport to achieve a health-based reduction of copper like the NSF International Standard 53 (NSF International, 2016). POE and POU water treatment devices should be selected based on understanding the water characteristics of the water to be treated. Several of the school and childcare center water testing studies reviewed indicate copper levels in excess of 3 mg/L. Therefore, the NSF International certified POE and POU devices are not certified to reduce copper levels at those buildings below the 1.3 mg/L health-based limit. No certification standards were found that purport to confirm POE and POU devices can reduce copper to less than 1.3 mg/L when copper is in excess of 3 mg/L.

Table 1.3. Test water quality challenge criterion for copper reduction reported by a product testing laboratory compared to characteristics for natural waters (private wells) and public water systems.

Parameter	NSF International Test Method		Real-World Waters, range	References
	Low pH	High pH		
Alkalinity, mg/L $CaCO_3$	10 to 30	100 to 250	< 50 to > 400	
Hardness, mg/L $CaCO_3$	10 to 30	100 to 250	0 to > 300 mg/L	USGS, 1975
pH	6.5 ± 0.25	8.5 ± 0.25	< 4.3 to > 10	USGS, 2002; Pieper et. al., 2018
Polyphosphate, mg/L as P	< 0.5	< 0.5		
TDS, mg/L	< 100	200 to 500		
Temperature, °C	20 ± 2.5 °C	20 ± 2.5 °C	7 to 26 °C	Whelton et. al., 2014; Salehi et. al., 2020
Turbidity, NTU	< 1	< 1	2.5	

In terms of addressing copper corrosion through an entire school, full-scale water treatment options such as aeration and chemical addition are available and have reliably prevented copper exceedances of 1.3 mg/L when maintained (Kirmeyer et. al., 1994; Lytle and Schock, 1998; Lytle et. al. 1998; Grace et. al., 2012). It is expected that certain conditions will stand-out as being aggressive toward copper: (1) low pH, low DIC water (typical of many New England ground water, for example), and (2) high DIC groundwater (typical of many Midwest ground water, for example). In the case of low pH and DIC source waters, whole school treatment options include basic chemical addition, aeration, and limestone contactors. Aeration is typically reserved for situations where the water has specific chemical composition. As said previously, copper solubility in water is dependent on pH and DIC and DIC sources include, carbonic acid (H_2CO_3), bicarbonate ion (HCO_3^-) carbonate ion (CO_3^{2-}), and carbonate metal complexes (e.g., $CaHCO_3^+$). Dissolved carbon

dioxide (CO_2), theoretically equal to the H_2CO_3* concentration, decreases the pH and increases the corrosivity of the water. By aerating the water (or passing it through a limestone contactor), CO_2 content can be reduced (Edwards et. al., 1996). To kinetically remove the DIC, aeration can be considered when the CO_2 concentration is >4 to 10 mg/L CO_2) prompting low pH (< 7) and high DIC concentration (>5 mg/L C). A case study at a New England 200-person school used a diffused bubble aeration system and was able to reduce copper levels to below 1.3 mg/L (Lytle et. al., 1998). Water from the bedrock well source was suitable for aeration (pH of 6.1 to 6.3, DIC 15 to 18 mg/L C and a CO_2 concentration of 30 to 40 mg/L). At this school, aeration effectively reduced the DIC to 6 to 7 mg/L C and increased the pH to 7.47 ± 0.09, thereby reducing observed copper concentration. When a water is not chemically suitable for aeration, chemical addition can be introduced in the means of orthophosphate. In the case of a childcare center in Ohio, orthophosphate was added at the building entry point, and this reduced copper levels throughout the building (Grace et. al., 2012).

1.5 Conclusion

Children are susceptible to acute and chronic copper toxicity through school drinking water systems. The literature review revealed that few studies have examined copper in school drinking water, including the health effects, occurrence, and chemistry making it difficult to fully understand the potential health risk and validate design and remediation options. In absence of evidence, there are also mixed opinions about water safety. Once a copper contamination problem is found, there is discrepancy between what actions are recommended and observations in the peer-review literature indicating flushing should not be relied upon. Flushing and water treatment installations each require labor and funding making the goal of long-term remediation difficult to study. Furthermore, while a PWS can be in compliance with federal law, the building itself may be delivering copper contaminated water to its faucets.

Due to limited available data for school and childcare center drinking water copper occurrence and remediation, studies should be conducted. Evidence suggests copper contamination in U.S. schools and childcare centers merits more attention. The lack of copper testing for new buildings also should be evaluated. Certain waters (i.e., high alkalinity) may prompt greater copper leaching than others, and thus copper and copper-containing plumbing components may be more susceptible to corrosion. It is likely higher levels of copper in school

drinking water may exist at less frequently used fixtures, after holidays, and where there is low building occupancy. Additional testing efforts for should be focused at schools and childcare centers, to understand the occurrences of copper exceedances, risk to children, and take action to reduce the exposures that pose a serious health risk.

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2. OVER THE WEEKEND: WATER STAGNATION AND CONTAMINANT EXCEEDANCES IN A GREEN OFFICE BUILDING

2.1 Abstract

Water stagnation (~60 hours) in a 2-story commercial office building was studied (January to February 2020) during three weekends. Chemical and biological parameters including pH, total chlorine, metals concentrations, Legionella spp. and total cell count were analyzed to understand the differences in water quality at the building entry point, and at eleven fixtures within the building's copper plumbing. Consistently, the total chlorine concentration decreased over the weekend ($p < 0.05$), was greatest at the building entry point (maximum 0.8 mg/L), and was lowest within the plumbing (maximum 0.28 mg/L). Total cell count levels were much greater on Monday compared to Friday ($p < 0.05$) at every sampling point. Legionella spp. was found to be highest at the fixture with no use recorded during sampling. Throughout the building, copper and lead levels increased over the weekend ($p < 0.05$). Copper exceedances above the federal health-based drinking water limit (1.3 mg/L) were found to be localized to four fixtures, branched from the same riser, that shared a pattern of variable use. Flushing was conducted at one location with consistent copper exceedances but 54 minutes were required to reach the public water supply. Flushing was not deemed a viable copper remediation method as it would need to be repeated every 19 hours at all fixtures to maintain copper below the action level. Drinking water testing should be required for building water systems before occupancy permits are issued, and after an extended stagnation period to understand worst case conditions. Testing should include disinfectant level, copper, lead, and legionella at the minimum.

2.2 Introduction

As of 2018, there were more than 5.9 million commercial buildings in the U.S. and roughly 972,000 were office buildings.[1] In 2019, more than 38,000 office buildings had green certifications from the United States Green Building Council (USGBC).[2] Green buildings are designed to conserve water or reduce the total volume water used compared to conventional buildings. Green buildings are designed by using water efficient fixtures and alternative water supplies. Over the past decade however, some green buildings have been associated with drinking water safety

issues.[3-9] A unique characteristic of office buildings is the decreased occupancy during weekends and holidays, which increases water residence time in building plumbing.[10] This longer residence time potentially increases the likelihood of greater amounts of heavy metals accumulating in the water as they leach from plumbing components. The combination of lower building water use and routine low occupancy periods may enable water quality deterioration.

Water stagnation in plumbing can affect the water's chemical and microbiological quality, and increase public health risks.[10] Common stagnation consequences include decreased disinfectant residual, accumulation of heavy metal and organic compounds due to leaching from the pipes and scaling, and an increase in bacterial growth including opportunistic pathogens.[12-24, 25, 26-32]. While there is no regulated amount of disinfectant residual and bacteria concentration in building water systems, copper and lead have a health-based safe drinking water limit of 1.3 mg/L and the American Academy of Pediatrics recommendation that no lead greater than 1 μg/L lead is safe for consumption.[31-33] To prepare a building plumbing system to code, water chemical and microbiological testing is not required or recommended.[4]

Few studies were found that described water quality and stagnation in commercial buildings. In an institutional building, Lipphaus et. al. (2014) found total cell counts (TCC) and intact cell counts (ICC) increased over one weekend and even more so during a 14-day stagnation period due to a winter holiday shutdown. TCCs and ICCs 100-fold between taps throughout the plumbing. After flushing was applied as a remedial method, it was TCC reductions occurred at cold water taps, but reductions were not as high at hot water taps.[11] TCC increased after a 6 day stagnation in an Illinois institutional building (2018).[14] Water use at different fixtures (e.g., showers, faucets) differed substantially and this may have contributed to the differential water quality at each location. In a new green commercial building in Arizona, as building occupancy increased observed copper levels decreased.[24] Chlorine levels were undetectable in 95% of the first and second draw samples collected.

The goal of the present study was to better understand chemical and microbiological quality in a green commercial office building plumbing due to weekend stagnation. Specific objectives were (1) to investigate characterize disinfectant, pH, as well as heavy metal and microbial contaminant levels at the building point-of-entry (POE) and fixtures throughout the building, (2) understand how water quality varied spatially and by fixture use frequency, and (3) investigate the

effectiveness of remedial actions on removing chemical or biological contaminants from the plumbing that may pose risks.

2.3 Materials and Methods

Water sampling was conducted in January and February 2020 in a 10-year-old, 3-story LEED certified office building (20,200 ft^2), in Indiana. A regulated public water system (PWS) delivered water to the property through a building service line (Figure 2.1). The buried service line consisted of three pipe segments (a 7.62 m [25 ft] galvanized pipe, and two copper pipes, 5.94 m [19.5 ft] and 22.1 m [72.5 ft]) and held 118.5 L [31.5 G]. Once the water entered the building all water traveled through soldered copper piping, a 59.7 L (16 G) water softener (maximum. flow 20 GPM), and then entered trunk and branch pluming with multiple risers to different fixtures. PWS water was used for drinking, appliances, and cleaning, while rainwater was collected and pipes separately for toilet flushing and irrigation. Hot water was created at each fixture with on-demand water heaters (EEMAX® Model: SP4208 and EX1608TC).

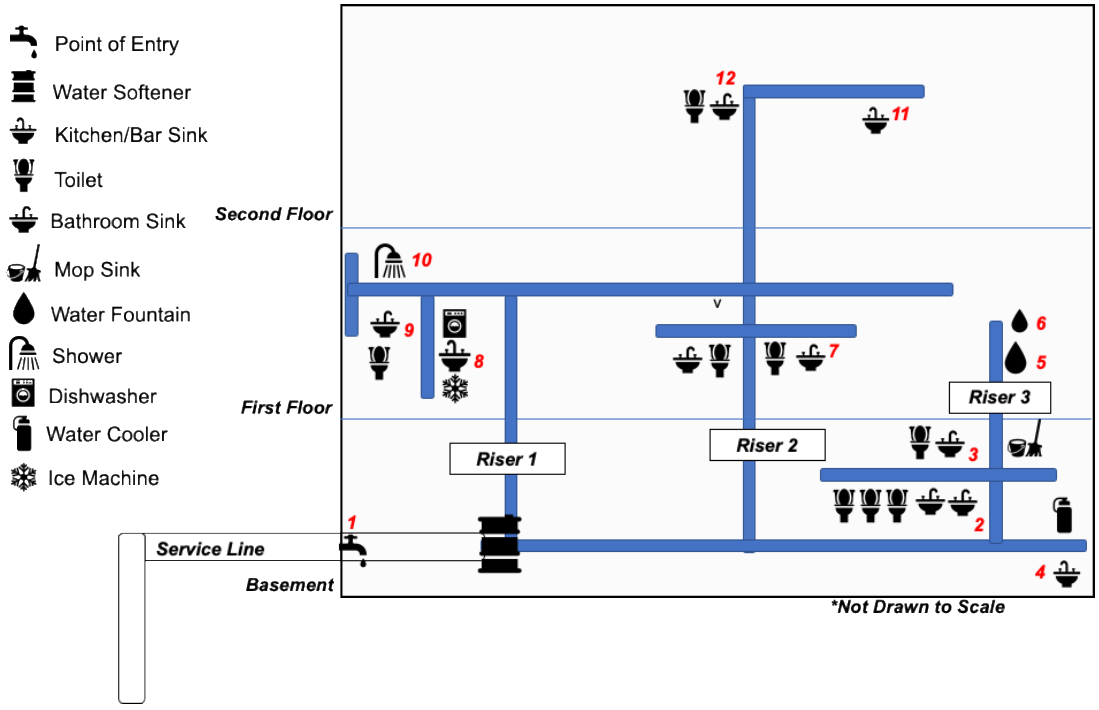

Figure 2.1. The building water system, including service line. Fire systems, irrigation systems (rainwater) are not included. On-demand water heaters are used, so cold water lines provide water almost all the way to sinks.

Twelve locations, including 11 of 18 water use locations and the utility room POE, were sampled over the two month period (Figure 2.1). A description of all water use locations can be found in Table 2.1. The bathroom sinks had motion sensors and only drew water from the thermostatic, on-demand water heaters during use (i.e., no temperature choice). Water for drinking was consumed from kitchen sinks and water fountains. A water cooler (WS 7000 Water Cooler by Wellsys®) connected to potable cold water copper piping (by crosslinked polyethylene tubing) was not sampled routinely, but was sampled once after copper levels greater than 1.3 mg/L were found at other locations.

Table 2.1 Defines the location numbers sampled in Figure 2.1.

Locations Sampled					
Location	***Floor***	***Riser***	***Description***	***Type***	***Volume to Water Main (G)***
1	*B*	*1*	*Point-of-entry (POE) (Not a regular water use point)*	*Cold water*	*31.0*
2	*B*	*3*	*Men's bathroom sink+*	*On-demand hot water w/ set temperature*	*51.0*
3	*B*	*3*	*Women's bathroom sink (1 of 2 in room) +*	*On-demand hot water w/ set temperature*	*51.0*
4	*B*	*3*	*Kitchen sink [double lever]*	*Cold and hot Water (Only cold was sampled)**	*48.2*
5	*1*	*3*	*48'' Drinking water fountain*	*Cold water**	*51.4*
6	*1*	*3*	*36'' Drinking water fountain*	*Cold water**	*51.4*
7	*1*	*2*	*Bathroom sink+*	*On-demand hot water w/ set temperature*	*50.8*
8	*1*	*1*	*Kitchen sink [double lever]*	*Cold and Hot Water (Only cold was sampled)**	*47.7*
9	*1*	*1*	*Bathroom sink+*	*On-demand hot water w/ set temperature*	*47.2*
10	*1*	*1*	*Shower*	*On-demand water heater with variable temperature*	*47.3*
11	*2*	*2*	*Bar sink [Single lever]*	*On-demand water heater with variable temperature**	-
12	*2*	*2*	*Bathroom sink+*	*On-demand hot water w/ set temperature*	*51.1*

2.3.1 Fixture Monitoring

The time of day each fixture was used was recorded on a weekly log sheet by the user. The fixtures were self-monitored from one week before the first sampling event through the end of the study. The timeline in Table 2.2 specifies when self-recording and sampling took place.

Table 2.2 Timeline of the study sampling.

Sampling Day	Sampling Detail
Monday, January 13	*New week of monitoring fixture use.*
Monday, January 21	*New week of monitoring fixture use.*
Friday, January 24	*Sample Event 1* *Start: 5:15 pm*
Monday, January 27	*Sample Event 2* *Start: 6:30 am.* *New week of monitoring fixture use.*
Friday, January 31	*Sample Event 3* *Start: 5:30 pm*
Monday, February 3	*Sample Event 4* *Start: 6:30 am* *New week of monitoring fixture use.*
Friday, February 7	*Sample Event 5* *Start: 5:30 pm*
Monday, February 10	*Sample Event 6* *Start: 6:40 am* *Flushing sampling*

2.3.2 Water Sampling and Analysis

Sampling occurred on Friday evenings and Monday mornings for three weekends (Table 2.2). The order of sample collection for the building began at the POE and proceeded through the building (Table 2.1). Water analysis methods were adapted from Ra et. al. (2020).[9] In total, approximately 2 L of water was collected during each sampling event. Each time a fixture was sampled, 200 to 400 mL beaker was used to collect the first draw sample for analysis of chlorine residual with a HACH® 131 Pocket Colorimeter (DPD Free and total chlorine) and pH probe. Next, two 100 mL high density polyethylene (HDPE) bottles, one holding 0.05 mL of 0.0025 N H_2SO_4

for preservation, were used to collect samples for metals and ions analysis. Metals (Al, As, Be, Cd Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, Zn) were analyzed using an iCAP 7400 Duo inductively coupled plasma- optical emission spectroscopy (ICP-OES) (Thermo Scientific) with an autosampler ASX-280 (CETAC Teledyne). Ions (Br^-, Cl^-, F^-, NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-}, NH_4^+, Ca^{2+}, Li^+, Mg^{2+}, K^+, Na^+) were analyzed using an An Metrohm 940 Professional IC Vario with a 850 Professional Sample Processor. Total organic carbon (TOC) and dissolved organic carbon (DOC) samples were collected next using a 250 mL amber bottle. For preservation 1 mL of HCl was added after collection for TOC/DOC samples. TOC/DOC concentrations were analyzed using a Shimadzu TOC-L CPH/CPN following USEPA method 415.1.[34]A 250 mL amber bottle was used to collect a sample for alkalinity analysis. Alkalinity was analyzed by an acid base titration of 50 mL of sample with 0.0025 N H_2SO_4. The TCC samples were collected using 15 mL falcon tubes and were analyzed using flow cytometry (FCM) by using SYBR Green I dye (SwissResearch method 366.1). BART™ biodetector tests were used to collect two 15 mL samples for nitrifying and denitrifying bacteria. Finally, a sample was collected for qPCR in a 1 L HDPE bottle (with 5 mL of sodium thiosulfate for preservation).

Approximately one liter of this water sample was filtered through polycarbonate filters (Milipore #HTTP047) with 47 mm diameter, and 0.4 μm pore size. DNA extractions were performed as described in EPA Method 1611.[35] Filters were transferred to a 2 mL semi-conical screw-top microcentrifuge tube with 0.3 g of acid-washed, 212 to 300 glass beads (Sigma-Aldrich, #G-1277) and 600 mL AE buffer (Qiagen, Valencis, CA, USA) were added. The tubes were sealed, bead milled at 5,000 reciprocations/minute for 60 seconds and centrifuged at 12,000 x g for one minute to pellet. The supernatants were transferred to clean, low retention, UV treated microcentrifuge tubes, and centrifuged for an additional five minutes. The supernatants were transferred to another clean, low retention micro-centrifuge tubes and stored at -80°C until qPCR analysis. The 23s rRNA of *Legionella* spp., and *mip* genes of *Legionella pneumophila* were enumerated by qPCR using previously published method.[36] The qPCR assays were performed using the StepOne Plus™ real-time PCR System (Applied Biosystems, Foster City, CA). Each assay had six 10-fold diluted standard curve points consisting of genomic *L. pneumophila* strain Philadelphia-1 (ATCC 152D-5) DNA, a non-template control (sterile reagent water), and environmental samples; each sample was tested in triplicate. The duplex *Legionella spp.* and *Legionella pneumophila* qPCR assays were amplified using a 25uL reaction mixture, with five μL

template DNA, five μL of 5 X Perfecta Multiplex qPCR ToughMix (QuentaBio), 500 μM of each primer, and 200 nM of each probe. The thermal cycling protocol was as follows: denaturation for 15 minutes at 95°C, followed by, 45 cycles of 15 seconds at 95°C and 60 seconds at 60°C. The qPCR efficiencies for T1, T2, T3, T4, T5, and T6 *Legionella* 23S rRNA and *L. pneumophila mip* genes were as follows, 90.906, 94.447, 93.182, 94.637, 93.157, and 100.83, respectively. The correlation coefficients of the standard curves were, 0.995, 0.999, 0.992, 0.999, 0.997, and 0.998. The following quality control measures were used, such as, PCR-grade water for negative controls, UV sterilization of PCR equipment, using aerosol-resistant tips, separate work spaces for reagent and sample preparation and amplification.

A water cooler in the basement was sampled for metals analysis when elevated copper levels were found in the building. A small-scale study was done with two purification pitchers, PUR® and ZeroWater®, on the last day of sampling. A 1 L sample was taken from the bathroom sink next to location 7 and was split between the purification system. After purification, the sample was analyzed for metal concentrations as described above.

2.3.3 Statistical Methods

Shapiro-Wilks test was applied to all the testing parameters before further data analysis to test for normality. A non-parametric method Kruskal-Wallis was applied to test for statistical difference between Friday (n = 36) and Monday (n = 36) water quality values. Bivariate Pearson tests were conducted to test the relationship between water quality parameters. A significance level of 0.05 was applied to all tests.

2.4 Results

2.4.1 Fixture Use

During the study, total fixture use was greatest on the first floor (856 recorded uses), followed by the 2nd floor (442 recorded uses), and then the basement (169 recorded uses). Fixture use was likely affected by office proximity and the total number of monitored fixtures on each floor (6 fixtures on first floor, 2 fixtures on second floor and 5 fixtures in the basement). The basement was primarily used infrequently for small conferences and events prompting irregular water use was irregular. Here, water use may have been under-reported by guests unfamiliar with

the recording system. The fixture with the greatest number of uses per week was location 12 (second floor bathroom sink) (80 to 104 events per week) (Figure 2.2). Use was likely highest here due to the small number of bathrooms and high number of offices on the second floor (i.e., high demand, low supply). The least used fixture was location 10, the fitness shower, which did not have any recorded use. The authors were told that the shower was often used seasonaly by active commuters (e.g., biking), but the present study occurred in the winter. The first floor bathroom sink next to location 7, which the authors did not sample, was the only location with recorded weekend use (3 times total).

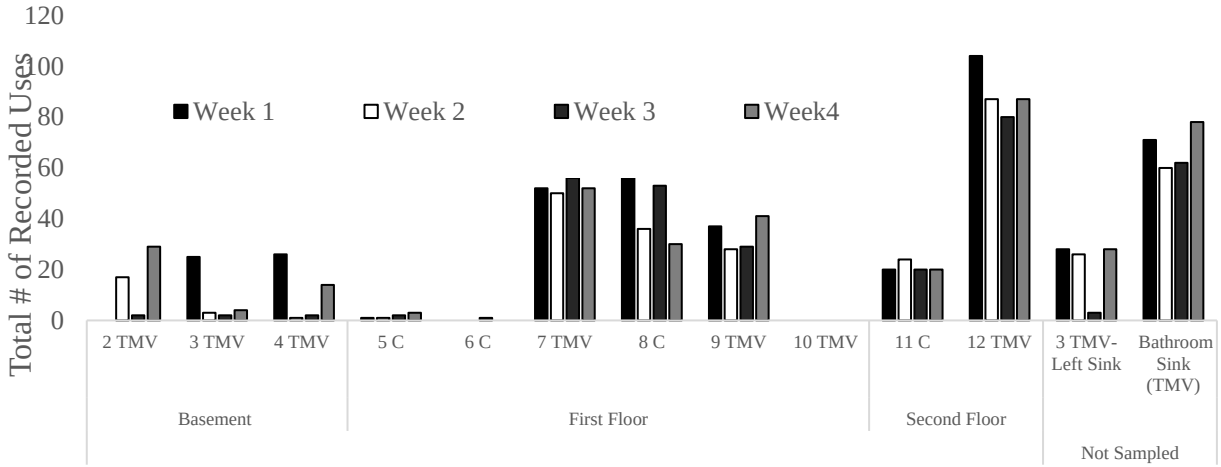

Figure 2.2 Usage frequency at each location throughout the study. Week of 1/20/2020 included a government holiday. Sampling location 3 had two sinks next to each other, the left sink was not sampled. Location 1 was the POE and is not shown.

2.4.2 Water quality variations seen at in-building locations

Water at the POE (location 1) throughout the study had pH of 7.0 to 7.5, 1.5 to 3.2 mg/L organic carbon, 0.39 to 0.8 mg/L as Cl_2, and an alkalinity of 200 to 289 mg/L as $CaCO_3$. For biological parameters, the POE had TCC of 3.72 to 4.90 (Log_{10} cells/L) and *Legionella* spp. at 1.94 to 2.36 Log_{10} gene copy number / 100 mL (Table 3). *Legionella pneumophila* was not detected in water samples in this study. Drinking water quality entering the building was comparable to the reported water quality in the utility's annual consumer confidence report and water quality monitoring station data for the PWS (Table SI-1).

Water quality differences were found between the three risers and individual faucets. This is likely a joint effect of the water sample's proximity to location 1 (POE), and the frequency of fixture use. Within the building (locations 2 to 12), chlorine levels were nearly always lower than

those at the POE (location 1) (Figure 2.3). The only fixtures where total chlorine was 0.2 mg/L as Cl_2 or greater, were first floor cold water (locations 6 and 8) on the same Friday. While water use was not recorded directly before this measurement at location 6 (water fountain), it was recorded one hour before sampling at location 8 (first floor kitchen sink). Disinfectant residual decline from the POE to other observation points within the building was expected and has been found by others.[25]

Copper was found in drinking water fountains in riser 3 (Figure 2.1) above 1.3 mg/L (consequently, these were shut-off), but copper was not found above 1.3 mg/L in other risers. The fixtures on riser 3 (all basement fixtures or first floor water fountains) did experience less and more variable use, compared to other risers as mentioned previously. This varied use may have affected copper solubility.

Legionella spp. was highest at locations 9 (bathroom sink) and 10 (shower), in the same bathroom on the first floor (maximum 4.25 Log_{10} gene copy number / 100 mL). Location 10 was the only fixture not used during the whole study except when sampled and it was a fixture that included plastic parts, located in the shower hose. The TCC (3.72 to 5.55 Log_{10} cells/L), pH (7.2 to 7.8), and alkalinity (171 to 278 as $CaCaO_3$ mg/L) inside the building were comparable to the values at the POE.

It is difficult to precisely identify why certain locations had differences in water quality, due to several factors. For example, location 6 was next to location 5 (both water fountains on the first floor) with less than 2 L of water (sampling volume) within their dedicated pipes, meaning fresher water was brought to location 6 when location 5 was sampled. The building water sampling plan was completed and began before the as-built drawings were made available. After drawing review, it was learned that while location 3 was sampled after location 2 (basement bathrooms), location 3's pipe was upstream in the system. Sampling point 11 (second floor bar sink) was not on the as-built drawing so the authors estimated its location in relation to other points, but its water quality was likely influenced by its proximity to location 12 (second floor bathroom sink).

2.4.3 Weekend stagnation affected Monday's water quality

On average, weekend stagnation influenced chemical and biological water quality. At the POE, total chlorine residual concentration was higher on Fridays than Mondays ($p < 0.05$) (Figure 3). The same trend was found at sampling points within the building ($p < 0.05$). As expected, with

lower chlorine levels on Monday mornings, TCC levels were also greater on Mondays compared to Fridays at building sampling points ($p < 0.05$). A significant difference in TCC was not found at the POE, where total chlorine detection remained higher than 0.2 mg/L as Cl_2 even on Monday morning. While water temperature was lower at the POE compared to other sampling locations, there was no significant difference of water temperature at the POE on Friday and Monday ($p > 0.05$). Temperatures (19 to 21°C) were often colder before the on-demand water heaters were able to heat up fresh water (i.e., very first draw). Once this happened the temperature would increase to about 34 to 36°C (i.e., by the end of sampling). No differences were detected for *Legionella* spp., pH, TOC, and DOC between Friday and Monday sampling periods ($p > 0.05$). The U.S. EPA has a maximum contaminant level goal (MCLG) of zero *Legionella* organisms.[37] It is known that legionella can be introduced into a building distribution system by way of a PWS and grow within building plumbing, but a consistent spatial pattern has not been reported.[38-39]

Fixture use frequency has previously been associated with cell counts and pathogenic growth, where a longer stagnation time can prompt a change in temperature and loss of residual.[4,8-19,24,40,41] There were select occasions where chlorine residual measured higher on Monday than the previous Friday, contradicting what was expected of the chlorine residual during weekend stagnation. This was likely due to the low water usage during the week by patrons (e.g., location 10 [shower] was not used except when sampled). For example, at location 10 when the sample was collected on Friday afternoon for on-site analysis, the chlorine residual was reflective of the stagnation from Monday to Friday (upwards of 106 hours). When location 10 was sampled on Monday morning for on-site analysis, the chlorine residual was reflective of only upwards of 60 hours of stagnation (weekend). Location 10 experienced 46% more stagnation time during the week than over the weekend. A comparable situation likely occurred at location 6 (water fountain) the week of February 3rd, after it was taken out of use. The stagnation prior to Friday's sampling point was likely longer than over the weekend (i.e., 5 days of no use during the week compared to 2 days over the weekend).

No significant difference was found for nitrogen containing compound concentrations after stagnation. NH_4-N was consistently lower at POE than the other locations within the building (Table 2.3). The only time NO_2-N was detected was at location 9 and 10 (first floor bathroom sink and shower), and this did not exceed the federal MCL of 10 mg/L.[37]

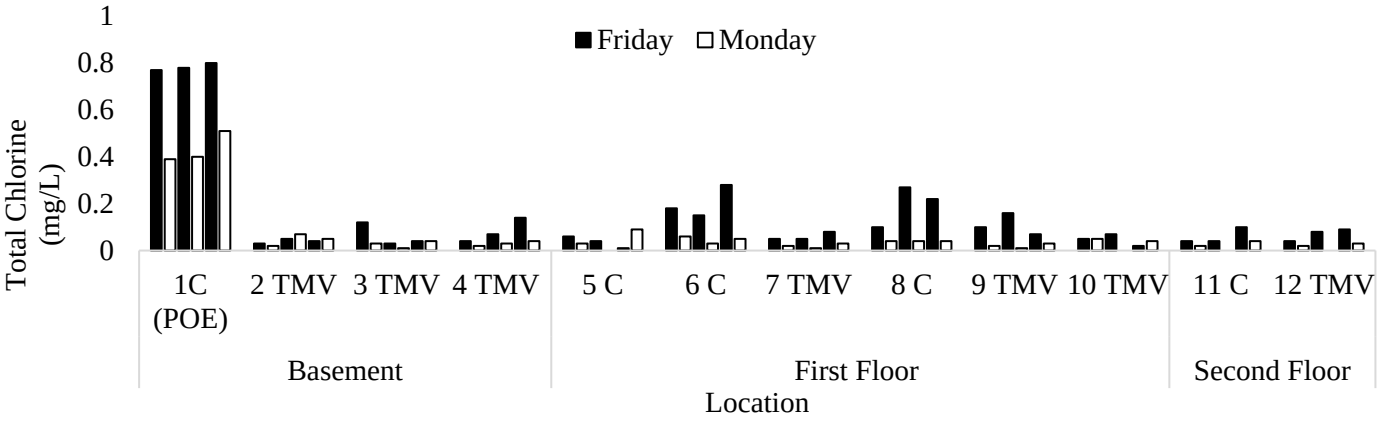

Figure 2.3. Total chlorine residual concentration detected at each location the six days of sampling.

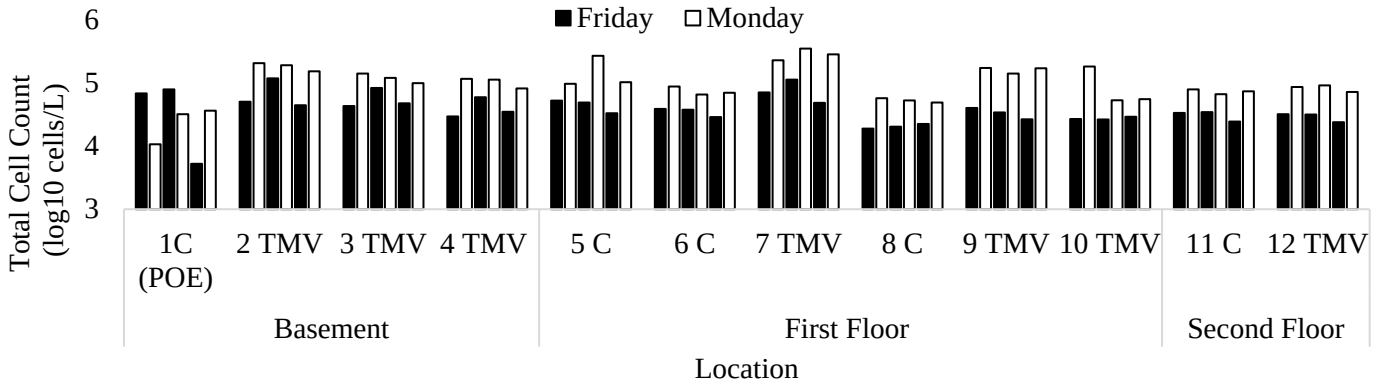

Figure 2.4.TCC results at each location the six days of sampling.

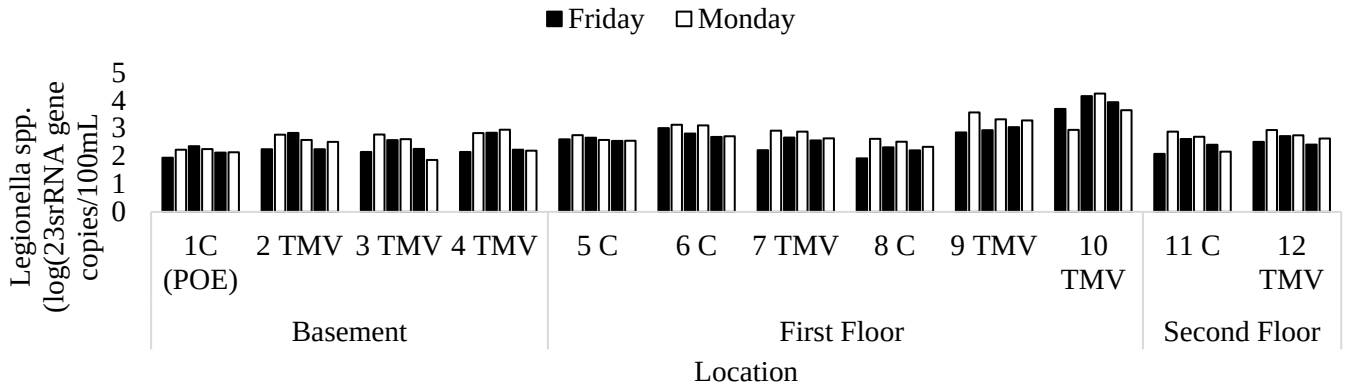

Figure 2.5. *Legionella spp.* results at each location the six days of sampling.

Table 2.3 Chemical and biological water quality range (n=3 samples per location) at point of entry and for each floor, before and after weekend long stagnation.

Parameter	*Point of Entry*		*Basement (locations 2 - 4)*		*First Floor (locations 5 - 10)*		*Second Floor (locations 11 and 12)*	
	Friday	*Monday*	*Friday*	*Monday*	*Friday*	*Monday*	*Friday*	*Monday*
General								
Temp (°C)	12.2 - 14.1	17.6 - 19.2	19.9 - 25.3	20.4 - 21.6	19.0 - 23.1	20.4 - 22.1	14..6 - 26.7	21.1 - 22.0
pH	7.05 - 7.22	7.46 - 7.53	7.29 - 7.82	7.45 - 7.78	7.40 - 7.79	7.24 - 7.79	7.30 - 7.75	7.46 - 7.83
Total Cl_2 (mg/L) <u>*MCL: 4 mg/L*</u>	0.77 - 0.8	0.39 - 0.51	0.03 - 0.14	0.01 - 0.07	0.01 - 0.28	0.00 - 0.09	0.04 - 0.10	0 - 0.04
Organics								
TOC (mg/L)	1.6 - 3.2	1.6 - 3.2	1.6 - 3.2	1.4 - 4.1	1.5 - 3.4	1.3 - 3.5	1.5 - 3.3	1.4 - 3.5
DOC (mg/L)	1.6 - 2.8	1.7 - 3.1	1.4 - 3.9	1.4 - 3.1	1.4 - 3.7	1.3 - 3.0	1.4 - 3.3	1.3 - 3.0
Biological								
TCC (Log_{10} cells/L))	3.72 - 4.90	4.03 - 4.56	4.47 - 5.07	4.91 - 5.31	4.28 - 5.05	4.73 - 5.55	4.38 - 4.54	4.82 - 4.96
Legionella spp. (Log_{10} gene copy # / 100 mL)	1.94 - 2.36	2.14 - 2.26	2.15 - 2.84	1.86 - 2.95	1.92 - 4.15	2.34 - 4.25	2.08 - 2.72	2.16 - 2.94
Nitrogen								
NH_4 -N(mg/L)	0.44 - 0.48	0.38 - 0.43	0.19 - 2.7	0.31 - 2. 31	0.12 - 2.37	0.09 - 2.67	0.14 - 0.92	0.08 - 2.24
NO_2 -N(mg/L) <u>*MCL: 1 mg/L*</u>	-	-	-	-	0.0 - 0.02	0 - 0.06	-	-
NO_3-N (mg/L) <u>*MCL: 10 mg/L*</u>	2.58 - 2.84	2.59 - 2.90	2.53 - 2.79	2.51 - 2.8	2.67 - 3.29	2.35 - 3.29	2.66 - 2.86	2.51 - 2.80

Stagnation can allow heavy metals that leach from the plumbing scales and materials to accumulate in the water.[10,26] Copper and lead were detected at the POE, at all fixtures, and some health-based drinking water exposure limit exceedances were found (Table 2.4). Copper limit exceedances (22%, 8 of 36) were only found for Riser 3 (Figure 1), which fed locations 2, 3, 4, and 6. Locations 2, 3, and 4 did not have consistent use. Location 6 had consistent low use and was taken out of use when elevated copper levels were found. Three first draw samples contained copper at a concentration equal to or greater than the 1.3 mg/L health-based action level on both Friday and Monday sampling events. Elevated copper levels have been found in similar commercial buildings.[9,24,25] Lead levels found at the POE always exceeded 1 μg/L, but not 5 μg/L. Inside the building, however, 8 of the 12 fixtures had sample events where lead exceeded 5 μg/L.

The office building was constructed after promulgation of the 1986 Safe Drinking Water Act, which instituted a "lead free" pipe regulation, but plumbing components were permitted to still contain lead. Specifically, the maximum lead concentration allowed until 2011, a year after this building was built, was 8 wt.% (a maximum of 0.2 wt.% lead for solder and flux).[41]

Table 2.4 Range of copper and lead concentrations at each fixture on Friday and Monday sampling events

Location Description		**Copper, mg/L**		**Lead, µg/L**	
		Friday	*Monday*	*Friday*	*Monday*
POE	1	0.05 - 0.96	0.19 - 0.29	2.4 - 4.4	3.1 - 4.1
Basement	2 TMV	**0.87 - 1.5** ***EX***	**1.1 - 1.4** ***EX***	3.6 - 6.8	4.1 - 5.0
	3 TMV	**0.80 - 1.6** ***EX***	**1.1 - 1.3** ***EX***	3.8 - 5.8	3.4 - 5.0
	4	**0.74 - 1.9** ***EX***	**1.4 - 1.7** ***EX***	3.1 - 5.4	3.1 - 4.5
First Floor	5	0.39 - 0.87	0.68 - 0.78	2.5 - 4.2	3.2 - 4.9
	6	0.49 - 0.69	**1.3 - 1.4** ***EX***	2.3 - 5.2	3.4 - 4.0
	7 TMV	0.37 - 0.96	0.86 - 1.0	2.7 - 5.5	4.6 - 5.6
	8	0.26 - 0.49	0.38 - 0.47	3.6 - 5.4	2.8 - 3.0
	9 TMV	0.43 - 0.47	0.41 - 0.44	4.5 - 6.7	4.0 - 4.6
	10 TMV	0.33 - 0.55	0.43 - 0.49	3.7 - 7.6	3.2 - 4.3
Second Floor	11 TMV	0.53 - 0.93	0.74 - 0.92	3.3 - 4.3	3.4 - 3.9
	12 TMV	0.04 - 0.87	0.68 - 0.77	1.8 - 4.2	3.7 - 3.8

2.4.4 Flushing only temporarily addressed copper exceedances

Flushing temporarily decreased copper levels and increased total chlorine concentration in the plumbing, but copper levels rebounded and chlorine levels decreased rapidly after flushing stopped. Flushing and sequential sampling was conducted at location 4 (basement kitchen sink), following the 6th regular sampling event. Location 4 was sampled regularly (2 L total collected after weekend stagnation) then, left alone for one hour (i.e., while other locations in the building were sampled), and then flushed for 100 minutes (2.18 L/min).

At location 4, a total of 218 L of water was flushed. The total volume of water between the water main and location 4 was calculated to be 183 L. The regularly scheduled sample collected for sample event 6 (after weekend stagnation) had a 1.5 mg/L concentration. Copper, at the beginning of the flush, was 1.4 mg/L (a slightly lower value likely attributable to water movement during sample collection). Copper concentration then decreased during 100 minutes of flushing from 1.4 to 0.09 mg/L (Figure 2.5). After flushing, the fixture was not used for 6 hours, though a

125 mL sample was collected each hour for metals analysis. Copper concentration, after the first hour was 0.32 mg/L and then reached 0.61 mg/L after the sixth hour. After this 6 hour stagnation period ended, the fixture was flushed for an additional 30 minutes and copper concentration subsequently decreased to 0.08 mg/L. As expected, chlorine concentration exhibited an opposite trend, where chlorine levels increased during flushing and decreased during stagnation. While the copper concentration rebounded at a rate of 0.061 mg/L per hour of stagnation (Figure 2.6), total chlorine decreased at a rate of 0.31 mg/L as Cl_2 per hour of stagnation. Based on these results, if the copper levels continued to rebound at the rate of 0.061 mg/L per hour, the copper level was predicted to reach 1.3 mg/L in less than 24 hours (starting from 0.09 mg/L, which was achieved after 100 minutes of flushing). During that same stagnation period, the total chlorine concentration would likely have decreased to less than 0.2 mg/L as Cl_2 within one hour. To avoid the 1.3 mg/L copper conditions at the faucet, the plumbing fixtures would need to be flushed every 24 hours. Manually flushing fixtures every day to keep copper levels below 1.3 mg/L would be onerous, and manually flushing to keep chlorine levels above 0.2 mg/L as Cl_2 (every hour) would be exponentially more labor intensive.

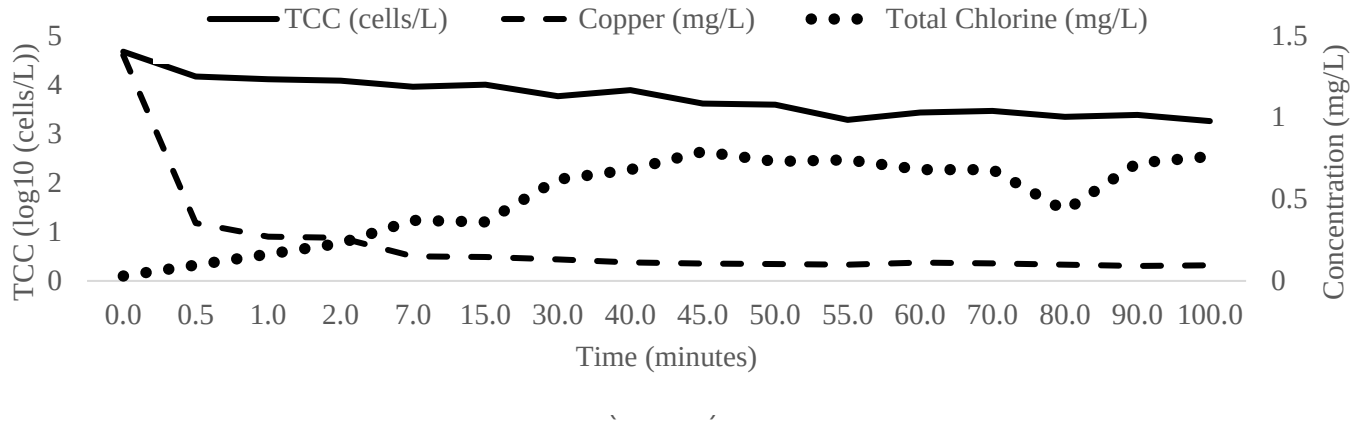

Figure 2.6 Location 4 flushing event, copper, total chlorine and TCC concentrations.

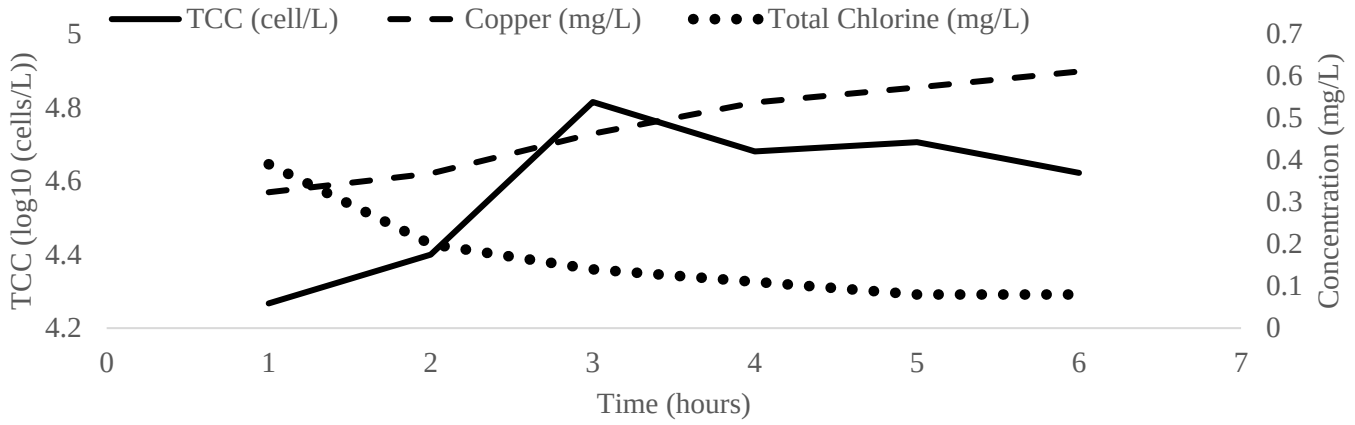

Figure 2.7 Location 4 six-hour stagnation and the corresponding copper, total chlorine and TCC concentrations at each hour.

2.4.5 Point-of-Use Treatment

Filtration can sometimes be used for remediating water with elevated copper levels,[42] and some "certified" POU devices are available. The water cooler in the basement, sampled only once, had no detectable levels of copper. The only detectable metals observed at the water cooler were aluminum and zinc, neither of which have a federal MCL. The water cooler was equipped with four types of filters which were NSF International Standard 61 certified and included a: (1) sediment filter, (2) a carbon filter, (3) a reverse osmosis system or ultra-filtration membrane and (4) BIO-SURE PLUS™ filter. According to the manufacturer, the third stage of filtration reportedly removed contaminants such as "solids, arsenic, pharmaceuticals, and metals." It was unknown when the filters were last changed or their replacement frequency. A manual for the unit in the

building was available.[43] The water cooler was new to the building and it was unknown if it had begun regularly serviced maintenance.

In a bench-scale test, water from the building with 0.63 mg/L copper was filtered using two new pitcher filters. The copper was reduced to 0.05 mg/L with the ZeroWater® system (NSF 42/53 certified but not for copper removal) and to 0.03 mg/L with the PUR® system (NSF certified but the standard number was not listed). POU water treatment with an ion exchange process is a potentially viable copper mitigation measure.[42] NSF International Standard 53 ion exchange resins are certified to reduce 3.0 mg/L of copper to a level below the health-based drinking water action level of 1.3 mg/L.[44] Interestingly though, at times the alkalinity found in the building water and reported by the PWS was greater than 250 mg/L as $CaCO_3$, and NSF International Standard 53 certified systems are only tested with an alkalinity of a maximum of 250 mg/L $CaCO_3$.[44,45] This observation indicates that certified POU systems were not tested to perform for all conditions found in the building tested.

2.5 Implications

During the 60 hours that offices were unoccupied, disinfectant residual consistently decreased to near non-detectable levels (in about 1 hour) while copper, lead, and TCC levels became elevated. Exceedances of the (acute) health-based drinking water limit for copper were found in one of the three risers, including at bathroom sinks, water fountains and kitchen sinks. The building owners explained that no water chemical testing had been conducted when the building was commissioned as it was not recommended or required, and the plumbing was constructed to code and certified for occupancy. Because copper leaching can decrease over time due to passivation, the duration of copper levels exceeding the health-based limit during the building's 10 years of service prior to this study is unknown. While the building has been commissioned for 10 years, pipes located in different parts of the building may show different levels of aging based on water use. Study results show characteristic fixture use patterns, which could cause various levels of stagnation. This stagnation can cause different levels of water age at the fixtures, causing the pipe age (noted by mineralogical scale or biological film formation on the inside of the pipe) to vary. To avoid situations where water that does not meet safe drinking water standards is dispensed at fixtures, chemical testing of building water systems before occupancy for

disinfectant residual stability, and copper and lead levels is recommended. If testing was not implemented in the present study, the copper exceedances would have continued undetected.

Interestingly, another building that received water from the same PWS was recently found to have copper exceedances (maximum 2.72 mg/L).[9] In that school building, copper levels consistently exceeded the 1.3 mg/L health-based drinking water exposure limit during the summer months (70% of samples) and even when school was in session (37% of samples). Discovery that two buildings had exceedances on the same PWS does not represent a statistically representative sample size. The present study does show that existing practices to prevent water from having excess levels of copper in building drinking water are inadequate, and wider building testing efforts are recommended. Because copper levels in the present study were isolated to one part of the plumbing, plumbing design and conditions that allow occupancy certification should be revisited. In the school building water study, extensive copper contamination was found through the entire plumbing, not isolated.

At the office building, flushing had temporary effectiveness at reducing copper levels, but copper rebounded to levels that exceeded the health-based drinking water exposure limits relatively quickly. Similarly, flushing was unable to remediate the copper problem at the school served by the same PWS.[9] For the office building, evidence indicated that flushing would need to be conducted every 19 hours to avoid 1.3 mg/L copper conditions. Based on flushing plans developed for the office building, this activity would take approximately 90 minutes each time.[46] The frequency of flushing, the labor needed, and the time it takes to conduct a single flush, makes flushing an untenable mitigation solution. Copper leaching is not necessarily a fixture problem, but a challenge throughout plumbing.[47] Using as-built drawing plans and a fixed flow rate (2.18 L/min), the authors determined that flushing for at least 54 minutes was required to reach fresh water from PWS, at the most distal fixture, location 4. Electronic motion detector faucets were particularly difficult to flush due their automatic shut off. Several other studies that examined flushing to reduce copper levels in commercial buildings also concluded flushing was not practical.[25,46-49]

A POU ion exchange system may be a less labor-intensive copper remediation solution for existing buildings, but this measure imparts an additional burden on the building owner. POU systems require testing (to determine they are effective) and routine maintenance. Before POU systems are chosen, the building owner would first need to understand worst case water quality

conditions the device would experience and compare it to the device certification criteria. As shown in the present study, not all waters may be representative of device certification conditions.

Based on these discoveries and limited available data found regarding drinking water quality in commercial buildings, there are several recommendations. First, the authors recommend that the Authorities Having Jurisdiction, which are often the health department and code officials who permit building occupancy, require disinfectant residual, copper, and lead drinking water testing be conducted before certificates of occupancy are granted. Testing would need to be conducted on water entering the building and, because stagnation would influence the amount of contaminant in the water, after a weekend or holiday stagnation period, at a representative number of drinking water locations. As part of the occupancy process, new buildings should be required to have as-built plumbing drawings and step-by-step plumbing flushing plans to help building owners (and possibly health officials who respond to an issue) troubleshoot water quality problems. Strategies and guidance for sampling office buildings, with complex plumbing, for chemical and microbiological contaminants are needed. Additional technology innovations are recommended that facilitate automatic water turnover in a building so water at the fixture does not exceed health-based drinking water exposure limits.

2.5 Conclusions

Weekend stagnation is enough to induce chemical and microbiological water quality changes in a green office building and prompt exceedance of the acute health-based copper drinking water limit. Monday morning's water quality consistently had a low chlorine residual concentration, greater TCC, and greater levels of copper and lead compared to water found on Friday afternoons. Fixture flushing was a short-term and impractical approach to reduce elevated copper and increase disinfectant residual levels. Even after flushing, copper levels rebounded to exceed 1.3 mg/L within 19 hours. In this same 6 hour period, chlorine residual decayed at a rate that would have levels below state required limits within an hour. A bench-scale ion exchange POU filter experiment indicated that treatment may be the most practical copper reduction method for existing building as long as the filter media is replaced at or before manufacturer recommended service-life. Although the water quality observed in the building deviated from how device performance was measured during certification.

Tracking water use, building occupancy, and having as built drawings aided the authors in understanding how building water use and plumbing design affected water quality. Water quality problems were not widespread through the building. Problems were localized showing that knowledge about plumbing configuration and proper sampling is needed. This building had only 3 floors and plumbing configurations in much larger buildings (e.g., 40+ floors) or those with multiple additions and wings may pose greater data collection and interpretation challenges. Future studies that could be helpful include the analysis of the role of low use water appliances in affecting building water quality, understanding how to find representative sampling for large commercial buildings, and beyond flushing, and evaluation of permanent solutions can be used for persistent water quality issues. Water testing at existing office buildings should be conducted to determine the extent water does not meet safe drinking water limits and take action to remediate these problems.

2.6 References

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2.7 Supplementary Index

Tables and Figure

Table SI-1: 2019 CCR Report for PWS

Table SI-2: Utility report from during sampling events

Table SI-3: Ion Concentrations (mg/L) average for all sampling locations on Monday and Friday.

Figure SI-3: pH levels per sampling event

Table SI-1: The 2019 CCR for the PWS.

Parameter	Average
Cl_2	1.7 mg/L
NO_2-N	0.79 mg/L
pH	7.7
TOC	3.8 mg/L

Table SI- 2: Utility Report during sampling at surrounding stations. The average total Chlorine level entering the distribution system to the downtown area was 2.39 Chlorine mg/L.

Parameter	
Cl_2	1.4 to 2.38 mg/L
NO_3-N	1.57 to 3.15 mg/L
NO_2-N	0.04 mg/L
NH_4-N	0.05 to 0.16 mg/L

Table SI-3: Ion concentrations (mg/L) average for all sampling locations on Monday and Friday.

	Cl^-	Br^-	PO_4^{3-}	SO_4^{2-}	Li^+	Na+	K^+	Mg^{2+}	Ca^{2+}
Friday	73.40 ± 7.15	0.07± 0.01	0.08 ± 0.03	43.54 ± 7.93	0.20	38.45 ± 5.08	3.01 ± 0.18	24.58 ± 2.18	85.46 ± 7.08
Monday	74.82 ± 7.19	0.06 ± 0.01	0.07 ± 0.03	43.73 ± 7.60	0.20	37.14 ± 5.60	3.02 ± 0.17	24.96 ± 2.15	86.43 ± 6.93

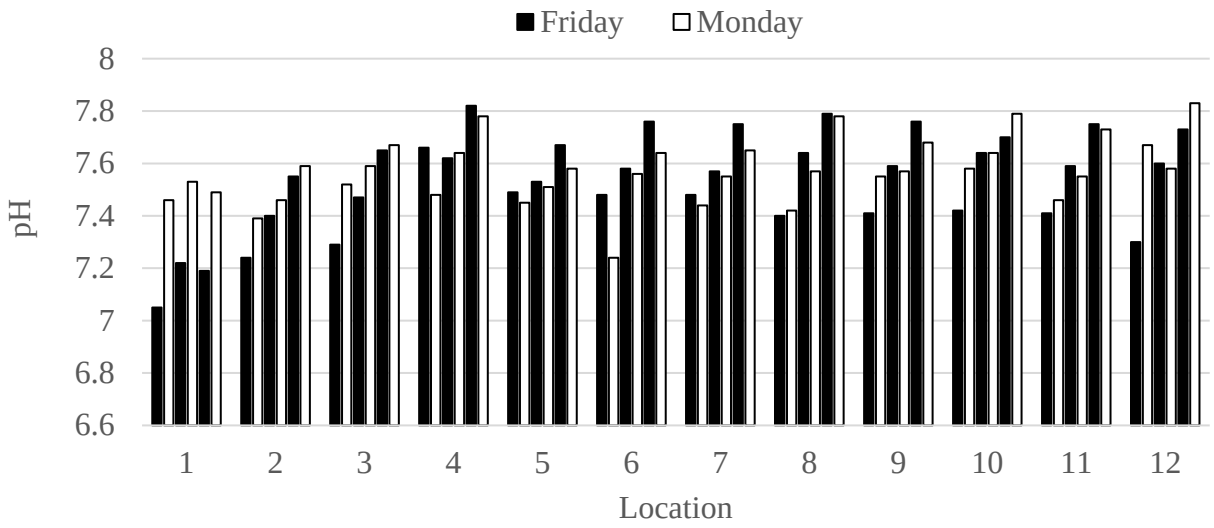

Figure SI-3: pH levels per sampling event