STAGNATION IMPACTS ON BUILDING DRINKING WATER SAFETY: THE PANDEMIC AND MICROPLASTICS

by

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Dedicated to my mentors, family and friends who supported me through this journey.

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TABLE OF CONTENTS

LIST OF TABLES 9
LIST OF FIGURES 10
ABSTRACT 13
1. FINDING BUILDING WATER QUALITY CHALLENGES IN A 7-YEAR OLD GREEN SCHOOL: IMPLICATIONS FOR BUILDING DESIGN, SAMPLING AND REMEDIATION 15
1.1 Abstract 15
1.2 Introduction 16
1.3 Materials and methods 18
1.3.1 School campus water use and plumbing characteristics 18
1.3.2 Water Sampling Approach 20
1.3.3 Building water quality in nearby commercial buildings 23
1.3.4 Statistical analysis 24
1.4 Results and discussions 24
1.4.1 Water delivered to the campus meter and transported to the school building 24
1.4.2 Water quality entering the building was consistent across sampling events 24
1.4.3 Building copper levels exceeded the health-based action level, were correlated to pipe length, and flushing was ineffective at their reduction 25
1.4.4 Building water carbon loading, bacteria, and nitrification differed before and after school returned to session 28
1.4.5 Water quality comparison to other off-campus commercial buildings 33
1.5 Limitations 33
1.6 Conclusions and recommendations 36
1.7 Acknowledgements 37
1.8 References 38
2. WATER QUALITY CHANGES AT LOW OCCUPANCY INSTITUTIONAL BUILDINGS DURING THE COVID-19 PANDEMIC 42
2.1 Abstract 43
2.2 Introduction 44

2.3 Materials and methods 46
2.3.1 Water supply and buildings studied 46
2.3.2 Water sampling approach 47
2.3.3 Total chlorine decay in plumbing 48
2.3.4 Flushing plans and confirmed fixture numbers and locations 49
2.3.5 Experience of commercial building owners 49
2.4 Results and discussions 49
2.4.1 Building owner activities 49
2.4.2 Building water use was reduced during the pandemic 50
2.4.3 First draw cold and drinking water fountain quality 55
2.4.3.1 Building owner actions may have influenced observed water quality 55
2.4.3.2 First draw cold water and drinking fountain samples 55
2.4.3.3 Cold water and drinking fountain metal samples at additional locations 56
2.4.3.4 Fate of cold water disinfectant residual in the buildings studied 59
2.4.4 Lack of education on proper building water quality management 60
2.5 Implications 61
2.6 Acknowledgement 63
2.7 References 64
3. INVESTIGATING WATER SAFETY IN AN ELEMENTARY SCHOOL BUILDING WATER SYSTEM AND REMEDIATION EFFECTIVENESS 70
3.1 Abstract 70
3.2 Introduction 71
3.3 Materials and methods 72
3.3.1 Water supply and site inspection 72
3.3.2 Water sampling and analysis approach 75
3.3.3 Flushing 76
3.4 Results and discussions 76
3.4.1 Observations of the closed buildings 76
3.4.2 First draw cold water quality 77
3.4.3 First draw hot water quality 79
3.4.4 Flushing did not result in an improvement of all water quality characteristics 80

3.4.5 Generally, water quality after two weeks of stagnation was similar to the 3-month stagnation period 81
3.5 Implications and recommendations 82
3.6 Acknowledgement 83
3.7 Conflict of interest 83
3.8 References 84
4. MICROPLASTICS IN BUILDING WATER SYSTEMS: AN EXPERIMENTAL STUDY OF FATE IN PLUMBING AND KNOWLEDGE-GAPS 89
4.1 Abstract 89
4.2 Introduction 90
4.3 Materials and methods 95
4.3.1 Literature review 95
4.3.2 Experiments: MP fate in piping systems 95
4.3.2.1 LDPE microplastics and plumbing pipe contamination 95
4.3.2.2 Characterizing water softener resin 96
4.3.2.2.1 Resin size measurements 96
4.3.2.2.2 Resin thermal characteristics 96
4.3.2.2.3 Resin contamination and removal from new and aged pipes 96
4.3.2.2.4 Resin damage process and integrity characterization 97
4.4 Results and discussions 99
4.4.1 Literature review: MPs in drinking water 99
4.4.1.1 What are MPs? 99
4.4.1.2 MPs in water collected from building fixtures and bottled water 100
4.4.1.3 Estimated fate in building drinking water systems 101
4.4.1.4 MP levels at the faucet and the contaminants they may carry 103
4.4.2 Bench-scale results 104
4.4.2.1 The retainment of new LDPE MPs depended on its size 104
4.4.2.2 Fate and impact of water softener resin: characteristics as-received polystyrene divinylbenzene spheres 105
4.4.2.3 New and aged PSDVB MPs impacted drinking water quality, but the aging treatments did not alter leaching or resin integrity 106

4.5 Implications and recommendations 109
4.6 Acknowledgement 111
4.7 Declaration of conflicts of interest 111
4.8 References 112
5. LIMITATIONS AND FUTURE WORK 120
APPENDIX SI.1 123
APPENDIX SI.2 134
APPENDIX SI.3 143
APPENDIX SI.4 150

LIST OF TABLES

Table 1-1. Cold and hot water sampling locations included the building entry point, inside the utility room, water heaters, recirculation loops, water fountains, and sink faucets. Utility room locations, the north part of the building (most used building portion during Summer break), and the south part of the building (least used building portion during Summer break). 22

Table 1-2. Water quality measurements of first draw samples..... 34

Table 2-1. Building characteristics. Total # of fixtures of two buildings are not 100% sure because as-built drawing is not available and laboratory equipment are not included (eye washes, safety showers, fume hood fixtures)..... 52

Table 2-2. Water quality measurements of first draw samples..... 58

Table 3-1. Number of locations where *L. Pneumophila* was detected and its (concentrations)... 79

Table 4-1. The definition of a microplastic varies based on the organization..... 91

Table 4-2. Plastics used in building plumbing that contact drinking water..... 93

Table 4-3. PSDVB MP removal and retainment in new and biofilm coated copper and PEX plumbing pipes..... 106

LIST OF FIGURES

Figure 1-1. (a) Timeline for sampling and major school events, (b) The water service loop at school campus, the service line comes off the road to provide water from the south of the school and circles the entire school campus. Red arrow is the domestic service line that goes into the utility room, (c) Water sampling locations (stars) and four hot water recirculation loops (colored lines). Black numbered stars are sampling locations at all 6 visits: #1 utility room (BE, AS, BWH, HWRa, HWRb, AWH), #2 closest bathroom (B1C, B1H), #3 student showers (SH1, SH2), #4 Farthest bathroom (B2C, B2H), #5 students' kitchen (SKC, SKH), #6 teachers' kitchen (TKC, TKH), #7 bathroom south (B3C, B3H), and #8 water bubblers (WF1, WF2). Yellow stars are additional locations that were sampled on last visit for metal analysis. 20

Figure 1-2**.** From June to October, 2018 total copper concentration was monitored at the building entry point (BE), water exiting the softener (AS), and (a) 8 cold water locations in the building, and (b) 4 hot water locations in the utility room and 5 hot water locations in the building. Each bar represents one sampling event and the results represent first draw samples only. Sampling location (left to right) is corresponds to distance from the water meter. The dashed horizontal lines indicate the health based AL of 1,300 μg/L, and aesthetic based secondary MCL of 1,000 μg/L. Trip and field blanks were free of contamination. BE = Entering building, AS = After softener, BWH = Before water heater, HWR = Hot water return, AWH = After water heater, B = Bathroom, C = Cold water, H = Hot water, SK = Student's classroom kitchen sink, TK = Teacher's lounge kitchen sink, WF = water fountain. 26

Figure 1-3. Total copper concentration of all collected (a) Cold, (b) Hot water samples compared to the faucet location's distance from the water meter. Dotted lines represent the health-based copper AL of 1,300 μg/L and aesthetic based secondary MCL of 1,000 μg/L 27

Figure 1-4. Heterotrophic plate count of first draw from building entry point (BE), water existing the softener (AS), and (a) 8 cold water locations in the building, and (b) 4 hot water locations in the utility room and 5 hot water locations in the building. Red dotted line is HPC drinking water guideline from the World Health Organization (500,000 CFU/100mL), and 500 CFU/100mL limit. BE = Entering building, AS = After softener, BWH = Before water heater, HWR = Hot water return, AWH = After water heater, B = Bathroom, C = Cold water, H = Hot water, SK = Student's classroom kitchen sink, TK = Teacher's lounge kitchen sink, WF = water fountain. 32

Figure 2-1. Sampling timeline. Few flushing dates that were close to sampling dates or on the day of sampling were added in this timeline because flushing occurred by school may have interrupted the stagnant sample for the study. 48

Figure 2-2. Authors building water sampling and flushing schedule by building owners. Stars indicates when the authors first visited the buildings to collect water samples; Red color indicates flushing building hot water; Blue color indicates flushing building color indicates flushing building cold water; Yellow color indicates flushing building cold and hot water on the same day. 53

Figure 2-3. Fixture conditions at (a) Building A, (b) Building C, (c) Building D, and colored water from (d) Building D in March 2020. A drinking water fountain from building A has been changed with new drinking water fountain with filters after buildings re-opened. 54

Figure 2-4. Total chlorine residual concentrations varied monitoring during continuous 30-minute flushing at building A. Red dotted line on 0.2 mg/L. See Figure SI-4 for other buildings. 59

Figure 2-5. Total chlorine concentration (as Cl_2) decayed over a 6 hour period at various fixtures within (a) Building A, (b) Building B, and (c) Building C. Building D did not have detectable chlorine residual at the service line even after flushing for 2.08 hours. 61

Figure 3-1. (a) Site property with building A, B and C with estimated location of public water supply pipe (blue), two water meters (sky blue circle) and service line to each building (sky blue) and where splits to deliver to building A (dotted sky blue), (b) Elkay drinking water fountains installed for kids' height, (c) All classrooms had their own sinks, drinking water fountain, and appliances, (d) Coffee maker connected to the plumbing in building A, and (e) Particulates on the aerator before removal. 74

Figure 3-2. Water quality measurements for buildings A, B, and C for (a) Total chlorine residual, and (b) Dissolved oxygen. For flush graphs, last recording data after flush was reported. 78

Figure 3-3. Chlorine residual fluctuated during the 10-minute cold water at the kitchen sink (building A) and the janitor sinks (building B and C). 80

Figure 4-1. Plastics used in plumbing are known to degrade and sometimes can find their way to drinking water faucets: (a) Inner copper pipe epoxy lining in a California home degraded and clogged aerators, (b) Water softener resin in a Texas home exited a tub spout due to the softener strainer mechanically failing. The structure of poly(styrene-co-divinylbenzene) water softener resin involves two polystyrene chains crosslinked with a divinylbenzene bond in the middle that makes the polymer more rigid. Water softener resin image courtesy of Seidel[27] 94

Figure 4-2. MPs can have different sizes, shapes, and bulk density values, and these factors should influence their fate in plumbing 99

Figure 4-3. (a) Potential MP fate pathways and sources in residential plumbing, (b) A pipe exposed to MPs indicating biofilm, scale, and flow phenomena that may influence fate, (c) Water softeners and water heater tanks can be a source of MPs and tanks may be a sink for MPs. Building water systems have plastic and metal water supply pipes, valves with gaskets, tubing, faucet connectors, and hoses, and sometimes polymer lined tubing. Water softeners and water heaters often have plastic components where the softener resin is a MP and can also include plastic dip tubes and gaskets. 102

Figure 4-4. Low density polyethylene MP spheres were not completely removed from new plastic and copper drinking water pipe segments even after flushing. Top row 3.5 mm diameter spheres and bottom row 350 μm diameter spheres. 105

Figure 4-5. PSDVB water softener resins leached notable amounts of organic carbon into drinking water, but leaching was not affected by (a) Thermally treating the resin or (b) Exposing it 10 times to 300 mg/L as Cl_2 super chlorinated drinking water. Mean and standard deviation values shown for three replicates. The basis of superchlorinated water was UPW. MPW was used for both control water and superchlorinated water during stagnation period. 108

Figure 4-6. ATR FTIR spectra of (a) (1) New resin, (2) 15 Year old resin, (b) (1) New resin shock chlorinated once, and (2) New resin shock chlorinated ten times. On 15 year old resin peak near 2900cm^{-1}, C-H bonds that are clearly different between new and old resin. Control: 3-hr shock in

ultrapure water then stagnated in tap water for 3 days, shock chlorination: 3-hr shock in 300mg/L bleach solution then stagnated in tap water for 3 days and repeated 10 times; old water softener resin is from old water softener with unknown product name and stagnation time; New resin and 15 year old resin were thermally exposed in the oven at 90℃ for 30 minutes. However, thermally exposed 15 year old resin had almost straight line which seemed there was a coating on the resin that inhibited transmittance after thermal exposure. 109

ABSTRACT

The pandemic prompted buildings globally to transition to low or no occupancy as social distancing to reduce the spread of Coronavirus Disease (COVID-19). This consequence prompted concerns about the chemical and microbiological safety of building drinking water due to stagnation. At the same time, microplastic (MP) pollution received increasing global attention due to their presence in the environment and recent discoveries within water distribution systems and at building faucets. MP sources have primarily been targeted as originating within the drinking water sources, but plastic plumbing components are less discussed and known to deteriorate into fragments and smaller pieces that reach faucets. Literature at the time of this work as sparse on stagnation impacts to drinking water quality and the fate of MPs in plumbing. In particular, health officials and building owners issued and received many differed guidance documents telling building owners do different things and no standard guideline was available to reduce the health risks caused by stagnant building drinking water. This dissertation examined three different types of buildings during closed to low water use conditions and conducted bench-scale testing to explore the phenomena observed in the field. Chapter 1 describes water quality impacts during a 7 year old 'green' middle school as it transitioned from Summer (low water use) to Fall (normal use). Field experiments revealed that more than half of first draw water samples exceeded the copper (acute) health-based action limit during low water use. Copper concentration within the school increased as distance from building entry point increased. Chapter 2 and 3 describe report on chemical and microbiological water quality in buildings at a university buildings (Chapter 2), and elementary school (Chapter 3). Chapters 2 and 3 revealed that stagnation negatively impacted chemical and microbiological building water quality (cold and hot) but flushing was effective at remediating high concentration of heavy metals and *Legionella pneumophila* at most locations. But in large buildings, where building plumbing system was more complicated, flushing did not always result in improved water quality. Also discovered was that water quality again deteriorated even after whole building water system was flushed. It is important to understand own building systems to maintain water quality as each building complexity requires specific knowledge and solutions. Chapter 4 describes current knowledge associated with MPs in drinking water and results of bench scale experiments on MP fate and transport in building plumbing. This work identified that while MPs have been reported at building faucets, sampling details lacking from

available studies often resulted in study results not being comparable across others. Based on the review of the issue, it was found that MPs have likely reached building faucets for decades but have received no characterization until recently. Bench-scale testing using two MPs, of different density, in copper and crosslinked polyethylene (PEX) pipes revealed size influenced the amount of MPs retained in a pipe. Research needs were identified to determine the fundamental factors that control MP fate in plumbing and their presence at building faucets.

1. FINDING BUILDING WATER QUALITY CHALLENGES IN A 7-YEAR OLD GREEN SCHOOL: IMPLICATIONS FOR BUILDING DESIGN, SAMPLING AND REMEDIATION

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1.1 Abstract

Water safety was investigated at a school certified as a green building. The study was conducted during low water use (summer break) to normal water use (after break) periods. The copper plumbed building contained water saving devices, a water softener, four hot water recirculation zones, and received chloraminated water from a public water system. Six sampling events at 19 in-building locations (and extra 19 locations for metal analysis) were conducted (June 2018 to October 2018). At the building entry point, 65% of the samples (n=74/114) had no detectable disinfectant residual, heterotrophic plate count ranged from 11 to 400 CFU/100 mL, and no copper action level (AL) exceedances were found; the AL is a health-based threshold. Inside the building, almost 70% of first draw cold samples exceeded the AL during summer, while 37% of samples exceeded the AL after classes resumed. Total copper concentration in the building was related to the distance from the building entry point. The softener was an incubator for bacterial growth and nitrification was detected throughout the plumbing (n=29/29 for hot, n=17/22 for cold). The state's recommended spot flushing remediation strategy for reducing copper concentration was ineffective. Water chemical and microbiological testing is recommended before new schools are placed into service and during the life of new and existing buildings. Building water system design standards lack explicit consideration of source water quality, plumbing operation, and material-water compatibility. School plumbing was designed and operated in a way that presented a risk to the health of its occupants.

1.2 Introduction

Safe water is vital to child development, as children have less sanitary habits and their immune systems are still in the developmental stage.[1] The U.S. Centers for Disease Control and Prevention (CDC) specifically emphasizes the importance of school drinking water safety.[2] While the American Academy of Pediatrics indicates there is no safe level of lead exposure for children,[3] school building water can be contaminated by lead, copper, and opportunistic pathogens.[4-6] Schools that are considered a public water system must comply with the *Lead and Copper Rule*. But, if these facilities receive water from a public water system they have no specific federal water testing and safety requirements.[7] In early 2019, the U.S. Environmental Protection Agency (USEPA) estimated that about 98,000 public schools were not regulated under the Safe Drinking Water Act,[8] meaning that these facilities may or may not conduct any water quality testing.

Copper piping is one of the most common materials for domestic cold and hot water transport, and copper contaminated drinking water can pose health (nausea and vomiting) and aesthetic problems (blue water).[9] The *Lead and Copper Rule* stipulates that the public water system must undertake a number of additional actions to control corrosion if more than 10% of the homes sampled in their service area exceed the health-based copper action level (AL) of 1.3 mg/L.[10] However, there is no federal requirement for a school, that receives water from a public water system, to have their in-building drinking water tested.

A literature review revealed that few school water testing studies have been conducted and some states have required school water testing in recent years. For example, in Massachusetts, more than 1,994 schools and childcare centers were tested and copper action level exceedances were found (n=2,302/84,153 samples collected were at or above 1.3 mg/L, with a maximum of 53.2 mg/L at a classroom faucet, and 39.8 mg/L at a drinking water bubbler).[11] Several studies have previously reported school drinking water copper levels in the U.S. and Canada (maximum of 10.2 mg/L),[12-17] but only one study reported other water quality information such as disinfectant residual levels.[13] In Hamilton County, Indiana, Johnson et al. (2018)[16] found 187 of 295 schools (63.4%) had a drinking water sample that exceeded the copper (maximum of 7.3 mg/L), but no other water quality parameter was reported. For the 2018 Indiana study, the sampling location, time of day and day of week the sample was collected, and other water quality factors were not reported. A 2020 study of copper levels in a new office building in Arizona indicated copper concentration (maximum of 1.7 mg/L) was significantly correlated to building occupancy.[17]

Little information was found for how to design building water systems that minimize copper drinking water concentrations, design building water sampling plans, and select remediation strategies. Current plumbing codes do not recommend chemical water testing when buildings are opened, nor is the type of source water mentioned in building water system design.[18,19] Copper release can be influenced by stagnation time,[20,21] water pH, alkalinity,[22,23] and water temperature.[24] Current USEPA "3Ts" guidance for responding to drinking water lead exceedances recommends building owners shutoff problem fixtures, conduct a cleaning program and follow up testing, but lacks recommendations for copper.[25] A few previous studies in the U.S. and Canada recommended using point-of-use (POU) devices to reduce copper at problem locations.[12,26,27] Much of the available recommendations emphasize implementing a flushing procedure, terminating faucets that had issues, and adding corrosion inhibitors. No guidance was found on determining if the source water is at high risk of copper leaching *before* building construction. No guidance was found that described how water quality should be considered in plumbing design, allowable copper pipe lengths, or post-construction copper testing.

Few studies were found that reported chemical and microbiological water quality characteristics of school building water systems. Chloramine residual disinfectant use is popular in the U.S.,[28,29] but no studies were found that reported nitrification in school buildings. Nitrification, the conversion of ammonia to nitrate, can generate a health risk as nitrate has a 10 mg/L maximum contaminant level. Nitrification is possible with total chlorine levels lower than 1.6 mg/L as Cl_2.[30] Doré et al. (2018)[13] found that average disinfectant residual in large institutional buildings (schools and non-residential buildings) in Canada measured after 10 minutes of flushing ranged 0.073 to 2.13 mg/L as Cl_2 of free chlorine. The minimum recommended chlorine level in drinking water is 0.2 mg/L as Cl_2,[31] but 2 of 10 locations did not reach the minimum disinfectant residual level within 10 minutes. Samples were also not classified as cold or hot water, but average temperature ranged from 17 to 26˚C after 30 seconds of flushing. Richard et al. (2020)[17] measured copper and chlorine concentration twice weekly in cold water and found 95% of first and second draw samples had disinfectant residual less than method detection limit (MDL) of 0.02 mg/L as Cl_2. The investigators hypothesized that the water softener ion exchange resin may have affected chlorine residual decay, and further study was recommended.[17]

The goal of the present study was to better understand the degree building water chemical and microbiological quality changes during the transition from summer break (low water use) and

during several weeks after classes resumed (normal use). The school building studied was certified in accordance with the U.S. Green Building Council Leadership in Energy and Environmental Design (LEED) program. Specific research objectives were to (1) document first draw water quality at 19 different cold and hot water locations, (2) determine the relationships between water quality and distance from the building entry point for the parameters examined, and (3) determine if water quality differed between summer break and after classes resumed.

1.3 Materials and methods

1.3.1 School campus water use and plumbing characteristics

The school campus was located in Indiana, USA. Chloraminated drinking water was provided to the campus through a single water meter by a public water system that served more than 800,000 people. Water originated from two different water treatment plants depending on their overall system demand (75% from a wellfield, 25% from a river). According to the water supplier, corrosion inhibitor has never been added and they have focused on maintaining alkalinity and pH levels for corrosion control. After passing through the campus water meter, the drinking water entered a 20.3 cm (8 in) diameter polyvinylchloride pipe campus loop system, which circled the building (**Figure 1-1**) (length 3,481 ft, volume 9,089 gallons). From the service loop, a dedicated 10.1 cm [4 inch] diameter domestic line branched off the fire line to the utility room 48.7 m [160 ft] length (530 L [104 gallons]) [ductile iron] service line conveyed water into to the school building. The 7-year-old building was the focus of this study, but water was also used for a campus irrigation system, the athletic field house, and concession stands. School campus water meter records were reviewed, but no records were available specifically for the school building.

A timeline of key events at the school can be found in **Figure 1-1**. Six sampling events were conducted inside the building, 3 during the summer break and 3 after the school returned in session. During summer break some water use occurred in the building (**Figure SI.1-1**). The building's north section was used for summer camps, primarily in the auditorium, gym, and athletic fields. Every weekend, the building's north section was also used for church services, and each service had a reported capacity of up to 500 people (two church services one in the morning, one in the afternoon every Sunday all year long). Before our sampling events, the north section of the building was used the most for the summer camps: up to 250 students were in sports camps, 50

students in orchestra camps in the music room, and 200 students in a band camp. During July, one music camp was held for 100 students in the auditorium in the building's north section before the second sampling event. In contrast, the south section of the building was the "academic" classroom side. This building section was primarily unused during the summer. When classes resumed in August 2018, about 830 students staff and faculty began inhabiting the building 5 days a week thereby increasing water use on the south section of the building.

All water that entered the school building passed through one of two water softeners (model # 2900 series 700 duplex, 198 L [7 cubic ft]) manufactured by Aqua Systems, Inc. (Fishers, IN). Next, water entered one of four water heaters (model # BTH-300, 492 L [130 gal.]) manufactured by A.O. Smith. Hot water exiting each heater entered one of four recirculation systems. The location of the four hot water recirculation zones can be found in **Figure 1-1(c)**. All piping was copper and as-built plumbing drawings were used to estimate the total length of pipe and volume of water in the plumbing between the water meter and each fixture. Pipe diameters inside the building varied (cold water pipes = 1.9 to 10.2 cm [0.75 to 4 in], and hot water pipes = 1.27 to 6.35 cm [0.5 to 2.5 in]). The distance from the point-of-entry to the furthest water outlet was longer than 152 m [500 ft] for both cold and hot. The building contained 363 water outlets: 81 cabinet/classroom sinks, 92 lavatory sinks, 25 drinking water bubblers, 33 showers, 5 mop/service sinks, and 127 toilets in the building. Cold and hot water sampling locations were sampled throughout the building (**Figure 1-1, Table 1-1**).

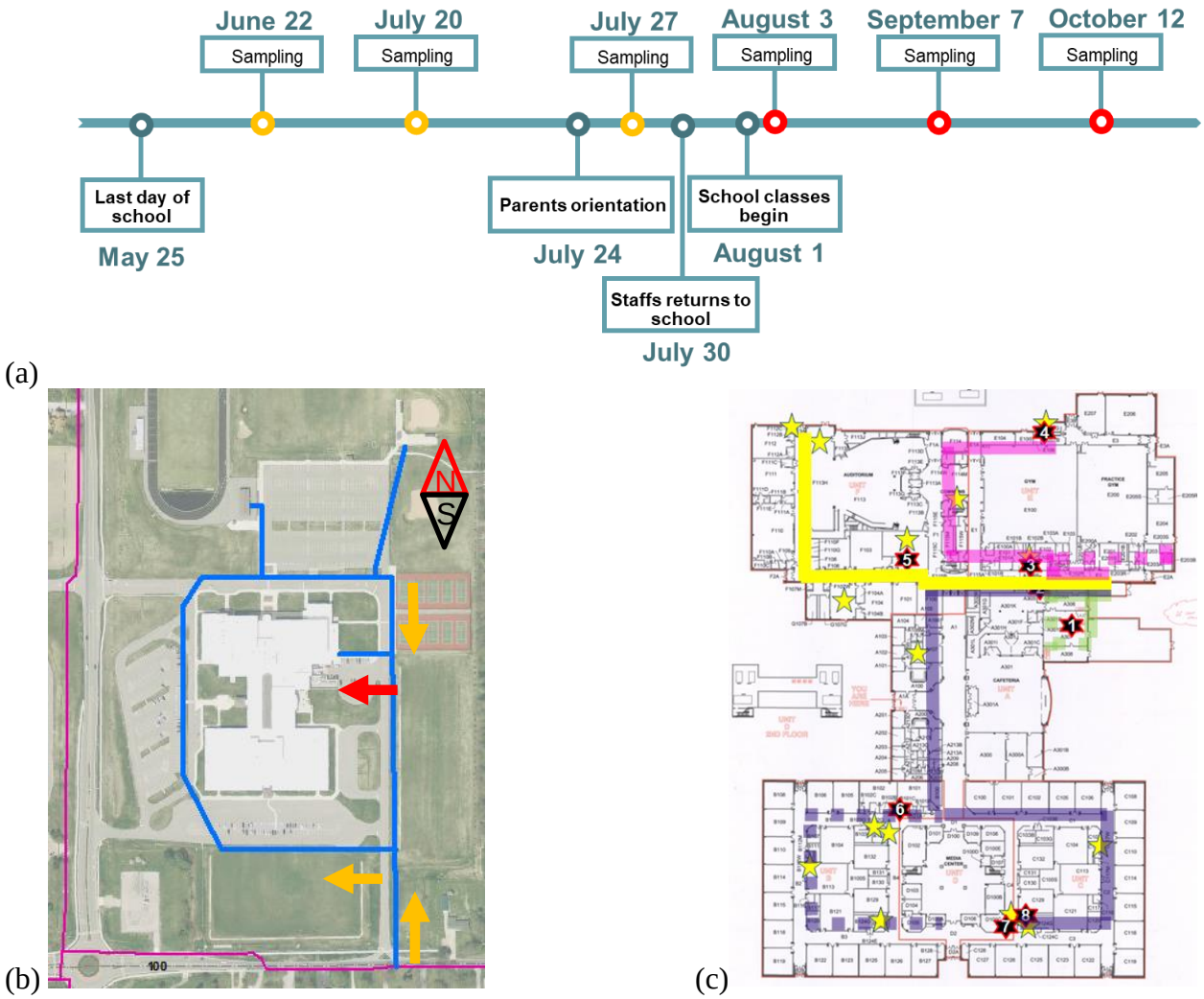


Figure 1-1. (a) Timeline for sampling and major school events, (b) The water service loop at school campus, the service line comes off the road to provide water from the south of the school and circles the entire school campus. Red arrow is the domestic service line that goes into the utility room, (c) Water sampling locations (stars) and four hot water recirculation loops (colored lines). Black numbered stars are sampling locations at all 6 visits: #1 utility room (BE, AS, BWH, HWRa, HWRb, AWH), #2 closest bathroom (B1C, B1H), #3 student showers (SH1, SH2), #4 Farthest bathroom (B2C, B2H), #5 students' kitchen (SKC, SKH), #6 teachers' kitchen (TKC, TKH), #7 bathroom south (B3C, B3H), and #8 water bubblers (WF1, WF2). Yellow stars are additional locations that were sampled on last visit for metal analysis.

1.3.2 Water Sampling Approach

Water sampling began between 7:00 am and 7:15 am on Fridays and samples were collected from 9 hot water and 9 cold water locations for 5 of the 6 events (**Figure 1-1, Table 1-1**). No students were there but a few faculty and staff members had arrived in the building before sampling. Drinking water was first collected where water entered the building (BE) and the authors

proceeded to sampling locations in the north section (the most used area during summer break and closer to the entry point) and then moved to the south section (least used during summer break). No water flowrate was measured, but all the stagnant water samples were collected at a slow flowrate. Water was constantly flowing while collecting each sample but closed the tap after collection. Approximately 150 mL of water was collected for immediate analyses (pH, temperature, dissolved oxygen, total chlorine, free chlorine, free ammonia, monochloramine). Next, several samples were collected for metals [125 mL HDPE bottles with 0.05 mL acid], metals [125 mL HDPE bottles without acid], total organic carbon (TOC) [250 mL amber glass], alkalinity [250 mL amber glass], total trihalomethanes (TTHM) [two 20 mL glass vials], total cell counts (TCC) [two 15 mL falcon tubes], heterotrophic plate count (HPC)/quantitative polymerase chain reaction (qPCR) [two 1 L HDPE bottles], nitrification/denitrification [two 15 mL bottles]. Samples were kept in coolers with ice packs, transported to the laboratory a 1.5 hr drive away and were immediately analyzed. Water was screened for nitrification and denitrification processes using biological activity reaction test (BART) kits at all locations in the utility room one shower, and a bathroom sink for cold and hot. In accordance with the manufacturer's instruction, samples were evaluated for nitrification 5 days after the water was collected, and every day for 4 days for denitrification.[32] A detailed explanation of chemical and microbiological analysis methods, including equipment, instrument and method detection limits, can be found in the **SI** section.

After the first sampling event, the copper concentration in the building water system became a significant focus of this study. Initial copper results indicated building-wide copper AL exceedances. The authors then collected additional water samples for metals analysis on sampling events 2, 5, and 6. These additional water samples (same volume as the routine samples analyzed for metals) were collected after all the other water samples had been collected at each location (2.8 L later per sampling location). After finding further copper exceedances, the school, public water supplier, health department, and state drinking water primacy agency discussed the issue. Next, the school followed the state primacy agency's recommendation to flush each fixture where the authors found copper in exceedance of the AL, not implement a school-wide flushing program. Because of the author's concerns that such an action would not reduce copper concentration for other locations in the building, the authors then added an additional 19 new cold water sampling locations for the final sampling event (trip 6 of 6). To mimic the sampling approach used at other faucets the authors had previously tested during sampling events 1-5, at each new location on event

6 the first 125 mL of cold water was discarded, then a sample (125 mL) was collected for metals analysis, and then 2.8 L of cold water was discarded again before another sample (125 mL) for metals analysis was collected. This extra water sample still represents the stagnant water in different plumbing sections between fixtures (a lot of cold water pipes would store more than 3.7 L between fixtures). This approach enabled direct comparison of data collected on sampling event 6 to all other sampling events.

Table 1-1. Cold and hot water sampling locations included the building entry point, inside the utility room, water heaters, recirculation loops, water fountains, and sink faucets. Utility room locations, the north part of the building (most used building portion during Summer break), and the south part of the building (least used building portion during Summer break).

Regular Routine Sampling Location [Room#]	**Acronym**	**Additional New Sampling Location [Room#]**	**Acronym**
Building entry point sampling tap [utility room]	BE	Shower room right sink faucet [E102B]	SRS
After Softener sampling tap [utility room]	AS	Shower room left sink faucet [E102B]	SLS
Before Water Heater (combined) sampling tap [utility room]	BWH	Bathroom 2 cold right sink faucet [E207J]	B2CR
Hot Water Recirculation Loop-a 120˚F temperature sampling tap [utility room]	HWRa	Bathroom 2 cold left sink faucet [E207J]	B2CL
Hot Water Recirculation Loop-b, 140˚F temperature sampling tap [utility room]	HWRb	Student kitchen sink faucet D [F102]	SKD
After Water Heater sampling tap [utility room]	AWH	Student kitchen sink faucet F [F102]	SKF
Bathroom outside utility room cold sink faucet [A306R]	B1C	Faculty kitchen sink faucet [A108]	FK
Bathroom outside utility room hot sink faucet [A306R]	B1H	Art room right sink faucet [F105]	ARRS

Table 1-1. continued

Shower head ADA compliant [E102S]	SH1	Auditorium back sink faucet [F113]	ABS
Farthest bathroom cold sink faucet [E207G]	B2C	Water fountain in coral room [F112]	WF3
Farthest bathroom hot sink faucet [E207G]	B2H	Bathroom sink faucet in office [A108M]	B9
Student's kitchen cold sink faucet [F102]	SKC	Drinking water fountain 5 [B103B]	WF5
Student's kitchen hot sink faucet [F102]	SKH	Bathroom 3 left sink faucet [C124B]	B3LS
Teacher's kitchen cold sink faucet [B102A]	TKC	Bathroom 4 next to sink 2 faucet [C124G]	B4
Teacher's kitchen hot sink faucet [B102A]	TKH	Bathroom 5 sink faucet [B103B]	B5
Men's bathroom cold sink faucet [C124B]	B3C	Bathroom 6 faucet [B124B]	B6
Men's bathroom hot sink faucet [C124B]	B3H	Staff bathroom sink faucet [B112W]	B7
Drinking water fountain [C124B]	WF1	Staff bathroom sink faucet [C112W]	B8
Drinking water fountain ADA compliant [C124B]	WF2		

1.3.3 Building water quality in nearby commercial buildings

Because of copper exceedances within the building, the authors collected first draw water samples at 21 nearby commercial restaurant and retail buildings from either water bubblers or bathroom sinks (**Figure SI.1-2**). These sites received drinking water from the same public water supplier. The sampling event was conducted on September 5, 2018 from 11:57 am to 5:50 pm. Similar methods applied at the school building were also applied for these water samples. For each sample, about 250 mL water was first collected in a glass beaker to directly measure at the site for

temperature, pH, dissolved oxygen (DO), total and free chlorine, monochloramine, free ammonia measurements. Then, a 125 mL amber bottle was filled for a metal water sample and all the metal samples were transported at 4˚C in the coolers with ice packs to the laboratory for analysis.

1.3.4 Statistical analysis

All water quality data were statistically analyzed using IBM SPSS Statistics 25. A multiple linear regression was applied to all water quality analysis done to better understand what variables affect the specific water quality measurement. Bivariate Pearson correlation analysis was also conducted to compare significant correlation between each water quality parameter. A significance level of 0.05 was used for all statistical analysis.

1.4 Results and discussions

1.4.1 Water delivered to the campus meter and transported to the school building

In August and September, water usage was much higher than any month in the previous three years (**Table SI.1-1, Figure SI.1-1**). The total campus water use ranged from 1.4M to 18M gallons per day and included irrigation, buildings, and other purposes (**Table SI.1-2**). The water supplier reported that, on average, 63 hours was needed for their treated drinking water to reach the campus water meter. Water use records and usage allocation information was not available for the main school building where water quality testing was conducted.

1.4.2 Water quality entering the building was consistent across sampling events

Drinking water at the building entry point (BE) had different characteristics than water reported in the public water supplier's annual report. Water entering the building however did not exceed any U.S. federal primary or secondary drinking water limits.[33] The water supplier reported that the average of total chlorine concentration entering their distribution system was 1.48 mg/L-Cl_2. The water supplier changes disinfectants from chloramine to free chlorine for few weeks each year. During 4 of the 6 sampling events (3 of 5 months) total chlorine was not detected entering the building according to Indiana State law's definition of "nondetectable" [<0.2 mg/L as Cl_2] (PWS,1996): June (0.20 mg/L as Cl_2), July (0.16, 0.14 mg/L as Cl_2), August (0.43 mg/L as Cl_2),

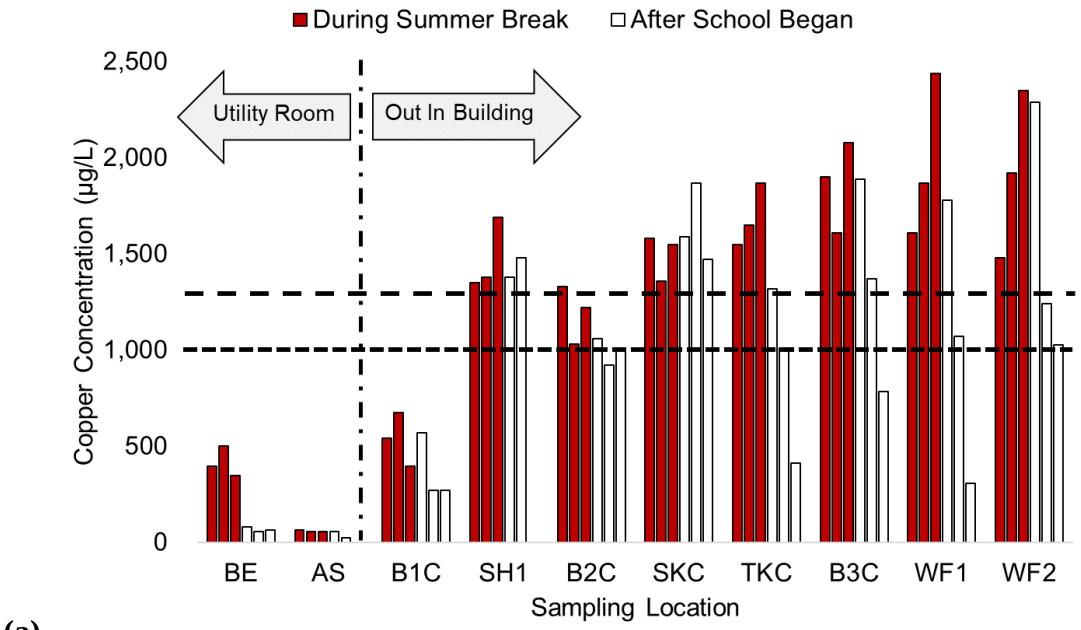
Sept (0.17 mg/L as Cl_2), Oct (BDL mg/L as Cl_2). The low disinfectant residual may be due to the long travel time from the water meter to the building. The public water supplier reported water pH ranged from 7.00 to 8.48, and a narrower range was found entering the building during the present study (7.62 to 7.87). Other organic (TTHM) and inorganic contaminants were also found entering the building but within levels reported by the water supplier (Al, Cl^-, Cr, F^-, Fe, Mn, Na, Ni, Zn, NO_3^-, NO_2^-, SO_4^{-2}, hardness) (**Table 1-2**, **Table SI.1-1**).

Additional water sampling was conducted at the BE location to better interpret in-building drinking water results. Slight differences were found at the building entry point throughout the sampling event for water temperature (20.4 to 27.3˚C), TOC (1.7 to 2.0 mg/L), HPC (11 to 400 CFU/100 mL), but much larger differences were found for TCC (30,200 to 433,533 cells/mL). Inorganic contaminants that were detected entering the building included NH_3 (0.8 to 2.8 mg/L-N), NO_3^- (0.82 to 2.78 mg/L-N), NO_2^- (0 to 0.06 mg/L-N), NH_4^+ (0.37 to 1.34 mg/L-N), and PO_4^{-3} (0 to 0.04 mg/L-P) were found (**Table SI.1-1**). Other contaminants were found at insignificant levels (Br^-, K^+). Alkalinity was also measured (>183 mg/L as $CaCO_3$) but no significant correlation between temperature, location, or water use was found (**Figure SI.1-3**).

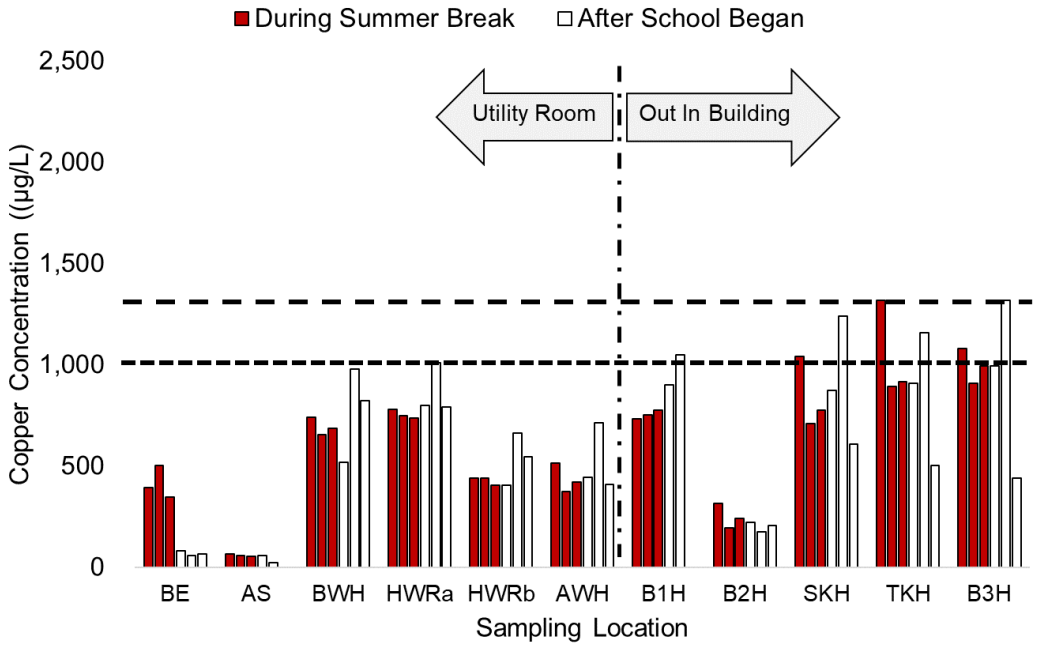
1.4.3 Building copper levels exceeded the health-based action level, were correlated to pipe length, and flushing was ineffective at their reduction

Water exiting the water softener never exceeded the copper AL, but the copper AL was frequently exceeded for cold water at building fixtures (**Figure 1-3**). More than half of the total first draw water samples [29 of 54] exceeded the copper AL. Within the building cold water, copper levels significantly reduced after the school returned to session (p=0.006) [Before 1.4 ± 0.66 mg/L (n=27); After 0.94 ± 0.57 mg/L (n=46)].

Hot water copper levels were often lower in magnitude than cold water copper levels at the same fixtures. In contrast to cold water, only 2 of 54 hot water samples collected exceeded 1.3 mg/L (**Figure 1-3**). Hot water copper levels did not differ before and after school returned to session (p=0.962): Before 0.69 ± 0.27 mg/L (n=27); After 0.69 ± 0.34 mg/L (n=7).



(a)



(b)

Figure 1-2**.** From June to October, 2018 total copper concentration was monitored at the building entry point (BE), water exiting the softener (AS), and (a) 8 cold water locations in the building, and (b) 4 hot water locations in the utility room and 5 hot water locations in the building. Each bar represents one sampling event and the results represent first draw samples only. Sampling location (left to right) is corresponds to distance from the water meter. The dashed horizontal lines indicate the health based AL of 1,300 µg/L, and aesthetic based secondary MCL of 1,000 µg/L. Trip and field blanks were free of contamination. BE = Entering building, AS = After softener, BWH = Before water heater, HWR = Hot water return, AWH = After water heater, B = Bathroom, C = Cold water, H = Hot water, SK = Student's classroom kitchen sink, TK = Teacher's lounge kitchen sink, WF = water fountain.

As distance from the water meter increased, the observed copper concentration increased for both cold and hot water (p<0.001) (**Figure 1-4**). A prior study indicated that total copper concentration increased in school plumbing as alkalinity increased and pH decreased,[8] but other variables such as DO, pH and before/after the break were also significantly correlated with copper concentration just for hot water samples (p <0.05). Unlike the prior study,[34] total chlorine, free ammonia, and alkalinity were not correlated with the observed copper concentration in the present study.

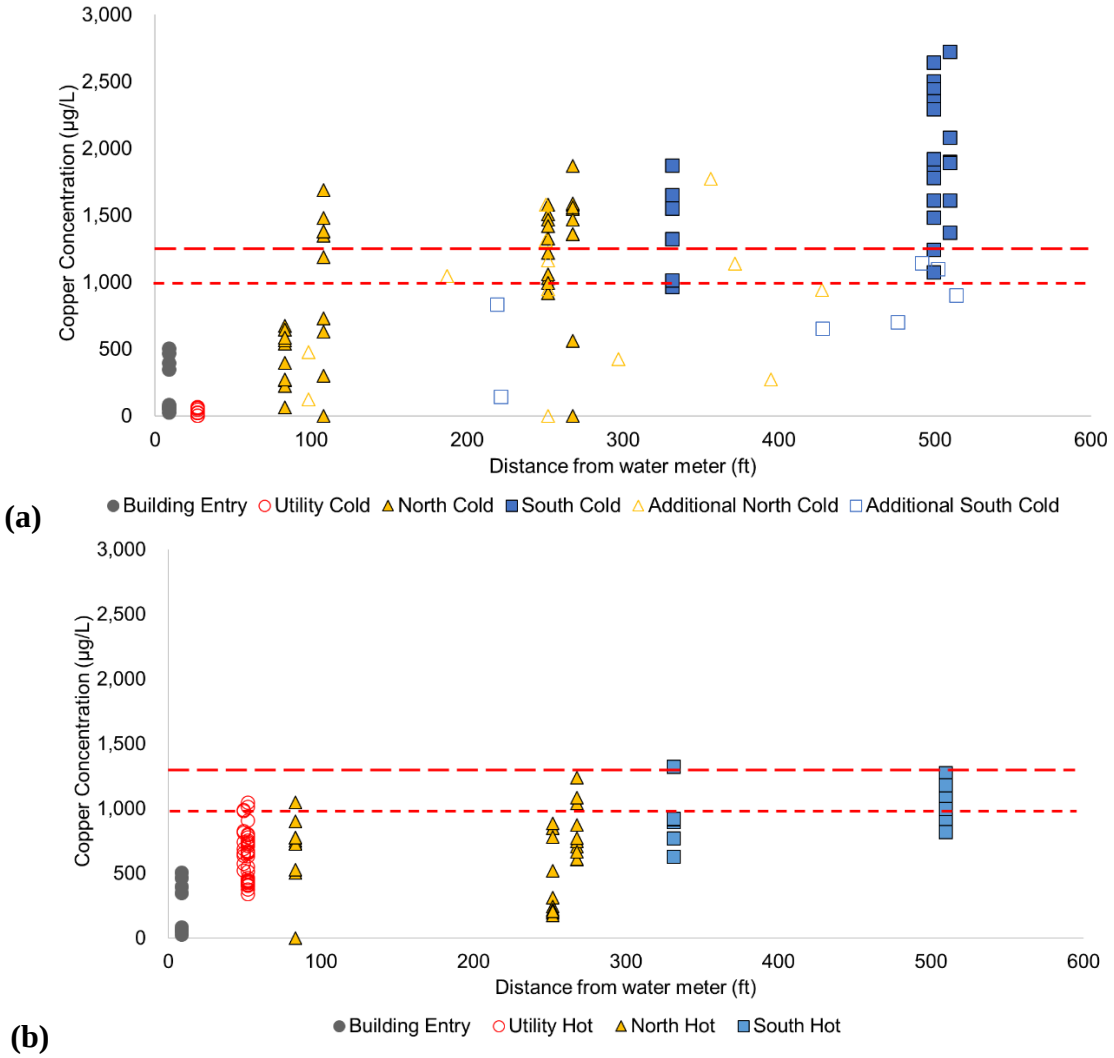


Figure 1-3. Total copper concentration of all collected (a) Cold, (b) Hot water samples compared to the faucet location's distance from the water meter. Dotted lines represent the health-based copper AL of 1,300 µg/L and aesthetic based secondary MCL of 1,000 µg/L

Flushing individual fixtures did not consistently reduce cold and hot water copper levels below the AL across the school. Of the 28 cold water locations (9 routine + 19 additional fixtures) sampled during the final sampling event, only 4 locations were found where copper exceeded the AL (4/28 exceeded). These were first draw samples. When a water sample was collected after all other water samples were drawn (2.8 L later), 3 *new* locations exceeded the AL (maximum of 1.47 mg/L), and 2 previously problematic locations again exceeded the AL (6/28 exceeded). Finally, after a 5 minute flush of the 9 routine fixtures, 1 location exceeded AL again. As-built drawings (pipe length and volume from location to location) indicated this water originated from one of the largest pipe volume sections for cold water in the building (~14.58 gallon [55 L] could be stored). Because copper pipes and fittings existed throughout the building, copper contaminated water elsewhere in the building water system likely was drawn to different fixtures during flushing. Also, many water outlet locations had long pipe lengths from faucet to faucet, which also meant a large volume of water was stored (these pipes would need greater than 5 minutes to flush out the water). This result underscores how applying finite flushing times, without understanding the building water system itself, to reduce copper contamination can fail. Others have reported that flushing did not consistently reduce cold water copper levels in school buildings.[11-13] Complete building water system turnover seems necessary to rid the building water system of copper contaminated water.

While hot water is not considered potable, none of the hot water samples exceeded the 1.3 mg/L level for first draw or 5 minute flushed samples (**Figure SI.1-4**). However, all 9 routine hot water samples increased copper levels for the second draw samples, then decreased for the third draw samples. Like the cold water copper observations, these changes can be attributed to water with varying levels of copper being drawn from different parts of the building water system to the sampled fixture. As distance from water entry point increased, water travel time also increased. Overall, copper concentration was greater in the cold water samples than hot water samples because copper is more soluble.[35]

1.4.4 Building water carbon loading, bacteria, and nitrification differed before and after school returned to session

Cold water samples always had a lower TOC concentration than hot water samples for the same location. TOC levels in cold water were not statistically different before and after school

returned to session (p=0.34). Cold water TOC levels ranged from 1.5 to 6.7 mg/L (n=54) compared to hot water 1.6 to 3.4 mg/L (n=54) (**Table 1-2, Figure SI.1-5**). The greatest TOC levels were found exiting the water softener during the summer break (2.1 to 6.7 mg/L), much greater than the levels found in water entering the building and other fixtures in the building. The water's TOC concentration entering the softener was 1.9 ± 0.16 mg/L. Prior evidence indicates softeners can be sources of biological activity, providing substrate for growth and possibly leaching organic carbon to support microbial processes.[36, 37] For hot water, TOC levels were significantly reduced after school returned to session (p<0.05). TOC and other variables (pH, DO, total Cl_2, NH_3-N, alkalinity and distance from the BE location) were evaluated with linear regression. Cold water TOC level was significantly correlated with pH (p<0.05) and total Cl_2 (p<0.05), while hot water TOC level was significantly correlated with alkalinity and NH_3-N.

Nitrifying bacteria were found in both cold and hot water samples, and their detection and magnitude differed between summer and fall, fixture location, and water temperature. Water entering the building often contained a low number of nitrifying bacteria (<1,000 CFU/mL). A previously reported nitrifying bacteria concentration in a chloraminated surface water was <850 CFU/mL.[38] Studies have shown that copper could limit nitrification (10% lower than PVC, brass and lead pipes),[39,40] but no correlation was found in this study. Cold water collected from a distal shower head (SH2) contained nitrifying bacteria up to 1,000 CFU/mL, but cold water collected from a distal bathroom (B3C) had a nitrifying bacteria level of ~1,000 to 100,000 CFU/mL. Hot water from the same distal bathroom fixture (B3H) had ~1,000 CFU/mL during the summer break and <1,000 CFU/mL when school was in session. Interestingly, when school returned to session the concentration of nitrifying bacteria exiting the water softener increased from no bacteria or 1,000 CFU/mL to about 10,000 CFU/mL. Coupled with the greater TOC values and nitrification bacteria loading at the softener, it is likely that the softener was a bioreactor for microbial growth.

Within the hot water recirculation systems, nitrifying bacteria levels differed between summer and fall months. During summer break, 4 of 4 water samples collected from hot water recirculation lines and water heaters contained nitrifying bacteria (~10,000 to 100,000 CFU/mL). When school returned to session, the amounts of bacteria at these locations gradually reduced as time goes, with much lower amounts of bacteria (~1,000 to 10,000 CFU/mL).

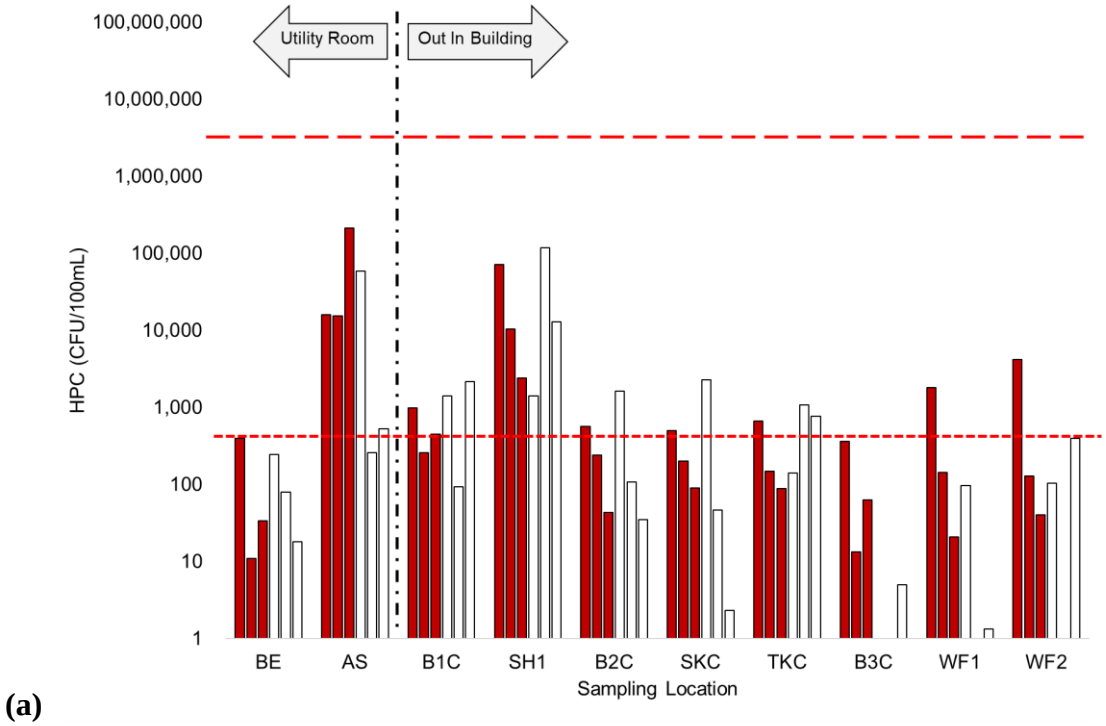
No relationship between nitrification, pH, and chloramine concentration was observed, while the literature indicates that increasing nitrification can decrease pH and chloramine

residual[41]. NO_3^- and NO_2^- were detected when nitrifying bacteria were found, and regression analysis showed NO_3^- concentration was significantly correlated (p<0.001) with nitrifying bacteria concentration while NO_2^- concentration was not. Others have reported that the ammonia-oxidizing bacteria population increased as monochloramine residual increased,[42] but no trend was found in this study. Denitrifying bacteria were detected in the present study (<350 CFU/mL) in 2 of 20 cold and 3 of 20 hot water samples.

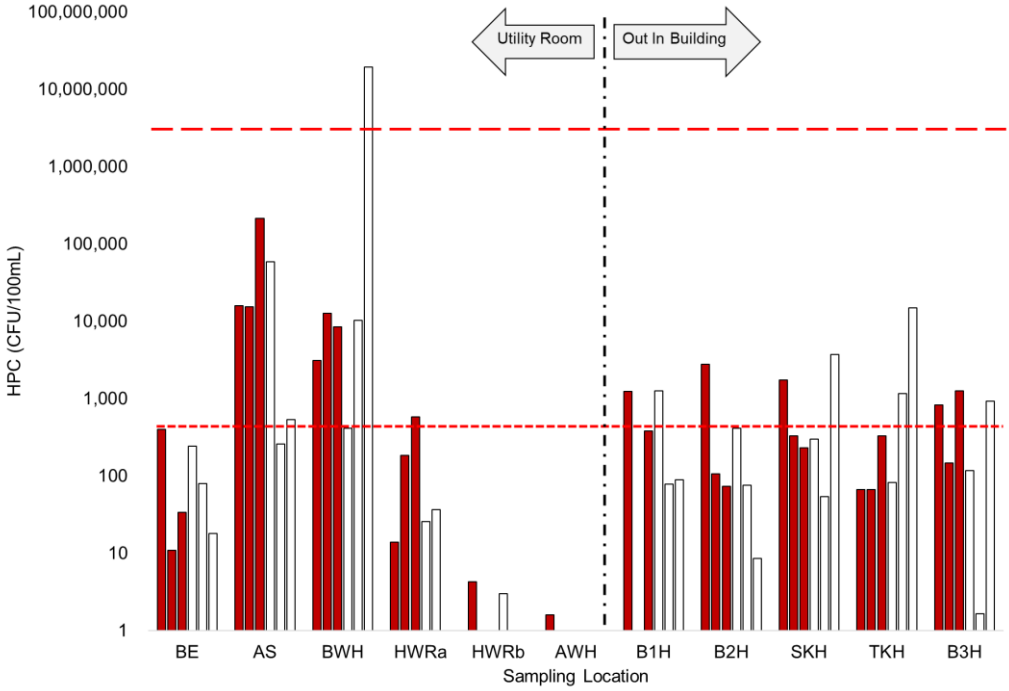
HPCs at the BE location (11 to 400 CFU/100mL) were within the range of levels found by others at reported service lines that used free chlorine disinfectant (3,300 to 23,100 CFU/100mL)[43] and (0 to 2.1 CFU/100mL)[34]. HPC levels increased by 3 orders of magnitude in the short distance from water entering the building to the softener (about 37 ft). It was expected that HPC values would be greater inside the building than at the BE location.[44] None of the in-building cold water samples exceeded the USEPA drinking water guideline of 500,000 CFU/100mL [45,46] except for one hot water location one time during the final sampling event (**Figure 1-5**). No significant difference for HPC between cold and hot water samples was observed for the same location, but HPC levels gradually decreased at the heater tanks (decreased more after the tank with higher temperature), but then increased again. As expected, HPC levels at the higher temperature hot recirculation loop (60˚C) was lower (1 to 4 CFU/100mL), than at the lower temperature loop (48.8˚C) (1 to 583 CFU/100mL).

A Pearson correlation analysis indicated a statistically significant correlation between HPC and TCC for cold water (p=0.01) but no relationship was found for hot water (p=0.471). HPC results were more variable across locations, temperatures and between sampling trips, while TCC results were less variable and consistent throughout the sampling trips and between locations (**Figure 1-5, Figure SI.1-6**). HPCs have been previously shown to be correlated with residence time and the presence of disinfectant residual.[43] HPCs in cold water samples were statistically correlated with distance from the water meter, while no relationship was found for HPCs in hot water to expected predictors (i.e., total chlorine, free ammonia, DO, pH, temperature, alkalinity, distance from the water meter). Past study indicated significant bacterial decline in the first 500 mL, similar level of HPC as the past study[45] were found even after collecting 2 L before HPC sample. Though, the study also indicated HPC significantly increased after only 1 hr of stagnation. Additional work should examine the relationship between HPC and presence and magnitude of pathogens like *Legionella pneumophila*, as this would be more relevant to understand building

water health risks.[47,48] No other trends for microbiological parameters and the distance from the water meter were observed.



(a)



(b)

Figure 1-4. Heterotrophic plate count of first draw from building entry point (BE), water existing the softener (AS), and (a) 8 cold water locations in the building, and (b) 4 hot water locations in the utility room and 5 hot water locations in the building. Red dotted line is HPC drinking water guideline from the World Health Organization (500,000 CFU/100mL), and 500 CFU/100mL limit. BE = Entering building, AS = After softener, BWH = Before water heater, HWR = Hot water return, AWH = After water heater, B = Bathroom, C = Cold water, H = Hot water, SK = Student's classroom kitchen sink, TK = Teacher's lounge kitchen sink, WF = water fountain.

1.4.5 Water quality comparison to other off-campus commercial buildings

Similar low disinfectant residual concentrations were found in restaurant and retail commercial buildings near the school campus (33% had less than 0.2 mg/L as Cl_2). Nearly all water samples from off-campus commercial building bathroom sinks did not exceed the copper AL (**Figure 1-2, Table SI.1-3**). Because the two locations that exceeded copper AL were drinking water fountains (maximum of 1.62 mg/L) also had low disinfectant residual, it is hypothesized water age was a contributing factor. Other water quality characteristics such as temperature (16.2 to 30.7˚C), pH (7.56 to 7.88), and DO concentration (3.63 to 8.46 mg/L) were similar to school building water quality results.

1.5 Limitations

This study provides water quality insights for a 7 year old green building where previous copper water testing had not previously been conducted. Six sampling events were conducted over a 5 month period due to the geographical distance from the author's laboratory and amount of work required for sample processing and analysis. Only discrete water samples were collected and prior studies have shown wide fluctuations of water quality entering buildings elsewhere when continuous online monitoring was conducted[34]. While water quality was only characterized at 10% of the water outlets (38 of 363), school wide copper water contamination was discovered. Also, the flushing recommendation given by others to the school was ineffective partly due to the fact that the recommendations did not consider plumbing design. School building water use data was not available for more detailed analysis. Further, few water quality studies pertaining to schools were found for comparison.

Table 1-2. Water quality measurements of first draw samples

Parameter		Summer									Fall								
		After meter (n=3)			Cold lines (n=27)			Hot lines (n=27)			After meter (n=3)			Cold lines (n=27)			Hot lines (n=27)		
		Min	$\bar{x}$	max	min	$\bar{x}$	max	min	$\bar{x}$	max	min	$\bar{x}$	max	min	$\bar{x}$	max	min	$\bar{x}$	max
General	Temp, °C	25.2	26.1	27.3	15.8	21.9	26.4	21.5	29.3	47.3	20.4	24.2	27.1	14.5	21.8	30.2	19.7	29.8	46.3
	pH	7.6	7.8	7.9	7.2	7.8	8.5	7.7	8	8.2	7.7	7.8	7.9	7.6	7.9	8.2	7.7	8	8.2
	DO, mg/L	8.9	9	9.1	2.6	6.9	10.2	3.1	5.6	8.9	7.4	8.4	9.2	4.4	7.4	9.2	3.2	6.6	9
	Total Cl_2, mg/L	0.1	0.2	0.2	0	0.1	1.4	0	0.1	1	0	0.2	0.2	0	0.03	0.3	0.01	0.03	0.13
	NH_2Cl, mg/L	0.1	0.2	0.3	0	0.08	0.5	0	0.04	0.1	0.07	0.5	0.94	0	0.07	0.41	0	0.1	0.7
	Free NH_3, mg/L	0	0.2	0.48	0	0.1	0.41	0.01	0.2	0.84	0	0.06	0.13	0	0.08	0.21	0.01	0.06	0.16
Organics	TOC, mg/L	1.7	1.9	2	1.5	2.2	6.7	2.9	3.4	3.8	1.8	2	2.2	1.5	1.9	2.3	1.6	2.3	3.4
	DOC, mg/L	1.7	1.9	2	1	2.1	6.5	2.6	3.3	3.6	1.8	2	2.1	1.4	1.9	2.2	1.7	2.2	3.3
Microbiology	HPC, cfu/100mL	11	148	400	13	12,614	214,000	0	1,284	12,667	18	114	245	0.667	7,489	117,670	0	720,894	19,430,000
	TCC, cell/mL x 10^4	3.02	20.9	35.6	4.79	23.8	62.8	54.8	81.6	116.1	5.89	80.5	43.4	6.86	19.9	32.8	15.4	34.2	79.8

Table 1-2. continued

Nitrogen	NH_4-N, mg/L	0.4	0.7	1.3	0.1	0.3	0.5	0.1	0.1	0.2	0.4	0.6	0.8	0.1	0.4	3.2	0.0	0.1	0.2
	NO_2-N, mg/L	-	-	-	-	-	-	0.0	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	NO_3-N, mg/L	0.8	1.5	2.8	0.8	1.9	3.0	0.9	1.3	1.7	1.2	1.4	1.5	1.0	1.5	2.6	1.0	1.3	2.2
Metal	Cu, µg/L	347	415	503	55	1,356	2,440	196	689	1,320	57	68	81	0	980	2,290	0	693	1,320
	Pb, µg/L	0	0	0	18.5	2.2	40.9	0	0	0	0	0	0	0	1.3	35.1	0	0	0

x = mean; lead was only detected in shower cold water, also detected for second draw (7.79 µg/L) but not for third draw on the last sampling event.

For all water samples, 68% did not detect disinfectant residual (BDL 0.05 mg/L), and 83% contained free ammonia (BDL 0.02 mg/L)

1.6 Conclusions and recommendations

The study goal was to better understand how drinking water chemical and microbiological parameters change in a school during the transition from summer break (low water use) and during several weeks after classes resumed (normal use). Specific objectives were to (1) document first draw water quality at 19 different cold and hot water locations, (2) determine the relationship between water quality and distance from the building entry point for the parameters examined, and (3) determine if water quality differed between before and after school returned to session. Clear trends of water quality changes at different locations and various analysis that increase level of understanding the water quality were found that can help inform building water sampling and plumbing design.

Building cold and hot water quality differed between the low and normal use session. Water entering the school building often contained less than the state government agency designated level for a detectable disinfectant residual concentration. Within the building, chemical and microbiological water quality depended on the pipe system (cold vs. hot) and fixture location. Copper contaminated drinking water was found throughout the school and during every sampling event (maximum of 2.72 mg/L). Copper leaching was likely influenced by stagnation time and also the high alkalinity water. A statistically significant relationship was found between copper concentration and the pipe length conveying the water to a fixture. Spot flushing, as recommended by a government agency, did not effectively reduce the copper level. Also found was that long times were needed for hot water to reach distal faucets, indicating the potential for increased bacterial growth conditions in temperate water.

Building water system design standards and plumbing code requirements are lacking that require an explicit consideration of source water quality, system operation, and material interactions to minimize cold and hot water quality impacts. The authors recommend both chemical and microbiological testing should be conducted before new construction is placed into service and periodically during the life of the building. Copper testing should be required for all new and renovated buildings. Water testing plans should be developed based on as-built plumbing drawings and types of the water outlets. Copper exceedances likely went undetected for 7 years because water quality testing was not conducted. Because copper leaching decreases with time, it is likely that higher copper levels were present during that 7 year period where children and other persons may have been exposed. Microbial contamination also went undetected for similar reasons. While the school building was LEED certified, and some

requirements were to meet environmental regulations, standards, and focus on water efficiency [51], the plumbing caused water inside the building to exceed safe drinking water limits.

Once school water safety problems are identified, restricting water use, installing in-building treatment, and/or point-of-use devices may be necessary. Spot flushing should not be relied upon to reduce copper levels, and can result in higher copper levels at the fixture. For high alkalinity groundwater with copper plumbing, additional schools may have similar drinking water safety problems. With the continued absence of codes and regulations that require initial and periodic water testing at schools, communities should initiate their own testing to determine if the plumbing poses a health risk to children and other occupants.

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1.8 References

1. Nwachuku, N., & Gerba, C. P. (2004). Microbial risk assessment: don't forget the children. *Current Opinion in Microbiology*, *7*(3), 206-209. DOI: 10.1016/j.mib.2004.04.011

2. Centers for Disease Control and Prevention (CDC). (2019). Water Access. Retrieved from https://www.cdc.gov/healthyschools/npao/wateraccess.htm

3. American Academy of Pediatrics (AAP). (2016). With No Amount of Lead Exposure Safe for Children, American Academy of Pediatrics Calls for Stricter Regulations. Retrieved April 18, 2020, from https://www.aap.org/en-us/about-the-aap/aap-press-room/Pages/With-No-Amount-of-Lead-Exposure-Safe-for-Children,-American-Academy-of-Pediatrics-Calls-For-Stricter-Regulations.aspx

4. Rosen, M. B., Pokhrel, L. R., & Weir, M. H. (2017). A discussion about public health, lead and Legionella pneumophila in drinking water supplies in the United States. *Science of The Total Environment*, *590*, 843-852. DOI: 10.1016/j.scitotenv.2017.02.164

5. U.S. Centers for Disease Control and Prevention (CDC). Surveillance for Waterborne Disease Outbreaks Associated with Drinking Water and Other Nonrecreational Water - United States, 2009–2010. (2013, September 6). Retrieved April 18, 2020, from https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6235a3.htm?s_cid=mm6235a3_w

6. Cech, I., Smolensky, M. H., Afshar, M., Broyles, G., Barczyk, M., Burau, K., & Emery, R. (2006). Lead and copper in drinking water fountains-Information for physicians. *Southern Medical Journal*, *99*(2), 137-142. DOI: 10.1097/01.smj.0000198495.41559.f6

7. USEPA (2005). *Lead and Copper Rule:* A *quick reference guide to schools and child care facilities that are regulated under the Safe Drinking Water Act*. EPA-816-F-05-030.

8. USEPA. (2019). Lead in Drinking Water in Schools and Childcare Facilities. Retrieved from https://www.epa.gov/dwreginfo/lead-drinking-water-schools-and-childcare-facilities

9. Gonzalez, S., Lopez-Roldan, R., & Cortina, J. L. (2013). Presence of metals in drinking water distribution networks due to pipe material leaching: a review. *Toxicological & Environmental Chemistry*, *95*(6), 870-889. DOI: 10.1080/02772248.2013.840372

10. USEPA. (2019, October 15). Lead and Copper Rule. Retrieved April 18, 2020, from https://www.epa.gov/dwreginfo/lead-and-copper-rule

11. Commonwealth of Massachusetts Energy & Environmental Affairs. (2018). Retrieved December 6, 2019, from https://eeaonline.eea.state.ma.us/portal#!/search/leadandcopper/results?FacilityType=School (SCH)&AnalyteName=COPPER&Result=Above Action Level.

12. Barn, P., Nicol, A. M., Struck, S., Dosanjh, S., Li, R., & Kosatsky, T. (2014). Investigating elevated copper and lead levels in school drinking water. *Environmental Health Review*, *56*(04), 96-102. DOI: 10.5864/d2014-006

13. Doré, E., Deshommes, E., Andrews, R. C., Nour, S., & Prévost, M. (2018). Sampling in schools and large institutional buildings: Implications for regulations, exposure and management of lead and copper. *Water Research*, *140*, 110-122. DOI: 10.1016/j.watres.2018.04.045

14. Murphy, E. A. (1993). Effectiveness of flushing on reducing lead and copper levels in school drinking water. *Environmental Health Perspectives*, *101*(3), 240-241. DOI: 10.1289/ehp.93101240

15. Cech, I., Smolensky, M. H., Afshar, M., Broyles, G., Barczyk, M., Burau, K., & Emery, R. (2006). Lead and copper in drinking water fountains-Information for physicians. *Southern Medical Journal*, *99*(2), 137-142. DOI: 10.1097/01.smj.0000198495.41559.f6

16. Johnson, K., Bowman, E., Fries, D. (2018). Drinking Water in Marion County, Indiana Schools. Retrieved from https://assets.documentcloud.org/documents/6671104/Drinking-Water-in-Marion-County-Schools.pdf

17. Richard, R., Hamilton, K. A., & Boyer, T. (2020). Tracking copper, chlorine, and occupancy in a multi-story, new, institutional green building. *Environmental Science: Water Research & Technology*. DOI: 10.1039/D0EW00105H

18. International Code Council (ICC) (2018). *International Plumbing Code.* Retrieved from https://codes.iccsafe.org/content/IPC2018/chapter-6-water-supply-and-distribution

19. International Association Plumbing and Mechanical Officials (IAPMO). (2018). *Uniform Plumbing Code 2018.* Retrieved from http://epubs.iapmo.org/2018/UPC/

20. Merkel, T. H., Groß, H. J., Werner, W., Dahlke, T., Reicherter, S., Beuchle, G., & Eberle, S. H. (2002). Copper corrosion by-product release in long-term stagnation experiments. *Water Research*, *36*(6), 1547-1555. DOI: 10.1016/s0043-1354(01)00366-9

21. Lytle, D. A., & Schock, M. R. (2000). Impact of stagnation time on metal dissolution from plumbing materials in drinking water. *Journal of Water Supply: Research and Technology-AQUA*, *49*(5), 243-257. DOI: 10.2166/aqua.2000.0021

22. Edwards, M., Schock, M. R., & Meyer, T. E. (1996). Alkalinity, pH, and copper corrosion by-product release. *Journal American Water Works Association*, *88*(3), 81-94. DOI: 10.1002/j.1551-8833.1996.tb06521.x

23. Lytle, D. A., & Schock, M. R. (2008). Pitting corrosion of copper in waters with high pH and low alkalinity. *Journal American Water Works Association*, *100*(3), 115-129. DOI: 10.1002/j.1551-8833.2008.tb09586.x

24. Boulay, N., & Edwards, M. (2001). Role of temperature, chlorine, and organic matter in copper corrosion by-product release in soft water. *Water Research*, *35*(3), 683-690. DOI: 10.1016/s0043-1354(00)00320-1

25. EPA. (2019). 3Ts for Reducing Lead in Drinking Water in Schools and Child Care Facilities. Retrieved from https://www.epa.gov/sites/production/files/2018-09/documents/final_revised_3ts_manual_508.pdf

26. Deshommes, E., Zhang, Y., Gendron, K., Sauvé, S., Edwards, M., Nour, S., & Prévost, M. (2010). Lead removal from tap water using POU devices. *Journal American Water Works Association*, *102*(10), 91-105. DOI: 10.1002/j.1551-8833.2010.tb10210.x

27. Bosscher, V., Lytle, D. A., Schock, M. R., Porter, A., & Del Toral, M. (2019). POU water filters effectively reduce lead in drinking water: a demonstration field study in flint, Michigan. *Journal of Environmental Science and Health, Part A*, *54*(5), 484-493. DOI: 10.1080/10934529.2019.1611141

28. Edwards, M., & Dudi, A. (2004). Role of chlorine and chloramine in corrosion of lead-bearing plumbing materials. *Journal American Water Works Association*, *96*(10), 69-81. DOI: 10.1002/j.1551-8833.2004.tb10724.x

29. Seidel, C. J., McGuire, M. J., Summers, R. S., & Via, S. (2005). Have utilities switched to chloramines? *Journal American Water Works Association*, *97*(10), 87-97. DOI: 10.1002/j.1551-8833.2005.tb07497.x

30. Fleming, K. K., Harrington, G. W., & Noguera, D. R. (2005). Nitrification potential curves: a new strategy for nitrification prevention. *Journal American Water Works Association*, *97*(8), 90-99. DOI: 10.1002/j.1551-8833.2005.tb07453.x

31. WHO. (2011). Measuring chlorine levels in water samples. Retrieved from https://www.who.int/water_sanitation_health/publications/2011/tn11_chlorine_levels_en.pdf

32. Droycon Bioconcepts, Inc. (DBI). (2004). *Biological Activity Reaction Test User Manual.* Retrieved from http://www.dbi.ca/BARTs/PDFs/Manual.pdf

33. Citizens Energy Group. (2018). *2018 Drinking Water Report of Indianapolis, Morgan Co., Westfield & South Madison.* Retrieved from https://www.citizensenergygroup.com/My-Home/Utility-Services/Water/Water-Quality/2018-Water-Quality-Report.pdf

34. Salehi, M., Odimayomi, T., Ra, K., Ley, C., Julien, R., Nejadhashemi, A. P., ... & Whelton, A. (2020). An investigation of spatial and temporal drinking water quality variation in green residential plumbing. *Building and Environment*, *169*, 106566. DOI: 10.1016/j.buildenv.2019.106566

35. Rushing, J. C., & Edwards, M. (2004). The role of temperature gradients in residential copper pipe corrosion. *Corrosion Science*, *46*(8), 1883-1894. DOI: 10.1016/j.corsci.2003.11.001

36. Stamm, J. M., Engelhard, W. E., & Parsons, J. E. (1969). Microbiological study of water-softener resins. *Applied Microbiology*, 18(3), 376-386.

37. Flemming, H. C. (1987). Microbial growth on ion exchangers. *Water Research*, 21(7), 745-756.

38. Lipponen, M. T., Suutari, M. H., & Martikainen, P. J. (2002). Occurrence of nitrifying bacteria and nitrification in Finnish drinking water distribution systems. *Water Research*, *36*(17), 4319-4329. DOI: 10.1016/S0043-1354(02)00169-0

39. Bradley, T. C., Haas, C. N., & Sales, C. M. (2020). Nitrification in Premise Plumbing: A Review. *Water*, *12*(3), 830. DOI: 10.3390/w12030830

40. Zhang, Y., Griffin, A., & Edwards, M. (2008). Nitrification in premise plumbing: role of phosphate, pH and pipe corrosion. *Environmental Science & Technology*, *42*(12), 4280-4284. DOI: 10.1021/es702483d

41. Wilczak, Andrzej, Joseph G. Jacangelo, Joseph P. Marcinko, Lee H. Odell, Gregory J. Kirmeyer, and Roy L. Wolfe. 1996. Occurrence of nitrification in chloraminated distribution systems. *Journal-American Water Works Association*, 88(7):74-85. DOI: 10.1002/j.1551-8833.1996.tb06586.x

42. Pintar, K. D., & Slawson, R. M. (2003). Effect of temperature and disinfection strategies on ammonia-oxidizing bacteria in a bench-scale drinking water distribution system. *Water Research*, *37*(8), 1805-1817. DOI: 10.1016/S0043-1354(02)00538-9

43. Prévost, M., Rompré, A., Baribeau, H., Coallier, J., & Lafrance, P. (1997). Service lines: their effect on microbiological quality. *Journal American Water Works Association*, *89*(7), 78-92. DOI: 10.1002/j.1551-8833.1997.tb08261.x

44. Xi, C., Zhang, Y., Marrs, C. F., Ye, W., Simon, C., Foxman, B., & Nriagu, J. (2009). Prevalence of antibiotic resistance in drinking water treatment and distribution systems. *Applied and Environmental Microbiology*, *75*(17), 5714-5718. DOI: 10.1128/AEM.00382-09

45. WHO. (2003). The role of HPC in managing the treatment and distribution of drinking-water. Retrieved from https://www.who.int/water_sanitation_health/water-quality/guidelines/HPC12.pdf?ua=1

46. USEPA. (2020). National Primary Drinking Water Regulations. Retrieved from https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations#three

47. Bédard, E., Laferrière, C., Déziel, E., & Prévost, M. (2018). Impact of stagnation and sampling volume on water microbial quality monitoring in large buildings. *PLoS One*, *13*(6), e0199429.

48. Proctor, C. R., Rhoads, W. J., Keane, T., Salehi, M., Hamilton, K., Pieper, K. J., ... & Whelton, A. J. (2020). Considerations for Large Building Water Quality after Extended Stagnation. *AWWA Water Science*, e1186. DOI: https://doi.org/10.1002/aws2.

49. USEPA. (2020). Restoring water quality in buildings for reopening. Retrieved from https://www.epa.gov/sites/production/files/2020-05/documents/final_checklist_for_maintaining_building_water_quality_5-6-2020.pdf

50. USEPA. (2018). *3Ts Flushing Best Practices.* Retrieved from https://www.epa.gov/sites/production/files/2018-09/documents/flushing_best_practices_factsheet_508.pdf

51. U.S. Green Building Council. (2019). Reference guide for building design and construction. Retrieved from https://build.usgbc.org/bdc-reference-guide-intro

2. WATER QUALITY CHANGES AT LOW OCCUPANCY INSTITUTIONAL BUILDINGS DURING THE COVID-19 PANDEMIC

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2.1 Abstract

Reduced building occupancy can cause water to stagnate in plumbing, and the potential water chemistry and microbiology consequences are of growing interest. Water quality during low water use in two relatively old and large (> 58 years) and two new and small (> 13 years) institutional buildings among the four buildings that were studied in COVID-19 pandemic period (March-July 2020). Water usage during the study period in smaller buildings significantly decreased while large buildings were similar to the previous year. First draw (200 mL) cold/drinking water samples rarely contained detectable residual chlorine (2 of 60). Other chemical and microbiological results such as pH, dissolved oxygen, total organic carbon, and total cell counts in first draw cold water samples were similar across all buildings. Heavy metal concentration ranges in large buildings were broader than small buildings. Cu, Mn, and Pb exceeded drinking water limits at cold water fixtures, but only sporadically throughout the study. (max. 2.7 mg Cu/L, 45.4 μg Pb/L, 1.9 mg Mn/L). Flushing 5 min resulted in detectable residual to the faucet in 3 buildings, while no residual chlorine was detected after 125-minutes of flushing in the largest and oldest building. The building owners conducted fixture flushing activities during the present study and may have influenced the results. No official flushing protocol was used by the building representatives during flushing activities where 1 to a few fixtures were operated per visit. Research is needed to understand the fundamental processes that control faucet water quality from service line to faucet. In absence of this knowledge, building owners should have as-built drawings and develop flushing plans so they can make evidence-informed decisions when it comes to plumbing flushing.

Keywords

COVID-19 pandemic, stagnation, drinking water quality, flushing

2.2 Introduction

During the COVID-19 pandemic, many commercial buildings shutdown or transitioned to low occupancy in early 2020 and some remained at low occupancy as of March 2022. These occupancy reductions prompted drastic reductions in building water use[1]. In response, numerous U.S. federal, state, county, and local health agencies expressed health concerns about the safety of the water in the plumbing[2–7]. Concerns were based on prior studies that showed chemical and microbiological water quality can deteriorate after short to long stagnation periods[8–17]. Since 2018, numerous building water quality studies have reaffirmed this phenomena[18–20]. Extended contact with plumbing and scales can prompt heavy metal concentrations to increase in bulk drinking water[21–23]. Reductions in disinfectant residual concentration can also occur enabling greater bulk water microorganism concentrations. Complicating these phenomena however are that different pH, hydraulic conditions, and even microbial communities in biofilm can provoke distinctive health risks[24].

Typically, drinking water delivered by U.S. public water systems is monitored for disinfectant residual concentration, pH, and heavy metal concentrations such as copper and lead. Free available chlorine is the most popular disinfectant applied (87%) and is used to limit microbial growth in water piping and storage systems[25]. The minimum recommended disinfectant chlorine concentration is 0.2 mg/L as Cl_2[26]. Water pH controls the relative amounts of HOCl and OCl^- (equilibrium at pK_a of 7.54 at 23C) and also influences metal precipitation[27]. A drastic pH change during extended stagnation could shift towards precipitating metal oxides such as those containing copper, iron, lead and zinc[22,28–31]. Heavy metals of concern like lead and copper originate from water infrastructure corrosion. Manganese is a common groundwater contaminant[32,33] (max. 1.6 mg/L in Indiana groundwater)[34,35]. Manganese concentration was depending on the types of aquifer (e.g. sand and gravel, sandstone, carbonate rock, etc), and the maximum 50th percentile was 49 µg/L in the U.S sampled by National Water Quality Assessment (NAWQA) program between 1992 to 2003[36]. In Indiana near Wabash river region, where this study took place, average total manganese concentration was 0.2 mg/L. Studies also revealed manganese deposition from water distribution systems (e.g. brass or lead pipe components[37,38]. Orthophosphate was a significant corrosion inhibitor[39–41], but metals can accumulate in scales of orthophosphate treated systems and release high concentrations when biofilm activities increased[42]. The maximum contaminant level goal (MCLG) for copper is 1.3 mg/L[43]. The MCLG for lead is 0 µg/L MCLG and 5 µg/L for a maximum allowable

concentration in bottled water, which is not a health based limit[44]. U.S. EPA's 1-day drinking water health advisory for manganese is 1 mg/L[45].

To minimize disinfectant residual decay and heavy metal concentrations in bulk water at the fixture, a short water age within plumbing is recommended. Water quality deterioration in large buildings however has been increasingly documented regardless of whether a pandemic reduced occupancy [22,46,47,18,48]. Buildings can contain a complex array of components such as pipes, valves, gaskets, softeners, water heaters, fixtures, aerators, among other devices[49]. The longer the water contacts these materials, the greater potential it's chemical and microbiological characteristics may differ from water that entered the plumbing. As buildings are renovated, they may also increase the complexity of plumbing systems especially if the purpose of building has completely changed. If the renovation design is not updated in the as-built drawings, it is important to know what type of plumbing components (fixtures, sinks, risers, etc.) have been removed and added in order to better maintain the building water system and interpret water quality data.

In response to reduced building occupancy prompted by the pandemic, some building owners worked to minimize the time water remained in their plumbing. Fixture flushing was recommended by numerous agencies and governments to limit the chance an occupant came into contact with water of degraded quality[3,6,50]. Close examination of the guidance however revealed very different procedures on flushing such as in-building locations and duration. Recommended fixture flushing times varied widely ranging from a few minutes to a couple hours depending on organizations issuing the guidance. During the conduct of this study, the authors were contacted by owners of buildings located in and outside Indiana who were confused by the various guidance documents available recommending different practices.

Some water quality monitoring results have emerged from commercial and institutional buildings shutdown or reduced to low occupancy during the pandemic[51–56]. Salehi et al.[18] found that by flushing fire hydrants every other day, building point of entry locations, and fixtures had reduced heavy metal concentrations. Another study[57] found that bacteria via qPCR rebounded a few days after flushing but 0.1 mg/L of total chlorine may still prevent some level of Legionella growth[58]. Metal and microbiological contaminants may be released by flushing and left behind in the plumbing system if flushing activities were improperly practiced[55]. Stagnant water has more "potential unintended consequences", and flushing may increase the microbial activity by "high shear sloughing of biofilm associated with flushing, and introducing rapid nutrient"[59] With the exception of these studies, few datasets are published

about the degree water quality in building water systems changed during the COVID-19 pandemic.

The goal of this study was to better understand the water chemical and microbiological quality in stagnant buildings during low occupancy. Four buildings of more than 250 buildings served by a public water system, were specifically examined. Specific research objectives were to (1) characterize the chemical and microbiological first draw water quality in stagnated buildings, (2) conduct flushing of each building water system and monitor changes in chemical and microbiological quality, and (3) determine the best strategy to maintain water quality during low water use and some of the faucets are still closed to keep social distancing.

2.3 Materials and methods

2.3.1 Water supply and buildings studied

Water quality was monitored within four buildings served by a public water system in Indiana from March to July 2020. The public water system obtained its raw water from 9 wells where it added free chlorine disinfectant as residual and fluoride for dental and bone strength. A proprietary phosphate blend (ortho- and poly- phosphate) WSU 389 from Water Solutions Unlimited, Inc. (Camby, IN) was used for the corrosion inhibitor. Typical total phosphate range in the distribution system was 1.0 to 1.2 mg/L. Water was provided to approximately 250 buildings and population of 55,000. All buildings were served from one storage tank in the distribution system to maintain pressure and fire service. Ductile iron was the most prevalent water main material. A small amount (5%) of the water mains were high density polyethylene (HDPE) and polyvinyl chloride (PVC).

The study buildings were located in different parts of the water distribution system. Building A was located in the Northern service area, building B in the Southwest, building C and D in the Southeast part of the water distribution system (**Figure SI.2-1**). In each building, water entered through a single service line, but then there were three types of water delivered throughout the building for various uses: Unsoftened cold water, softened drinking water, and hot water. Only at building A, hot water was softened and had a deionized water line for laboratories. Both cold water and softened cold water were used for potable water applications, but due to renovations over the past 30 years complexity was encountered within single buildings. For example, in building A, on the east side cold water was being softened, but on the west side of the building two softeners were empty (no resin) but water still passed through

the tanks. Building B had the smallest water heater (151.4 L). An electric water meter was installed in building B, C and D. Building C and D were right across the street from one another drawing off the same water main. The distance between service lines between two buildings was about 198 m. Building C had a 145.9 L tankless water heater (steam heated). In building D, one water softener and water heaters were still connected to the plumbing and water still went through the tanks without regenerating (**Figure SI.2-2**). Regeneration frequency of water softener (buildings A and D only) was unknown.

2.3.2 Water sampling approach

From March to July 2020 building site visits and water sampling was conducted (**Figure 2-1**). As part of the sampling study, the sampling team notified the building owner before each building was visited. Buildings were formally reduced to low occupancy on March 16th by the building owner. Before buildings were officially shutdown, the authors collected water samples from buildings A, C, and D in March 2020. Building B was added later because of its unique characteristics. No sampling was conducted in April 2020 for any building. From May to July 2020, the authors collected water samples from all buildings once per month. In each building, water samples were collected from drinking water fountains, cold and hot water fixtures at bathroom and kitchen sinks (**Table SI.2-1**). At building D, a few drinking water fountains were inoperable.

Generally, water sampling began around 8:30 am and one building was sampled by the authors at a time. Two buildings were sampled in a day, and it took around 2 hours for each smaller building and 3-4 hours for each larger building. Only about 6-8% of all fixture locations were sampled in building A, C and D, and 25% of fixture locations were sampled in building B. Samples were transported to the laboratory within two hours after sample collection and stored at 4ºC. Plumbing drawings were not provided by the building owner before the sampling plan was developed.

For each building, cold drinking water from kitchen faucets and drinking water fountains were collected. Hot water was collected after cold water was sampled at the same kitchen sinks. At most bathroom sinks, hot water only was collected, in part due to fixed temperature faucets. Faucets that seemed to be located closest to the service line on lowest floor were sampled first, and samples were then collected on upper floors. The authors tried to designate sampled fixtures by balancing spatial (e.g., longitudinal and vertical distance from the service line) and also fixture type.

Approximately 1.5 L of water was collected for analysis. First, about 200 mL water was collected in a beaker to measure pH, temperature, dissolved oxygen, and total chlorine residual. Next, about 780 mL of water was collected in different bottles for each measurement (two 125 mL for total metal, two 15 mL for total cell count (TCC), and two 250 mL for total organic carbon (TOC)). After first draw sampling, at several same and new locations within each building, additional water samples for metals analysis were collected after 5-minute flushing. All water samples were collected at a slow flowrate because of splashing associated with some fixtures. Though, authors opened the fixtures for a slow flowrate, water flowrate was not consistent at all fixtures. Water flowrate was measured at several bathroom sinks of building B (5.82-7.68 L/min, 1.36 L/min) and building D (8.29 L/min, 8.98 L/min). Several fixtures in all buildings had automatic sensors that prompted water sampling difficulty (i.e., start and stop water flows automatically every 20 seconds).

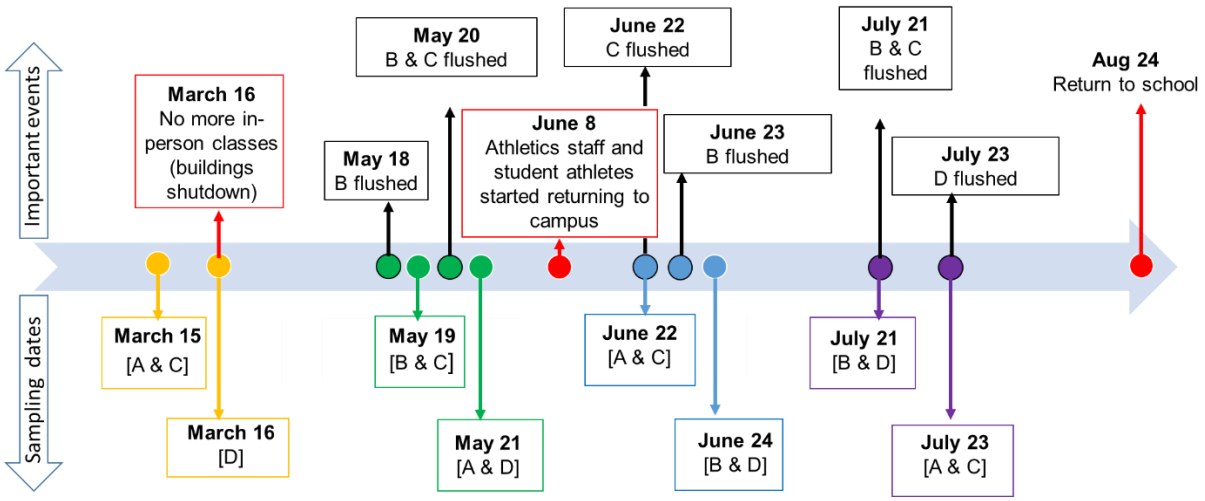


Figure 2-1. Sampling timeline. Few flushing dates that were close to sampling dates or on the day of sampling were added in this timeline because flushing occurred by school may have interrupted the stagnant sample for the study.

2.3.3 Total chlorine decay in plumbing

Disinfectant chlorine residual monitoring was conducted in buildings A, B and C at few kitchen and bathroom sinks to quantify total chlorine residual decay. Each fixture was flushed for 20 minutes first to bring fresh water to the fixture being studied. Water temperature, pH and total chlorine residual concentration were then measured for each sample immediately. Then, chlorine concentration and pH were measured from the same fixture over a 6-hour period by collecting small aliquots. To determine if the plumbing had any effect on chlorine residual

decay reduction, a 1-L of control samples were collected at building A and B, and measured chlorine residual over a 6-hour period.

2.3.4 Flushing plans and confirmed fixture numbers and locations

As-built drawings of all four buildings were provided by the owners in June 2020. In September, building owners provided the number of equipment fixtures in each building, and most locations were confirmed by the authors. Few locations reported by the building owners in buildings A and D were not visually confirmed due to limited access (i.e., locked doors).

2.3.5 Experience of commercial building owners

An online building owner survey was conducted at the request of US Green Building Council Michigan in July to August 2020. The purpose of the survey was to better understand the attitudes and experiences associated with buildings during pandemic. The survey was distributed to building design, construction, and management trade associations to its members. The facility manager for study buildings was also invited to complete the survey.

2.4 Results and discussions

2.4.1 Building owner activities

The authors began conducting water sampling in March 2020, and in April 2020, the building owner began periodic cold and hot water fixture flushing but did not notify the authors. Weekly, the building owner reviewed water use records, and if a building's water use was less than 30% of weekly water use collected before March 23, the building was visited the following week by staff. This approach was applied to the more than 250 buildings owned by the building owner. About 20 staff visited buildings across campus each week in two different groups, a cold water and hot water group. In May 2020, the authors learned of this flushing activity and asked the building owner to delay flushing the four study buildings (A, B, C, D) until after the authors had collected their own samples each day. In May, the building owner placed all softeners into a weekly regeneration cycle.

Cold water fixture flushing by the building owner did not follow a standard operating procedure or building specific flushing plans. Each building owner representative personally decided what day and time they visited the building they were assigned, which cold water

fixture(s) they opened, and how long they would run those fixture(s). Discussions with the building owner indicated that sometimes only one to two fixtures were operated by staff in a building with a varying number of floors for various time periods. Fixtures that were flushed included kitchen sink faucets, bathroom sink faucets, and toilets, and fixture flushing was not conducted on all floors. When the building owner assigned the same staff member to visit the same building multiple times during the study period, that person sometimes chose to open different fixtures for different durations on different floors. Sometimes buildings that were visited by one individual were visited by someone else a subsequent week and this person opened different fixtures and for different durations. Fixtures were generally run for shorter periods at smaller buildings (B and C) compared to larger buildings (A and D). Building B had the shortest fixture flushing duration (3 minutes), and records indicated flushing was stopped after free chlorine concentration was 0.2 mg/L as Cl_2. The longest recorded single fixture flushing duration was 7.7 hours in building D and the chlorine concentration at that location post-flushing was 0.1 mg/L as Cl_2.

Limited information was recorded by building representatives who visited buildings. Staff only recorded information such as the name of the building visited, the date and time they opened a fixture, the initial chlorine residual concentration, and time they closed the fixture. But, sometimes this information was not recorded. Staff sometimes used a SenSafe® free chlorine water test strip kit to measure chlorine residual (method detection limit 0.05 mg/L as Cl_2). Some staff measured the starting chlorine residual using the test strip and flushed until a chlorine residual was detected.

Hot water fixture flushing was also conducted but by a separate group of building owner staff. Hot water fixture flushing was sometimes, but not always, conducted on the same day in the same building as the cold water fixture group's activity. When flushing occurred, water heaters and hot water recirculation loops were not drained. After the present study was completed the building owner provided the authors the hot water flushing schedule but did not provide the procedure or water quality results.

2.4.2 Building water use was reduced during the pandemic

Water usage for the small buildings during the study period was lower compared to previous years, but no trend was found for the large buildings (**Table 2-1**). The small buildings had a 40-75% lower monthly water use during the pandemic. Monthly water use in large buildings was similar to levels in previous years **(Figure SI.2-3**). Based on recorded data, the

authors used a maximum fixture flushing duration to estimate the building owner flushing volumes. Calculations indicated 0.04 to 8% of the monthly water volume during the study period was associated by building representative fixture flushing (Building B > D > C > A). For small buildings, flushing activity did not approach monthly water use from prior years.

For the two lowest water use buildings (B and C) an analysis of as-built drawings indicated that a much longer flushing duration was required to remove stagnant water than the building owner applied. Even for these two buildings, differences in flushing durations to remove the stagnant water from all the piping was significant (Building B - 2.85 hours; Building C - 14.9 hours). This difference between buildings is partly because of different plumbing component sizes and designs (**Table SI.2-2**). The author's calculated flushing time did not consider draining or flushing water heaters. To fully remove stagnant water, the building owner would have needed much more time and many more staff. Because updated as-built drawings for buildings A and D were not available, authors were not able to estimate flushing duration.

Because building owner flushing volumes did not approach the overall monthly building water use volumes, building water use was primarily a function of building inhabitant activity. The author's firsthand experiences also indicate that internal building water pressure and fixture condition also influenced water use. For example, several fixtures including drinking water fountains in building A, C and D were not in great condition and some water samples had colors (**Figure 2-3**). A study in 2010 indicated that people hesitate using public drinking water fountain because of their appearance, poor taste, and concerned about the water safety[60]. Some drinking water fountains had discolored and water samples from building D were cloudy and yellow (**Figure 2-3**). Building D was found to be especially problematic. It was a group residential building that was renovated into an office building, but with the exception of removing showers the building owner indicated that the internal plumbing largely remained unchanged despite significantly altered usage. In March, on Floor 5, one drinking water fountain had little flow and its flow stopped few seconds later. Interestingly, water pressure at one of Floor 5 bathroom sink cold water fixtures on floor 5 was much greater than the other fixtures. On Floor 10, one drinking water fountain had no flow. Flow problems existed even on Floor 1 where there were drinking water fountains next to one another, but only one was working. The building owner had asked that the authors not remove aerators and other fixture components so further investigation of the causes behind different flows between nearby fixtures could not be investigated.

Table 2-1. Building characteristics. Total # of fixtures of two buildings are not 100% sure because as-built drawing is not available and laboratory equipment are not included (eye washes, safety showers, fume hood fixtures).

Name	Year Built	Size,m^2	Floors	Purpose	Total # fixtures	# of 17 Weeks Bldgs were Flushed By Owner		March – July Monthly Water Use Min - Max (Average) [Liters]				
						Cold	Hot	Study period 2020	2019	2018	2017	2016
A	1952	27,526	6	Classrooms, offices, research labs	>193	2	14	820,064 – 1,426,509 (1,102,262)	606,805 – 2,386,903 (1,824,095)	794,508 – 1,621,303 (1,061,634)	945,043 – 1,374,592 (1,163,157)	371,640 – 1,178,928 (736,659)
B	2007	4,639	2	Offices, research labs	32	13	14	7,949 – 31,620 (18,442)	37,684 – 43,173 (40,485)	39,069 – 44,551 (42,215)	42,434 – 78,824 (51,840)	39,997 – 47,026 (43,937)
C	2003	11,644	5	Classrooms, offices	114	17	13	19,029 – 141,559 (46,201)	106,851 – 317,585 (180,583)	112,730 – 307,410 (181,677)	111,753 – 449,472 (215,867)	121,743 – 265,065 (173,310)
D	1962	19,966	10	Offices	~215	16	14	185,818 – 1,202,735 (445,141)	412,821 – 1,717,400 (762,151)	205,532 – 252,278 (226,500)	117,605 – 273,102 (212,112)*	167,379 – 229,963 (198,857)

*Building D in July 2017 was not measured. Average was only calculated March – June.

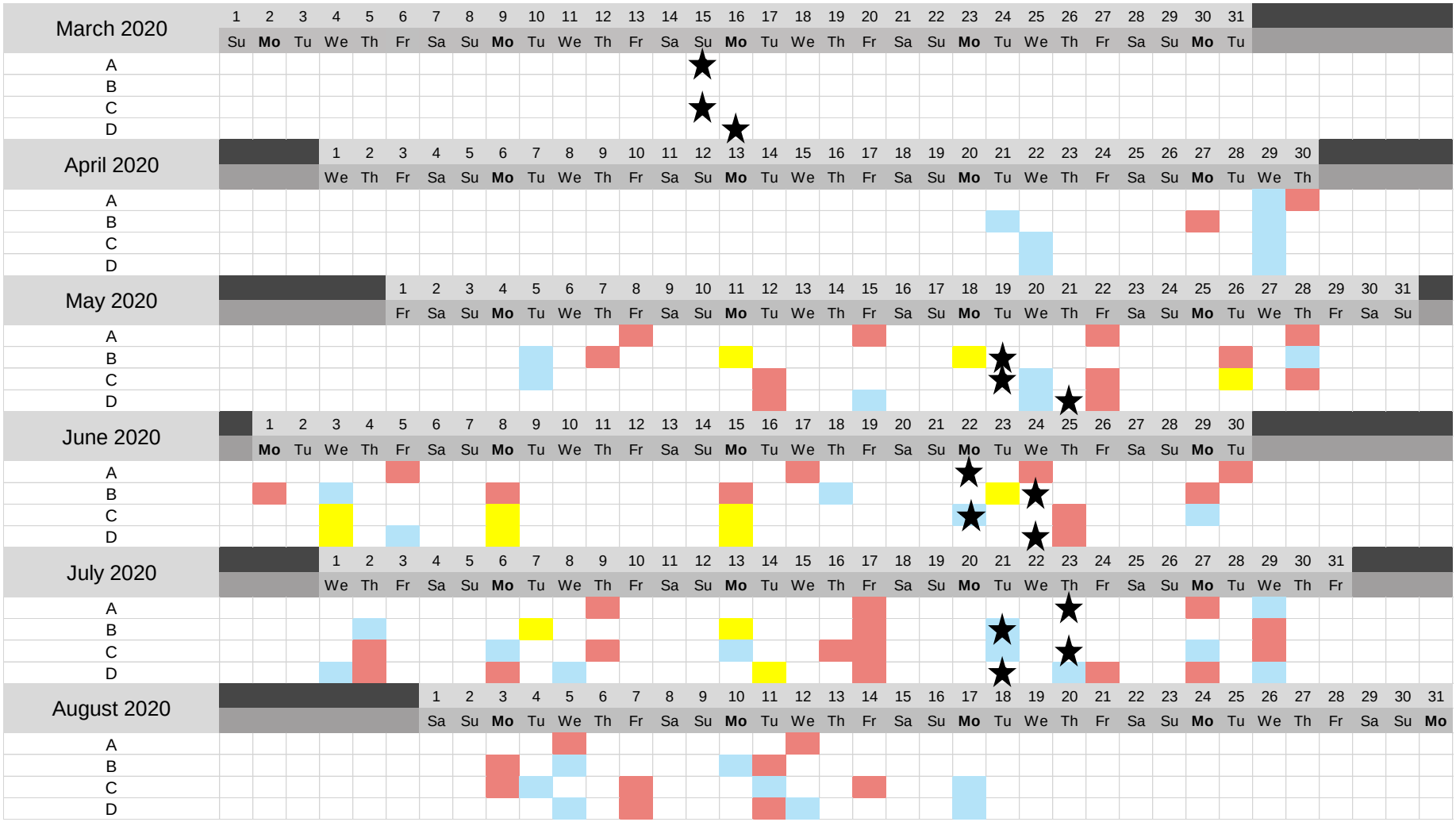


Figure 2-2. Authors building water sampling and flushing schedule by building owners. Stars indicates when the authors first visited the buildings to collect water samples; Red color indicates flushing building hot water; Blue color indicates flushing building color indicates flushing building cold water; Yellow color indicates flushing building cold and hot water on the same day.

(a)  (b) 

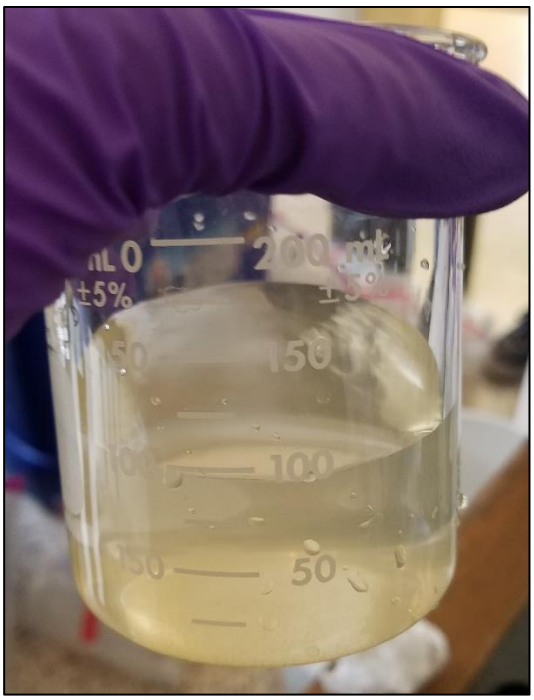
(c)  (d) 

Figure 2-3. Fixture conditions at (a) Building A, (b) Building C, (c) Building D, and colored water from (d) Building D in March 2020. A drinking water fountain from building A has been changed with new drinking water fountain with filters after buildings re-opened.

2.4.3 First draw cold and drinking water fountain quality

2.4.3.1 Building owner actions may have influenced observed water quality

The authors' water quality results may have been influenced by the building owner's fixture running activities in response to the pandemic. Prior to every author sampling event, the building owners visited the large buildings on average 4.7 to 5.6 days and small buildings on average 0.6 to 3 days. For buildings B (July) and C (June), staff were found running fixtures inside the building while the authors were sampling that building.

2.4.3.2 First draw cold water and drinking fountain samples

Cold water fixtures (i.e., sinks) and drinking water fountains were sampled and compared against drinking water limits because both fixture types were used for potable water activities. First draw cold water and drinking fountain water quality was similar across all buildings and all water types for chlorine residual concentration, pH, DO, TOC concentration and TCC levels (**Table 2-2**). Few cold water samples (2/46) across the study buildings had a detectable chlorine residual concentration. Two locations where chlorine was detected were both at drinking water fountains in building A.

The public water system reported having a total chlorine level in the water distribution system of 0.78 to 1.0 mg/L as Cl_2 [61]. Water pH for cold water and drinking fountain water samples was 7.0 to 7.7. DO levels in cold water (2.05 to 9.36 mg/L) were slightly higher than in drinking fountain water (1.0 to 6.2 mg/L). TOC (0.33 to 0.83 mg/L) and TCC levels (3.44 to 5.43 log cells/mL) for cold water and drinking fountain water were in the same range. A recent study revealed that an increase in building water use significantly impacted microbial communities after flushing[48]. While complete building plumbing flushing was not practiced in the present study, no significant differences between months and locations for TCC were observed, nor was a correlation with monthly water use and TCC found. From March through June, culturing was conducted for community analysis at all the first draw locations. Only one location at building A seemed to have bacterial growth for *Legionella pnemophila.* In July, water from same and different fixtures were analyzed using IDEXX® Legiolert. None of the selected locations (0/3 drinking water fountain, 0/2 cold and 0/2 hot) detected *L. pnemophila* by Legiolert (all 1<MPN/100mL).

Metal levels were comparatively higher in the larger buildings than in the smaller buildings. The maximum metal levels were always found in building D, the old dormitory renovated into an office building. Building A also had a greater number of problematic locations than the other smaller building and had more variable results between locations while locations in small buildings had similar ranges of results. Greater range concentration was observed in large buildings and this may be due to complexity of buildings such as building age, scale of stagnation, and water usage, etc. Drinking water contained heavy metals (Cu, Pb, Mn) that sometimes exceeded health-based drinking water limits, but not consistently. Copper and lead levels sometimes exceeded the public water system's 90th percentile values in their annual water quality report (Cu_{90} 0.529 mg/L, Pb_{90} <1.0 μg/L)[61]. Copper exceeded the 1.3 mg/L health-based drinking water limit at few drinking water locations in building D (2/43, max. 2.8 mg/L) and one cold water location at building A (1/14, max 2.04 mg/L). Lead levels found at drinking fountain water and cold water in building A, B, and C were higher than 1 μg/L but less than 5 μg/L. In building D, one drinking fountain exceeded 5 μg/L in March (45 μg/L) and May (29.5 μg/L). In June, no lead was detected but lead exceeded 1 μg/L again in July at the same drinking water fountain.

Manganese was detected at all locations in all buildings, and the concentration was relatively higher in drinking water fountains. In building D, 50% of the drinking water fountains exceeded 0.1 mg/L, while 0.1 mg/L was exceeded 0 to 25% of the respective water samples. In building D, drinking water fountains at basement, 1st floor, and 5th floor drinking water fixtures exceeded the U.S. EPA 1 day health advisory for a child (1 mg/L) in all four visits (max 1.4 mg/L). Two other drinking water fountains were below 0.1 mg/L.

2.4.3.3 Cold water and drinking fountain metal samples at additional locations

To better understand the range of heavy metal concentrations at building cold water fixtures, additional sampling locations were visited in each building (A: +52, B: +15, C: +96, D: +84). Copper did not exceed the 1.3 mg/L action limit at any of these locations. In all buildings, the number of samples with detectable lead were noticeably more abundant in July (Mar: 0-1, May: 0-2, June: 0-3, July: 1-4). Similar to first draw water samples, no sample exceeded 5 μg Pb/L but 1 μg Pb/L was exceeded in buildings A, B and C. At one cold water location in building D, lead exceeded 5 μg Pb/L in May (14.3 μg Pb/L), June (12.7 μg Pb/L), and July (24.2 μg Pb/L). Manganese levels were higher in drinking water fountains than in cold water, with exception of building D. At a same cold water location that had a lead exceedance

also exceeded the manganese health advisory level of 1 mg/L: May (1.9 mg/L), June (1.9 mg/L), and July (1.6 mg/L). Prior studies indicate that copper concentration could peak after 24 hours of stagnation during a 7 day stagnation period, and decrease after peaking [21]. At several same cold and drinking water fountains that had manganese or lead exceedance for first draw samples did not significantly decreased metal concentration even after about 1 L of water has been used. No trend was found between for copper, lead, and manganese concentrations in first draw water samples.

Results of the present study are comparable to findings by other investigators. In related work where water quality monitoring was conducted in 30-70 year old buildings in Tennessee during the pandemic, heavy metal concentrations in cold water (Pb, Cu, Zn, and Fe) rarely exceeded health based limits[18]. The range of concentrations for Cu and Pb in present study was wider and maximum levels detected were greater. An effectiveness of corrosion inhibitor may be reduced after extended stagnation[39], but also due to orthophosphate being more effective than the blend of ortho- and poly-phosphate used in the present study[62].

Table 2-2. Water quality measurements of first draw samples

Parameter		Building A+D (larger and older)									Building B+C (smaller and newer)								
		Drinking water fountain (n=24)			Cold (n=8)			Hot (n=56)			Drinking water fountain (n=22)			Cold (n=6)			Hot (n=25)		
		Min	$\bar{x}$	max	min	$\bar{x}$	max	min	$\bar{x}$	max	min	$\bar{x}$	max	min	$\bar{x}$	max	min	$\bar{x}$	max
General	Temp, °C	11.1	15.45	21.2	20.4	22.75	25.8	18.3	24.25	39.8	11	13.9	21.8	20	21.7	22.8	14.4	22.9	34.4
	pH	7.17	7.44	7.71	7.05	7.28	7.45	7.01	7.3	7.86	7.01	7.23	7.39	7.18	7.3	7.55	6.96	7.32	7.90
	DO, mg/L	1.06	2.05	6.15	2.05	3.51	7.52	1.04	3.78	8.44	1.77	2.6	3.4	2.39	3.99	4.87	1.86	5.32	8.03
	Total Cl_2, mg/L	0	0	0.09	0	0.01	0.03	0	0.01	0.08	0	0	0.01	0	0.01	0.02	0	0.01	0.1
Organics	TOC, mg/L	0.39	0.46	0.78	0.39	0.46	0.78	0.37	0.55	1.22	0.36	0.44	0.83	0.35	0.43	0.46	0.33	0.23	0.54
Microbiol	TCC, log cells/mL	4.22	4.64	5.43	3.71	4.56	5.22	3.68	4.65	5.35	3.44	4.34	4.95	3.68	4.14	4.47	3.44	4.19	4.83
Metal	Cu, µg/L	3.57	129	2779	101	332	508	63	373	2044	234	349	845	246	293	348	75	371	679
	Pb, µg/L	1.91	2.38	45.4	2.05	2.05	2.05	2.02	2.36	3.77	2.32	2.36	2.39	1.93	2.35	2.78	1.91	2.38	2.39
	Mn, µg/L	46.8	88.7	1468	10.7	37.4	78.9	8.14	21.3	119.2	27.0	55.3	116.6	21.2	50.9	69.7	15.3	35.3	141

2.4.3.4 Fate of cold water disinfectant residual in the buildings studied

Of buildings A, B and C, only 2 of 57 cold/drinking water first draw samples had detectable chlorine, and both detections were in building A. To explore how quickly chlorine residual reached building faucets during fixture use, 7 fixtures across buildings A, B and C were run every month for 5 minutes and 4 fixtures for 30 minutes. In building D, no chlorine residual was detected after 125 minutes of flushing the service line, so flushing was not examined here.

During fixture flushing, chlorine residual concentration sometimes changed by 0.2 mg/L as Cl_2 (**Figure SI.2-4**). Of 7 different locations flushed for 5 minutes, only 1 location (building A) always had detectable chlorine residual during the study period (**Figure 2-4**). Though, chlorine level dropped below 0.2 mg/L at 20 minutes and bounced back in June and July at building A. In July, when the water use during the study period was highest (except for building A), chlorine residual after 5 minutes increased slightly more than the previous months. Results indicated that fixture water quality varied even during use. Two locations had less than 0.2 mg/L as Cl_2 after the 5-minute flush. For the 30-minute flush, chlorine residual decreased below 0.1 mg/L as Cl_2 at some locations. During the 30-minute flush, chlorine concentration never reached the range reported by the public water system[61].

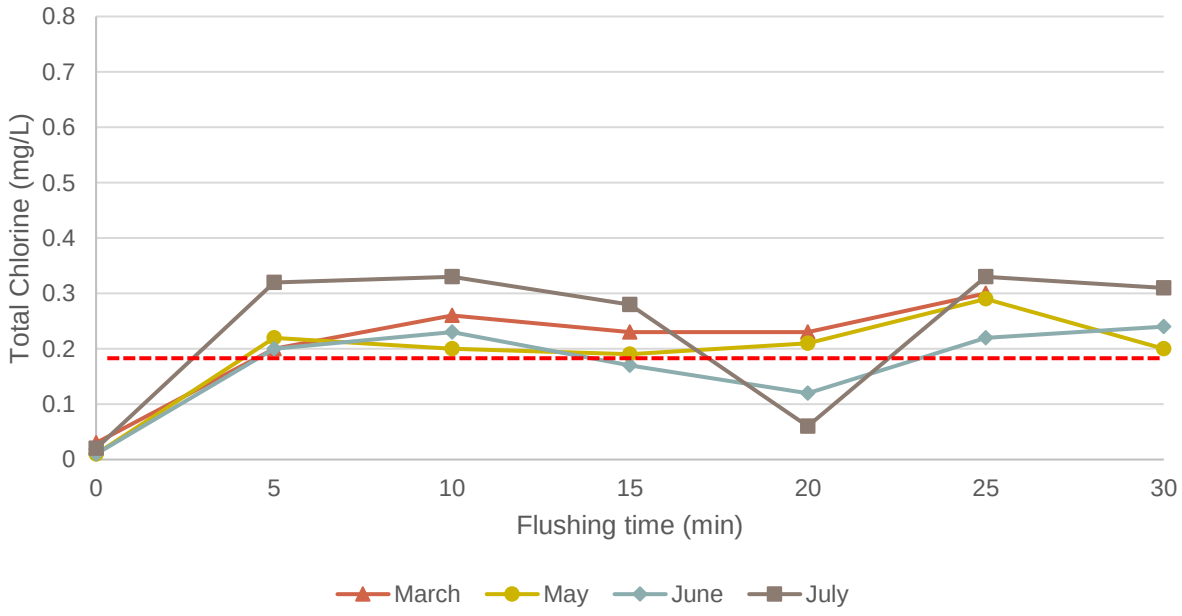


Figure 2-4. Total chlorine residual concentrations varied monitoring during continuous 30-minute flushing at building A. Red dotted line on 0.2 mg/L. See Figure SI-4 for other buildings.

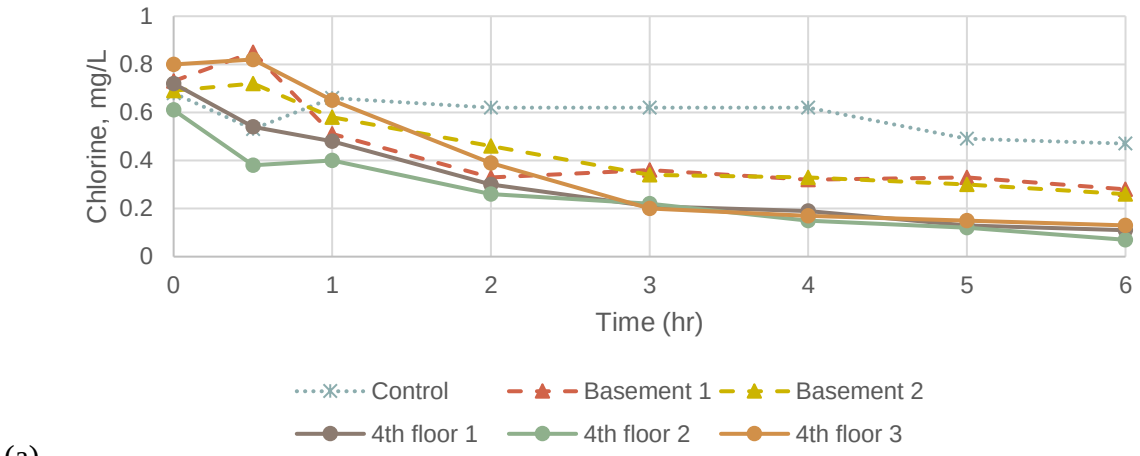
When water with at least 0.4 mg/L as Cl_2 was brought to the faucet, the concentration remained above 0.2 mg/L as Cl_2 over a 6-hour period for most locations (14/18) (**Figure 2-5**).

Chlorine decay was similar across fixtures, floors, and buildings, with the exception of building A. For building A, chlorine decayed fastest at two locations (basement and 4th floor); after 4 hours levels decreased below 0.2 mg/L as Cl_2. The highest rate of decay was observed at building A, especially on the 4th floor. A LEED certified healthcare building had a higher starting chlorine residual and end up with lower than 0.2 mg/L of chlorine residual concentration [12]. The decay rate during 5 hours at the health care building was more similar to building A's 4th floor decay rate.

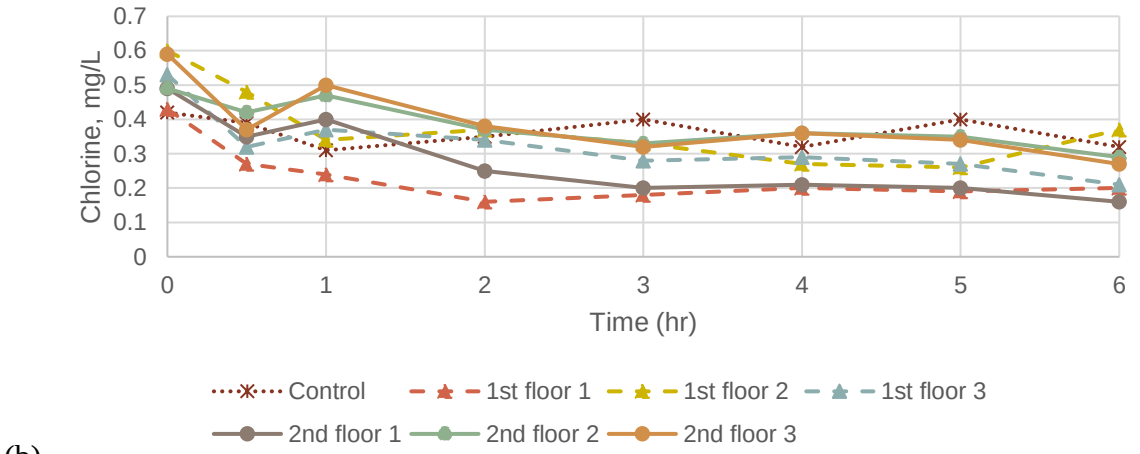
The smaller buildings (B and C) had similar chlorine decay responses within different locations. In comparison, a 10 year old LEED copper-plumbed building in Indiana had a much greater decay rate (0.31 mg/L as Cl_2 per hour, starting at 0.4 mg/L as Cl_2 to 0.05 mg/L as Cl_2) than any building of the present study [63]. For the present study, water pH was relatively similar across all locations (7.0-7.6). While chlorine speciation and thus reactivity varies based on water pH, no significant correlation was observed for total chlorine and pH ($p > 0.05$).

2.4.4 Lack of education on proper building water quality management

Many building owners and facility managers contacted did not seem to know about their building plumbing design or had plans about what to do after building closure or long periods of no use. Only 2 of 9 building owners indicated they had heard about the term "building water management plan"; 8 reported that their building water quality was never monitored or did not know if it had been. Only one respondent indicated their building had water testing conducted, and this involved *Legionella*, total bacteria, heavy metals, and residual disinfectants. Half of the respondents (5 of 10) did not participate in building water quality training activities since COVID-19 pandemic began.



(a)



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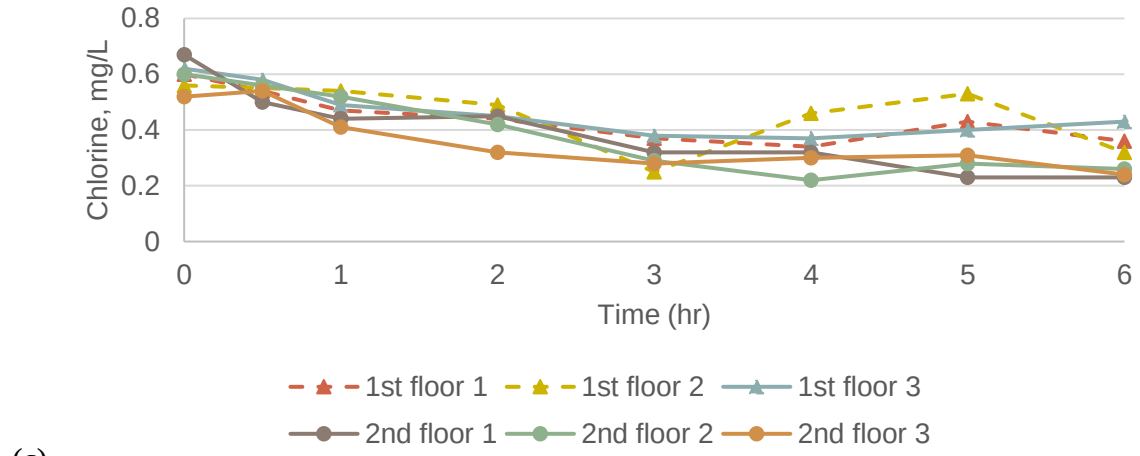

(c)

Figure 2-5. Total chlorine concentration (as Cl_2) decayed over a 6 hour period at various fixtures within (a) Building A, (b) Building B, and (c) Building C. Building D did not have detectable chlorine residual at the service line even after flushing for 2.08 hours.

2.5 Implications

Widespread potable water heavy metal exceedances were not found during the present study, but health-based drinking water limits were exceeded at some locations. Like prior

studies in institutional buildings, chlorine concentration was nearly always not detectable in first draw stagnant samples[12,14,16,18]. This phenomena is not unique here, and has also been observed in commercial buildings during normal use periods[46,63]. In the present study, only at a few locations and repeatedly at a single drinking water fountain, Cu, Pb, and Mn exceeded health-based drinking water limits.

Despite the limitation of sampling a small number of fixtures, the authors found water quality problems in existing, previously untested buildings. Results presented represent a snapshot in time as the buildings were only visited monthly and at a few of the total number of fixtures they contained (13.5% A, 40.6% B, 29.8% C, 17.2% D). Automatic sensor faucets turning on and off may have prompted hydraulic transients and dislodged scale and biofilm that was collected in water samples. Building plumbing differed significantly across and even within some buildings, likely inhibiting trends to be detected.

While many guidance documents recommend building owners should flush stagnant water from their plumbing before the building is reopened as explained by Proctor et al. 2020 and elsewhere[6,64], there remains ambiguity on exactly how flushing should be conducted. For the buildings investigated in the present study, the public water system directed the building occupants to flush drinking water faucets for 0.5 to 2 minutes before using water when the water has been stagnated for several hours to minimize potential lead exposure. Prior to pandemic, CDC also issued guidance on fixture flushing and water use for low occupancy buildings[2]. But the inconsistent fixture flushing actions applied by building owners in the current study represents an echo of confusing guidance found publicly. Broadly, some pandemic building flushing guidance documents recommended continuous flushing fixtures at minimum of 10 minutes or vaguely says flush all equipment connected to the water lines[5]. But, authors have seen a large building that has long distances between faucets that may take up to 30 minutes of flush for one faucet[65]. Some guidance documents[4] recommend flushing each outlet up to 30 minutes, but guidance does not explain details such as how to ensure new water is in the system. In absence of an explicit understanding of health risks posed by low building occupancy and thus stagnant water, building owners do not have evidence-based practices for reducing health risks after a long stagnation periods.

To predict health risks at building faucets, research is needed to understand the relationship between chemical and microbiological water quality at the faucet, at the service line, and how plumbing design, materials, and operation influence observed water quality. To date, a single study[66] has examined this phenomena at scale, and it was focused on residential

buildings. While important and involving more than 220,000 labor hours over a year for a single-family home, total chlorine residual concentration, Legionella, heavy metal concentration at faucets were found to be strongly influenced by influent water quality, service line length, and water use frequency. The complexity of building water quality was also elucidated using the large data set that revealed legionella concentration was influenced by interactions between variables such as water age, total chlorine residual, DO, temperature, TOC, HPC, TCC, etc[67]. This area of work requires additional scrutiny, as water quality at the faucet and plumbing design can vary[68,69].

In absence of this fundamental understanding, certain actions can be implemented to help building owners better manage their plumbing. First, knowledge of building characteristics such as plumbing layout, pipe size, characteristics of the water devices and number of fixtures are important to design a flushing plan. As-built plumbing drawings should be created for each new building and renovation. For the present study, it was difficult to design sampling and flushing plan when as-built drawings were not available, especially for larger buildings that had been remodeled after decades. Also, there could be other factors may influence flushing such as water pressure change. Water testing of buildings periodically could enable a better understanding of baseline water quality. Prior to the present study, testing for disinfectant residual, Pb, and Cu were conducted, primarily at the building's service line. Results revealed water quality problems at some, not all, fixture locations in the building. Each building should have its own plumbing operations and maintenance plan. Periodic water testing, plumbing inspection, and maintenance should be considered during the building's service-life, especially to avoid water quality problems near the abandoned fixtures in old buildings.

2.6 Acknowledgement

Laboratory assistance from Dr. Nadya Zyaykina, Elizabeth Montagnino, Maria Palmegiani, Sruthi Dasika, Ryan Day at Purdue University was greatly appreciated. Thanks are extended to Dr. Robin Ridgway and building owner representatives for their feedback.

2.7 References

1. Faust, K. M., Katz, L. E., Kirisits, M. J., Kinney, K. A., Sela, L., Kopytkovskiy, M., Russell, C., & Kaminsky, J. (2021). Consider How Social Distancing Policies Can Affect Drinking Water Infrastructure Performance. *Journal - American Water Works Association*, *113*(2), 76–77. https://doi.org/10.1002/awwa.1673

2. CDC. (2021). *Reopening Buildings After Prolonged Shutdown or Reduced Operation*. https://www.cdc.gov/nceh/ehs/water/legionella/building-water-system.html

3. EPA. (2020). *Maintaining or restoring water quality in buildings with low or no use*. https://www.epa.gov/sites/default/files/2020-05/documents/final_maintaining_building_water_quality_5.6.20-v2.pdf

4. San Francisco Public Utilities commission. (2020). *Flushing Guidance for Building Water Systems Following Extended Shutdown Guidance for All Buildings*.

5. Arkansas Department of Health Engineering. (2020). *Flushing Guidance for Buildings with Low Occupancy or No Occupancy During Covid-19*.

6. IDEM. (2020). *Guidance for Flushing Public Water Systems*. 1–2.

7. California Water Boards. (2020). *Public Water Systems - COVID-19 Info | California State Water Resources Control Board*. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/covid-19.html

8. Bédard, E., Laferrière, C., Déziel, E., & Prévost, M. (2018). Impact of stagnation and sampling volume on water microbial quality monitoring in large buildings. *PLOS ONE*, *13*(6), e0199429. https://doi.org/10.1371/JOURNAL.PONE.0199429

9. Doré, E., Deshommes, E., Andrews, R. C., Nour, S., & Prévost, M. (2018). Sampling in schools and large institutional buildings: Implications for regulations, exposure and management of lead and copper. *Water Research*, *140*, 110–122. https://doi.org/10.1016/j.watres.2018.04.045

10. Ji, P., Parks, J., Edwards, M. A., & Pruden, A. (2015). Impact of Water Chemistry, Pipe Material and Stagnation on the Building Plumbing Microbiome. *PloS One*, *10*(10), e0141087. https://doi.org/10.1371/journal.pone.0141087

11. Rhoads, W. J., Ji, P., Pruden, A., & Edwards, M. A. (2015). Water heater temperature set point and water use patterns influence Legionella pneumophila and associated microorganisms at the tap. *Microbiome*, *3*(1), 67. https://doi.org/10.1186/S40168-015-0134-1/FIGURES/7

12. Rhoads, W. J., Pruden, A., & Edwards, M. A. (2016). Survey of green building water systems reveals elevated water age and water quality concerns. *Environmental Science: Water Research and Technology*, *2*(1), 164–173. https://doi.org/10.1039/c5ew00221d

13. Ling, F., Whitaker, R., LeChevallier, M. W., & Liu, W.-T. (2018). Drinking water microbiome assembly induced by water stagnation. *The ISME Journal*, 1. https://doi.org/10.1038/s41396-018-0101-5

14. Lipphaus, P., Hammes, F., Kötzsch, S., Green, J., Gillespie, S., & Nocker, A. (2013). *Environmental Technology Microbiological tap water profile of a medium-sized building and effect of water stagnation*. https://doi.org/10.1080/09593330.2013.839748

15. Salehi, M., Odimayomi, T., Ra, K., Ley, C., Julien, R., Nejadhashemi, A. P., Hernandez-Suarez, J. S., Mitchell, J., Shah, A. D., & Whelton, A. (2020). An investigation of spatial and temporal drinking water quality variation in green residential plumbing. *Building and Environment*, *169*, 106566. https://doi.org/10.1016/J.BUILDENV.2019.106566

16. Ra, K., Odimayomi, T., Ley, C., Aw, T. G., Rose, J. B., & Whelton, A. J. (2020). Finding building water quality challenges in a 7 year old green school: Implications for building design, sampling, and remediation. *Environmental Science: Water Research and Technology*, *6*(10), 2691–2703. https://doi.org/10.1039/d0ew00520g

17. Ley, C. J., Proctor, C. R., Singh, G., Ra, K., Noh, Y., Odimayomi, T., Salehi, M., Julien, R., Mitchell, J., Nejadhashemi, A. P., Whelton, A. J., & Aw, T. G. (2020). Drinking water microbiology in a water-efficient building: stagnation, seasonality, and physicochemical effects on opportunistic pathogen and total bacteria proliferation. *Environmental Science: Water Research & Technology*, *6*(10), 2902–2913. https://doi.org/10.1039/D0EW00334D

18. Salehi, M., Desimone, D., Aghilinasrollahabadi, K., & Ahamed, T. (2021). A case study on tap water quality in large buildings recommissioned after extended closure due to the COVID-19 pandemic. *Environmental Science: Water Research and Technology*, *7*(11), 1996–2009. https://doi.org/10.1039/d1ew00428j

19. Shima Ghoochani, Maryam Salehi, Dave DeSimone, Esfandarani, M. S., & Linkon Bhattacharjee. (2022). Studying the impacts of non-routine extended schools' closure on heavy metal release into tap water. *Environmental Science: Water Research & Technology*. https://doi.org/10.1039/D2EW00149G

20. Spearing, L. A., Thelemaque, N., Kaminsky, J. A., Katz, L. E., Kinney, K. A., Kirisits, M. J., Sela, L., & Faust, K. M. (2021). Implications of Social Distancing Policies on Drinking Water Infrastructure: An Overview of the Challenges to and Responses of U.S. Utilities during the COVID-19 Pandemic. *ACS ES&T Water*, *1*(4), 888–899. https://doi.org/10.1021/acsestwater.0c00229

21. Zlatanović, L., van der Hoek, J. P., & Vreeburg, J. H. G. (2017). An experimental study on the influence of water stagnation and temperature change on water quality in a full-scale domestic drinking water system. *Water Research*, *123*, 761–772. https://doi.org/10.1016/j.watres.2017.07.019

22. Lytle, D. A., & Schock, M. R. (2000). Impact of stagnation time on metal dissolution from plumbing materials in drinking water. *Journal of Water Supply: Research and Technology - AQUA*, *49*(5), 243–257. https://doi.org/10.2166/aqua.2000.0021

23. Turek, N. F., Kasten, L., Lytle, D. A., & Goltz, M. N. (2011). Impact of plumbing age on copper levels in drinking water. *Journal of Water Supply: Research and Technology - AQUA*, *60*(1), 1–15. https://doi.org/10.2166/aqua.2011.014

24. Fish, K. E., Reeves-McLaren, N., Husband, S., & Boxall, J. (2020). Unchartered waters: the unintended impacts of residual chlorine on water quality and biofilms. *Npj Biofilms and Microbiomes 2020 6:1*, *6*(1), 1–12. https://doi.org/10.1038/s41522-020-00144-w

25. AWWA. (2018). *2017 Water utility disinfection survey report*. https://www.awwa.org/Portals/0/AWWA/ETS/Resources/2017DisinfectionSurveyReport.pdf?ver=2018-12-21-163548-830

26. CDC. (2008). Chlorine Residual Testing Fact Sheet. *Centres for Disease Control and Prevention*, 4. https://www.cdc.gov/safewater/chlorine-residual-testing.html

27. Huang, X., Zemlyanov, D. Y., Diaz-Amaya, S., Salehi, M., Stanciu, L., & Whelton, A. J. (2020). Competitive heavy metal adsorption onto new and aged polyethylene under various drinking water conditions. *Journal of Hazardous Materials*, *385*. https://doi.org/10.1016/J.JHAZMAT.2019.121585

28. Huang, X., Zhao, S., Abu-Omar, M., & Whelton, A. J. (2017). In-situ cleaning of heavy metal contaminated plastic water pipes using a biomass derived ligand. *Journal of Environmental Chemical Engineering*, *5*(4), 3622–3631. https://doi.org/10.1016/J.JECE.2017.07.003

29. Salehi, M., Li, X., & Whelton, A. J. (2017). Metal Accumulation in Representative Plastic Drinking Water Plumbing Systems. *Journal - American Water Works Association*. https://doi.org/10.5942/jawwa.2017.109.0117

30. Mcneill, L. S., & Edwards, M. (2001). *IRON PIPE corrosion IN DISTRIBUTION SYSTEMS; IRON PIPE corrosion IN DISTRIBUTION SYSTEMS*. https://doi.org/10.1002/j.1551-8833.2001.tb09246.x

31. Edwards, M., Powers, K., Hidmi, L., & Schock, M. R. (2001). *The role of pipe ageing in copper corrosion by-product release*. http://iwaponline.com/ws/article-pdf/1/3/25/408416/25.pdf?casa_token=rc0UhueQLxEAAAAA:mD0N62hLMC_QVKdKeH3fYhd67zXAQG6-oVdKFcUNeKbK_exV932v-6wCybeLh

32. McMahon, P. B., Belitz, K., Reddy, J. E., & Johnson, T. D. (2019). Elevated Manganese Concentrations in United States Groundwater, Role of Land Surface−Soil−Aquifer Connections. *Environ. Sci. Technol*, *53*, 29–38. https://doi.org/10.1021/acs.est.8b04055

33. Gora, S. L., Trueman, B. F., Anaviapik-Soucie, T., Gavin, M. K., Ontiveros, C. C., Campbell, J., L', V., Hérault, H., Stoddart, A. K., & Gagnon, G. A. (2020). Source Water Characteristics and Building-specific Factors Influence Corrosion and Point of Use Water Quality in a Decentralized Arctic Drinking Water System. *Cite This: Environ. Sci. Technol*, *54*. https://doi.org/10.1021/acs.est.9b04691

34. Indiana Department of Natural Resources. (2002). *Ground-water quality*. https://www.in.gov/dnr/water/files/WFWR_web.pdf

35. Banaszak, K. J. (1986). *Indiana ground-water quality*. https://pubs.usgs.gov/of/1987/0724/report.pdf

36. USGS. (2011). *Trace elements and radon in groundwater across the United States, 1992-2003*. https://pubs.usgs.gov/sir/2011/5059/pdf/sir2011-5059_report-covers_508.pdf

37. Li, G., Ma, X., Chen, R., Yu, Y., Tao, H., & Shi, B. (2019). Field studies of manganese deposition and release in drinking water distribution systems: Insight into deposit control. *Water Research*, *163*, 114897. https://doi.org/10.1016/J.WATRES.2019.114897

38. Gerke, T. L., Little, B. J., & Barry Maynard, J. (2016). Manganese deposition in drinking water distribution systems. *Science of The Total Environment*, *541*, 184–193. https://doi.org/10.1016/J.SCITOTENV.2015.09.054

39. McNeill, L. S., & Edwards, M. (2000). Phosphate Inhibitors and Red Water in Stagnant Iron Pipes. *Journal of Environmental Engineering*, *126*(12), 1096–1102. https://doi.org/10.1061/(ASCE)0733-9372(2000)126:12(1096)

40. Trueman, B. F., Gregory, B. S., McCormick, N. E., Gao, Y., Gora, S., Anaviapik-Soucie, T., L'Hérault, V., & Gagnon, G. A. (2019). Manganese Increases Lead Release to Drinking Water. *Environmental Science and Technology*, *53*(9), 4803–4812. https://doi.org/10.1021/ACS.EST.9B00317/SUPPL_FILE/ES9B00317_SI_001.PDF

41. Schock, M. R., & Lytle, D. A. (1995). *Effect of pH, DIC, Orthophosphate and Sulfate on Drinking Water Cuprosolvency. Water Supply and Water Resources Division National Risk Management Research Laboratory U.S. Environmental Protection Agency.*

42. Ginige, M. P., Wylie, J., & Plumb, J. (2011). *Biofouling The Journal of Bioadhesion and Biofilm Research Influence of biofilms on iron and manganese deposition in drinking water distribution systems*. https://doi.org/10.1080/08927014.2010.547576

43. US EPA. (2007). *Lead and Copper Rule: A Quick Reference Guide Public Health Benefits*. http://water.epa.gov/drink

44. ATSDR. (2019). *Lead Toxicity*. https://www.atsdr.cdc.gov/csem/leadtoxicity/safety_standards.html

45. US EPA. (2018). *Lead and Copper Rule: A quick reference guide to schools and child care facilities that are regulated under the Safe Drinking Water Act* (p. 816– 05–030).

46. Richard, R., Hamilton, K. A., Westerhoff, P., & Boyer, T. H. (2020). Tracking copper, chlorine, and occupancy in a new, multi-story, institutional green building. *Environmental Science: Water Research and Technology*, *6*(6), 1672–1680. https://doi.org/10.1039/d0ew00105h

47. Merkel, T. H., Groß, H. J., Werner, W., Dahlke, T., Reicherter, S., Beuchle, G., & Eberle, S. H. (2002). Copper corrosion by-product release in long-term stagnation experiments. *Water Research*. https://doi.org/10.1016/S0043-1354(01)00366-9

48. Vosloo, S., Huo, L., Chauhan, U., Cotto, I., Gincley, B., Vilardi, K. J., Yoon, B., Pieper, K. J., Stubbins, A., & Pinto, A. (2022). Systematic recovery of building plumbing-associated microbial communities after extended periods of altered water demand during the COVID-19 pandemic. *MedRxiv*, 2022.01.17.22269440. https://doi.org/10.1101/2022.01.17.22269440

49. Water Works Association, A. (2020). *A Framework for Building Managers*.

50. Proctor, C. R., Rhoads, W. J., Keane, T., Salehi, M., Hamilton, K., Pieper, K. J., Cwiertny, D. M., Prévost, M., & Whelton, A. J. (2020). Considerations for large building water quality after extended stagnation. *AWWA Water Science*, *2*(4). https://doi.org/10.1002/aws2.1186

51. Ye, C., Xian, X., Bao, R., Zhang, Y., Feng, M., Lin, W., & Yu, X. (2022). Recovery of microbiological quality of long-term stagnant tap water in university buildings during the COVID-19 pandemic. *Science of The Total Environment*, *806*, 150616. https://doi.org/10.1016/J.SCITOTENV.2021.150616

52. D'Alessio, M., Rushing, G., & Gray, T. L. (2021). Monitoring water quality through citizen science while teaching STEM undergraduate courses during a global pandemic. *Science of The Total Environment*, *779*, 146547. https://doi.org/10.1016/J.SCITOTENV.2021.146547

53. Vosloo, S., Huo, L., Chauhan, U., Cotto, I., Gincley, B., Vilardi, K. J., Yoon, B., Pieper, K. J., Stubbins, A., & Pinto, A. (2022). Systematic recovery of building plumbing-associated microbial communities after extended periods of altered water demand during the COVID-19 pandemic. *MedRxiv*, 2022.01.17.22269440. https://doi.org/10.1101/2022.01.17.22269440

54. Liang, J., Swanson, C. S., Wang, L., & He, Q. (2021). Impact of building closures during the COVID-19 pandemic on Legionella infection risks. *American Journal of Infection Control*, *49*(12), 1564–1566. https://doi.org/10.1016/j.ajic.2021.09.008

55. Rhoads, W. J., & Hammes, F. (2021). Growth of: Legionella during COVID-19 lockdown stagnation. *Environmental Science: Water Research and Technology*, *7*(1), 10–15. https://doi.org/10.1039/d0ew00819b

56. Richard, R., Boyer, T. H., Treavor Boyer, C. H., Editor, A., & Mo, W. (2021). *Pre-and post-flushing of three schools in Arizona due to COVID-19 shutdown*. https://doi.org/10.1002/aws2.1239

57. Hozalski, R. M., Lapara, T. M., Zhao, X., Kim, T., Waak, M. B., Burch, T., & Mccarty, M. (2020). Flushing of Stagnant Premise Water Systems after the COVID-19 Shutdown Can Reduce Infection Risk by Legionella and Mycobacterium spp. *Environmental Science and Technology*, *54*(24), 15914–15924. https://doi.org/10.1021/acs.est.0c06357

58. Donohue, M. J., Vesper, S., Mistry, J., & Donohue, J. M. (2019). Impact of Chlorine and Chloramine on the Detection and Quantification of Legionella pneumophila and Mycobacterium Species. *Applied and Environmental Microbiology*, *85*(24). https://doi.org/10.1128/AEM.01942-19/FORMAT/EPUB

59. Rhoads, W. J., Sindelar, M., Margot, C., Graf, N., & Hammes, F. (2022). Variable Legionella Response to Building Occupancy Patterns and Precautionary Flushing. *Microorganisms*, *10*(3). https://doi.org/10.3390/MICROORGANISMS10030555/S1

60. Patel, A. I., Bogart, L. M., Uyeda, K. E., Rabin, A., & Schuster, M. A. (2010). Peer Reviewed: Perceptions About Availability and Adequacy of Drinking Water in a Large California School District. *Preventing Chronic Disease*, *7*(2). /pmc/articles/PMC2831793/

61. Purdue University. (2020). *Consumer Confidence Report on Water Quality*. *June*, 1–6. https://www.purdue.edu/physicalfacilities/units/energy-utilities/ccr-report.pdf

62. Edwards, M., Hidmi, L., & Gladwell, D. (2002). Phosphate inhibition of soluble copper corrosion by-product release. *Corrosion Science*, *44*(5), 1057–1071. https://doi.org/10.1016/S0010-938X(01)00112-3

63. Montagnino, E., Proctor, C. R., Ra, K., Ley, C., Noh, Y., Vigil, K., Aw, T. G., Dasika, S., & Whelton, A. J. (2022). Over the weekend: Water stagnation and contaminant exceedances in a green office building. *PLOS Water*, *1*(3), e0000006. https://doi.org/10.1371/journal.pwat.0000006

64. CDC. (2020). *Reopening Buildings After Shutdown*. https://www.cdc.gov/coronavirus/2019-ncov/php/building-water-system.html

65. Purdue University. (2020). *Example Procedure for Flushing an Actual School Building*. https://engineering.purdue.edu/PlumbingSafety/resources/Example-Flush-Procedure-Actual-School-2020-04-03.pdf

66. Palmegiani, M. A., Whelton, A. J., Mitchell, J., Nejadhashemi, P., & Lee, J. (2022). New developments in premise plumbing: Integrative hydraulic and water quality modeling. *AWWA Water Science*, *4*(2), e1280. https://doi.org/10.1002/AWS2.1280

67. Julien, R., Saravi, B., Nejadhashemi, A., Whelton, A. J., Aw, T. G., & Mitchell, J. (2022). Identifying water quality variables most strongly influencing Legionella concentrations in building plumbing. *AWWA Water Science*, *4*(1), e1267. https://doi.org/10.1002/AWS2.1267

68. NIST. (2018). *Measurement Science Research Needs for Premise Plumbing Systems*. https://doi.org/10.6028/NIST.TN.2088

69. Julien, R., Dreelin, E., Whelton, A. J., Lee, J., Aw, T. G., Dean, K., & Mitchell, J. (2020). Knowledge gaps and risks associated with premise plumbing drinking water quality. *AWWA Water Science*, *2*(3), e1177. https://doi.org/10.1002/AWS2.1177

3. INVESTIGATING WATER SAFETY IN AN ELEMENTARY SCHOOL BUILDING WATER SYSTEM AND REMEDIATION EFFECTIVENESS

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3.1 Abstract

Elementary school water quality was monitored before and after reopening the campus after three months of no building water use. First draw water quality at three small buildings did not contain detectable disinfectant residual, but nickel and lead sometimes exceeded the health-based action limits for cold water (max. 144 μg Ni/L, 3.4 μg Pb/L). Stagnant cold water at a bathroom sink (188 MPN/100 mL) and drinking water fountain (141.6 MPN/100 mL), in the same building, exceeded the *L. pneumophila* thresholds advised by WHO (10 CFU/mL) and AIHA (100 CFU/mL). If the AIHA guidance was followed shock chlorination of the plumbing should have been conducted. Though, fixture flushing was conducted to remove cold and hot stagnant water and no *L. pneumophila* was detected immediately after flushing. After two weeks of subsequent no building water use, chemical and microbiological contaminant levels were found to be similar to those prior to flushing with one exception. The maximum *L. pneumophila* level (kitchen sink, hot water: 61.1 MPN/100 mL) was found in a different building than the prior maximum detections. No repeat positive locations for *L. pneumophila* were found during the second visit, but new fixtures were positive the organism. When this study was conducted no evidence-based guidelines for plumbing recommissioning were available. A single plumbing flush was effective at reducing heavy metal and *L. pneumophila* levels below WHO and AIHA thresholds.

Keyword

School, children, legionella, lead, drinking water, plumbing, safety

3.2 Introduction

Water with high levels of chemicals and microorganisms at schools can pose health risks to children and adults. Typically, school buildings have not been a focus of routine drinking water testing and lack formal water management programs[1]. The pandemic, coupled with confirmed Legionnaires Disease illnesses of school custodians and a fatality[2], prompted concerns in Ohio about stagnant water health risks in shutdown school water systems. Because there were more than 124,000 U.S public and private schools shutdown across the U.S. in response to the pandemic[3], school water safety concerns became nationally important.

Prior to the pandemic it was well-known that water safety could deteriorate in large buildings due to water stagnation, and many studies were conducted during the pandemic to explore this phenomenon. Prior to the pandemic one school water testing study found that lower Summer water use prompted greater cold and hot water copper and bacteria levels (*Mycobacterium avium, Mycobacterium spp. Legionella spp*., and total cell count [TCC])[4,5]. Even weekend stagnation has been found to sometimes cause copper levels to exceed health-based drinking water limits and TCC levels to increase[63]. During the pandemic researchers often did not detect chlorine disinfectant residual in first draw stagnant water samples. Sometimes stagnant water copper, lead, and zinc concentrations exceeded the health based limits[7–10]. Microbial contamination (*Legionella spp.*, *Mycobacteria*, Heterotrophic plate counts [HPC], and TCC) in stagnant water samples were mostly found to be greater than the flushed water samples[11–14].

To start using plumbing that had remained unused during the pandemic, many guidelines were issued by local, state, federal agencies as well as trade associations and companies[15–19]. Instructions were often vague, different organizations contradicted other organizations, and guidance rarely recommended water testing[50]. Generally, removing water from the stagnant cold and hot water systems by flushing was recommended[20], though some organizations recommended shock disinfection[21–23]. However, when testing accompanied flushing activities, it was sometimes found that heavy metal and microbial contaminants were not reduced completely. In one study, lead concentration significantly decreased after flushing but 28 μg/L remained which is still above the American Academy of Pediatrics recommended limit of 1 μg/L[7]. In another study, copper and lead concentration significantly decreased after flushing but iron levels increased by 200% possibly due to scale destabilization[8]. Most flushed water samples had lower *Legionella spp*. levels[10,12], but sometimes these levels were greater

after flushing[7]. Also found that *Legionella spp.* was not detected immediately after flushing, but was detected again two to four days later.

Plumbing flushing and shock chlorination have previously shown to improve chemical and microbiological water quality[8,24,25]. The WHO and American Industrial Hygiene Association (AIHA) recommend shock disinfection when Legionella levels are greater than 10 CFU/mL[26] and 100 CFU/mL[21]. Specifically,[21] AIHA (2015) stated that when greater than 100 CFU/mL is found, "immediate steps to clean and disinfect the system" are required. In comparison, Hamilton et al.[27] recommends faucet activities present a risk at a concentration of 102 CFU/mL using annual infection risk metric for a scenario when the faucet is used 20 times per day and 30 seconds per use. Though, while much discussion has been focused on the health risks posed by *Legionella* in stagnant building water systems, it was rare to find U.S guidelines that recommended testing or explained where to sample. Though, British Health and Safety Executive Guidelines recommended "routine sampling and testing for general bacteria including *Legionella* species"[28]. The CDC also described routine sampling and testing for *Legionella* that may be helpful for various conditions, but it did not recommended these actions[29]. The lack of specificity on water sampling and effectiveness of flushing practices is a gap in knowledge.

The goal of the study was to better understand water quality in low to no occupancy buildings and the effectiveness of flushing to reducing chemical and microorganism levels at the fixtures. Specific research objectives were to (1) document chemical and microbiological first draw water quality after 3 months of stagnation in three separate school buildings in one property, (2) conduct flushing of each building water system and monitor flushing effectiveness, and (3) determine the limitations of flushing.

3.3 Materials and methods

3.3.1 Water supply and site inspection

The study site was an elementary school campus in Indiana with three detached buildings (**Figure 3-1**). The campus was served by a single public water system through two different service lines, each with a water meter. Buildings A and B were served off a single meter, while Building C was served by its own meter. The public water system utilized 8 groundwater wells. The public water system served water to about 35,000 people. Free chlorine disinfectant and a polyphosphate-orthophosphate blend of corrosion inhibitor were added to

the water before water entered the water distribution system. In a separate study, service line water quality monitoring for one year was conducted in the same water distribution system 2.6 miles (4.2 km) away from the campus and the following water quality characteristics were reported (pH: 7.22 to 7.81; total Cl_2: 0 to 2.10 mg/L; free Cl_2: 0 to 1.40 mg/L; Dissolved oxygen [DO]: 4.50 to 11.12 mg/L)[30].

None of the campus buildings were originally designed to be school buildings (**Figure 3-1**). Buildings A (2 floors, 2,423 m^2) and B (1 floor, 1,024 m^2) were constructed in 1966 as multi-purpose buildings on the property. In 2001, the property changed owners, buildings were renovated to be used as an elementary school, but the plumbing was not modified. In 2006, another building was constructed on the property (building C). Buildings A and B are served by a single service line entering the West side of the property while building C is served by a service line on the North side of the property. Another water meter was located underground near the building C (114 m^2). The estimated distance from the water meter to the building B was about 78 meters, and to building C was 8 meters.

Figure 3-1. (a) Site property with building A, B and C with estimated location of public water supply pipe (blue), two water meters (sky blue circle) and service line to each building (sky blue) and where splits to deliver to building A (dotted sky blue), (b) Elkay drinking water fountains installed for kids' height, (c) All classrooms had their own sinks, drinking water fountain, and appliances, (d) Coffee maker connected to the plumbing in building A, and (e) Particulates on the aerator before removal.

Plumbing designs and components were relatively similar across buildings. The domestic water plumbing was soldered copper pipe with cross-linked polyethylene (PEX) faucet connectors and Elkay drinking water fountains. Each building had a different volume water heater (A: 151 L, B: 113 L, C: 189 L). In building A there were two pressure tanks (179.8 L each) and single water softener. Buildings B and C did not have water softeners. In buildings A and B, each classroom had one sink, one mini- or typical size refrigerator, and dishwasher. In building A, the main faculty/staff break room had one refrigerator with an icemaker and coffee maker appliance connected to the plumbing. Building A had 1 classroom on the first floor, 3 classrooms on the second floor; building B had 2 classrooms, building C had 2 classrooms. Two outdoor drinking water fountains connected to building B's plumbing were located at the playground.

The authors visited the site on June 19, 2020 for an initial inspection. In mid-March 2020 the school went on Spring Break, then switched to online learning due to the pandemic. Once transitioned to online learning, students did not return to campus until mid-August 2020. During the initial inspection visit, the authors learned that even though the campus was closed from March to August, the building owner was using water from building C (hose spigot) to water the grass. Water used for irrigation occurred weekly starting in June. Through discussions, the authors learned that the building owner also explained that for a few days they flushed water from select fixtures because government agencies recommended schools consider flushing fixtures periodically in response to low or no building occupancy. The school planned to reopen on July 1, 2022, but after authors' initial investigation, the school did not reopen for in-person learning until mid-August. Building owners did not have as-built plumbing drawings or understand the components and water quality of their system. Prior to the author's study, the building owner had never tested water from the plumbing except for drinking water lead samples collected a few years prior by a consultant.

3.3.2 Water sampling and analysis approach

On June 26, 2022, the authors visited the property to collect samples at 9:00 am. First draw samples were collected, followed by samples collected during and after flushing, and then again two weeks later. At each building, all cold water samples were collected first then hot water samples were collected. Samples were collected from kitchen sinks, bathroom sinks and drinking water fountains (**Table SI.3-1**). The authors first sampled water in building C, followed by building B and then building A. From each fixture about 150 mL water was first collected in a beaker for total chlorine, pH, temperature, and DO followed by samples for [total or dissolved] metals (125 mL for each), *L. pneumophila* by Legiolert (125 mL), total cell counts [TCC] (Two 15 mL), total organic carbon [TOC] (125 mL). Approximately 1,000 mL was then flushed followed by a sample collected for total trihalomethanes [TTHMs] (10 mL). Hot water samples were collected in the same order. All stagnant water samples were collected at a slow flow rate. For metal samples, 3N HCl was added to the bottle and for TOC, Na_2SO_4 was added to preserve samples. All samples were stored in the cooler until it delivered to the laboratory.

Onsite analysis for chlorine measurement was determined using HACH® DR300 Pocket Colorimeter with DPD total chlorine (detection limit = 0.02 mg/L as Cl_2). Water pH, temperature, and DO were measured using HACH® SL1000 PPA Portable Parallel Analyzer. For heavy metals analysis, iCAP ™ 7400 ICP-OES with an autosampler (ASX-280, CETAC

Teledyne) was used and 0.45 μm nylon filter was used to filter for dissolved metal samples. IDEXX® Legiolert with quanti-tray system was used to determine *L. pneumophila*, and trays were incubated for a week at 39℃. Locations that had less than 1 MPN/100 mL were not counted as detected. A cytoflex flow cytometer (Beckman-Coulter Inc.) was used to determine total cell counts with method 366.1[31]. TOC concentration was measured using Shimadzu TOC-L CPH/CPN with EPA method 415.1[32]. A 7890B Gas Chromatography system (Agilent Technologies) was used to determine TTHM levels.

3.3.3 Flushing

After all cold and hot water stagnant water samples from all buildings were collected, the authors removed all water from the plumbing by first running cold water from the janitor sinks with highest flowrate. Flushing also started in the order of building C, B then A and did not stop until greater than 0.2 mg/L as Cl_2 chlorine residual concentration was found. While flushing, water samples were collected every one minute to monitor for chlorine and temperature. After flushing stopped, the authors removed and cleaned all aerators by scrubbing them with a new toothbrush and soaking them in food grade vinegar for 30 minutes. Toilets were flushed three times. All toilets near the classroom were child sized toilet (about 4.84 L per flush). After all fixtures were flushed, authors returned to the janitor sink and flushed building hot water. The gas water heaters were subsequently drained by plumbers hired by the building owner after the authors left. The building owner also followed the authors recommendation to operate dishwashers three times, and discard three batches of ice from the icemaker. Two weeks after the flushing (July 10th), the authors revisited the school to again collect first draw water samples. The sampling and analysis approach was similar to the first visit except aerators were neither removed nor cleaned and flushing was not conducted. The authors were informed that irrigation had continued to be conducted using an outdoor spigot from building B.

3.4 Results and discussions

3.4.1 Observations of the closed buildings

While the campus closed in mid-March, from April to June 2020 building C water usage was nondetectable (**Figure SI.3-1**), while Buildings A and B had detectable water use in April (3,785 L) but not through June. Prior to building closure, building C's 2019 average

monthly water use was 4,967 L and the daily water use was 170 L. For buildings A and B, the 2019 average water monthly usage was 15,431 L and daily average was 510 L. Even though the building owner began using water for irrigation in June once per week the public utility had no record of customer water usage. During the first visit the authors also found that the building owner shutoff air conditioning in all three buildings to save money. Maximum outdoor air temperatures during the building closure period ranged from 25 ºC to 35 ºC (**Figure SI.3-2**).

3.4.2 First draw cold water quality

Like other buildings studied by the authors elsewhere and by other investigators, no chlorine residual was detected in the stagnant water in the present study (**Figure 3-2**)[9,16,33–35]. Typically, the water supplier reported chlorine residual values of 1.3 mg/L as Cl_2 leaving the treatment plant; 0.94 to 1.48 mg/L as Cl_2 in the distribution system[36]. Though, the previous study of a service line delivered water by the same water supplier in the same water distribution system sometimes did not have chlorine residual entering a customer service line 25% of the time and chlorine residual entering the service line varied seasonally (0 to 2.1 mg/L as Cl_2)[30]. Therefore, it is unknown if the water sampled from the campus buildings always contained a detectable chlorine residual when it was delivered to the water meter. TTHM levels in the school buildings (0.5 to 7.3 μg/L) were often much lower than the levels reported by the water supplier (9.2 to 9.8 μg/L) and a service line of the nearby home (0 to 10.18 μg/L)[30]. It was expected that TTHM levels increase inside plumbing (max. 40.83 μg/L) like seen elsewhere in the water distribution system, but levels in stagnant water were low. This may be due to the absence of chlorine residual. Cold water temperatures were relatively consistent (20 ℃ to 23℃) and drinking water fountains had the coldest water (12 ℃ to 22℃).

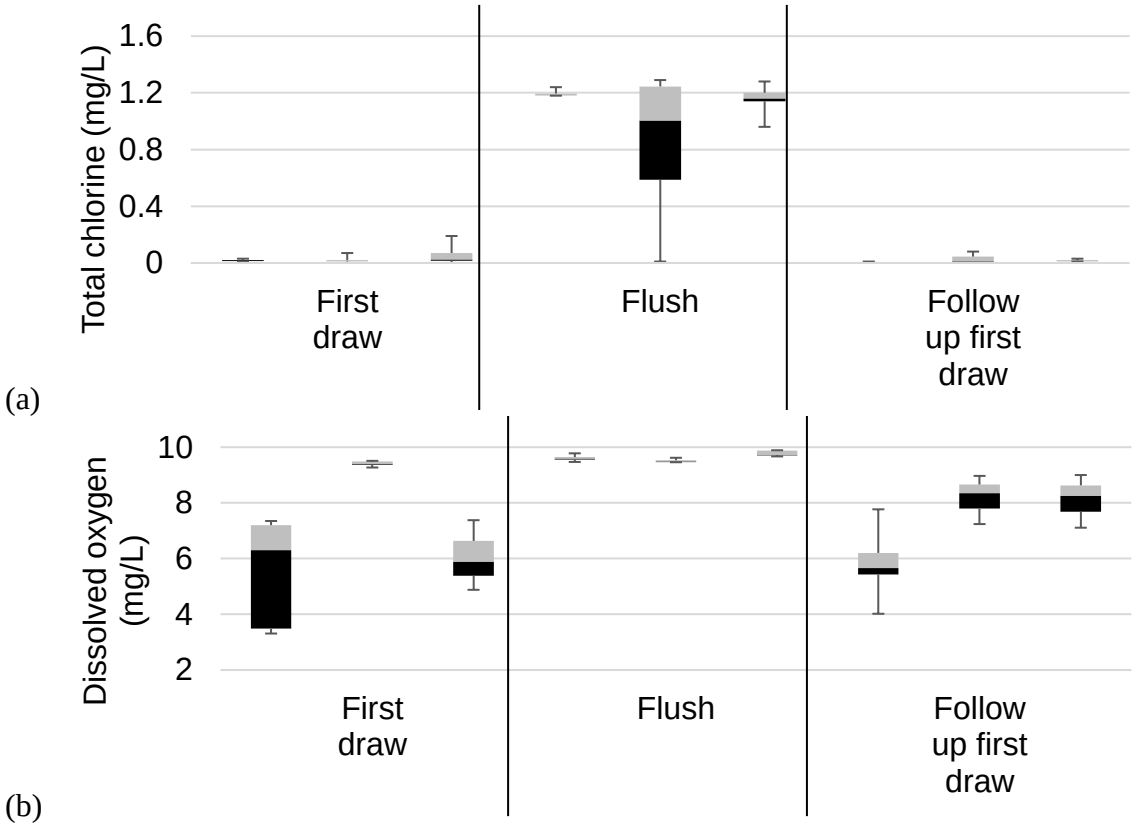

Figure 3-2. Water quality measurements for buildings A, B, and C for (a) Total chlorine residual, and (b) Dissolved oxygen. For flush graphs, last recording data after flush was reported.

Except for nickel and lead, no heavy metals exceeded health or aesthetic based drinking water thresholds. Two cold water fixtures had a noticeably higher nickel level than the average level (18.8 µg Ni/L) found at fixtures: building B (144 µg Ni/L), building C (75.7 µg Ni/L). Nickel's health-based drinking water threshold is 100 µg/L [38]. Lead was detected in cold water (12/15) including at drinking water fountains (2/4) at a maximum of 3.3 µg/L. The health-based drinking water lead threshold , the maximum contaminant level goal, is 0 µg/L, and no level of lead is safe[39]. The American Academy of Pediatrics recommends that school water fountains should not exceed 1 µg Pb/L[40]. The maximum copper concentration found was 0.6 mg/L, while iron and manganese levels were less than the minimum concentrations reported by the supplier (<0.01 mg Fe/L, <0.007 mg Mn/L).

Total cell count and *L. pneumophila* levels were similar to those reported by others for school and office buildings under stagnant and non-stagnant scenarios[6,41–44], but differed across school buildings, between cold and hot water, and locations. Drinking water fountains generally had higher TCC levels (5.02 to 5.64 log cells/mL) than the other cold water fixtures (3.00 to 5.05 log cells/mL), and this was consistent across all three buildings. The highest *L. pneumophila* level was detected at the building C bathroom sink cold water (188.2 MPN/100

mL) and a drinking water fountain (141.6 MPN/100 mL). At building A, only a single kitchen sink cold water sample was positive (1.1 MPN/100 mL). *L. pneumophila* was not detected at any cold or drinking water fixture in building B. Of 25 cold water samples from buildings A, B and C, two samples from building C exceeded the WHO limit (10 CFU/mL) and the AIHA (100 CFU/mL) thresholds (**Table 3-1**). Although, 1 CFU is not same as 1 MPN (approximately 1.2 CFU = 1 MPN)[45], few samples still exceeded the WHO (8.3 MPN/mL) and AIHA (83 MPN/mL) thresholds. One other location at building A also detected *L. pneumophila* but did not exceed the WHO limit. No *L. pneumophila* detections were found at building B.

Table 3-1. Number of locations where *L. Pneumophila* was detected and its (concentrations)

Fixture		Building A			Building B			Building C		
		Stagnant	Post flush	Stagnant 2 weeks later	Stagnant	Post flush	Stagnant 2 weeks later	Stagnant	Post flush	Stagnant 2 weeks later
Cold	Bathroom sink	0/3	-	0/2	0/2	-	-	1/1 (188.2)	-	0/2
	Kitchen classroom sink	1/2 (1.1)	0/4	0/3	0/2	-	0/2	0/1	-	-
	Fountains	0/2	-	1/2 (5.8)	0/1	-	0/1	1/1 (141.6)	-	0/1
	Janitor sink	-	-	-	0/6	-	-	0/4	-	-
Hot	Bathroom sink	0/3	-	2/2 (1.1, 2.3)	0/1	-	0/1	0/1	-	0/1
	Kitchen classroom sink	0/5	0/4	3/3 (2.2, 15.5, 61.1)	0/2	-	1/2 (2.3)	0/1	-	0/1
	Janitor sink	-	-	-	1/4 (2)	-	0/1	0/4	-	-

Units are MPN/100 mL; Locations that had less than 1 MPN/100 mL were not counted as detected, and no repeat positive locations were found on follow-up visit first draw water samples

3.4.3 First draw hot water quality

Hot water sample temperatures never exceeded 41 ºC, and to reduce *L. pneumophila* potential water heater settings of 60 ºC are recommended [22,46–49]. *L. pneumophila* growth can occur at temperatures as low as 20 ºC[22]. Interestingly, the International Plumbing Code defines hot water as having a "water temperature greater than or equal to 43 ºC[50]. It is possible that

thermostatic mixing valves were present at bathroom fixtures to prevent kids being exposed to hot water. Chemically, the hot water was similar to cold water (**Table SI.3-2**), but microbiological differences were apparent. TCC levels were (4.8 to 6.2 log cells/mL), and greater than the cold water (non-drinking water fountain fixtures). *L. pneumophila* was found at a janitor sink at building B at 2 MPN/100 mL. While 1 MPN was equivalent to 1.2 CFU, building C had a greater level of TCC than the other two buildings. Interestingly, building C had less water use than both buildings A and B. Of 21 first draw hot water samples from buildings A, B and C, only one sample at building B detected *L. pneumophila* and concentrations were less than the WHO and AIHA thresholds (**Table 3-1**).

3.4.4 Flushing did not result in an improvement of all water quality characteristics

Total chlorine residual and DO concentration had the greatest magnitude increase after flushing, and pH ranged from 7.1 to 8.2 (**Figure 3-2, Table SI.3-2**). For two locations however detectable chlorine was found during flushing but was not detected after 10 minutes of fixture flushing (**Figure 3-3**). It is unclear why this phenomenon was observed. Buildings B and C were located closer to the water main and should have theoretically had a greater starting chlorine residual concentration, than building A. Based on water distribution system sampling in the service area by others however water without a detectable amount of chlorine disinfectant could have been delivered to the buildings[5,30]. Heavy metal concentrations were lower after flushing, and nickel and lead levels were reduced below their drinking water thresholds (p<0.05) (**Figure SI.3-3**).

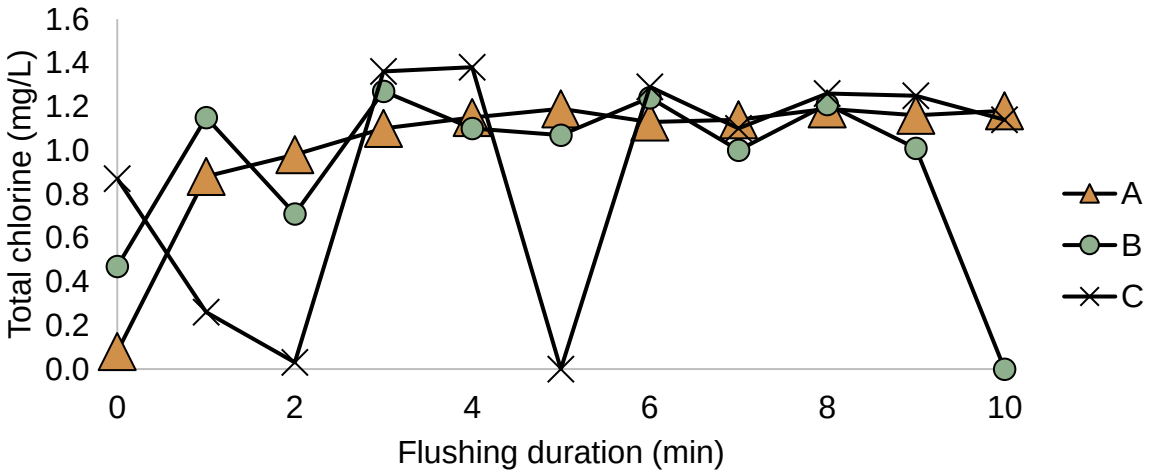

Figure 3-3. Chlorine residual fluctuated during the 10-minute cold water at the kitchen sink (building A) and the janitor sinks (building B and C).

Post-flush TCC levels were slightly less than stagnant water levels for cold and hot water. Mean cold water TCC levels reduced from 4.34 to 3.59 log cells/mL and for hot water reduced from 5.48 to 4.13 log cells/mL. TCC levels in the present study before and after flushing were slightly lower than the other studies, while post-flush TCC levels were similarly lower than stagnant water[42,51]. Building A, the site of the main school office, faculty/staff kitchen, and was the only two-story building, was targeted for *L. pneumophila* sampling post-flush. *L. pneumophila* was not detected at either cold (4) or hot (4) water locations sampled.

3.4.5 Generally, water quality after two weeks of stagnation was similar to the 3-month stagnation period

Similar to the prior visit, first draw chemical and microbiological water quality characteristics were similar except that *L. pneumophila* was at levels less than the stagnant water concentrations (**Table SI.3-3**). None of cold water fixtures or drinking water fountains had detectable chlorine. No heavy metals exceeded their drinking water thresholds (**Table SI.3-4**). TCC levels at drinking water fountains (4.7 to 5.26 log cells/mL) were again generally greater than levels at other cold water fixtures (3.53 to 4.84 log cells/mL). The range of values detected were similar for the 3-month stagnated water. For *L. pneumophila*, no previously positive locations were found on this follow-up visit, but the organism was detected at new, previously negative, locations. Of the 12 samples collected in building A, *L. pneumophila* was detected at one drinking water fountain (5.8 MPN/100 mL), as hot water from 3 kitchen sinks (max. 61.1 MPN/100 mL), and from two bathroom sinks (max. 2.3 MPN/100 mL). These values exceeded the maximum concentration in the building previously of 1.1 MPN/100 mL (cold water stagnant). Of the 7 samples collected in building B, no cold water samples were positive for the organism, but one hot water kitchen sink sample was positive (max. 2.3 MPN/100 mL). Building C had no detections of *L. pneumophila* unlike the prior visit where this building had the greatest concentrations detected (**Figure SI.3-4**). Of 13 cold water samples, only one sample at building A had detectable *L. pneumophila* but the concentration was less than the WHO threshold (**Table 3-1**). Six of 11 hot water samples (five from building A and one from building B) detected *L. pneumophila*, and two samples exceeded the WHO threshold but did not exceed the AIHA threshold.

3.5 Implications and recommendations

This study was conducted to better understand chemical and microbiological water quality in a 3-month stagnated plumbing at an elementary school, and the impact of flushing on chemical and microbial contaminant levels. Before the author's study, the building owner had never tested the water entering or within their plumbing. The owner did not have drawings that outlined the plumbing components (location, types, sizes, lengths, etc.). The public water supplier and state health department specifically advised the building owner to flush out stagnant water[52,53].

After 3 months of stagnation first draw water samples had no detectable chlorine residual concentration and nickel and lead exceeded health-based drinking water thresholds. *L. pneumophila* was found at its greatest concentration in the 3-month stagnated water (188 MPN 100 mL). Fixture flushing reduced heavy metal levels below health-based drinking water limits. Flushing sometimes, but not always, resulted in water with a chlorine residual being detected at fixtures. *L. pneumophila* concentrations were reduced due to flushing. Though, *L. pneumophila* was detected at different fixture locations and lower concentrations 2 weeks later after the stagnant water flush (max. 61 MPN/100 mL). *L. pneumophila* resides in biofilms so it is not surprising that it was found in the plumbing after flushing[54,55]. Results from the present study indicate that shock disinfection[21–23] was not needed to reduce *L. pneumophila* levels below 100 CFU/mL, the AIHA level for shock disinfection.

Results of the present study agree with some of the existing literature but underscore several knowledge-gaps. Flushing did not always prompt disinfectant levels to be found at faucets and this may be because unchlorinated water was delivered to the building, or chlorine residual decayed as water was drawn to the faucet. Better understanding the chemical and microbiological variability of water delivered to service lines is needed. Here, *L. pneumophila* concentrations were reduced by flushing found like others[12,42] but alternatively others have found *L. pneumophila* concentrations increased after flushing[25]. Future work should focus on understanding the sources of *L. pneumophila* and conditions that cause greater *L. pneumophila* levels post-flushing. This will require better understanding plumbing complexity and monitoring. Additionally, culture, and qPCR methods for *L. pneumophila* and other organisms may provide greater insights.

For building owners who desire to better manage water quality, the following actions can be considered: (1) periodically flush water outlets to remove water with higher metal and microorganism contaminant concentrations, (2) maintain total chlorine residual of at least 0.2

mg/L at fixtures to minimize biofilm growth similar to goals worked towards by public water suppliers, (3) maintain the hot water temperature at the highest temperature allowable by state regulation and code. To maintain desired disinfectant levels within plumbing, continuous water treatment disinfection may be necessary. A single plumbing flush was effective at reducing heavy metal concentrations, bringing in disinfected water, and reducing *L. pneumophila* levels.

3.6 Acknowledgement

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3.7 Conflict of interest

AW and CP provided guidance to USEPA and CDC on their building water flushing guidance which was issued by the agencies during the conduct of the present study.

3.8 References

1. Montagnino, E., Lytle, D. A., Rose, J., Cwiertny, D., & Whelton, A. J. (2022). School and childcare center drinking water: Copper chemistry, health effects, occurrence, and remediation. *AWWA Water Science*, *4*(2), e1270. https://doi.org/10.1002/AWS2.1270

2. WHIO News. (2020). *Kettering schools taking safety measures after Legionella found in water at Fairmont High – WHIO TV 7 and WHIO Radio*. https://www.whio.com/home/kettering-schools-taking-safety-measures-after-legionella-find-fairmont-high/IE5UMGUA2ZDHJHUAGA5BMMXW2U/

3. Education Week. (2020). *Map: Coronavirus and School Closures in 2019-2020*. https://www.edweek.org/leadership/map-coronavirus-and-school-closures-in-2019-2020/2020/03

4. Ra, K., Odimayomi, T., Ley, C., Aw, T. G., Rose, J. B., & Whelton, A. J. (2020). Finding building water quality challenges in a 7 year old green school: Implications for building design, sampling, and remediation. *Environmental Science: Water Research and Technology*, *6*(10), 2691–2703. https://doi.org/10.1039/d0ew00520g

5. Aw, T. G., Scott, L., Jordan, K., Ra, K., Ley, C., & Whelton, A. J. (2022). Prevalence of opportunistic pathogens in a school building plumbing during periods of low water use and a transition to normal use. *International Journal of Hygiene and Environmental Health*, *241*, 113945. https://doi.org/10.1016/J.IJHEH.2022.113945

6. Montagnino, E., Proctor, C. R., Ra, K., Ley, C., Noh, Y., Vigil, K., Aw, T. G., Dasika, S., & Whelton, A. J. (2022). Over the weekend: Water stagnation and contaminant exceedances in a green office building. *PLOS Water*, *1*(3), e0000006. https://doi.org/10.1371/journal.pwat.0000006

7. Salehi, M., Desimone, D., Aghilinasrollahabadi, K., & Ahamed, T. (2021). A case study on tap water quality in large buildings recommissioned after extended closure due to the COVID-19 pandemic. *Environmental Science: Water Research and Technology*, *7*(11), 1996–2009. https://doi.org/10.1039/d1ew00428j

8. Shima Ghoochani, Maryam Salehi, Dave DeSimone, Esfandarani, M. S., & Linkon Bhattacharjee. (2022). Studying the impacts of non-routine extended schools' closure on heavy metal release into tap water. *Environmental Science: Water Research & Technology*. https://doi.org/10.1039/D2EW00149G

9. Ye, C., Xian, X., Bao, R., Zhang, Y., Feng, M., Lin, W., & Yu, X. (2022). Recovery of microbiological quality of long-term stagnant tap water in university buildings during the COVID-19 pandemic. *Science of The Total Environment*, *806*, 150616. https://doi.org/10.1016/J.SCITOTENV.2021.150616

10. Richard, R., Boyer, T. H., Treavor Boyer, C. H., Editor, A., & Mo, W. (2021). *Pre-and post-flushing of three schools in Arizona due to COVID-19 shutdown*. https://doi.org/10.1002/aws2.1239

11. Vosloo, S., Huo, L., Chauhan, U., Cotto, I., Gincley, B., Vilardi, K. J., Yoon, B., Pieper, K. J., Stubbins, A., & Pinto, A. (2022). Systematic recovery of building plumbing-associated microbial communities after extended periods of altered water demand during the COVID-19 pandemic. *MedRxiv*, 2022.01.17.22269440. https://doi.org/10.1101/2022.01.17.22269440

12. Hozalski, R. M., Lapara, T. M., Zhao, X., Kim, T., Waak, M. B., Burch, T., & Mccarty, M. (2020). *Flushing of Stagnant Premise Water Systems after the COVID-19 Shutdown Can Reduce Infection Risk by Legionella and Mycobacterium spp*. https://doi.org/10.1021/acs.est.0c06357

13. Liang, J., Swanson, C. S., Wang, L., & He, Q. (2021). Impact of building closures during the COVID-19 pandemic on Legionella infection risks. *American Journal of Infection Control*, *49*(12), 1564–1566. https://doi.org/10.1016/J.AJIC.2021.09.008

14. Rhoads, W. J., Sindelar, M., Margot, C., Graf, N., & Hammes, F. (2022). *Variable Legionella Response to Building Occupancy Patterns and Precautionary Flushing*. 1–18.

15. EPA. (2020). *Maintaining or restoring water quality in buildings with low or no use*. https://www.epa.gov/sites/default/files/2020-05/documents/final_maintaining_building_water_quality_5.6.20-v2.pdf

16. Proctor, C. R., Rhoads, W. J., Keane, T., Salehi, M., Hamilton, K., Pieper, K. J., Cwiertny, D. M., Prévost, M., & Whelton, A. J. (2020). Considerations for large building water quality after extended stagnation. *AWWA Water Science*, *2*(4). https://doi.org/10.1002/aws2.1186

17. EPA. (2020). *Restoring water quality in buildings for reopening*. https://www.epa.gov/sites/production/files/2020-05/documents/final_checklist_for_maintaining_building_water_quality_5-6-2020.pdf

18. EPA. (2021). *Ensuring Drinking Water Quality in Schools During and After Extended Closures 3Ts: TRAINING, TESTING, TAKING ACTION Developed in collaboration with the signatory agencies and organizations of the Memorandum of Understanding (MOU) on Reducing Lead Levels i*. https://www.epa.gov/

19. CDC. (2020). *Guidance for COVID-19 Prevention in K-12 Schools | CDC*. https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/k-12-guidance.html?CDC_AA_refVal=https%3A%2F%2Fwww.cdc.gov%2Fcoronavirus%2F2019-ncov%2Fcommunity%2Fschools-childcare%2Foperation-strategy.html

20. CDC. (2021). *Reopening Buildings After Prolonged Shutdown or Reduced Operation*. https://www.cdc.gov/nceh/ehs/water/legionella/building-water-system.html

21. AIHA. (2015). *Recognition, Evaluation, and Control of Legionella in Building… | AIHA*. https://www.aiha.org/education/marketplace/legionella-guide

22. CDC. (2021). *Controlling Legionella in Potable Water Systems | CDC*. https://www.cdc.gov/legionella/wmp/control-toolkit/potable-water-systems.html

23. EPA. (2015). *Office of Water Draft-Technologies for Legionella Control: Scientific Literature Review*.

24. Orsi, G. B., Vitali, M., Marinelli, L., Ciorba, V., Tufi, D., Del Cimmuto, A., Ursillo, P., Fabiani, M., De Santis, S., Protano, C., Marzuillo, C., & De Giusti, M. (2014). Legionella control in the water system of antiquated hospital buildings by shock and continuous hyperchlorination: 5 years experience. *BMC Infectious Diseases*, *14*(1), 1–10. https://doi.org/10.1186/1471-2334-14-394/TABLES/5

25. Richard, R., Boyer, T. H., Treavor Boyer, C. H., Editor, A., & Mo, W. (2021). Pre- and post-flushing of three schools in Arizona due to COVID-19 shutdown. *AWWA Water Science*, *3*(5), e1239. https://doi.org/10.1002/AWS2.1239

26. WHO. (2017). *Drinking Water Parameter Cooperation Project Support to the revision of Annex I Council Directive 98/83/EC on the Quality of Water Intended for Human Consumption (Drinking Water Directive)*.

27. Hamilton, K. A., Hamilton, M. T., Johnson, W., Jjemba, P., Bukhari, Z., Lechevallier, M., Haas, C. N., & Gurian, P. L. (2019). Risk-Based Critical Concentrations of Legionella pneumophila for Indoor Residential Water Uses. *Environmental Science and Technology*, *53*(8), 4528–4541. https://doi.org/10.1021/ACS.EST.8B03000/ASSET/IMAGES/LARGE/ES-2018-03000K_0004.JPEG

28. Health and Safety Executive. (2013). *Legionnaires ' disease : Technical guidance*. 1–57.

29. CDC. (2021). *Routine Testing for Legionella | CDC*. https://www.cdc.gov/legionella/wmp/control-toolkit/routine-testing.html

30. Salehi, M., Odimayomi, T., Ra, K., Ley, C., Julien, R., Nejadhashemi, A. P., Hernandez-Suarez, J. S., Mitchell, J., Shah, A. D., & Whelton, A. (2020). An investigation of spatial and temporal drinking water quality variation in green residential plumbing. *Building and Environment*, *169*, 106566. https://doi.org/10.1016/J.BUILDENV.2019.106566

31. Hammes, F., Berney, M., Wang, Y., Vital, M., Köster, O., & Egli, T. (2008). Flow-cytometric total bacterial cell counts as a descriptive microbiological parameter for drinking water treatment processes. *Water Research*, *42*(1–2), 269–277. https://doi.org/10.1016/J.WATRES.2007.07.009

32. EPA. (1999). *TOTAL ORGANIC CARBON in Water EPA Method 415.1 (Combustion or Oxidation) EPA Method 415.2 (UV Promoted, Persulfate Oxidation) or SW-846 Method 9060 Table 1. Summary of Contract Required Detection Limits, Holding Times, and Preservation for Total Organic C*.

33. Lipphaus, P., Hammes, F., Kötzsch, S., Green, J., Gillespie, S., & Nocker, A. (2013). *Environmental Technology Microbiological tap water profile of a medium-sized building and effect of water stagnation*. https://doi.org/10.1080/09593330.2013.839748

34. Zlatanović, L., van der Hoek, J. P., & Vreeburg, J. H. G. (2017). An experimental study on the influence of water stagnation and temperature change on water quality in a full-scale domestic drinking water system. *Water Research*, *123*, 761–772. https://doi.org/10.1016/j.watres.2017.07.019

35. Rhoads, W. J., & Hammes, F. (2021). Growth of: Legionella during COVID-19 lockdown stagnation. *Environmental Science: Water Research and Technology*, *7*(1), 10–15. https://doi.org/10.1039/d0ew00819b

36. Indiana American Water. (2020). *2020 Annual Water Quality Report*. https://www.amwater.com/ccr/WestLafayette_2020.pdf

37. Indiana American Water. (n.d.). *Typical Water Quality West Lafayette Typical Water Quality Information PWSID Number: 5279020 Area Served: City of West Lafayette and Wabash and Tippecanoe townships Where Does My Water Come From?*

38. EPA. (1998). *Ambient Water Quality Value for Protection of Sources of Potable Water for Nickel*.

39. EPA. (2022). *Basic Information about Lead in Drinking Water | US EPA*. https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water

40. AAP. (2016). *With No Amount Of Lead Exposure Safe For Children*. https://www.aap.org/en-us/about-the-aap/aap-press-room/Pages/With-No-Amount-of-Lead-Exposure-Safe-for-Children,-American-Academy-of-Pediatrics-Calls-For-Stricter-Regulations.aspx

41. Bédard, E., Laferrière, C., Déziel, E., & Prévost, M. (2018). Impact of stagnation and sampling volume on water microbial quality monitoring in large buildings. *PLOS ONE*, *13*(6), e0199429. https://doi.org/10.1371/JOURNAL.PONE.0199429

42. Rhoads, W. J., Sindelar, M., Margot, C., Graf, N., & Hammes, F. (2022). Variable Legionella Response to Building Occupancy Patterns and Precautionary Flushing. *Microorganisms*, *10*(3). https://doi.org/10.3390/MICROORGANISMS10030555/S1

43. Ley, C. J., Proctor, C. R., Jordan, K., Ra, K., Noh, Y., Odimayomi, T., Julien, R., Kropp, I., Mitchell, J., Nejadhashemi, A. P., Whelton, A. J., & Aw, T. G. (2020). Impacts of Municipal Water-Rainwater Source Transitions on Microbial and Chemical Water Quality Dynamics at the Tap. *Environmental Science and Technology*, *54*(18), 11453–11463. https://doi.org/10.1021/ACS.EST.0C03641/SUPPL_FILE/ES0C03641_SI_001.PDF

44. Bédard, E., Paranjape, K., Lalancette, C., Villion, M., Quach, C., Laferrière, C., Faucher, S. P., & Prévost, M. (2019). Legionella pneumophila levels and sequence-type distribution in hospital hot water samples from faucets to connecting pipes. *Water Research*, *156*, 277–286. https://doi.org/10.1016/J.WATRES.2019.03.019

45. Dowdell, K. S., Greenwald, H. D., Joshi, S., Grimard-Conea, M., Pitell, S., Song, Y., Ley, C., Kennedy, L. C., Vosloo, S., Huo, L., Haig, S.-J., Hamilton, K. A., Nelson, K. L., Pinto, A., Prévost, M., Proctor, C. R., Raskin, L. M., Whelton, A. J., Garner, E., … Rhoads, W. J. (2022). Legionella pneumophila occurrence in reduced-occupancy buildings in 11 cities during the COVID-19 pandemic. *MedRxiv*, 2022.06.28.22277022. https://doi.org/10.1101/2022.06.28.22277022

46. Rhoads, W. J., Ji, P., Pruden, A., & Edwards, M. A. (2015). Water heater temperature set point and water use patterns influence Legionella pneumophila and associated microorganisms at the tap. *Microbiome*, *3*(1), 67. https://doi.org/10.1186/S40168-015-0134-1/FIGURES/7

47. Bédard, E., Fey, S., Charron, D., Lalancette, C., Cantin, P., Dolcé, P., Laferrière, C., Déziel, E., & Prévost, M. (2015). Temperature diagnostic to identify high risk areas and optimize Legionella pneumophila surveillance in hot water distribution systems. *Water Research*, *71*, 244–256. https://doi.org/10.1016/j.watres.2015.01.006

48. Blanc, D. S., Carrara, P., Zanetti, G., & Francioli, P. (2005). Water disinfection with ozone, copper and silver ions, and temperature increase to control Legionella: seven years of experience in a university teaching hospital. *The Journal of Hospital Infection*, *60*(1), 69–72. https://doi.org/10.1016/J.JHIN.2004.10.016

49. Lavoie, M., Lévesque, B., & Sergerie, D. (2003). *Prevention of scalding and legionellosis associated with hot tap water in private homes**. www.inspq.qc.ca.

50. IPC. (2021). *CHAPTER 2 DEFINITIONS, 2021 International Plumbing Code (IPC) | ICC Digital Codes*. https://codes.iccsafe.org/content/IPC2021P1/chapter-2-definitions

51. Vosloo, S., Huo, L., Chauhan, U., Cotto, I., Gincley, B., Vilardi, K. J., Yoon, B., Pieper, K. J., Stubbins, A., & Pinto, A. (2022). Systematic recovery of building plumbing-associated microbial communities after extended periods of altered water demand during the COVID-19 pandemic. *MedRxiv*, 2022.01.17.22269440. https://doi.org/10.1101/2022.01.17.22269440

52. Indiana Department of Health. (2020). *BUILDING WATER SYSTEM STARTUP GUIDANCE*. https://engineering.purdue.edu/PlumbingSafety/covid19/Guidance-Evaluation-Tool.pdf

53. American Water. (2020). *Indiana American Water Recommends Building Operators and Schools Flush Pipes to Maintain Water Quality*. *21*(1), 1–9. https://www.amwater.com/press-room/press-releases/indiana/indiana-american-water-recommends-building-operators-and-schools-flush-pipes-to-maintain-water-quality

54. LeChevallier, M. W. (2019). Occurrence of culturable Legionella pneumophila in drinking water distribution systems. *AWWA Water Science*, *1*(3), e1139. https://doi.org/10.1002/AWS2.1139

55. Proctor, C. R., & Hammes, F. (2015). Drinking water microbiology — from measurement to management. *Current Opinion in Biotechnology*, *33*, 87–94. https://doi.org/10.1016/J.COPBIO.2014.12.014

4. MICROPLASTICS IN BUILDING WATER SYSTEMS: AN EXPERIMENTAL STUDY OF FATE IN PLUMBING AND KNOWLEDGE-GAPS

Kyungyeon Ra, Caitlin R. Proctor, Andrew J. Whelton

4.1 Abstract

Microplastic (MP) pollution is a growing environmental problem and MPs have been recently found exiting drinking water faucets. In 2018, the State of California passed the first U.S. regulation pertaining to MPs in drinking water, requiring testing of water entering public water distribution systems. The study goal was to better understand MP fate in building drinking water plumbing. Specific objectives were to (1) review the literature to understand existing knowledge associated with MPs at building faucets, (2) conduct MP fate experiments with new and aged plumbing pipes, and (3) identify knowledge-gaps and prioritized research needs that can help guide future studies and human health risk predictions. The literature review revealed a wide variety of MP polymers, of varying densities, have been found exiting building faucets, but no trends in type or size. Limited information about published study sampling and analysis procedures inhibited broader understanding of MP origin, properties, and fate. MPs exiting building faucets can originate from within plumbing, and bench-scale studies with polyethylene and water softener resin MPs revealed these materials can be retained even after flushing. MP size influenced fate, but no differences were found between new copper and crosslinked polyethylene pipes, different flow rates, or the presence of a biofilm. Aged water softener resin MPs did not chemically leach carbon compounds different than new resin when exposed to heat or ten superchlorinated water treatments. The discovery that MPs can be retained within plumbing pipes and reach building faucets prompted research need identification.

Keywords: Microplastic; plumbing; public health

4.2 Introduction

Plastic is one of the most widely used artificial materials and microplastic (MP) pollution is a growing global environmental and population health concern. In recent years, MPs have been discovered in air, groundwater, wastewater, drinking water, beer, table salt, and human feces[1–6]. The topic of MPs in drinking water has received comparatively little study despite 10,000 metric tons of plastic debris entering major drinking water sources like the Great Lakes every year[7]. About 227 million metric tons of plastic waste will be in the world oceans by 2025[8].

Until the State of California enacted a 2018 law regarding MPs in drinking water [9,10], there were no drinking water regulations pertained to MP monitoring in the U.S. Prior to this law, U.S. federal law addressed one type of MP called microbeads. Here, microbeads were defined as "any solid plastic particle that [was] less than 5 mm in size intended to be used to exfoliate or cleanse the human body or any part thereof"[11,12]. However, there are many types of MPs, and different organizations define MPs differently (**Table 4-1**). In 2021, the State of California began requiring public drinking water systems to detect and quantify MP concentration as drinking water enters water distribution systems, or systems that provide water to more than 25 people for at least 60 days per year[13]. In May 2022, California approved standard operating procedures for MP identification to include Infrared (MPs > 50 μm) and Raman spectroscopy (MPs > 20 μm)[14,15]. The California MP drinking water monitoring guideline was released in November 2021. The standard method for MP detection was released in May 2022. California drinking water data is expected to be publicly available in Fall 2023.

Table 4-1. The definition of a microplastic varies based on the organization

Organization	Year	Definition
World Health Organization[16]	2019	"Plastic particles smaller than 5 mm in length. However, this is a rather arbitrary definition and is of limited value in the context of drinking water since particles at the upper end of the size range are unlikely to be found in treated drinking-water. Some groups define a lower bound at about 1 μm…. A subset of microplastics smaller than 1 μm in length are often referred to as nanoplastics, but again with an inconsistent upper bound."
State of California[17]	2018	"Defined as solid polymeric materials to which chemical additives or other substances may have been added, which are particles, which have at least three dimensions that are greater than 1 nm and less than 5,000 μm, the polymers derived in nature that have not been chemically modified (other than by hydrolysis) are excluded."
Group of Experts on the Scientific Aspects of Marine Environmental Protection[18]	2015	Particles less 1 nm to 5 mm in size
Environmental and Climate Change Canada[19]	2015	Defined as plastics less than 5 mm in size

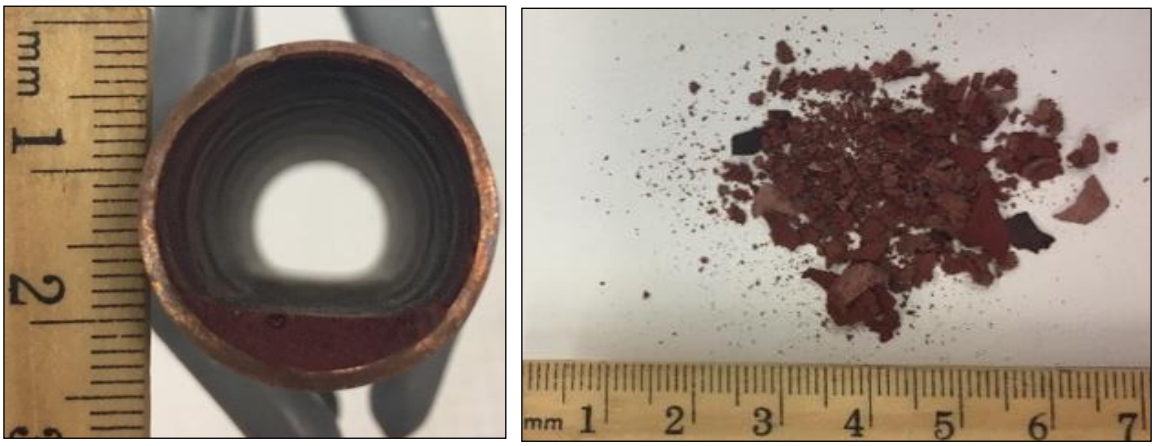
Plastic have been used for drinking water transport and storage in the U.S. since the 1960s copper shortage (**Table 4-2**), though awareness about MPs at drinking water faucets remains limited. Plastics water distribution and plumbing components are used because they are often less costly and can involve less labor to install than their metal counterparts. As plastic water system components age, they can deteriorate and release particles that reach drinking water faucets (**Figure 4-1**). For example, elastomeric gaskets used for faucets can be degraded by chloramine disinfectant exposure prompting organic compounds leaching and black particulates to be present in drinking water[20–22]. Water softeners, used for removing divalent

cations from water, have sometimes mechanically failed and released the ion exchange (plastic) resin beads into plumbing[23–28]. This phenomenon can clog aerators, valves, and flushing for long times has been recommended to remove these materials. Interestingly, water softener resin beads are typically within 0.3 mm to 1.2 mm size. Therefore, by definition, these materials would be considered MPs (< 5 mm). No chemical or size characterization of plastic particles that originated from within plumbing was found.

Table 4-2. Plastics used in building plumbing that contact drinking water

Component	Type of polymer	
Pipes, tubing, faucet connectors, water heater dip tubes, shower hoses, flow restrictor	High density polyethylene (HDPE) Medium density polyethylene (MDPE) Low density polyethylene (LDPE) Polyvinylchloride (unplasticized) (uPVC) PVC (plasticized)	Poly(1-butene) (PB) Crosslinked polyethylene (PEX) Chlorinated PVC (CPVC) Polypropylene (PP) Polyvinylidene fluoride (PVDF)
Gaskets and seals	Ethylene propylene diene monomer (EPDM) Nitrile Fluorocarbon (Viton)	Neoprene Nylon Silicone
Fittings	Polyphenylsulfone (PPSU) HDPE PVC PEX	CPVC PP PVDF
Water treatment device components	Polysulfone (PSf) Polystyrene divinylbenzene	PVC PEX
Pipe and tank linings	Epoxy	Polyurea
Tanks, tank liners, pressure tank bladders	High density polyethylene (HDPE) PP	EPDM
Thread sealants	Polytetrafluoroethylene (PTFE) paste and tape	

(a)



(b)

Figure 4-1. Plastics used in plumbing are known to degrade and sometimes can find their way to drinking water faucets: (a) Inner copper pipe epoxy lining in a California home degraded and clogged aerators, (b) Water softener resin in a Texas home exited a tub spout due to the softener strainer mechanically failing. The structure of poly(styrene-co-divinylbenzene) water softener resin involves two polystyrene chains crosslinked with a divinylbenzene bond in the middle that makes the polymer more rigid. Water softener resin image courtesy of Seidel[27].

The study goal was to better understand MP fate in building drinking water plumbing. Specific objectives were to (1) review the literature to understand existing knowledge associated with MPs at building faucets, (2) conduct MP fate experiments with new and aged plumbing pipe, and (3) identify knowledge-gaps and prioritized research needs that can help guide future studies and human health risk predictions. The growing interest in MP characterization and fate has prompted regulatory backed drinking water testing in the U.S., and results from this study can help future efforts.

4.3 Materials and methods

4.3.1 Literature review

A literature review was conducted to identify current knowledge-gaps associated with MPs in drinking water from building faucets. Faucet water sampling studies were reviewed as well as the sampling and contaminant analysis techniques. Because few studies on MPs in drinking water were found, other studies including MPs in bottled water and some ocean, ground, and surface water studies were reviewed. Studies were also reviewed pertaining to biofilm and hydraulic impacts on particle fate and transport.

4.3.2 Experiments: MP fate in piping systems

4.3.2.1 LDPE microplastics and plumbing pipe contamination

Two different sized LDPE pellets (0.35 mm and 3.5 mm) were obtained from Fisher Scientific (NH, USA) and 0.762 m of 19.05 mm diameter drinking water copper and PEX pipes were obtained from local plumbing supply stores. Copper and PEX were chosen because both are commonly used in the water supply lines. Approximately 80 g of new 3.5 mm LDPE pellets and 20 g of new 0.35 mm LDPE were mixed with 1 L of municipal potable water (MPW) to create stock MP solutions. Next, the MP solutions were poured into the new copper and PEX pipe sections. Each pipe end was plugged with silicon stoppers wrapped with PTFE tape. Pipes were set horizontally and left stagnant for 1 hr, 24 hr, and 72 hr. After stagnation, MP water was collected in stainless-steel sieves from Fisherbrand™ (pore size <300 µm or 48 and 150 Mesh size) and water was flushed through the pipe once using connected hose at the building drinking water sink with 0.25 min/L flowrate. Collected MPs were oven dried (95°C) for 1 hr before weighing on a scale (Mettler Toledo™ analytical balance, limit of detection 0.1 mg). The pipe flushing and draining process based on procedures plumbers sometimes employ for removing water softener resin that has entered plumbing pipes.

4.3.2.2 Characterizing water softener resin

4.3.2.2.1 Resin size measurements

New polystyrene gel strong acid cation ion exchange resin for potable water softening (1 ft^3 bag size) was purchased from a distributor. According to the product data sheet, the particle size of the resin was 300 to 1,200 μm, and less than 1% was smaller than 300 μm[29]. To evaluate the particle size distribution, the diameter of new and wet particles was quantified using a Malvern Mastersizer 3000. Wet particles were first stagnated in the water for 3 days. Hydrodispersion mode was used for the particle measurements while particles are stirred in the water at 2,500 rpm and continuous ultrasound at intensity of 50% to help even dispersion. The final particle size was automatically calculated based on the four readings by the laser diffraction sensor (light scattering). The advanced focal plane detector would measure larger particles automatically to resolve small diffraction angles[30].

4.3.2.2.2 Resin thermal characteristics

TA instrument Q50 Thermogravimetric Analyzer (TGA) was used to characterize the new resin. A 20 mg sample of new resin was placed on a platinum pan and heated at a rate of 100℃/min until 500℃. Nitrogen (40 mL/min) and air (60 mL/min) atmospheres were applied.

4.3.2.2.3 Resin contamination and removal from new and aged pipes

Like LDPE experiments, 1.52 m of 19.05 mm diameter new copper and PEX pipe sections were examined. Each pipe sets had three replicates. To grow biofilm for aged pipes, pipes were filled with municipal potable water (MPW) obtained from building tap water. This water was obtained, dumped and refilled every 3 days for 1 month, and then dumped and refilled once per week after a month for three months. To determine if microbial growth (biofilm) occurred inside the pipes, a few stagnant water samples were collected and analyzed by flow cytometry (CytoFLEX Beckman-Coulter Inc, Brea, CA, USA). Flow cytometric measurements involved diluting water samples and SYBR Green I dye stain. The sample was then incubated at 37℃ for 10 min, and duplicate samples were analyzed for all samples.

To mimic how water softener resin enters and flows into plumbing pipes when it has left the resin tank, a 18.9 L (5 gallon) bucket was used to hold the MP contaminated water before flowing into each pipe. At the bottom of each food grade bucket, a drinking water

certified spigot was connected to each pipe replicate. The resin to water ratio was calculated based on the typical residential water softener tank size and number of people per household[31]. According to the water softener industry, about 0.028 m^3 or 22.6 kg of resin is used for "9x40" to "10x40" residential tanks, or about 55 to 80% of water softener would be filled depending on the size of the tank and the water consumption. Then author used the lower bound resin amount (55%) in the real water softener and calculated the resin to water ratio in the real softener (540 g resin/1 L of water). This would pertain about 4.05 kg of resin in needed for 7.5 L each replicate. Therefore, about 1/80 resin to water ratio was applied for the MP retainment experiment to scale down the bench-scale experiment. About 7.5 L of MPW was filled in the 18.9 L bucket and each time a 50 g of new resin was added and stirred at 500 rpm. The pipe was horizontally declined by 35 degrees, and a stainless-steel sieve (150 mesh or 89 μm) was used to capture resin exiting the pipe. The spigot was opened for a minute at low (1.89 LPM or 0.5 GPM) and high (8.32 LPM or 2.2 GPM) flow. These flowrates were selected based on typical flowrates at building faucets[32]. In present study, water velocity for low flow was about 0.00035 m/s and high flow was 0.00153 m/s. For comparison, required flow to remove particles for 19.05 mm diameter pipe would be 5 GPM or 18.93 LPM[33] which is a much greater flowrate than the average kitchen faucet flowrate (1 to 2.2 gpm). After the spigot was closed, the pipe was disconnected and flushed with new water to capture the resin that remained inside the pipe. Resin was dried using a similar process that was used for LDPE before weight measurement.

4.3.2.2.4 Resin damage process and integrity characterization

Resin was exposed to heat and superchlorinated drinking water solutions to mimic conditions experienced in a water heater and then longer-term chemical damage by drinking water disinfectant. To estimate the impact of heat on resin leaching and surface chemistry changes, new resin was heated in the water and air (as the control) at 90°C. For heating experiments, a glass jar was filled with resin and building drinking water and heated in the water for 30 min. For resin that was heated in the air, resin was placed into a convection oven, and heated in a glass jar for 30 min. Next, chemical leaching caused by these resin treatments was examined by stagnating new and heat exposed resins in MPW and ultrapure water (UPW) at 23ºC for 3 days in the dark. Water was characterized for TOC and total sulfur concentrations. For TOC analysis a Shimadzu TOC-L CPH/CPN was used and calibrated at 0.25 mg/L, 0.5 mg/L, 1 mg/L, 2 mg/L, 5 mg/L, 10 mg/L, and 50 mg/L using $HOOCC_6H4COOK$ (r^2>0.99). For total sulfur analysis, water samples were first filtered through 0.45 μm nylon filter and

diluted 100 times with HNO_3 to prevent contamination by high concentration. The ICP-OES iCAP 7400 by Thermo scientific with autosampler ASX-280 by CETAC Teledyne instrument was used. Calibration standards were conducted using the sulfur stock at 10 μg/L, 50 μg/L, 100 μg/L, 250 μg/L, 500 μg/L, 750 μg/L, 1000 μg/L, and 10,000 μg/L with a calibration curve correlation coefficient of 0.998.

To understand the impact of chlorinated water exposure on water softener resin leaching and surface chemistry, new resin was exposed to superchlorinated water (300 mg/L as Cl_2) ten times. A chlorine stock was diluted from concentrated bleach purchased from the store (Great value, contains 7.13% chlorine), using UPW, and pH was adjusted to between 7 to 8. A resin to water ratio similar to residential water softeners was used for the glass jars and new resin and stagnated in a 300 mg/L as Cl_2 solution for 3 hrs. Like the MP retainment experiment, author mimicked a real softener with resin to water ratio (135 g per 250 mL). Next, the jars and resin were rinsed thoroughly with UPW, followed by the addition of MPW and the resin stagnated for 3 days (chlorine residual range 0.05 to 0.32 mg/L as Cl_2). Control samples (no chlorine, resin only) were also exposed to UPW for 3 hrs and stagnated in the same MPW for 3 days.

For comparison purposes, a 15 year old water softener was removed from a home in West Lafayette, Indiana in 2021 and dissembled in the author's laboratory. The softener received drinking water from a public water system. Upon analysis, water samples were collected from the inside of water softener and analyzed for TOC and total sulfur concentration. Resin was also collected and analyzed by Attenuated total reflectance Fourier-transform infrared spectroscopy (ATR FTIR) spectroscopy. ATR FTIR analysis was conducted using a PerkinElmer Spectrum 100 FTIR with diamond crystal at 4 cm^{-1} resolution. Scans (15) were conducted from 500 to 4000 cm^{-1} wavelength. New water softener resin, heat exposed, as well as superchlorinated water exposed resins were examined by ATR FTIR spectroscopy.

4.4 Results and discussions

4.4.1 Literature review: MPs in drinking water

4.4.1.1 What are MPs?

MPs can be primary or secondary contaminants and have varying physical and chemical properties. Primary MPs are considered materials deliberately manufactured for a purpose. Secondary MPs are those formed due to physical, chemical, and microbiological degradation of larger plastics. As mentioned, most prior efforts have focused on MP presence in natural waters. MPs most often found in the surface waters and ground waters have included polymers such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PU), and polyethylene terephthalate (PET). Each polymer has different bulk density properties and MPs can be of various sizes and shapes (**Figure 4-2**). MPs may also be coated with other materials (i.e., biofilm, scales) and be composites to include more than one polymer.

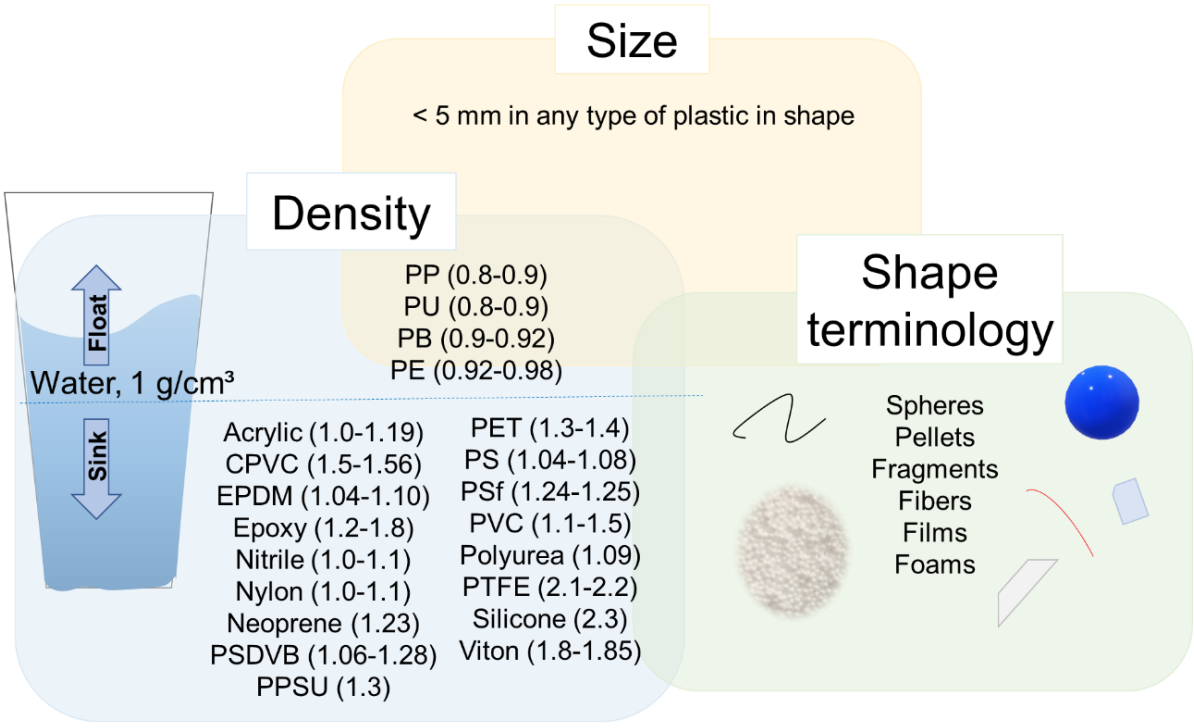


Figure 4-2. MPs can have different sizes, shapes, and bulk density values, and these factors should influence their fate in plumbing

4.4.1.2 MPs in water collected from building fixtures and bottled water

Only a few studies have been conducted to detect MPs in drinking water collected from drinking water faucets and in bottled water (**Table SI.4-1**). In the U.S., the only investigation of MPs at drinking water faucets was conducted in 2018, where MPs were detected in 19 U.S. city tap waters (0-60.9 MP particles/L)[34]. Cities surveyed included Alpena (MI), Buffalo (NY), Chicago (IL), Duluth (MN), Los Angeles (CA), New York (NY), and Washington, D.C. At each location, investigators flushed the "tap water source" for 1 minute, filled and dumped their 500 mL HDPE bottles twice, before collecting a sample. Specific sampling location or the building type were not described. Samples were vacuum filtered using pore size 2.5 μm Whatman® cellulose filter, subjected to staining, and a microscope was used to identify MPs. Most MPs found were found to be 0.10 to 5 mm size fibers, but fragment and film MPs were also reported. It is unclear what type of polymers were found, the sampling location (i.e., kitchen sink vs. bathroom sink), if aerators were present or removed, if the water sample represented cold or hot water, or the condition of the plumbing (i.e., presence of water softener, epoxy lined pipes, age, etc.). The detection of MPs in faucet water is notable and warrants follow-up study.

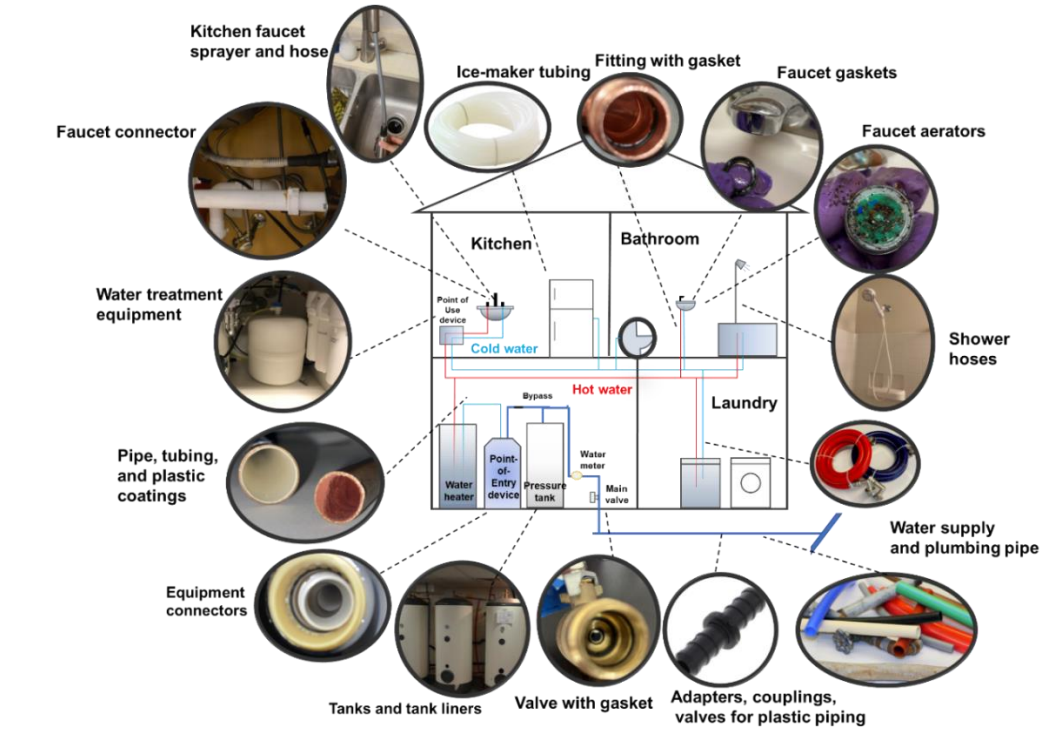
Faucet drinking water sampling in other countries has revealed MPs present at building taps. Kosuth et al., (2018) sampled and analyzed faucet water from 13 countries (North and South America, Africa, Europe, and South Asia) and found 0 to 23.3 MP particles/L[34]. In Denmark, 4 to 30 MP particles per 50 L larger than 100 μm (mostly cellulose-like, and some PP and PET fiber fragments) were found exiting building faucets served by 17 different water supply networks[35]. Prior to sample collection, water was flushed about two minutes. Then, about 50 L of water was passed through a 11 to 12 μm stainless steel filter to collect MPs at each site. It is unclear what fixture was sampled, if the sample was from the cold or hot water system, or if aerators were removed. The type of MP polymers was not identified. In Hong Kong, faucets were flushed at 110 different locations in public and private buildings served by a single water provider, for 1 minute and 1 L of water was collected. The sampling sites included "libraries, markets, sports centers, toilets, parks, private properties". MPs were detected in drinking water at the majority of locations (78%), ranging from 0 to 8 MPs/L (50 to 4,830 μm size)[36]. Similar to a prior study, the authors did not identify the fixture(s) that were sampled, whether the water was from the cold or hot water plumbing, or if aerators were removed. More recently in Brazil, 24 to 597 MP particles (6 to 50 μm size) were also found in all of 32 samples collected from commercial buildings served by a single water distribution

system[37]. About 500 mL was collected for each water sample and no aerators or filters were removed prior to collection. The type of MP polymers was not identified; MPs were only identified through microscope and majority were reported to be fibers.

Because limited MP faucet drinking water studies were found, bottled water studies were reviewed. The earliest study documenting MPs present in bottled water was published in 2018. There, 252 of 259 water bottles purchased from nine different countries and including multiple brands had MP contamination[38]. A mean of 325 MP particles per bottle were found and PP fibers were most commonly found in the range of 6.5 to 100 μm. Of the 11 brands analyzed, bottled water for two brands originated from the U.S. brands. In another study where bottled water purchased in Germany was tested, 80% of the MP particles found were 5 to 20 μm size and the most common polymers were PET followed by PP[39]. Researchers have theorized that because bottled water caps are often either PET, HDPE or PP polymer, the MPs in the water are artifacts of packaging[39]. Winkler et al.[40] found that opening and closing caps did result in greater amounts of PET and HDPE MP particles in bottled water. Though, PET, PE, and PP MPs have also been found in bottled water packaged in glass containers ranging from 4 to 156 MP particles/L. Another study reported a greater MP particle concentration in glass bottled water (6,292 MPs/L)[41]. Both building faucet water and bottled water can contain MPs and evidence is still emerging about the widespread nature of these contaminants and factors that control their presence.

4.4.1.3 Estimated fate in building drinking water systems

If water containing MPs enters a building water service line or the MPs originate from within the plumbing, this water can be subjected to different velocities/flowrates, temperatures, and contact various materials. All of these factors may influence whether or not the MP reaches a building faucet and the concentration observed. Similar to the fate of other contaminants in water distribution systems (i.e., sediment), it is possible that plumbing components could become a MP reservoir due to MP entrainment influenced by the water's intermittent flow and greater prevalence of biofilm on plumbing component surfaces (**Figure 2**). Chu et al. (2022)[42] recently reported that MPs were found in water distribution system scales. Pipe scales themselves, if released or destabilized, may release MPs into drinking water[42]. MPs in plumbing could encounter number of different components (**Figure 4-3**). In particular, bulk density may prompt MPs ($\rho > 1.0$ g/cm^3) settling out inside water heater tanks.



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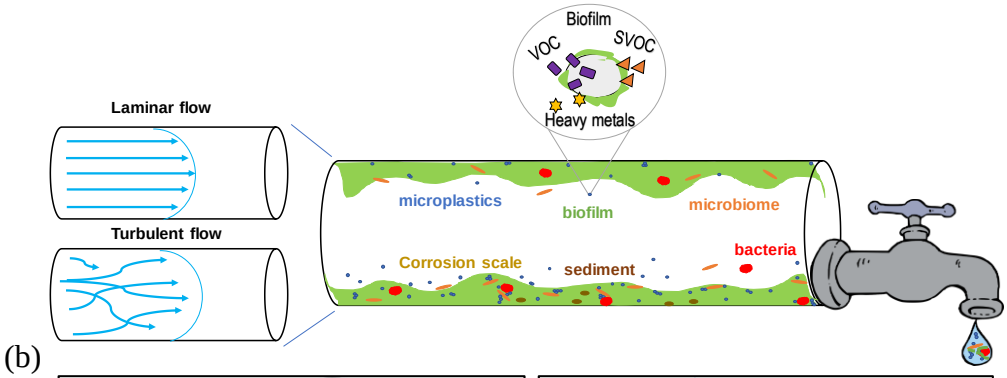

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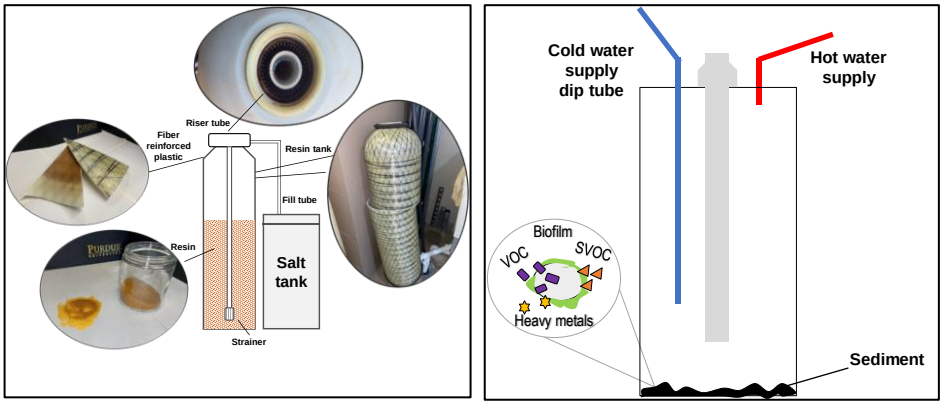


(c)

Figure 4-3. (a) Potential MP fate pathways and sources in residential plumbing, (b) A pipe exposed to MPs indicating biofilm, scale, and flow phenomena that may influence fate, (c) Water softeners and water heater tanks can be a source of MPs and tanks may be a sink for MPs. Building water systems have plastic and metal water supply pipes, valves with gaskets, tubing, faucet connectors, and hoses, and sometimes polymer lined tubing. Water softeners and water heaters often have plastic components where the softener resin is a MP and can also include plastic dip tubes and gaskets.

Once MPs are present within plumbing they can likely be released to the bulk water and reach building faucets. Under normal water flow and stagnation conditions, MPs in the bulk water may contact biofilms and scale. MP shape would influence this phenomenon. For example, it is known that fiber deposition efficiency is lower than for spheres[43], and sphere settling velocity is likely higher than fibers due to Stoke's Law. Researchers found different microbial communities in different types (PS and PE) of spheres may be due to morphology and surface of polymer surfaces[44,45]. PS had more diverse communities than PP and PE spheres[46] while biofilm did not grow well on PS surface than PE and PP[47]. No significant correlation between MP hydrophobicity and biofilm formation was found.

Biofilms also grow differently depending on the water flow inside the pipe. Biofilms grown under laminar flow were uneven with some gaps while filamentous biofilms grown under turbulent flow[48]. Laminar flow may minimize major biofilm sloughing events, where higher loadings of MPs are present. Transitional and turbulent flow regimes also occur based on plumbing design, use, and these could prompt scale, biofilm and/or MP release into bulk water. Studies have shown biofilm may detached from the pipe surface affected by shear stress and hydraulic dynamics[49–52]. Other perturbations such as water hammer incidents could release scales and/or biofilm containing MPs which could ultimately reach faucets. For buildings with separate cold and hot water plumbing (no on-demand water heaters), those separate systems may have different MP loadings.

4.4.1.4 MP levels at the faucet and the contaminants they may carry

Due the lack of data, the health risk posed by MP at building faucets remains unclear[53]. In 2019, published MP drinking water studies did not include enough data to conclude potential health risks[54]. In 2019, the WHO also declared health risks from MPs in drinking water appeared to be low[16], but also cited that limited data were available for their determination. Two challenges that building inhabitants generally face with drinking water contaminants is that sometimes there are no water treatment barriers between the water and the drinking water user. In other cases there are point-of-entry devices or point-of-use devices used for removing certain contaminants[55]. At present, an industry supported building water treatment device testing protocol has prompted "certifications" for MP removal from drinking water[56], but test methods primarily involve challenging devices to dust contaminated water, not MPs[57]. Some independent work has been conducted to evaluate POU device removal effectiveness[58], but this area is open for further study.

The potential for MPs to sorb chemical contaminants and then those contaminated MPs reach building faucets has not been explored. Though, arsenic was found in ion exchange resins[28], which means that contaminant adsorbed into the resin also may be reached faucets when resin released. Many researchers have documented that heavy metals, persistent organic pollutants such as polychlorinated biphenyls, polynuclear aromatic hydrocarbons, and volatile organic chemicals can sorb onto or into MPs found in natural waters and storm water[59–63]. The health risk posed by chemically contaminated MPs reaching building faucets has not been investigated and should be considered in future work.

Little work has focused on whether MPs not only offer a protective niche for colonizers in the environment[62,64–67], but the degree these organisms can reach building faucets. Literature indicates that biofilms attach more rapidly to MPs than non-plastics because of hydrophobicity[62], and MPs can possibly transport pathogens (Frère et al., 2018; Kirstein et al., 2016). A complicating factor in examining MP fate in full-scale systems is that different materials can support different magnitudes of biofilm[68,69], and these biofilms may interact differently with MPs (i.e., retention). Previous studies have shown biofilms can increase contaminant accumulation on surfaces including organics, sediments, and heavy metals[70–72]. Drinking water biofilms can form within 4 to 28 weeks[73], but pipe material, stagnation time, flow rate, and temperature can strongly expedite or slow their formation[73,74]. Biofilms that form on the surface of MPs may also affect particle mass and thus fate. There is a lack of data on whether the transport of microbial communities on MPs could be partly responsible for changing the downstream microbial community. Better understanding MP fate in contact with contaminants in building water systems can assist scientists, health officials, and policy makers better understand water supply risks.

4.4.2 Bench-scale results

4.4.2.1 The retainment of new LDPE MPs depended on its size

Stagnation of a LDPE pellet drinking water solution in copper and PEX pipes followed by flushing revealed LDPE MPs were susceptible to entrainment in drinking water piping networks (**Figure 4-4**). For both copper and PEX pipes, a greater amount of smaller (350 μm) MPs were retained (58 ± 6.5 to 71 ± 5.8%) compared to larger (3.5 mm) MPs (2 ± 1.3 to 16 ± 11.2%). No significant relationships were found for retainment between either pipe material type or the time the contaminated water remained stagnant in the pipes. Because pipes

examined in the present study were new, the authors did not expect to see significantly different results with the short stagnation time (72 hrs). LDPE is not known to adsorb water or change in size (i.e., swelling). At room temperature, a maximum water absorption for LDPE was 0.015%[75]. Because biofilm formation within new plastic and metal pipes occurs within 4 to 28 weeks[73] results are representative for newly installed plumbing pipes. MPs retained were likely influenced by water droplet bridging or adhesion forces between the MP and pipe surface[76]. The greater mass of smaller MPs retained inside the new pipes compared to the large MPs may be due to greater contact pressure with the smaller MPs with the pipe surface according to the Hertzian contact theory[77].

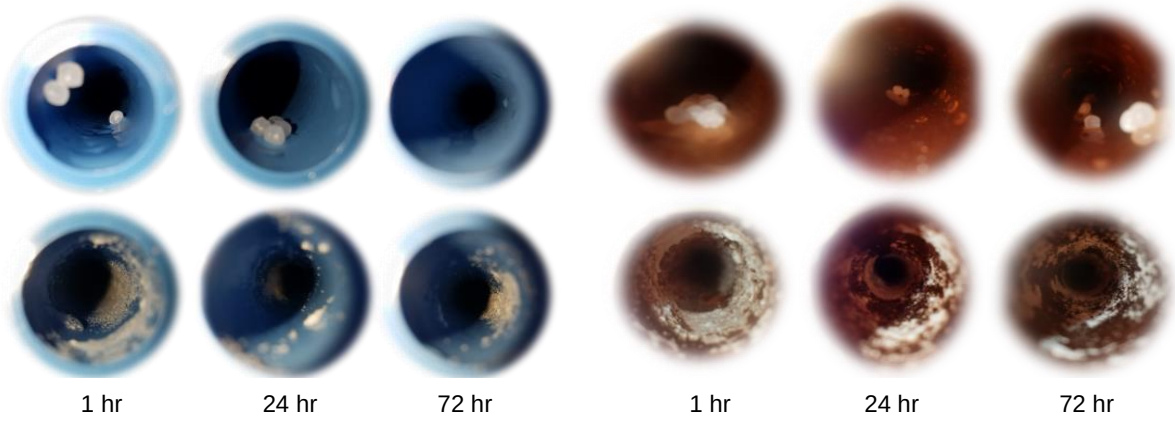


Figure 4-4. Low density polyethylene MP spheres were not completely removed from new plastic and copper drinking water pipe segments even after flushing. Top row 3.5 mm diameter spheres and bottom row 350 μm diameter spheres.

4.4.2.2 Fate and impact of water softener resin: characteristics as-received polystyrene divinylbenzene spheres

Before pipe contamination experiments were conducted the PSDVB MPs were characterized. These MPs had various sizes where 10% of the as-received beads were smaller than 517 μm [D_{10},], and D_{50} and D_{90}values were 695 μm and 943 μm, respectively. After the beads were immersed in water for 3 days, the measured diameters of the resin beads increased by up to 28% (D_{10}, D_{50}, and D_{90} values were 663 μm, 792 μm, and 952 μm respectively). This increase was expected as PSDVB MPs used in water softeners are known to swell when in contact with water. These larger resin beads were still classified as MPs (< 5 mm). TGA results revealed that for new PSDVB MPs about 40% weight loss occurred during the first decomposition stage reaching 120℃ (**Figure SI.4--1**). This weight loss was likely associated with volatile material and some water, and the 120℃ temperature was the manufacturer's

reported limit for the resin[29]. Next, weight loss did not change until 400℃ where a sharp drop was observed likely due to polymer chain scission.

PSDVB MPs were retained in new and aged plumbing pipes, but pipe type, flowrate, and biofilm did not prompt detectable differences in MP retainment (**Table 4-3**). The high variance in retainment was likely a result of the collection and analysis methods and experimental conditions. Biofilm was established on the aged pipes before MPs were added as indicated by TCC monitoring (**Figure SI.4--2**). TCC levels in the aged pipes were similar to the typical biomass levels found in previous drinking water studies, 10^3 to 10^6 cells/mL[78,79]. While copper and PEX pipes have different c-roughness coefficients (150 vs. 130),[80] no difference in the amount of MP retained was found. Additional work is recommended to examine the fundamental factors that influenced MP fate. This work could include pipes with more established biofilms, scales, different flow regimes, as well as different MP shapes, sizes, and types.

Table 4-3. PSDVB MP removal and retainment in new and biofilm coated copper and PEX plumbing pipes

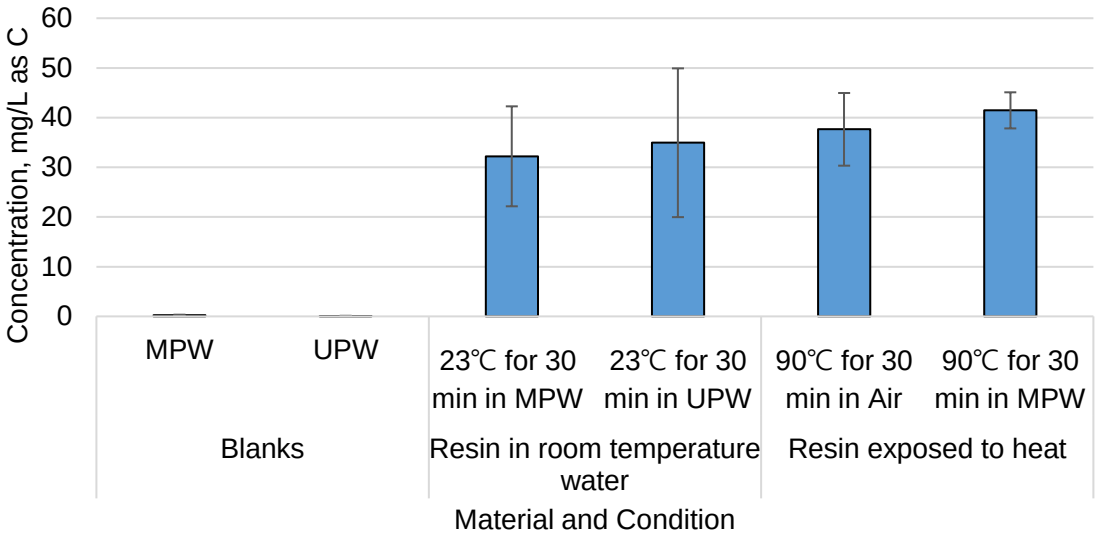
Pipe	Low flow (0.5 GPM)		High flow (2.2 GPM)	
	% exit	% retained	% exit	% retained
New Copper	97.64 ± 1.11	2.36 ± 1.11	99.72 ± 0.39	0.28 ± 0.14
New PEX	99.18 ± 0.76	0.82 ± 1.09	98.71 ±0.28	1.29 ±1.50
Aged Copper	91.71 ± 0.36	8.29 ± 8.52	95.11 ± 0.35	4.89 ± 7.45
Aged PEX	99.04 ± 0.11	0.96 ± 0.93	97.84 ± 0.07	2.16± 1.55

Mean and standard deviation values shown for three replicates.

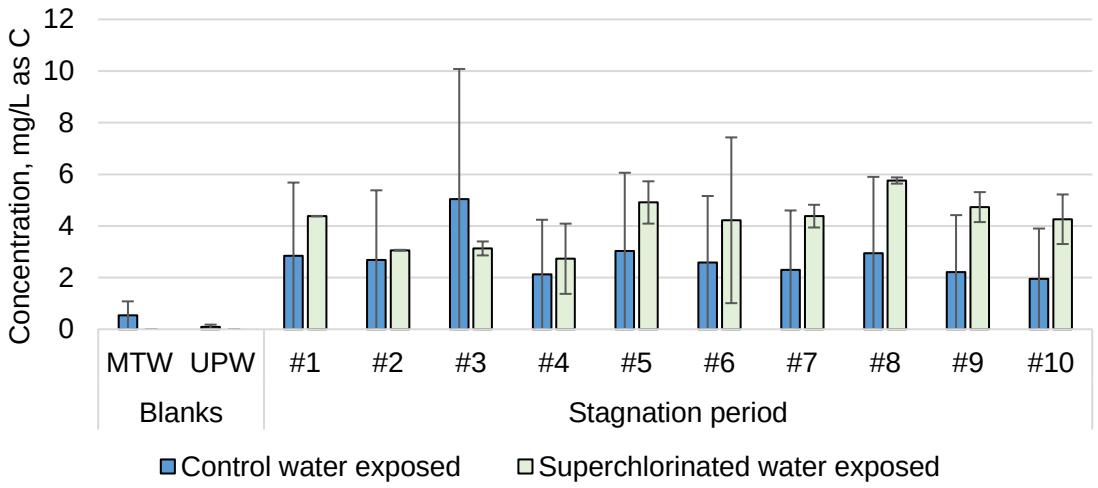
4.4.2.3 New and aged PSDVB MPs impacted drinking water quality, but the aging treatments did not alter leaching or resin integrity

At room temperature, new and aged MPs released organic carbon compounds (measured as TOC) into MPW and UPW (**Figure 4-5**), while some sulfur leaching was also detected. Sulfur is a main component of the PSDVB softener resin. Sulfur release was only detected when UPW was applied as MPW had a background sulfur concentration of 19 to 23 mg/L (**Table SI.4--2**). Neither heat exposure nor superchlorinated water exposure prompted PSDVB to release a greater amount of organic carbon or sulfur than new PSDVB (**Table SI.4-3**). Though, high amounts of TOC and total sulfur in water were found in water sampled from at the base of a 15 year old water softener resin tank (**Table SI.4-4**).

Closer examination of the results revealed that neither thermal exposure nor shock chlorination periods impacted resin integrity (**Figure 4-6**). ATR FTIR results of laboratory aged resins indicated that neither heat nor superchlorination treatments prompted changes to PSDVB surface chemistry. Analyses showed that peaks near 1600-1700 cm^{-1} were present for all resins and these are attributed to the >C-C< bond of the styrene ring[81], and this peak had lower intensity for the aged and shock chlorinated samples. A similar trend was also found in the peaks associated with sulphonic groups near 1040 and 1250 cm^{-1}. No significant differences for sulphonic group benzene ring and the divinylbenzene crosslinking were also found near 730 and 835 cm^{-1}, as expected since that the bond strength was stronger for the crosslinked bond [82]. Aldehyde functional groups with bands near 1741, and 2856 cm^{-1} were only detected for the 15 year old resin. In conclusion, if new or aged PSDVB beads were to be transported from the water softener into the water heater and to other parts of the plumbing (i.e., pipes, aerators, etc.) evidence here indicates that they would leach similar amounts of TOC. Leaching of these MPs however has not been studied previously. Because homo-polystyrene resins may leach toluene and PSDVB that contains sulfonic acid groups may leach benzene sulfonate, the toxicity of these compounds and potential degradation products in drinking water should be examined.

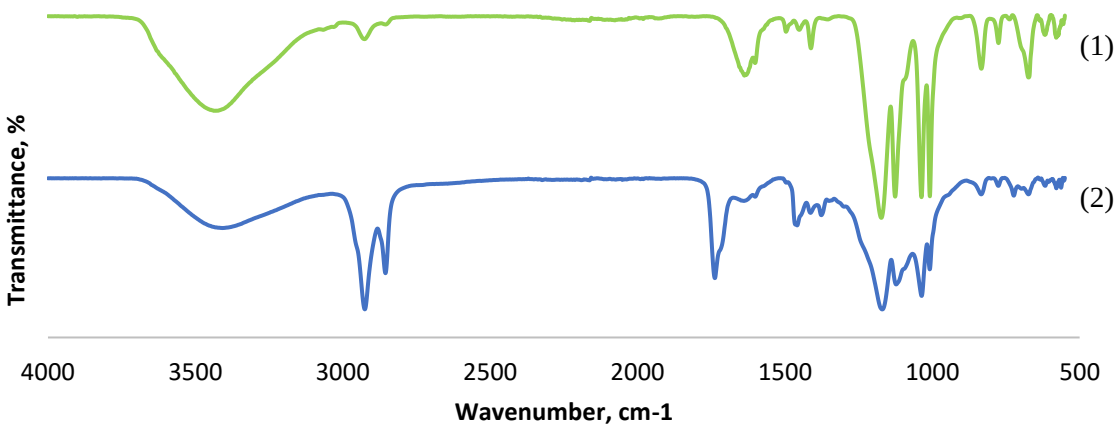


(a)

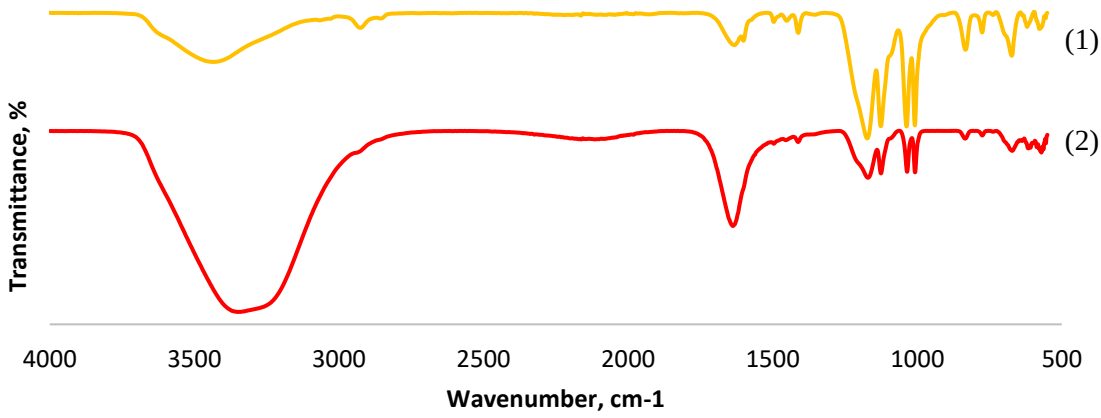


(b)

Figure 4-5. PSDVB water softener resins leached notable amounts of organic carbon into drinking water, but leaching was not affected by (a) Thermally treating the resin or (b) Exposing it 10 times to 300 mg/L as Cl_2 super chlorinated drinking water. Mean and standard deviation values shown for three replicates. The basis of superchlorinated water was UPW. MPW was used for both control water and superchlorinated water during stagnation period.



(a)



(b)

Figure 4-6. ATR FTIR spectra of (a) (1) New resin, (2) 15 Year old resin, (b) (1) New resin shock chlorinated once, and (2) New resin shock chlorinated ten times. On 15 year old resin peak near 2900cm^{-1}, C-H bonds that are clearly different between new and old resin. Control: 3-hr shock in ultrapure water then stagnated in tap water for 3 days, shock chlorination: 3-hr shock in 300mg/L bleach solution then stagnated in tap water for 3 days and repeated 10 times; old water softener resin is from old water softener with unknown product name and stagnation time; New resin and 15 year old resin were thermally exposed in the oven at 90℃ for 30 minutes. However, thermally exposed 15 year old resin had almost straight line which seemed there was a coating on the resin that inhibited transmittance after thermal exposure.

4.5 Implications and recommendations

MPs have likely reached drinking water faucets for more than four decades where the MPs originated from degraded or failed plastic plumbing components and devices. According to the residential water softening industry, for example, this technology has been used since the early 1900s. MPs reaching building faucets may also have passed through water treatment facilities as recent studies show[2,83–85] entering water distribution systems, and reaching building faucets. Various types (PET, PVC, PE, PA and epoxy resin) and sizes (50 to 150 μm) of MPs

have been found in different stages of drinking water treatment[2,84–87]. About 2.5 L of samples were filtered through 3 μm stainless steel cartridge filters. Similarly, other studies also collected samples through filters (0.45 μm[83]) but no flushing was done before sample collection. Different types of filtration processes can remove different sizesd MPs (i.e. membrane to remove > 0.1 μm and GAC filtration to remove > 10 μm), but smaller than 10 μm sized MPs are challenging[88]. A recent study also indicated MPs may be created inside drinking water treatment plants[89]. The relative contribution of MPs that enter drinking water distribution systems is not currently known but is expected to be better understood in the coming years, in part, by testing required by the State of California.

The discovery that MPs can be retained within drained plumbing pipes after flushing in the present work underscores the importance prioritizing MP research needs. No prior studies were found that examined MP fate in plumbing and a number of follow-up investigations are recommended. Several questions were prioritized to advance this understanding:

1. What are the types, amounts, and characteristics (size, shape, density) of MPs entering building plumbing and exiting building faucets?
2. What hydraulic, water quality, and plumbing microbiome factors influence MP accumulation and MP release onto and from cold and hot water plumbing?
3. What role do water heaters, biofilms, scales, and aerators play on MP accumulation and release into drinking water?
4. How do faucet water sampling (i.e., aerator removal, volume collected, flushing time) and processing methods (i.e., sample concentration, filtration) influence MP detection limits?
5. Do MPs entering building plumbing contain heavy metal, VOC, and SVOC contaminants that can be released into plumbing drinking water and pose health risks to building inhabitants?
6. What conditions are needed for point-of-entry and point-of-use building water treatment devices to reduce or eliminate the MPs at the faucet?

In the immediate-term, to better improve the comparability of MP drinking water sampling results across studies researchers, in addition to MP types and concentrations reported, should consider reporting: (1) the specific faucet type that was sampled, (2) whether or not the water was from the cold or hot water system, (3) plumbing component characteristics (presence

of softeners, filters, polymer coated pipes, etc.), and (4) the presence and removal of aerators. Water quality information about the source of the water (i.e., distribution system, private well, etc.) would also be helpful. As MPs continue to accumulate in marine and freshwaters, their prevalence in drinking water distribution systems and ultimately plumbing will likely also increase. MPs are already present in faucet drinking water and plumbing, and knowledge to better understand their fate in plumbing and possible health risks is needed.

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4.7 Declaration of conflicts of interest

The authors declare no conflicts of interest.

4.8 References

1. Mason, S. A., Welch, V. G., & Neratko, J. (2018). Synthetic Polymer Contamination in Bottled Water. *Frontiers in Chemistry*, *6*(September). https://doi.org/10.3389/fchem.2018.00407

2. Mintenig, S. M., Löder, M. G. J., Primpke, S., & Gerdts, G. (2019). Low numbers of microplastics detected in drinking water from ground water sources. *The Science of the Total Environment*, *648*, 631–635. https://doi.org/10.1016/J.SCITOTENV.2018.08.178

3. Panno, S. V., Kelly, W. R., Scott, J., Zheng, W., McNeish, R. E., Holm, N., Hoellein, T. J., & Baranski, E. L. (2019). Microplastic Contamination in Karst Groundwater Systems. *Ground Water*, *57*(2), 189–196. https://doi.org/10.1111/GWAT.12862

4. Thompson, R. C., Olson, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W. G., McGonigle, D., & Russell, A. E. (2004). Lost at sea: where is all the plastic? *Science (New York, N.Y.)*, *304*(5672), 838. https://doi.org/10.1126/SCIENCE.1094559

5. Zhang, Q., Xu, E. G., Li, J., Chen, Q., Ma, L., Zeng, E. Y., & Shi, H. (2020). A Review of Microplastics in Table Salt, Drinking Water, and Air: Direct Human Exposure. *Environmental Science and Technology*, *54*(7), 3740–3751. https://doi.org/10.1021/ACS.EST.9B04535/SUPPL_FILE/ES9B04535_SI_001.PDF

6. Allen, S., Allen, D., Phoenix, V. R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S., & Galop, D. (2019). Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nature Geoscience*, *12*(5), 339–344. https://doi.org/10.1038/S41561-019-0335-5

7. Hoffman, M. J., & Hittinger, E. (2017). Inventory and transport of plastic debris in the Laurentian Great Lakes. *Marine Pollution Bulletin*, *115*(1–2), 273–281. https://doi.org/10.1016/J.MARPOLBUL.2016.11.061

8. Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., Narayan, R., & Law, K. L. (2015). Plastic waste inputs from land into the ocean. *Science*, *347*(6223), 768–771. https://doi.org/10.1126/SCIENCE.1260352/SUPPL_FILE/JAMBECK.SM.PDF

9. California Water Boards. (2022). *Microplastics Drinking Water | California State Water Resources Control Board*. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/microplastics.html

10. SCCWRP. (2022). *History of California Microplastics Legislation - Southern California Coastal Water Research Project*. https://www.sccwrp.org/about/research-areas/additional-research-areas/trash-pollution/microplastics-health-effects-webinar-series/history-california-microplastics-legislation/

11. US Public Law. (2015). *H.R.1321 - 114th Congress (2015-2016): Microbead-Free Waters Act of 2015 | Congress.gov | Library of Congress*. https://www.congress.gov/bill/114th-congress/house-bill/1321

12. FDA. (2022). *The Microbead-Free Waters Act: FAQs | FDA*. https://www.fda.gov/cosmetics/cosmetics-laws-regulations/microbead-free-waters-act-faqs

13. EPA. (2021). *Information about Public Water Systems | US EPA*. https://www.epa.gov/dwreginfo/information-about-public-water-systems

14. Wong, C. S., & Coffin, S. (2022). *Standard Operating Procedures for Extraction and Measurement by Infrared Spectroscopy of Microplastic Particles in Drinking Water*.

15. Wong, C. S., & Coffin, S. (2022). *SWB-MP2-rev1 Standard Operating Procedures for Extraction and Measurement by Raman Spectroscopy of Microplastic Particles in Drinking Water*.

16. WHO. (2019). *Microplastics in drinking-water*. http://apps.who.int/bookorders.

17. Portantino. (2018). *Bill Text - SB-1422 California Safe Drinking Water Act: microplastics.* https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB1422

18. GESAMP. (2015). *SOURCES, FATE AND EFFECTS OF MICROPLASTICS IN THE MARINE ENVIRONMENT: PART 2*. http://www.gesamp.org/site/assets/files/1275/sources-fate-and-effects-of-microplastics-in-the-marine-environment-part-2-of-a-global-assessment-en.pdf

19. Environmental and Climate Change Canada. (2015). *Microbeads - A Science Summary*. https://www.ec.gc.ca/ese-ees/ADDA4C5F-F397-48D5-AD17-63F989EBD0E5/Microbeads_Science Summary_EN.pdf

20. Larson, D. (2011). Understand Chloramine's Effect on Elastomer Components. *Opflow*, *37*(8), 10–10. https://doi.org/10.1002/J.1551-8701.2011.TB02363.X

21. Nagisetty, R. M., Rockaway, T. D., & Willing, G. A. (2014). Drinking water quality concerns from chloramine-induced degradation of elastomeric compounds. *Journal - American Water Works Association*, *106*(9), E402–E407. https://doi.org/10.5942/JAWWA.2014.106.0077

22. Reiber, S. (1993). Investigating the Effects of Chloramines on Elastomer Degradation. *Journal - American Water Works Association*, *85*(8), 101–111. https://doi.org/10.1002/J.1551-8833.1993.TB06047.X

23. Water Medic. (2017). *WATER MEDIC: Resin from water softener in your home - YouTube*. https://www.youtube.com/watch?v=ylbF1lnaL4U

24. Scully, E. (2020). *YouTuber blocks his neighbourhood drain system when he tries to empty a bath full of orbeez | Daily Mail Online*. https://www.dailymail.co.uk/femail/article-8064777/YouTuber-blocks-neighbourhood-drain-tries-bath-orbeez.html

25. Plumbing Express. (2018). *Water Softener Resin Burst Into Water Lines - Tempe, AZ - YouTube*. https://www.youtube.com/watch?v=LqOziiz5xls

26. My Essential Plumber. (2020). *Water Softener Breaks and Releases Resin into Water Lines in House - YouTube*. https://www.youtube.com/watch?v=_1jR_qAS1Hc

27. Seidel, B. (2021). *Water Softener Beads Coming Out of the Faucet | Water Softener Problems - YouTube*. https://www.youtube.com/watch?v=e75OO6RTgGc

28. Rockafellow-Baldoni, M., Spayd, S. E., & Robson, M. G. (2022). Water Treatment Media Breakthrough: Arsenic and Water Softener Media in Private Well Drinking Water. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.4087105

29. Purolite. (2022). *Purolite® C100E*. https://www.purolite.com/product/c100e

30. Malvern. (2019). *MASTERSIZER 3000 Smarter particle sizing*. https://www.malvernpanalytical.com/en/assets/MRK1872-07-EN_MS3000_Broch_BrandUpdate_LR_web_tcm50-17232.pdf

31. Aquatell. (2022). *How to Properly Size a Water Softener - Aquatell*. https://www.aquatell.com/pages/how-to-properly-size-a-water-softener

32. Welter, G. (2016). Typical Kitchen Faucet-Use Flow Rates: Implications for Lead Concentration Sampling. *Journal - American Water Works Association*, *108*(7), E374–E380. https://doi.org/10.5942/JAWWA.2016.108.0085

33. WRF. (2014). *Effective Microbial Control Strategies for Main Breaks and Depressurization | The Water Research Foundation*. https://www.waterrf.org/research/projects/effective-microbial-control-strategies-main-breaks-and-depressurization

34. Kosuth, M., Mason, S. A., & Wattenberg, E. V. (2018). Anthropogenic contamination of tap water, beer, and sea salt. *PLOS ONE*, *13*(4), e0194970. https://doi.org/10.1371/JOURNAL.PONE.0194970

35. Strand, J., Feld, L., Murphy, F., Mackevica, A., & Hartmann, N. B. (2018). *AU Scientifi c Report from DCE-Danish Centre for Environment and Energy ANALYSIS OF MICROPLASTIC PARTICLES IN DANISH DRINKING WATER*.

36. Lam, T. W. L., Ho, H. T., Ma, A. T. H., & Fok, L. (2020). Microplastic Contamination of Surface Water-Sourced Tap Water in Hong Kong—A Preliminary Study. *Applied Sciences 2020, Vol. 10, Page 3463*, *10*(10), 3463. https://doi.org/10.3390/APP10103463

37. Pratesi, C. B., Almeida, M. A. A. L. S., Paz, G. S. C., Teotonio, M. H. R., Gandolfi, L., Pratesi, R., Hecht, M., & Zandonadi, R. P. (2021). Presence and Quantification of Microplastic in Urban Tap Water: A Pre-Screening in Brasilia, Brazil. *Sustainability 2021, Vol. 13, Page 6404*, *13*(11), 6404. https://doi.org/10.3390/SU13116404

38. Mason, S. A., Welch, V. G., & Neratko, J. (2018). Synthetic Polymer Contamination in Bottled Water. *Frontiers in Chemistry*, *6*, 407. https://doi.org/10.3389/FCHEM.2018.00407/BIBTEX

39. Schymanski, D., Goldbeck, C., Humpf, H. U., & Fürst, P. (2018). Analysis of microplastics in water by micro-Raman spectroscopy: Release of plastic particles from different packaging into mineral water. *Water Research*, *129*, 154–162. https://doi.org/10.1016/J.WATRES.2017.11.011

40. Winkler, A., Santo, N., Ortenzi, M. A., Bolzoni, E., Bacchetta, R., & Tremolada, P. (2019). Does mechanical stress cause microplastic release from plastic water bottles? *Water Research*, *166*, 115082. https://doi.org/10.1016/J.WATRES.2019.115082

41. Oßmann, B. E., Sarau, G., Holtmannspötter, H., Pischetsrieder, M., Christiansen, S. H., & Dicke, W. (2018). Small-sized microplastics and pigmented particles in bottled mineral water. *Water Research*, *141*, 307–316. https://doi.org/10.1016/J.WATRES.2018.05.027

42. Chu, X., Zheng, B., Li, Z., Cai, C., Peng, Z., Zhao, P., & Tian, Y. (2022). Occurrence and distribution of microplastics in water supply systems: In water and pipe scales. *Science of The Total Environment*, *803*, 150004. https://doi.org/10.1016/J.SCITOTENV.2021.150004

43. Chen, Y. K., & Yu, C. P. (1991). Sedimentation of fibers from laminar flows in a horizontal circular duct. *Aerosol Science and Technology*, *14*(3), 343–347. https://doi.org/10.1080/02786829108959496

44. Parrish, K., & Fahrenfeld, N. L. (2019). Microplastic biofilm in fresh- And wastewater as a function of microparticle type and size class. *Environmental Science: Water Research and Technology*, *5*(3), 495–505. https://doi.org/10.1039/c8ew00712h

45. Långmark, J., Storey, M. V., Ashbolt, N. J., & Stenström, T. A. (2005). Accumulation and fate of microorganisms and microspheres in biofilms formed in a pilot-scale water distribution system. *Applied and Environmental Microbiology*, *71*(2), 706–712. https://doi.org/10.1128/AEM.71.2.706-712.2005

46. McGivney, E., Cederholm, L., Barth, A., Hakkarainen, M., Hamacher-Barth, E., Ogonowski, M., & Gorokhova, E. (2020). Rapid Physicochemical Changes in Microplastic Induced by Biofilm Formation. *Frontiers in Bioengineering and Biotechnology*, *8*, 205. https://doi.org/10.3389/FBIOE.2020.00205/BIBTEX

47. Ayush, P. T., Ko, J.-H., & Oh, H.-S. (2022). Characteristics of Initial Attachment and Biofilm Formation of Pseudomonas aeruginosa on Microplastic Surfaces. *Applied Sciences 2022, Vol. 12, Page 5245*, *12*(10), 5245. https://doi.org/10.3390/APP12105245

48. Stoodley, P., Boyle, J. D., & Lappin-Scott Hilary, H. (1999). *Biofilm Structure and Influence on Biofouling under Laminar and Turbulent Flows Biofilm Therapeutics View project Biofilms and marine fouling View project*. https://www.researchgate.net/publication/312938349

49. Maria Duarte Manuel, C. (2007). *Biofilm Dynamics and Drinking Water Stability: Effects of Hydrodynamics and Surface Materials*.

50. Ramasamy, P., & Zhang, X. (2005). Effects of shear stress on the secretion of extracellular polymeric substances in biofilms. *Water Science and Technology*, *52*(7), 217–223. https://doi.org/10.2166/WST.2005.0204

51. Rochex, A., Godon, J. J., Bernet, N., & Escudié, R. (2008). Role of shear stress on composition, diversity and dynamics of biofilm bacterial communities. *Water Research*, *42*(20), 4915–4922. https://doi.org/10.1016/J.WATRES.2008.09.015

52. Tsagkari, E., & Sloan, W. T. (2018). *Biofilm Growth in Drinking Water Systems under Stagnant Conditions*. 707–717. http://eprints.gla.ac.uk/164294/http://eprints.gla.ac.uk

53. Coffin, S., Bouwmeester, H., Brander, S., Damdimopoulou, P., Gouin, T., Hermabessiere, L., Khan, E., Koelmans, A. A., Lemieux, C. L., Teerds, K., Wagner, M., Weisberg, S. B., & Wright, S. (2022). Development and application of a health-based framework for informing regulatory action in relation to exposure of microplastic particles in California drinking water. *Microplastics and Nanoplastics 2022 2:1*, *2*(1), 1–30. https://doi.org/10.1186/S43591-022-00030-6

54. Koelmans, A. A., Mohamed Nor, N. H., Hermsen, E., Kooi, M., Mintenig, S. M., & De France, J. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. *Water Research*, *155*, 410–422. https://doi.org/10.1016/j.watres.2019.02.054

55. EPA. (2006). *Point-of-Use or Point-of-Entry Treatment Options for Small Drinking Water Systems*.

56. NSF. (2012). *Listing Category Search Page | NSF International*. https://info.nsf.org/certified/dwtu/

57. NSF. (2020). *NSF/ANSI 401-2020 - Drinking Water Treatment Units - Emerging Compounds/Incidental Contaminants*. https://webstore.ansi.org/Standards/NSF/NSFANSI4012020

58. Cherian, A. G. (2021). *Microplastic Removal from Drinking Water Using Point-of-Use Devices*.

59. Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J., Ingram, I., Nadal, A., & Romano, D. (2018). Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures. *Environmental Sciences Europe*, *30*(1), 1–14. https://doi.org/10.1186/S12302-018-0139-Z/FIGURES/1

60. Munier, B., & Bendell, L. I. (2018). Macro and micro plastics sorb and desorb metals and act as a point source of trace metals to coastal ecosystems. *PLOS ONE*, *13*(2), e0191759. https://doi.org/10.1371/JOURNAL.PONE.0191759

61. Alimi, O. S., Farner Budarz, J., Hernandez, L. M., & Tufenkji, N. (2018). Microplastics and Nanoplastics in Aquatic Environments: Aggregation, Deposition, and Enhanced Contaminant Transport. *Environmental Science and Technology*, *52*(4), 1704–1724. https://doi.org/10.1021/ACS.EST.7B05559/SUPPL_FILE/ES7B05559_SI_001.PDF

62. Rummel, C. D., Jahnke, A., Gorokhova, E., Kühnel, D., & Schmitt-Jansen, M. (2017). Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. *Environmental Science and Technology Letters*, *4*(7), 258–267. https://doi.org/10.1021/ACS.ESTLETT.7B00164/ASSET/IMAGES/LARGE/EZ-2017-00164X_0001.JPEG

63. Brennecke, D., Duarte, B., Paiva, F., Caçador, I., & Canning-Clode, J. (2016). Microplastics as vector for heavy metal contamination from the marine environment. *Estuarine, Coastal and Shelf Science*, *178*, 189–195. https://doi.org/10.1016/J.ECSS.2015.12.003

64. Ogonowski, M., Motiei, A., Ininbergs, K., Hell, E., Gerdes, Z., Udekwu, K. I., Bacsik, Z., & Gorokhova, E. (2018). Evidence for selective bacterial community structuring on microplastics. *Environmental Microbiology*, *20*(8), 2796–2808. https://doi.org/10.1111/1462-2920.14120

65. Arias-Andres, M., Klümper, U., Rojas-Jimenez, K., & Grossart, H. P. (2018). Microplastic pollution increases gene exchange in aquatic ecosystems. *Environmental Pollution (Barking, Essex : 1987)*, *237*, 253–261. https://doi.org/10.1016/J.ENVPOL.2018.02.058

66. Keswani, A., Oliver, D. M., Gutierrez, T., & Quilliam, R. S. (2016). Microbial hitchhikers on marine plastic debris: Human exposure risks at bathing waters and beach environments. *Marine Environmental Research*, *118*, 10–19. https://doi.org/10.1016/J.MARENVRES.2016.04.006

67. Zettler, E. R., Mincer, T. J., & Amaral-Zettler, L. A. (2013). Life in the "plastisphere": Microbial communities on plastic marine debris. *Environmental Science and Technology*, *47*(13), 7137–7146. https://doi.org/10.1021/ES401288X/SUPPL_FILE/ES401288X_SI_001.PDF

68. Yu, J., Kim, D., & Lee, T. (2010). Microbial diversity in biofilms on water distribution pipes of different materials. *Water Science and Technology*, *61*(1), 163–171. https://doi.org/10.2166/WST.2010.813

69. Silhan, J., Corfitzen, C. B., & Albrechtsen, H. J. (2006). Effect of temperature and pipe material on biofilm formation and survival of Escherichia coli in used dinking water pipes: A laboratory-based study. *Water Science and Technology*, *54*(3), 49–56. https://doi.org/10.2166/wst.2006.447

70. Farag, A. M., Woodward, D. F., Goldstein, J. N., Brumbaugh, W., & Meyer, J. S. (1998). Concentrations of Metals Associated with Mining Waste in Sediments, Biofilm, Benthic Macroinvertebrates, and Fish from the Coeur d'Alene River Basin, Idaho. *Archives of Environmental Contamination and Toxicology 1998 34:2*, *34*(2), 119–127. https://doi.org/10.1007/S002449900295

71. Cunningham, A. B., Characklls, W. G., Abedeen, F., & Crawford, D. (1991). Influence of Biofilm Accumulation on Porous Media Hydrodynamics. *Environmental Science and Technology*, *25*(7), 1305–1311. https://doi.org/10.1021/es00019a013

72. Schorer, M., & Eisele, M. (1997). Accumulation of inorganic and organic pollutants by biofilms in the aquatic environment. *Water, Air, & Soil Pollution*, *99*(1–4), 651–659. https://doi.org/10.1007/BF02406904

73. Lehtola, M. J., Miettinen, I. T., Keinänen, M. M., Kekki, T. K., Laine, O., Hirvonen, A., Vartiainen, T., & Martikainen, P. J. (2004). Microbiology, chemistry and biofilm development in a pilot drinking water distribution system with copper and plastic pipes. *Water Research*, *38*(17), 3769–3779. https://doi.org/10.1016/J.WATRES.2004.06.024

74. Eboigbodin, K. E., Seth, A., & Biggs, C. A. (2008). A review of biofilms in domestic plumbing. *Journal / American Water Works Association*, *100*(10), 131–138. https://doi.org/10.1002/j.1551-8833.2008.tb09753.x

75. Omnexus. (2022). *Water Absorption 24 Hour - (ASTM D570) Test of Plastics*. https://omnexus.specialchem.com/polymer-properties/properties/water-absorption-24-hours

76. Samuel, B., Zhao, H., & Law, K. Y. (2011). Study of wetting and adhesion interactions between water and various polymer and superhydrophobic surfaces. *Journal of Physical Chemistry C*, *115*(30), 14852–14861. https://doi.org/10.1021/JP2032466/SUPPL_FILE/JP2032466_SI_001.PDF

77. Sheng Chen, G., & Liu, X. (2016). Friction. *Friction Dynamics*, 91–159. https://doi.org/10.1016/B978-0-08-100285-8.00003-1

78. Inkinen, J., Jayaprakash, B., Ahonen, M., Pitkänen, T., Mäkinen, R., Pursiainen, A., Santo Domingo, J. W., Salonen, H., Elk, M., & Keinänen-Toivola, M. M. (2018). Bacterial community changes in copper and PEX drinking water pipeline biofilms under extra disinfection and magnetic water treatment. *Journal of Applied Microbiology*, *124*(2), 611–624. https://doi.org/10.1111/jam.13662

79. Neu, L., & Hammes, F. (2020). Feeding the building plumbing microbiome: The importance of synthetic polymeric materials for biofilm formation and management. *Water (Switzerland)*, *12*(6). https://doi.org/10.3390/w12061774

80. Uponor. (2016). *Uponor Hydronic Piping Design Assistance Manual (HPDAM)*.

81. Lazar, L., Bandrabur, B., Tataru-f, R., Drobot, M., Bulgariu, L., & Gutt, G. (2014). *Ftir Analysis of Ion Exchange Resins With Application*. *13*(9), 2145–2152.

82. Zagorodni, A. A., Kotova, D. L., & Selemenev, V. F. (2002). Infrared spectroscopy of ion exchange resins: Chemical deterioration of the resins. *Reactive and Functional Polymers*, *53*(2–3), 157–171. https://doi.org/10.1016/S1381-5148(02)00170-0

83. Na, S. H., Kim, M. J., Kim, J. T., Jeong, S., Lee, S., Chung, J., & Kim, E. J. (2021). Microplastic removal in conventional drinking water treatment processes: Performance, mechanism, and potential risk. *Water Research*, *202*, 117417. https://doi.org/10.1016/J.WATRES.2021.117417

84. Shen, M., Song, B., Zhu, Y., Zeng, G., Zhang, Y., Yang, Y., Wen, X., Chen, M., & Yi, H. (2020). Removal of microplastics via drinking water treatment: Current knowledge and future directions. *Chemosphere*, *251*, 126612. https://doi.org/10.1016/J.CHEMOSPHERE.2020.126612

85. Pivokonsky, M., Cermakova, L., Novotna, K., Peer, P., Cajthaml, T., & Janda, V. (2018). Occurrence of microplastics in raw and treated drinking water. *Science of The Total Environment*, *643*, 1644–1651. https://doi.org/10.1016/J.SCITOTENV.2018.08.102

86. Novotna, K., Cermakova, L., Pivokonska, L., Cajthaml, T., & Pivokonsky, M. (2019). Microplastics in drinking water treatment – Current knowledge and research needs. *Science of The Total Environment*, *667*, 730–740. https://doi.org/10.1016/J.SCITOTENV.2019.02.431

87. Pivokonský, M., Pivokonská, L., Novotná, K., Čermáková, L., & Klimtová, M. (2020). Occurrence and fate of microplastics at two different drinking water treatment plants within a river catchment. *Science of The Total Environment*, *741*, 140236. https://doi.org/10.1016/J.SCITOTENV.2020.140236

88. Xue, J., Samaei, S. H. A., Chen, J., Doucet, A., & Ng, K. T. W. (2022). What have we known so far about microplastics in drinking water treatment? A timely review. *Frontiers of Environmental Science & Engineering*, *16*(5). https://doi.org/10.1007/S11783-021-1492-5

89. Ding, H., Zhang, J., He, H., Zhu, Y., Dionysiou, D. D., Liu, Z., & Zhao, C. (2021). Do membrane filtration systems in drinking water treatment plants release nano/microplastics? *Science of The Total Environment*, *755*, 142658. https://doi.org/10.1016/J.SCITOTENV.2020.142658

90. Di, M., Liu, X., Wang, W., & Wang, J. (2019). Manuscript prepared for submission to environmental toxicology and pharmacology pollution in drinking water source areas: Microplastics in the Danjiangkou Reservoir, China. *Environmental Toxicology and Pharmacology*, *65*, 82–89. https://doi.org/10.1016/J.ETAP.2018.12.009

91. Di, M., & Wang, J. (2018). Microplastics in surface waters and sediments of the Three Gorges Reservoir, China. *Science of The Total Environment*, *616–617*, 1620–1627. https://doi.org/10.1016/J.SCITOTENV.2017.10.150

92. Anderson, P. J., Warrack, S., Langen, V., Challis, J. K., Hanson, M. L., & Rennie, M. D. (2017). Microplastic contamination in Lake Winnipeg, Canada. *Environmental Pollution (Barking, Essex : 1987)*, *225*, 223–231. https://doi.org/10.1016/J.ENVPOL.2017.02.072

93. Leslie, H. A., Brandsma, S. H., van Velzen, M. J. M., & Vethaak, A. D. (2017). Microplastics en route: Field measurements in the Dutch river delta and Amsterdam canals, wastewater treatment plants, North Sea sediments and biota. *Environment International*, *101*, 133–142. https://doi.org/10.1016/J.ENVINT.2017.01.018

94. Hoellein, T. J., McCormick, A. R., Hittie, J., London, M. G., Scott, J. W., & Kelly, J. J. (2017). Longitudinal patterns of microplastic concentration and bacterial assemblages in surface and benthic habitats of an urban river. *Freshwater Science*, *36*(3), 491–507. https://doi.org/10.1086/693012

95. McCormick, A. R., Hoellein, T. J., London, M. G., Hittie, J., Scott, J. W., & Kelly, J. J. (2016). Microplastic in surface waters of urban rivers: Concentration, sources, and associated bacterial assemblages. *Ecosphere*, *7*(11). https://doi.org/10.1002/ecs2.1556

96. Lusher, A. L., Tirelli, V., O'Connor, I., & Officer, R. (2015). Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. *Scientific Reports 2015 5:1*, *5*(1), 1–9. https://doi.org/10.1038/srep14947

97. Faure, F., Demars, C., Wieser, O., Kunz, M., Alencastro, L. F. de, Faure, F., Demars, C., Wieser, O., Kunz, M., & Alencastro, L. F. de. (2015). Plastic pollution in Swiss surface waters: nature and concentrations, interaction with pollutants. *Environmental Chemistry*, *12*(5), 582–591. https://doi.org/10.1071/EN14218

98. McCormick, A., Hoellein, T. J., Mason, S. A., Schluep, J., & Kelly, J. J. (2014). Microplastic is an abundant and distinct microbial habitat in an urban river. *Environmental Science and Technology*, *48*(20), 11863–11871. https://doi.org/10.1021/ES503610R/SUPPL_FILE/ES503610R_SI_001.PDF

5. LIMITATIONS AND FUTURE WORK

Building Water Quality: In General

Water quality at building faucets due to periods of low or no water use or and the presence of MPs cannot yet be predicted for a variety of reasons, but additional work in these areas is needed. Since the COVID-19 pandemic began many researchers across and outside the U.S. have initiated and completed building water quality studies on the topic of stagnation. These studies have helped identify the knowledge-gaps that exist and additional work needed. The complexity of predicting water safety at faucets is influenced by different plumbing design and operational characteristics, water quality entering the building, hot water heating practices, materials, and other factors. Variabilities such as plumbing scale, biofilm, age of pipe, component degradation, water usage, and other factors likely influence faucet water quality. To better understand and ultimately predict contaminant levels at building faucets additional work is needed.

Even though building water quality cannot be predicted at building faucets, to reduce the chance of disease caused by the plumbing, building owners can currently take several actions. First, building owners can learn about their own plumbing so they understand how water travels, and limit the age of the water in their system, for example. Routine water quality monitoring during and after building startup would help to reduce the ambiguity in baseline water quality. Large buildings with hundreds of fixtures may pose challenges to determining the number of samples to collect for a representative sample. In the author's building water quality studies (chapters 1, 2 and 3), only about 6 to 25% of all water outlets per building were sampled. Despite this, the water sampling and analysis labor and supply costs per building were significant. Work is needed to create evidence-based guidance for building owners on how to select sampling locations and frequencies to accurately characterize building water quality. Conducting water sampling any time the building stagnates (i.e., overnight, weekends, extended holiday weekends, shutdowns, transition to lower usage, etc.) would be informative but cost prohibitive for building owners based on technological limitations.

To begin to understand water quality in their building, owners could create building water quality management plans that describe their plumbing, past water quality at different locations and times, and pose procedures for responding to adverse water quality (sampling, flushing, or both). Studies conducted by the author during pandemic and discussions with other

investigators indicated to the author such a thought-out plan is lacking for many commercial building owners. When responding to stagnant water building owners often did not test faucet water quality but instead flushed the water from their plumbing different ways). Some of the building owners encountered flushed their plumbing but also quantified chlorine residual concentration at fixtures using chlorine test strips because it was easier and cheaper than handheld spectrophotometer chlorine meters that water utility staff, public health officials, and researchers use. In the author's experience, it was rare for building owners to conduct more thorough chemical or microbiological testing. Future studies should consider examining the reliability of disinfectant test strips, across brands, and determine what building water system questions this technology is best to answer.

Building water system design standards and plumbing code requirements are needed to help avoid building water quality issues during the design and operational phases. The lack of requiring building plumbing to be confirmed as not posing a health risk to building occupants, before occupancy permits are issued, is gap. There are also no requirements to design plumbing in a way that limits copper plumbing leaching or determine if, under certain copper pipe/water quality conditions, in-building treatment is necessary. Also, when *Legionella* is detected in building water systems, there is no standard response practice. Shock chlorination is recommended by some organizations for the entire building system if certain thresholds are exceeded. Though, there is no industry-public health-research sector agreement on the threshold (*Legionella* concentration) of enacting such a remediation measure. During the author's work, small buildings with relatively simple plumbing designs could be remediated (and reach lower *Legionella* levels) simply by flushing. Going back to the initial problem however is the overall lack of industry-public health-research sectors having a baseline understanding of contaminants (like *Legionella*) in buildings. In addition to initial building water sampling during the commissioning period, the author recommends chemical and microbiological water quality testing after long stagnation periods. Continued and expanded work by others and advancement in communicating risk to building owners as well as inhabitants, can help establish best practices for building water quality and better understand plumbing complexity.

Water quality chemical and microbiological characteristics and variability at the service line (not just within the building) require more understanding. This lack of temporal variability inhibits understanding how faucet drinking water changes.

Microplastics at Building Faucets

MPs like water softener resin likely have left resin tanks and found their way to faucets, but MP fate in water systems and plumbing remains poorly understood. Additional MPs from degraded plastic components (i.e., gaskets, epoxy linings) have also likely been present, but incidents have not been characterized. Only recently (in 2021) have standardized methods been developed for detecting and quantifying MPs in drinking water. With California requiring MP in drinking water that enters public water distribution systems I the next year, new information MP types should emerge.

The present MP study was limited to LDPE and water softener resin MPs. For PSDVB, no significant difference in the amount of MP retained in pipes was found when resin was physically and chemically damaged. Larger LDPE MPs however were removed more so than smaller MPs, and this work however should be expanded in breadth and depth. The role of biofilms, as well as shear stress and hydraulic phenomena for transport in different plumbing settings should be explored. The author hypothesized that some MPs will remain inside the plumbing because (1) biofilm stabilizes MPs against re-suspension, (2) the cohesive effects between water molecules and MPs that makes strong adhesion to pipe surface, and (3) the some smaller MPs that may have greater contact pressure with the pipe surface according to the Hertzian contact theory. Though, hydraulics, materials, temperature for plumbing complicate the permutations of factors that may influence MP fate. Further complicating the issue is that MPs have various types, shapes, and sizes.

Whether or not MPs that enter plumbing deposit or release sorbed contaminants is another unexplored area of work. Degradation products or potential leaching compounds of MPs inside plumbing (e.g., water softener resin) reaching drinking water faucets has not been studied. If contaminants carried by MPs to building faucets leach harmful compounds, MPs may pose a new unaccounted for health risk for drinking water. To better understand fate in plumbing, detecting andquantifying MPs at the building entry point is needed.

APPENDIX SI.1

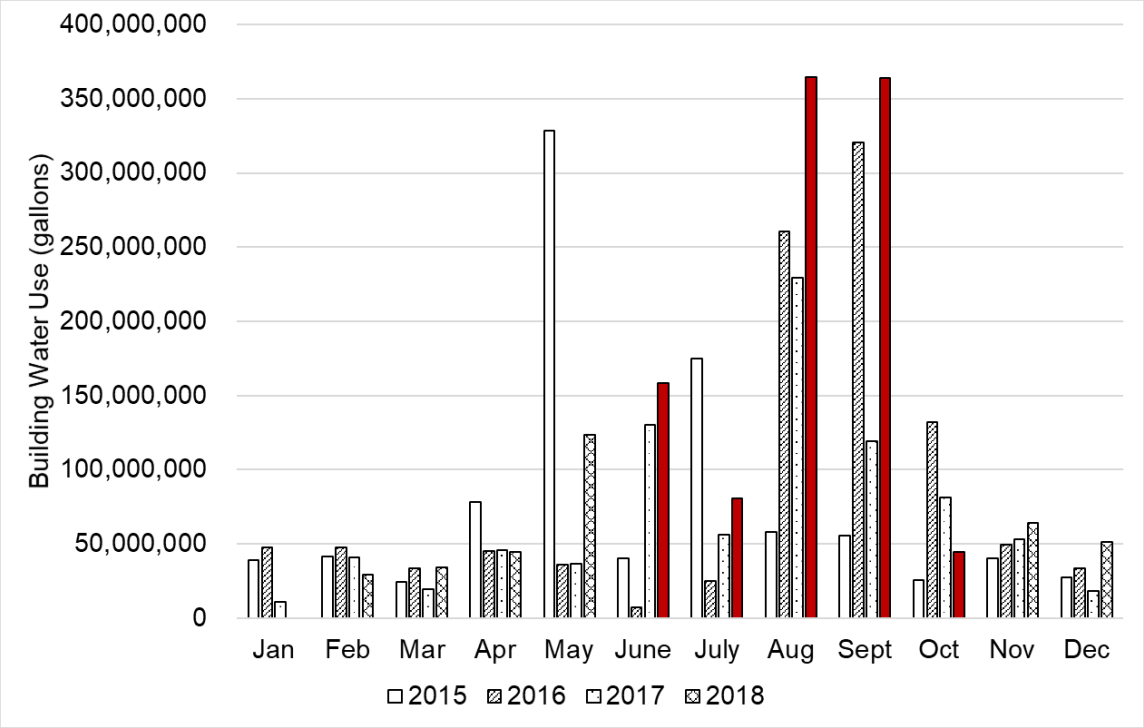


Figure SI.1-1. School water usage for last four years. Red colored bars are when the water sampling event was conducted (June 22, July 20, July 27, August 3, September 7, October 12).

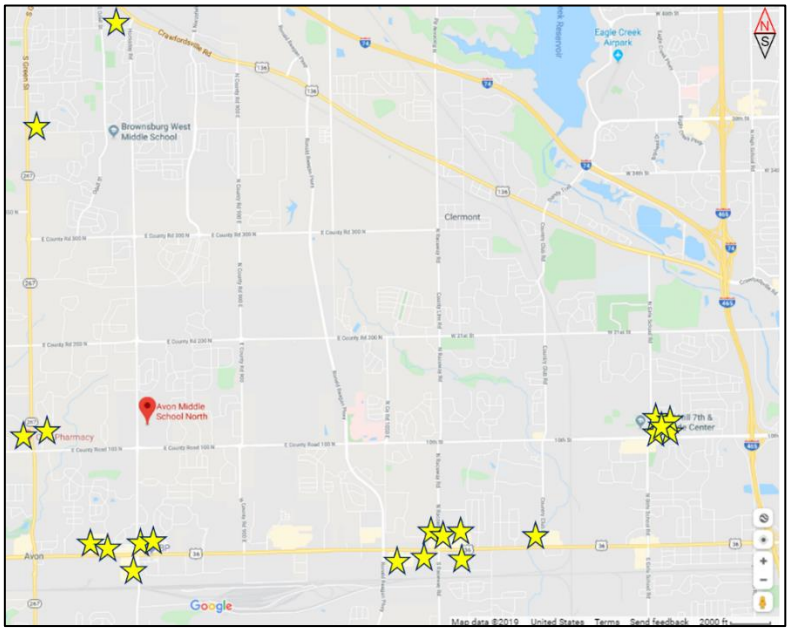


Figure SI.1-2. Location of water sample collection outside the school campus. Yellow stars indicate the approximate location of the commercial building water samples (21 locations). Scale and compass are on the right corner.

Onsite Water Quality Analysis

Total chlorine, free chlorine, monochloramine and free ammonia were analyzed onsite using HACH® 131 pocket colorimeter (DPD method). Water pH, DO, and temperature was measured using an Orion Star A329 portable pH meter (Thermo Scientific). Method detection limit (MDL) for total chlorine was 0.05 mg/L, free ammonia was 0.02 mg/L, and monochloramine was 0.04 mg/L.

TOC and DOC Quantifications

A Shimadzu TOC-L CPH/CPN was used to analyze TOC and DOC concentration. To get DOC samples, 50 mL of water sample was filtered through 0.5 µm glass fiber filter. The instrument was calibrated at 0.25 mg/L, 0.5 mg/L, 1 mg/L, 2 mg/L, 5 mg/L, 10 mg/L, and 50 mg/L TOC using $HOOCC_6H4COOK$ (r^2>0.99).

Total and Dissolved Heavy Metals Quantifications

To get dissolved metal samples, 30 mL of water sample was filtered through 0.45 µm nylon filter. Total and dissolved metal samples were analyzed by iCAP 7400 Duo ICP-OES (Thermo Scientific), and autosampler ASX-280 (CETAC Teledyne). Mixture of metals including Al, As, Be, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, and Zn was analyzed. The instrument was calibrated at 1 µg/L, 2 µg/L, 5 µg/L, 10 µg/L, 25 µg/L, 50 µg/L, 100 µg/L and 250 µg/L (r^2>0.99).

Ion Chromatography

An Metrohm 940 Professional IC Vario with a 850 Professional Sample Processor was used to analyze ion chromatography. The anions including bromide, chloride, fluoride, nitrate, nitrite, phosphate, and sulfate, and the cations including ammonium, calcium, lithium, magnesium, potassium, and sodium were analyzed. A mixture of 3.2mM sodium carbonate and 1mM sodium bicarbonate was used for the anion eluent, and a 3.5mM oxalic acid was used for the cation eluent. Custom anion mix 3 (Metrohm Cat No. REAIC1230), and custom cation mix 2 (Metrohm Cat no. REAIC1035) were used. The instrument was calibrated at 0.2 mg/L to 100 mg/L (r^2>0.99).

TTHM Analysis

An Agilent Technologies 7890B Gas Chromatography was used to analyze TTHMs. From collected water samples, only 5 mL water sample was transferred to headspace vials to extract TTHMs. 1 mL sample extracted by sampler was heated in an agitator for 15 min at 80°C. Then the gas phase sample was injected to 1:10 to 1:50 split ration column for analysis. The program was set for 5 min at 40°C, ramped to 240°C at 20°C/min, and then held at 240°C

for 5 min. The analytical standard mix including $CHCl_3$, $CHBrCl_2$, $CHBr_2Cl$, and $CHBr_3$ purchased from Supelco™ was used.

HPC Analysis

The water samples in the field were collected in 1L HDPE bottles and transferred to the laboratory. Sterilized water was filtered first using a PALL® 47mm magnetic filter funnels, and Advantec® sterilized MCE filters with pore size 0.45 μm was used. Each sample was filtered at least 300 mL volume three times, and filters were placed on agar plates. Agar plates were incubated at 35˚C for 48 hours before colonies were counted.

TCC Analysis

FCM analysis was conducted to quantify the total number of microbial cells in each water sample using SYBR Green I dye which binds specifically to nucleic acid (Swiss Research method 366.1). Each water sample was stained 1:100 with SYBR-Green I nucleic acid gel stain diluted in filtered dimethylsulfoxide (DMSO). The samples were incubated in a 96-well plate in the dark at 37℃ for 13 minutes. Triplicate samples from each fixture were analyzed using FCM (CytoFLEX, Beckman-Coulter Inc., Brea, CA, USA). A constant and uniform gating strategy was applied to all samples.

Nitrification/Denitrification Analysis

Nitrifying and denitrifying bacteria were measured using BART™ test. For both tests, water samples were collected in the provided tubes. For nitrification, the cap was replaced with a reactor cap after 5 days. Reaction was observed after the tube was rest for 3 hours. For denitrification, tubes were incubated at room temperature for 4 days to observe any bacteria growth each day.

Table SI.1-1. A comparison of water quality entering the building to the public water supplier's annual report

Measurement	Drinking water standard	2018 system range reported by the public water supplier	School sampling results from June - October
pH	6.5 – 8.5	7.00 – 8.48	7.62 – 7.87
Chlorine as Cl_2	4 ppm	0.02 – 2.9 ppm	BDL – 0.43 ppm
E. coli	1	0	-
Giardia (org/10L)	0 org/10L	ND	-
Hardness (ppm)	-	138 – 453 ppm	286 – 358 ppm

Total Coliforms	-	0 – 2.4%	-
Turbidity	-	0.075 – 0.19 NTU	-
2,4-D	70 ppb	ND	-
Aluminum	200 ppb	ND – 175 ppb	0 ppb
Ammonium nitrogen	-	-	0.37 – 1.34 ppm
Antimony	6 ppb	ND	-
Arsenic	10 ppb	ND – 1.9 ppb	-
Atrazine	3 ppb	ND- 1.8 ppb	-
Barium	2 ppm	0.037 – 0.29 ppm	-
Benzo[a]pyrene	0 ppb	ND	-
Bromide	0.5 ppm	N/A	0.32 – 0.46 ppm
Chloride	250 ppm	25 – 139 ppm	65.6 – 101.9 ppm
Chromium	100 ppb	ND – 3.2 ppm	-
Copper	1.3 ppm health-based limit	0.27 (90^{th} percentile) – 0.43 ppm	0 – 2.7 ppm
Fluoride	4 ppm	0.24 – 1.2 ppm	0.68 – 0.83 ppm
Haloacetic acids (HAA5)	-	8.9 – 90 ppb	-
Iron	0.3 ppm	ND – 0.21 ppm	0 – 0.038 ppm
Lead	15 ppb for corrosion control	8.2 (90^{th} percentile) – 36 ppb	0 – 40.9 ppb
Manganese	0.05 ppm	ND	0 – 0.00176 ppm
Nitrate	10 ppm	ND – 4.8 ppm	0.82 – 2.78 ppm
Nitrite	3 ppm	N/A	ND – 0.06 ppm
Nickel	-	ND – 2.3 ppb	0 – 3.18 ppb
Phosphate	-	N/A	ND – 0.04 ppm
Potassium	-	N/A	0.68 – 3.69 ppm
Simazine	4 ppb	ND – 1.2 ppb	-
Sodium	-	14 – 86 ppm	0 – 65.92 ppm
Sulfate	250 ppm	8.8 – 165 ppm	44.61 – 63.03 ppm
Toluene	1,000 ppb	ND – 1.5 ppb	-
Total Xylenes	10,000 ppb	ND	-

Total Trihalomethanes (TTHMs)	80 ppb	18 – 82 ppb	13.65 – 26.86 ppb

Table SI.1-2. 2018 Total water use at the school campus

Month	Total Gallons/Month	Gallons per day
Jan	0	0
Feb	29,174,028	1,458,701
Mar	33,942,859.5	1,697,143
Apr	44,434,288.8	2,221,714
May	123,709,100	6,185,455
Jun	158,493,518	7,924,676
Jul	80,621,304.3	4,031,065
Aug	364,843,662	18,242,183
Sept	364,114,311	18,205,716
Oct	44,378,184.9	2,218,909
Nov	64,238,965.5	3,211,948
Dec	51,278,964.6	2,563,948
Total	*44,434,288.8*	*67,961,459*

School water use (GPD) was calculated with assumtion of 20 days of water use per month.

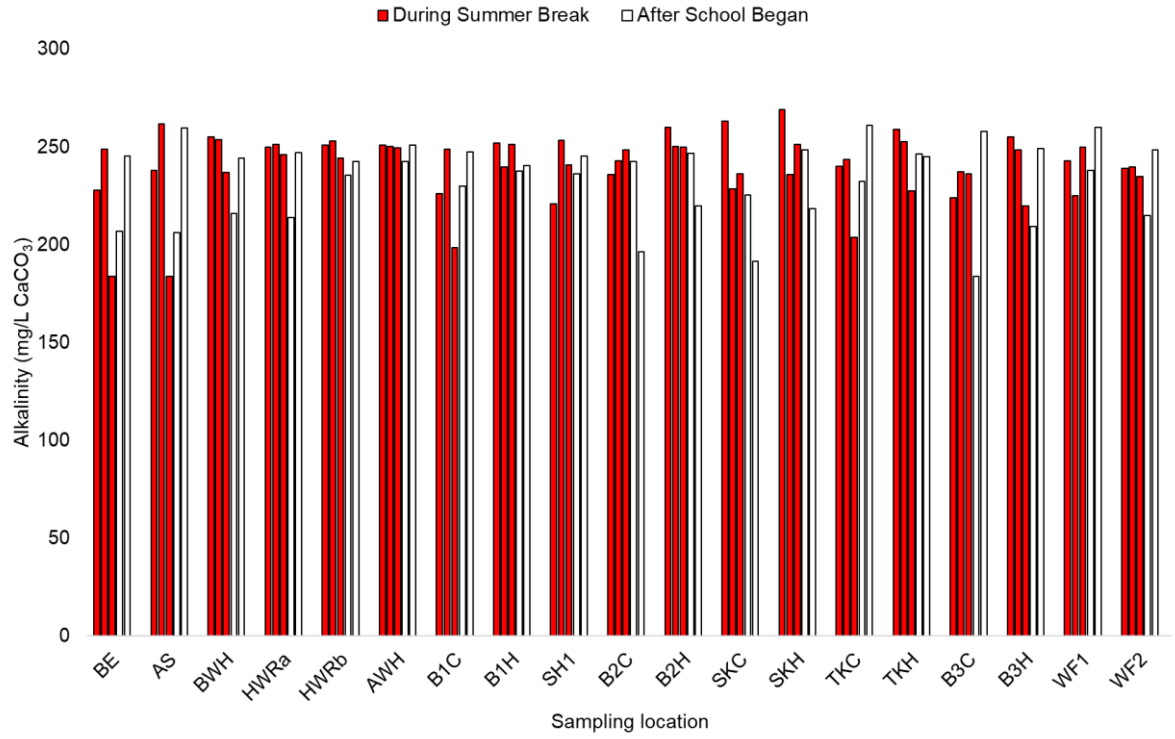


Figure SI.1-3. Alkalinity concentration as $CaCO_3$ at routine sampling locations

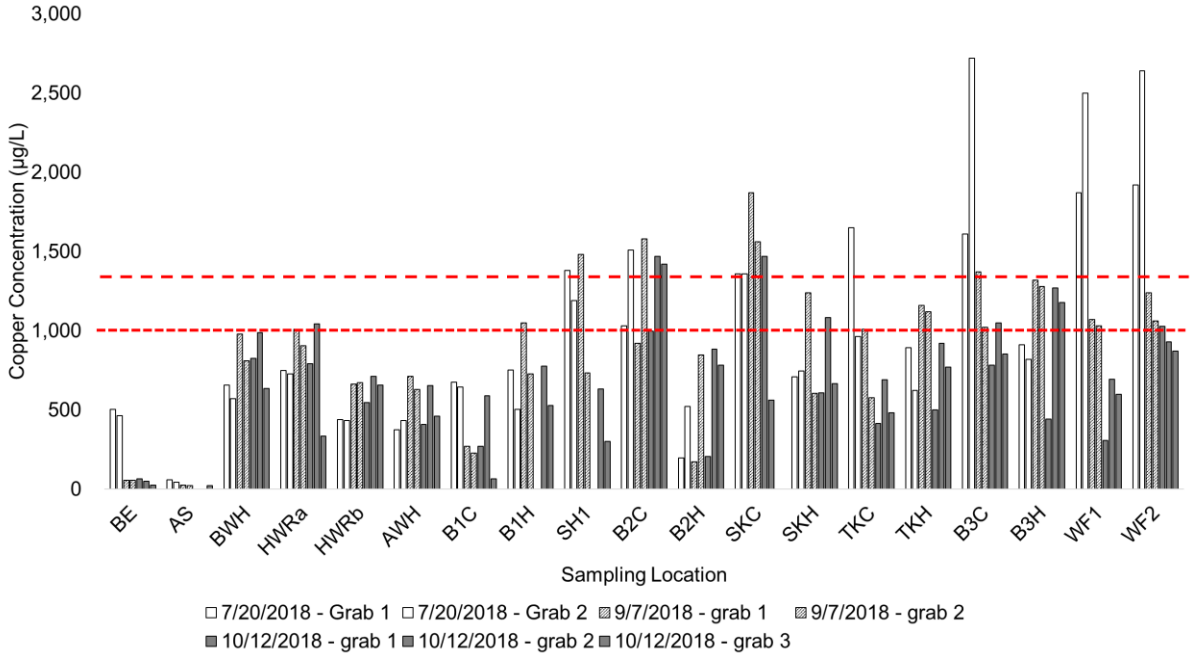


Figure SI.1-4. Copper concentration of multiple grabs from routine sampling locations. The 1.0 mg/L SMCL and 1.3 mg/L MCL are shown.

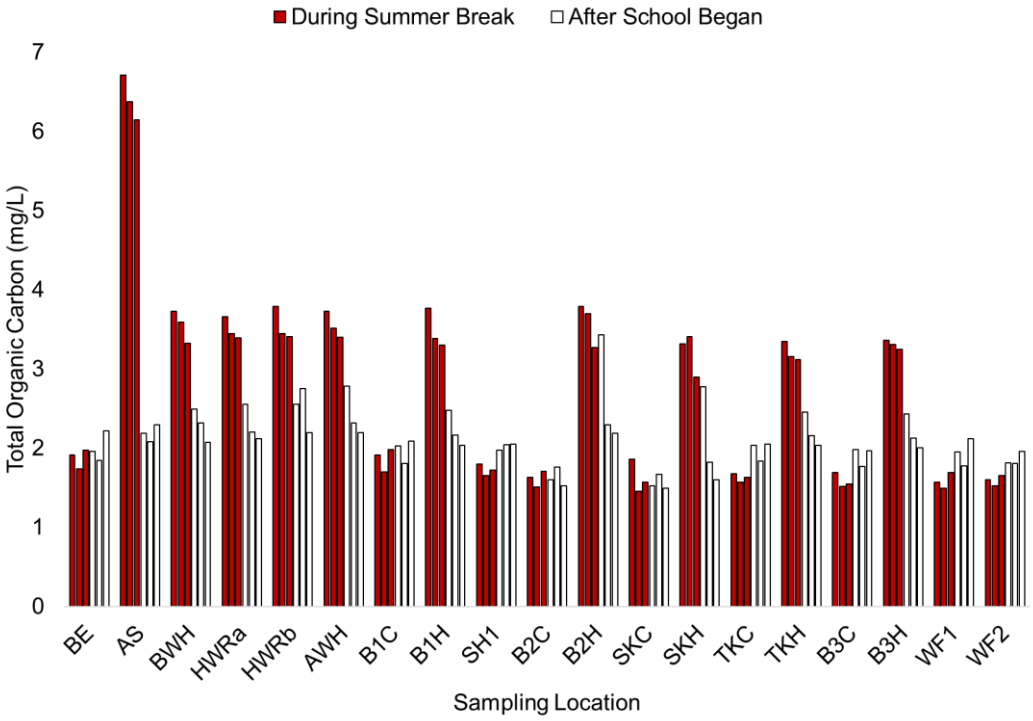


Figure SI.1-5. Total organic carbon concentration of first draw water samples

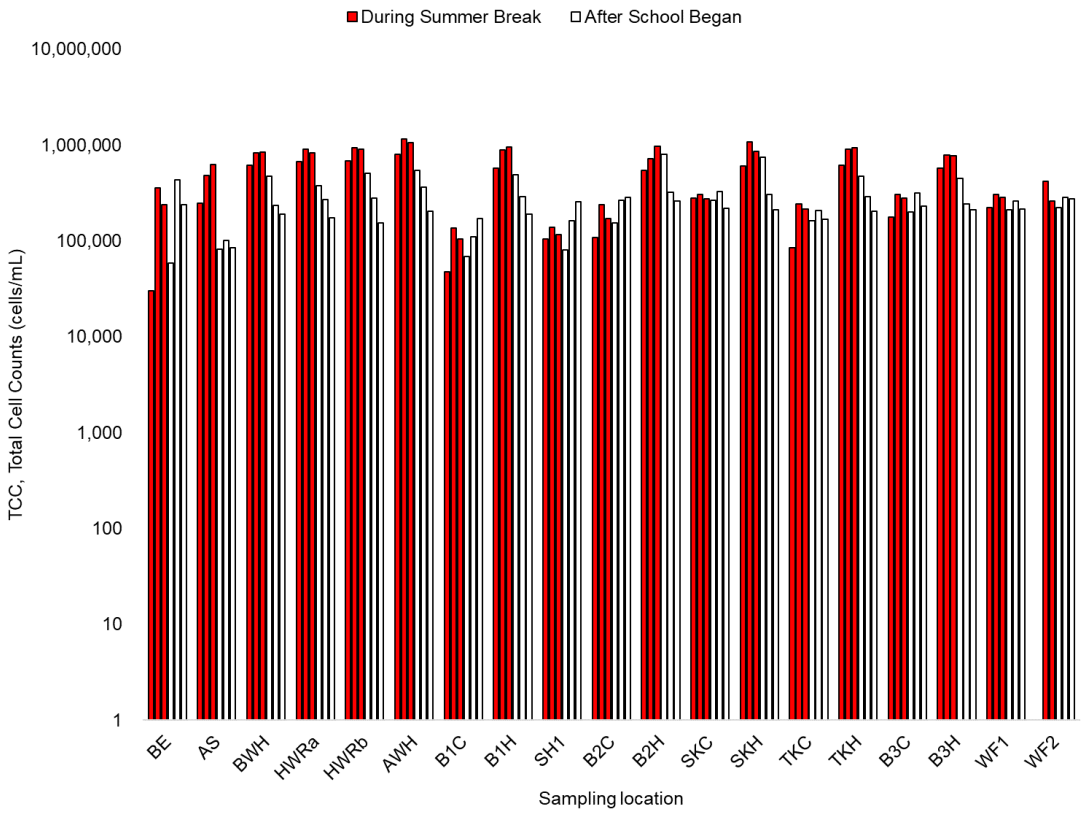


Figure SI.1-6. Total cell count concentration at routine sampling locations

Table SI.1-3. Water quality test results for water sampling outside the school campus

Location	Temp. (˚C)	pH	DO (mg/L)	Total Cl_2 (mg/L)	Free Cl_2 (mg/L)	NH_2Cl (mg/L)	NH_3-N (mg/L)	Copper (µg/L)
1	27.3	7.85	7.95	0.57	0.52	1.39	0.12	91.4
2	25.1	7.8	7.62	0.54	0.45	1.16	0.14	137
3	25.8	7.86	7.91	0.44	0.39	0.97	0.16	76.9
4	30.7	7.75	7.24	0.61	0.51	1.33	0.14	26.1
5	25.7	7.88	7.94	0.25	0.2	0.56	0.18	163
6	23.7	7.77	7.44	0.58	0.52	1.29	0.17	69.6
7	28.2	7.77	7.75	0.28	0.26	0.12	0.15	764
8	26.1	7.68	7.69	0.44	0.33	1.05	0.16	46.9
9	27.4	7.56	7.03	0.05	0.03	0.09	0.17	1,140
10	25.6	7.87	8.46	0.54	0.5	1.3	0.14	149
11	30.6	7.78	7.41	0.3	0.28	0.68	0.1	89.6
12	26.8	7.81	8.2	0.67	0.61	1.53	0.07	17.1

13	22.8	7.76	7.64	0.14	0.11	0.27	0.08	861
14	23.1	7.56	8.22	0.03	0.02	0.08	0.03	147
15	20.8	7.84	8.08	0.04	0.01	0	0.17	1,620
16	26.9	7.86	8.38	0.54	0.49	1.31	0.11	46.9
17	27.4	7.77	7.85	0.22	0.2	0.45	0.19	548
18	27.7	7.7	7.81	0.32	0.26	0.78	0.16	232
19	18.9	7.75	8.03	0.03	0.01	0	0.03	1,590
20	27.3	7.73	7.51	0.04	0.03	0.1	0.13	725
21	16.2	7.6	3.63	0.04	0.03	0.01	0.17	999

Other heavy metals found and water corrosivity

Other heavy metals associated with metal plumbing component corrosion were detected throughout the building but below MCL and SMCLs (**TABLE SI.1-4**). Nickel and zinc were found at a much greater concentration outside the utility room (max. 20.4 μg/L for nickel, max. 1,180 μg/L for zinc) compared to inside the utility room (0 to 3.2 μg/L for nickel, 7.9 to 177 μg/L for zinc). Lead was only detected at the shower head location (3 of 6 first grab samples), and all first three grabs exceeded the action level of 15 μg/L (**Table 1-2**). Corrosivity estimated using school water quality data does not seem helpful to predict none of copper or lead leaching. Although hot water was predicted to be slightly more corrosive than other cold locations (Langelier Index from -0.56 to -0.05), more aggressively corrosive locations did not always have high heavy metal concentrations.

Table SI.1-4. Other heavy metal water sampling results from the school

Heavy metal	MCL and SMCL (mg/L)	School water entering point (mg/L)	School sampling range in cold (mg/L)	School sampling range in hot (μg/L)
Aluminum	0.05, 0.2	0	0 – 0.087	0 – 0.039
Copper	1.3, 1.0	0.026 – 0.50	0 – 2.72	0 – 1.32
Iron	10, 0.3	0 – 0.0104	0 – 0.062	0 – 0.026
Manganese	0.05	0 – 0.00112	0 – 0.0052	0 – 0.0011
Nickel	0.1	0 – 0.0032	0 – 0.056	0 – 0.093
Lead	0.0015, 0	0	0 – 0.041	0

Zinc	5	0 – 0.18	0 – 11.8	0 – 10.2

Other contaminants

No specific trend or statistically significant found for TTHM, but the biggest difference found in the utility room. TTHM was similar for all six visits for the water entering the building but decreased after softener (**Figure SI-7**). TTHM levels entering the building were 13.6 to 26.4 µg/L while the water supplier reported a water distribution system annual average TTHM concentration of 18 to 82 µg/L (Citizens Energy Group, 2018) (**Table 2**). Other organic (TTHM) and inorganic contaminants were also found entering the building but within levels reported by the water supplier (Al, Cl-, Cr, F-, Fe, Mn, Na, Ni, Zn, NO3-, NO2-, SO4-2, hardness) (**Table SI-1**). Distance from the entry point to location was correlated with TTHM concentration ($p=0.03$), but no difference between before and after students returned to school. None of the locations exceeded the TTHM limit of 80 µg/L (EPA, 2002).

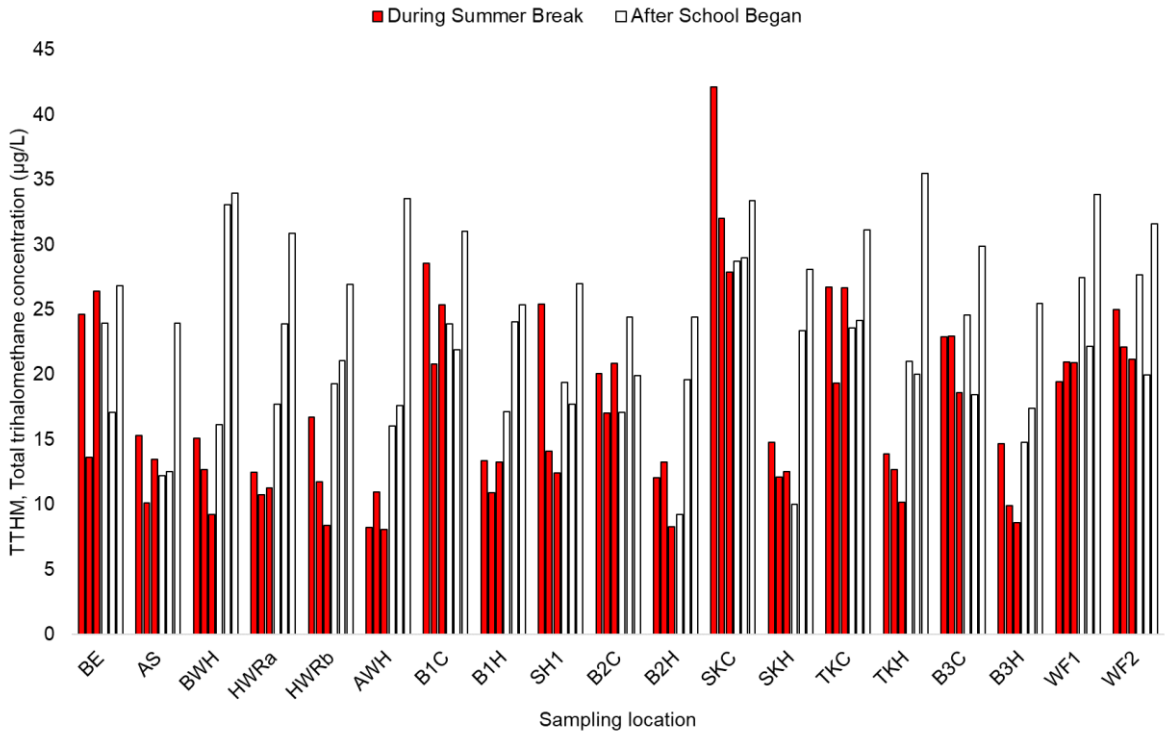


Figure SI.1-7. Total trihalomethane concentration at routine water sampling locations

Water temperature monitoring

Hot water recirculation lines should be prevented from getting below 55˚C but 60˚C line returned at 48˚C and the other lines returned at 35˚C (according to in-line sensors). Because authors concerned about some locations may not get the hot water, temperature monitoring at

3 distal fixtures was conducted for 5 minutes (**Figure SI.1-8, Table SI.1-5**). No location reached the hot water recirculation line temperature threshold (48.8˚C). SKH had shorter distance from BE increased temperature much faster, but still did not reach the threshold. B3H had longest distance from BE never reached above 28˚C within 5 minutes. Although only three locations were monitored for temperature, a possible problem that may have with the recirculation system with large dead ends in certain parts of the school was noticed. This may mean that many locations do not reach certain temperature that are in a perfect temperature zone for microbial growth.

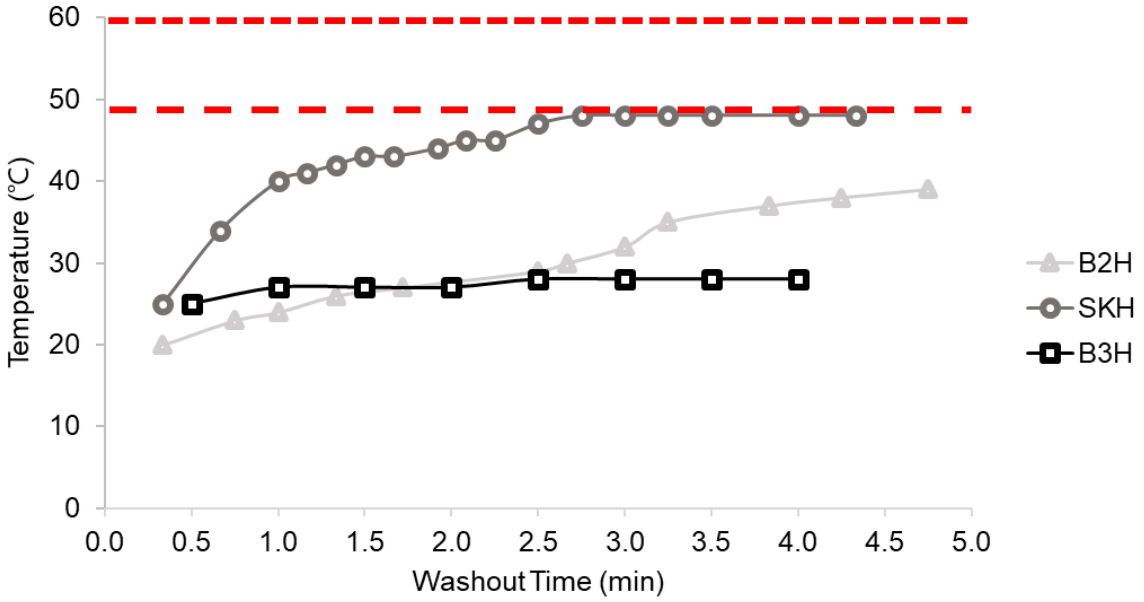


Figure SI.1-8. Temperature washout curves for hot water. Red lines are the temperature threshold (60˚C and 48.8˚C) that are supposed to be achieved based on the water heating equipment set points.

Table SI.1-5. Estimated delivery and return pipe length for the water temperature monitoring

Water deliver	Delivery length	Water returns	Return length	Total length
BE to B3H	509.97 ft	B3H to HWRC	496.75 ft	1006.72 ft
BE to B2H	252.002 ft	B2H to HWRC	215.49 ft	467.492 ft
BE to SKH	267.75 ft	SKH to HWRC	282.3 ft	550.05 ft

APPENDIX SI.2

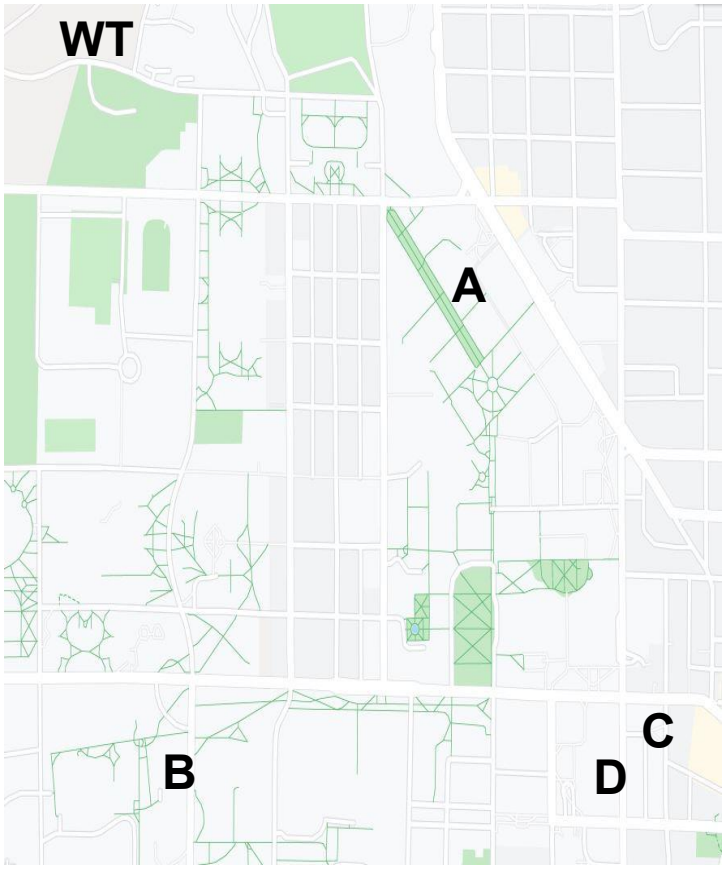


Figure SI.2-1. Location of buildings A, B, C, and D, as well as the public water system water storage tank (WT).

(a-1) 

(a-2) 

(b) 

(c) 

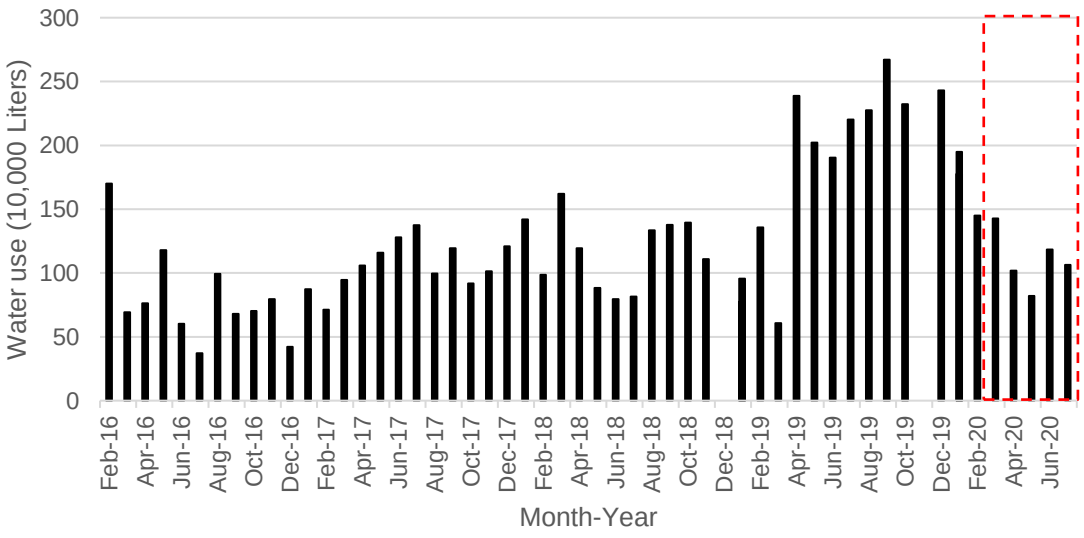
(d) 

Figure SI.2-2. Water devices in buildings (a) A, B, C, and D. (a-1) water heater and two water softeners (not regenerated or water only goes through the softener but not being softened) in West side of building A, (a-2) water heater and water softeners in East side of building A; (b) water heater at building B; (c) a tankless steam heated system at building C; (d) two water heaters and water softeners at building D.

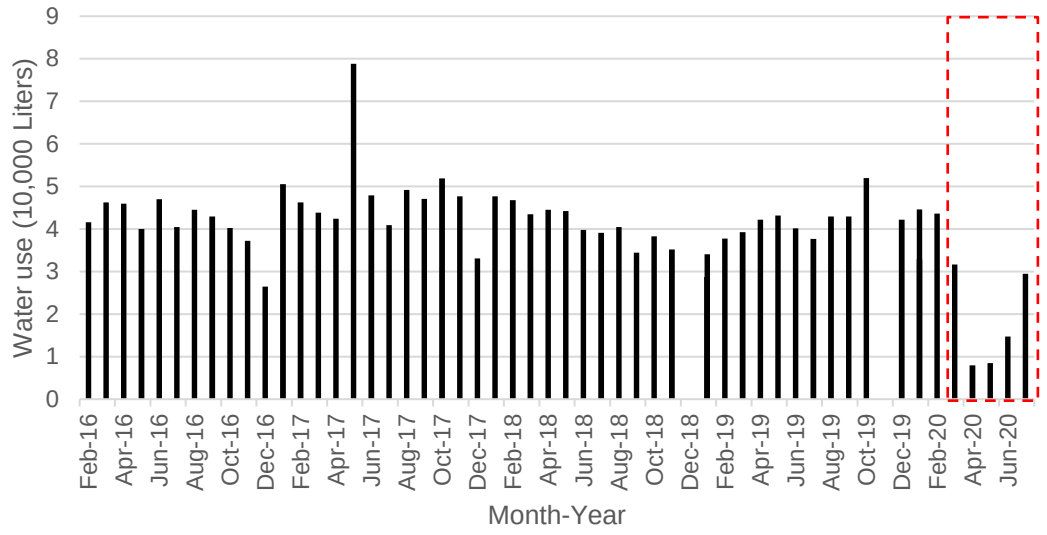
TABLE SI.2-1. First draw sampling location description. All bathrooms were lady's bathroom unless described.

Location	Floor	Location description	Type
A – 1	1	Kitchen, East side	Cold, stagnated
A – 2	1	Kitchen, East side	Cold, 5 min flushed
A – 3	1	Kitchen, East side	Hot, stagnated
A – 4	1	Drinking water fountain, West side	Cold, stagnated
A – 5	1	Bathroom, West side	Hot, stagnated
A – 6	1	Bathroom, East side right sink	Hot, stagnated
A – 7	1	Bathroom, East side left sink	Hot, stagnated
A – 8	1	Bathroom, East side right sink	Hot, 5 min flushed
A – 9	4	Drinking water fountain, West side	Cold, stagnated
A – 10	4	Bathroom, West side	Hot, stagnated
A – 11	4	Bathroom, East side right sink	Hot, stagnated
A – 12	4	Bathroom, East side left sink	Hot, stagnated
A – 13	4	Bathroom, East side right sink	Hot, stagnated
B – 1	1	Drinking water fountain	Cold, stagnated
B – 2	1	Bathroom, left side	Cold, stagnated
B – 3	1	Bathroom, right side	Hot, stagnated
B – 4	1	Bathroom, right side	Hot, 5 min flushed
B – 5	2	Kitchen	Cold, stagnated
B – 6	2	Kitchen	Hot, stagnated
B – 7	2	Kitchen	Cold, 5 min flushed
B – 8	2	Drinking water fountain	Cold, stagnated
C – 1	1	Drinking water fountain, short	Cold, stagnated
C – 2	1	Water fountain, tall	Cold, stagnated
C – 3	1	Bathroom, left sink	Hot, stagnated
C – 4	1	Bathroom, right sink	Hot, stagnated
C – 5	4	Drinking water fountain, tall	Cold, stagnated
C – 6	4	Drinking water fountain, short	Cold, stagnated
C – 7	4	Bathroom, left sink	Hot, stagnated
C – 8	4	Bathroom, right sink	Hot, stagnated

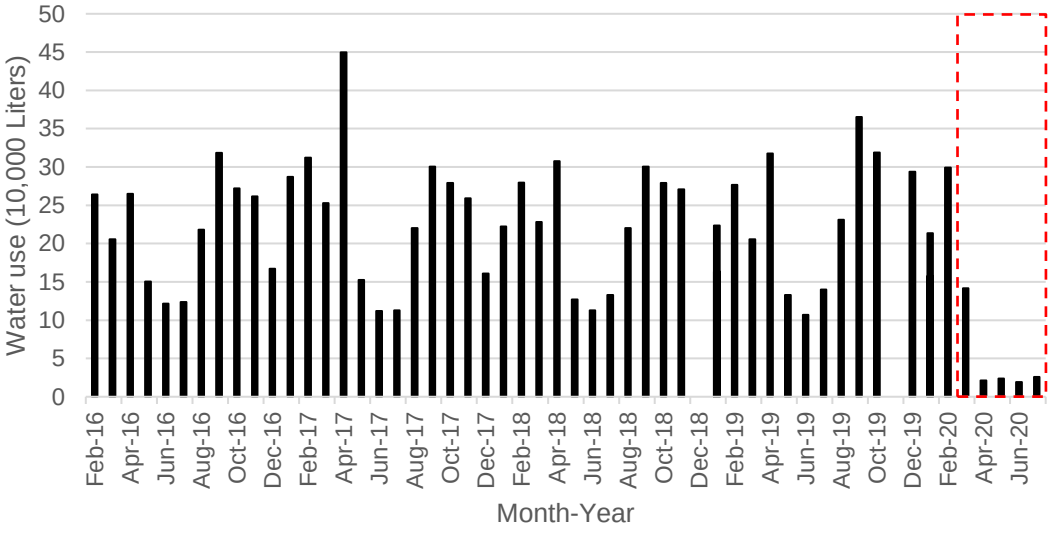
C – 9	4	Bathroom, right sink	Hot, 5 min flushed
C– 10	1	Bathroom, left sink	Hot, 5 min flushed
D – 1	1	Bathroom, left sink	Hot, stagnated
D – 2	1	Drinking water fountain, only working	Cold, stagnated
D – 3	1	Bathroom, left sink	Hot, stagnated
D – 4	1	Unisex bathroom, left sink	Hot, 5 min flushed
D – 5	5	Drinking water fountain, North side	Cold, stagnated
D – 6	5	Bathroom, North side middle sink	Hot, stagnated
D – 7	5	Drinking water fountain South side	Cold, stagnated
D – 8	5	Bathroom, South side middle sink	Hot, stagnated
D – 9	5	Bathroom, South side middle sink	Hot, 5 min flushed
D – 10	10	Bathroom, North side left sink	Hot, stagnated
D – 11	10	Drinking water fountain, North side	Cold, stagnated
D – 12	10	Bathroom, South side left sink	Hot, stagnated
D – 13	10	Bathroom, South side left sink	Hot, 5 min flushed
D – 14	10	Kitchen	Cold, stagnated
D – 15	10	Kitchen	Hot, stagnated
D - 16	10	Kitchen	Cold, stagnated



(a)


Water use (10,000 Liters)
0
1
2
3
4
5
6
7
8
9
Feb-16
Apr-16
Jun-16
Aug-16
Oct-16
Dec-16
Feb-17
Apr-17
Jun-17
Aug-17
Oct-17
Dec-17
Feb-18
Apr-18
Jun-18
Aug-18
Oct-18
Dec-18
Feb-19
Apr-19
Jun-19
Aug-19
Oct-19
Dec-19
Feb-20
Apr-20
Jun-20
Month-Year

(b)


Water use (10,000 Liters)
0
5
10
15
20
25
30
35
40
45
50
Feb-16
Apr-16
Jun-16
Aug-16
Oct-16
Dec-16
Feb-17
Apr-17
Jun-17
Aug-17
Oct-17
Dec-17
Feb-18
Apr-18
Jun-18
Aug-18
Oct-18
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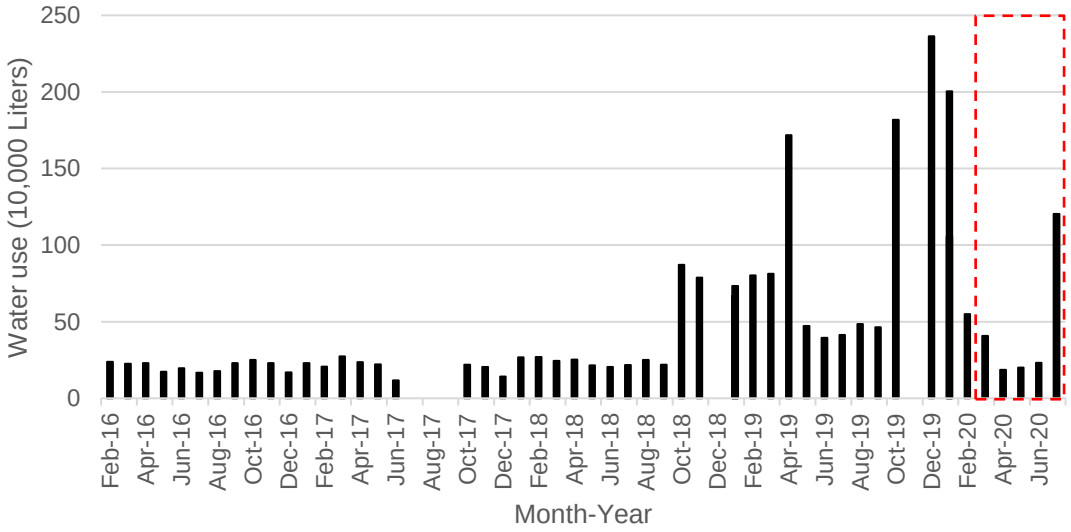
Dec-19
Feb-20
Apr-20
Jun-20
Month-Year

(c)


Water use (10,000 Liters)
0
50
100
150
200
250
Feb-16
Apr-16
Jun-16
Aug-16
Oct-16
Dec-16
Feb-17
Apr-17
Jun-17
Aug-17
Oct-17
Dec-17
Feb-18
Apr-18
Jun-18
Aug-18
Oct-18
Dec-18
Feb-19
Apr-19
Jun-19
Aug-19
Oct-19
Dec-19
Feb-20
Apr-20
Jun-20
Month-Year

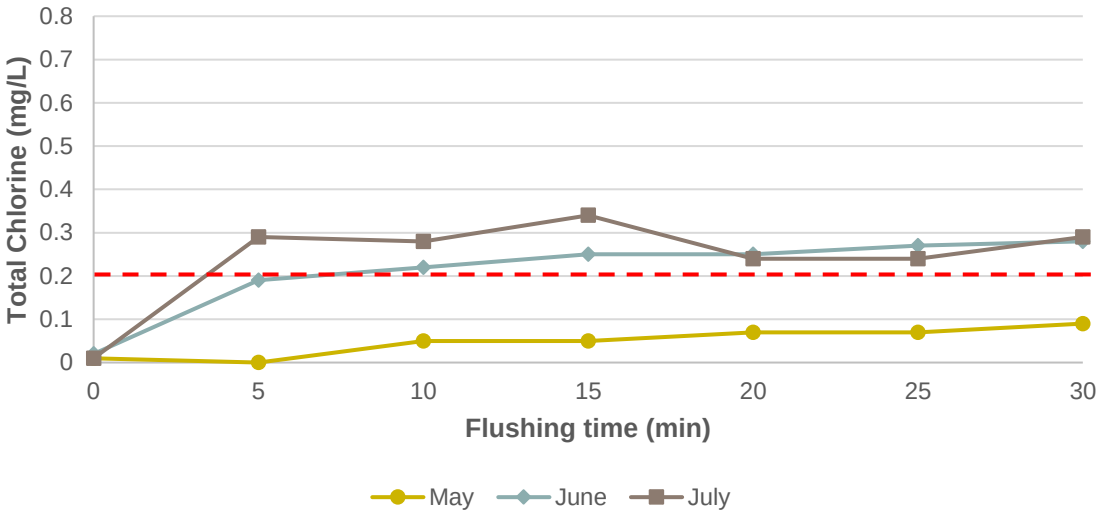
(d)

Figure SI.2-3. Water usage for past 5 years in (a) Building A, (b) Building B, (c) Building C, and (d) Building D. Dashed box around certain time is when the buildings shut down during the pandemic. Blanks are when the building water meter changed out to new meter or no data available.

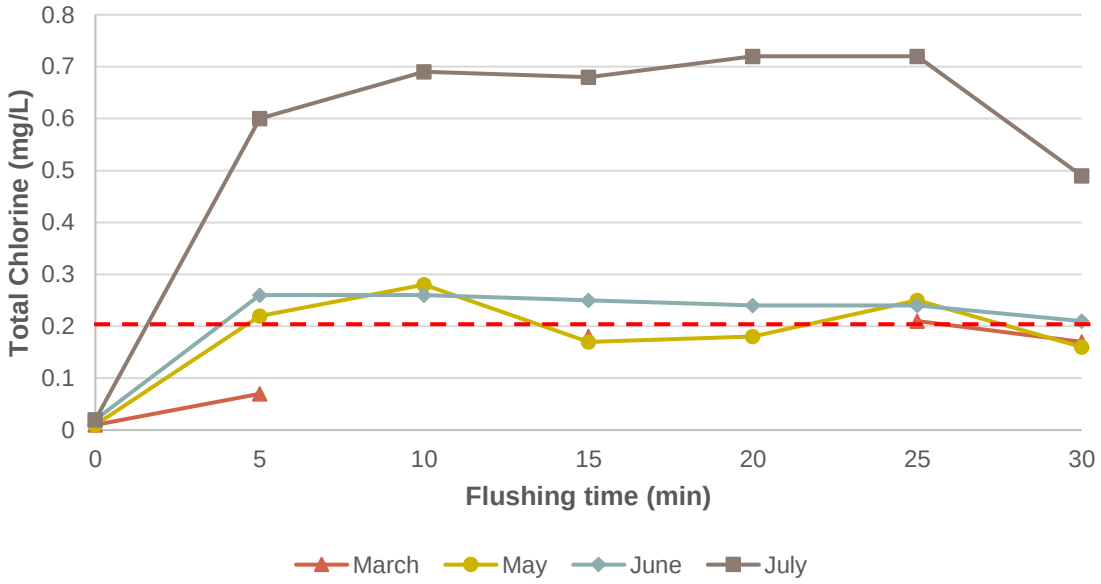
Pipe diameter for cold water and hot water were different within the same building (1.27 to 3.18 cm for cold water, and 1.27 to 1.91 cm for hot water). Water heater tank at building B was 181 L, and a tankless steam heating system was used for building C. The total length of pipe within each building was estimated as 675.4m (B) and 3253.8m (C) for cold, and 475.4m (B) and 1431.2m (C) for hot water. Hot water return line was preset in both buildings. Toilets, urinals, sinks, ice machines and wall hydrant device were present in both buildings, but at different numbers. Because pipe diameter and length from fixture to fixture were different, a shortest length at building B was used to show (**Table SI.2-2**) how flushing time can vary depending on the plumbing design.

Table SI.2-2. Example flushing time calculation with 1.89 LPM flow rate assumption. Pipe length was from shortest distance between fixtures at building B.

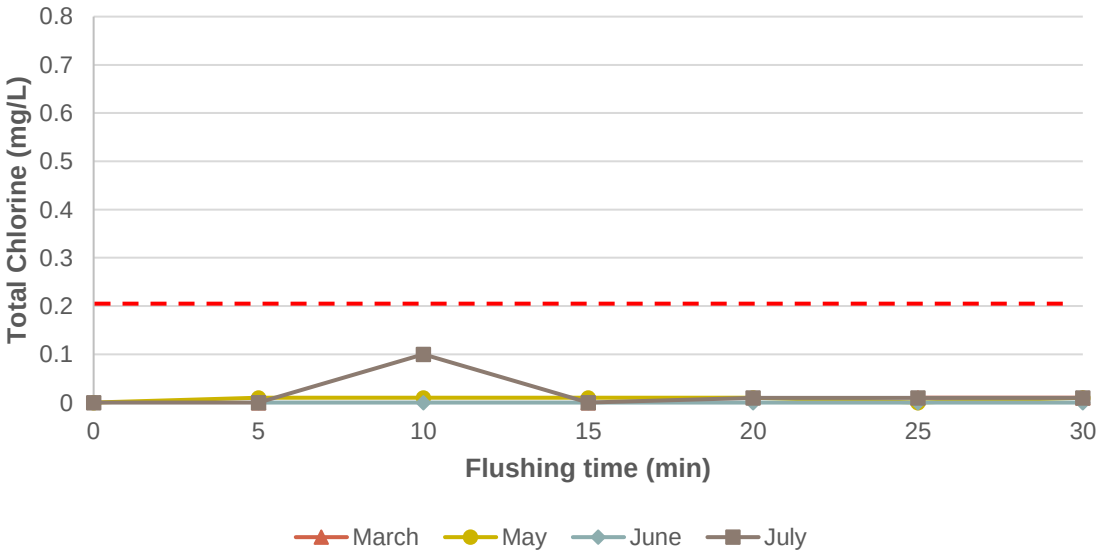
Pipe diam. (cm)	Pipe length (cm)	Volume (cm^3)	Flushing time (min or sec)
1.27	121.9	154.4	0.08 or 4.9
1.91	121.9	349.3	0.18 or 11.1
2.54	121.9	617.7	0.33 or 19.6
3.18	121.9	968.2	0.51 or 30.8


Total Chlorine (mg/L)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
Flushing time (min)
May
June
July

(a)


Total Chlorine (mg/L)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
Flushing time (min)
March
May
June
July

(b)


Total Chlorine (mg/L)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25
30
Flushing time (min)
March
May
June
July

(c)

Figure SI.2-4. Total chlorine residual concentrations during continuous 30-minute flushing at building (a) Building B, (b)Building C, (C) Building D. Red dotted line on 0.2 mg/L as Cl_2 which is the minimum chlorine residual concentration allowable in the public water distribution system providing drinking water to the building.

First draw hot water samples

A few hot water samples (2/85) across the buildings had a detectable chlorine residual concentration at building A and B. Water pH levels were ranged from 6.9 to 7.9. DO levels were ranged from 1.0 to 8.4. TOC levels ranged from 0.3 to 1.2 mg/L. TCC levels ranged from 3.4 to 5.3. One location seemed to have bacterial growth for *Legionella pnemophila* in May, but the same and few other locations did not detect by Legiolert in July.

A few locations exceeded metal action limits for hot water. Similar to cold water, metal levels in larger buildings were higher than smaller buildings. For the first draw hot water sample, only 1 location at building D exceeded 1.3 mg Cu/L in July (1.37 mg Cu/L). Though, several additional locations exceeded at building A (1/24), B (0/9), C (3/44), and D (1/40) with maximum 1.5 mg Cu/L at building A. None of lead detected in first draw samples for hot water from all buildings exceeded 5 μg Pb/L. But in additional samples, 2 locations at building C had 6.6 and 10.6 μg Pb/L while all other locations detected lead was greater than 1 μg Pb/L but less than 5 μg Pb/L. At one of same location, manganese also exceeded 0.1 mg/L while none of other locations did.

A Definition of "What is Flushing?" and "What Improves Water Quality?" is Needed

A stepwise flushing plan was developed after the study began and was compared to the building owner's flushing practices for building B and C. Flushing plan for only two of smaller and newer buildings (B and C) were created. A lot of information was missing especially for larger and older buildings (A and D) after buildings were renovated. After the sampling was initiated the building owner provided as-built drawings for all buildings, but building A and D were missing information after renovation. Using these drawings, the authors developed a stepwise procedure for removing all of the stagnant water from the plumbing. Plumbing component sizes inside the buildings differed significantly: pipe diameter (6.35 to 19.05 mm for cold water, and 12.7 to 19.05 mm for hot water), water softener tank size (no water softeners at building B and D), water heater tank size (181 L for building B and tankless steam heated for building D). Length of pipe in each building was estimated as 675.4m (B) and 3253.8m (C) for cold, and 475.4m (B) and 1431.2m (C) for hot water. Hot water return line

was also considered in building B. All available water fixtures including urinals, sinks, ice machines and wall hydrant device were considered in the flushing plan design. Each fixture was assumed to be flushed individually not simultaneously to lessen the chance pressure reductions would decrease flowrate. The assumed flowrate of every fixture was 1.89 LPM. Flushing was initiated at the fixture closet to the water meter and then fixtures were subsequently flushed deeper into the building. The author's calculated flushing time did not consider draining or flushing softener or water heaters.

The building owner flushing activity was not comparable to the stepwise procedure created based on as-built drawings for building B and C. In all buildings, building owners only visited few fixtures randomly, and did not consider to remove old water and bring new water to the building. To replace the stagnant water in Building B with fresh water 2.85 hours was estimated. This building contained 32 fixtures such as sink faucets, toilets, and urinals. Building C had 114 fixtures and the predicted flushing time was estimated to be 14.9 hours. Even if the author's assumed fixture flowrate was greater than lowest flowrate measured in building B, flushing a fixture for 3 min (Building B) would be much less than the hour to remove all the water. Building owners did not record all flushing activities and some fixtures were only flushed for few minutes, while authors found longer flushing duration needed for "proper flushing". At the time this study was conducted, dissimilar recommendations were available from different government, industry, and academic organizations about how to remove stagnant water from plumbing.

APPENDIX SI.3

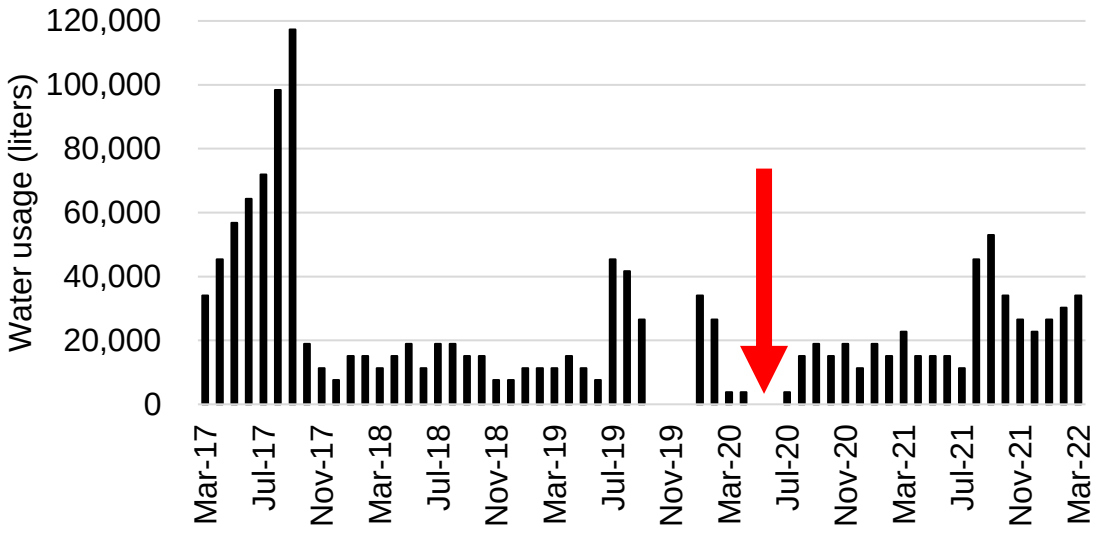
Table SI.3-1. Sample location and description

Building/sample #	Fixture description	Water type	2nd visit*
A-1	Lower level drinking water fountain near office	Cold	Yes
A-2	Lower level kitchen sink	Cold	Yes
A-3	Lower level classroom sink	Cold	Yes
A-4	Lower level classroom bathroom	Cold	Yes
A-5	Main floor hallway bathroom sink by stairs	Cold	Yes
A-6	Main floor classroom 1 sink	Cold	
A-7	Main floor drinking water fountain in front of classroom 1	Cold	Yes
A-8	Main floor bathroom sink	Cold	
A-9	Main floor classroom 2 sink	Cold	
A-10	Main floor classroom 3 sink	Hot	Yes
A-11	Main floor bathroom next to classroom 3	Cold	
A-12	Lower level kitchen sink	Hot	
A-13	Lower level classroom kitchen sink	Hot	Yes
A-14	Lower level bathroom sink	Hot	Yes
A-15	Main floor hallway bathroom sink by stairs	Hot	
A-16	Main floor classroom 1 sink	Hot	Yes
A-17	Main floor bathroom sink next to drinking water fountain	Hot	
A-18	Main floor classroom 2 sink	Hot	Yes
A-19	Main floor bathroom sink inside the classroom 3	Hot	Yes
B-1	Classroom 1 kitchen sink	Cold	Yes
B-2	Hallway bathroom sink	Cold	

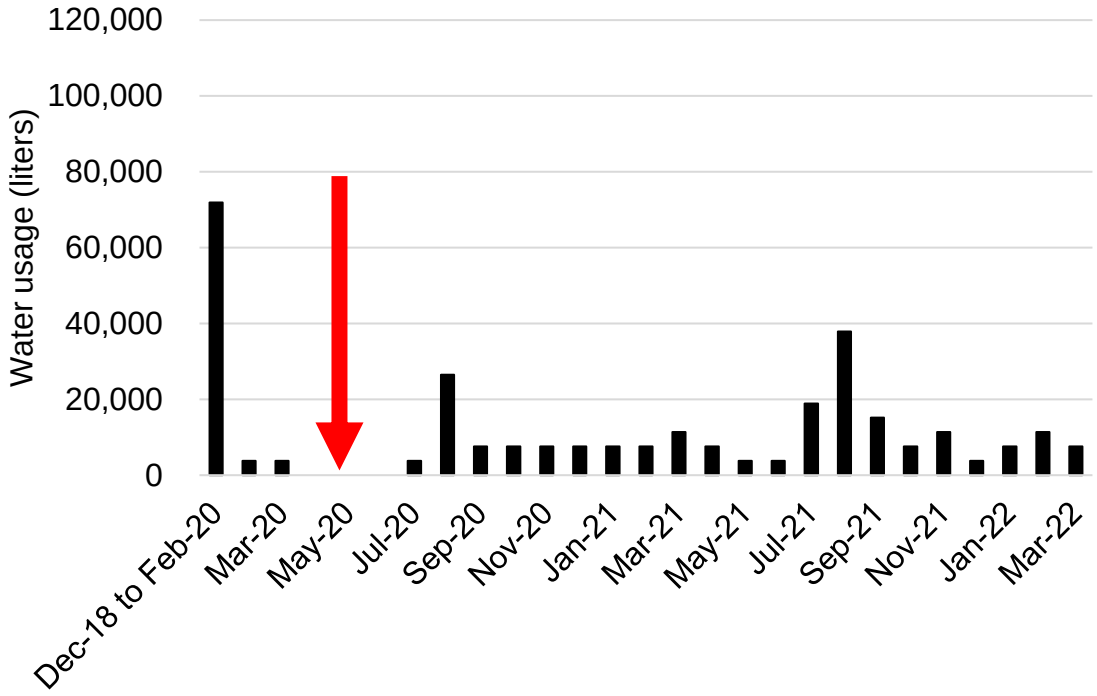
B-3	Drinking water fountain next to hallway bathroom	Cold	Yes
B-4	Classroom 2 kitchen sink	Cold	Yes
B-5	Bathroom sink near the utility room	Cold	
B-6	Classroom 1 kitchen sink	Hot	Yes
B-7	Hallway bathroom sink	Hot	Yes
B-8	Classroom 2 kitchen sink	Hot	Yes
C-1	Bathroom sink	Cold	Yes
C-2	Kitchen sink	Cold	
C-3	Drinking water fountain	Cold	Yes
C-4	Bathroom sink	Hot	Yes
C-5	Kitchen sink	Hot	Yes
C-6	Bathroom sink	Cold	Yes

*Listed locations were all collected on first visit, but on second visit for follow-up, selected locations were collected for few water quality testing.

SI Results



(a)



(b)

Figure SI.3-1. Water usage in (a) building A and B, and (b) building C. Only average water use in building C from Dec. 2018 to beginning of Feb. 2020 was reported by the utility (71,915 L). Red arrows are when the building was closed (May to June for building A and B, April to June for building C).

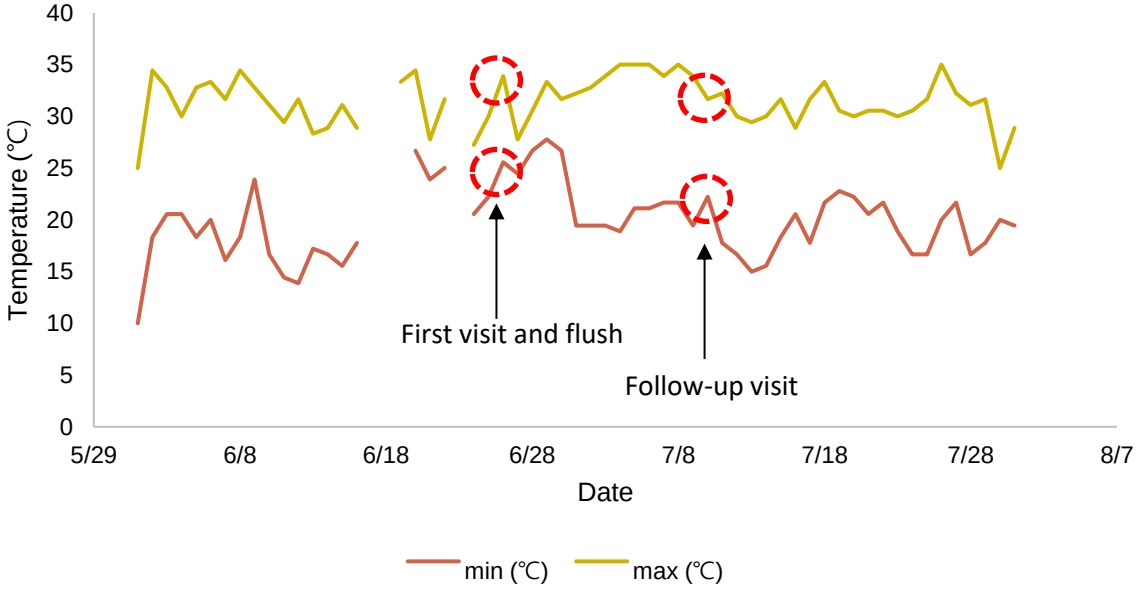
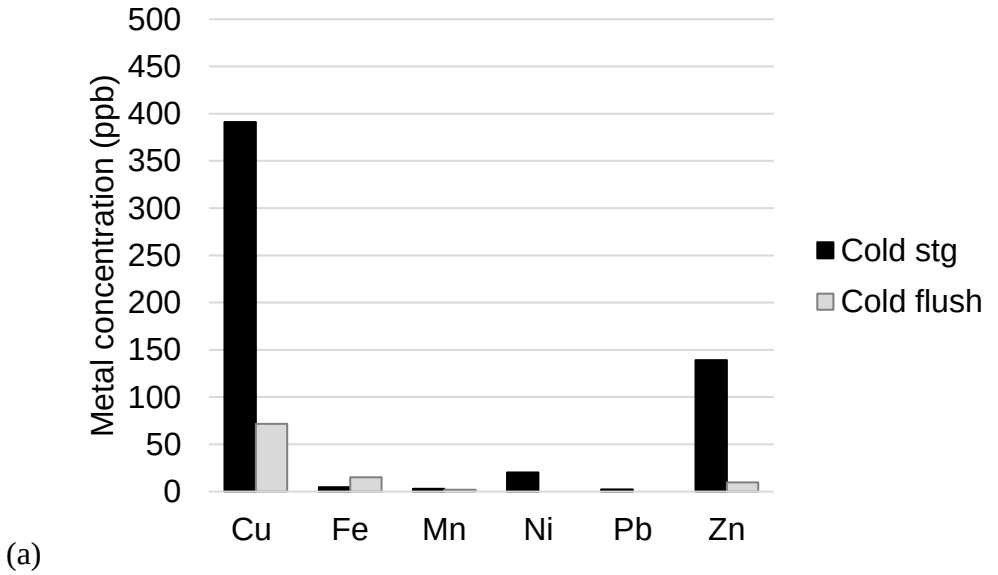


Figure SI.3-2. Outside air temperature of June and July 2020 [191,192]**.**

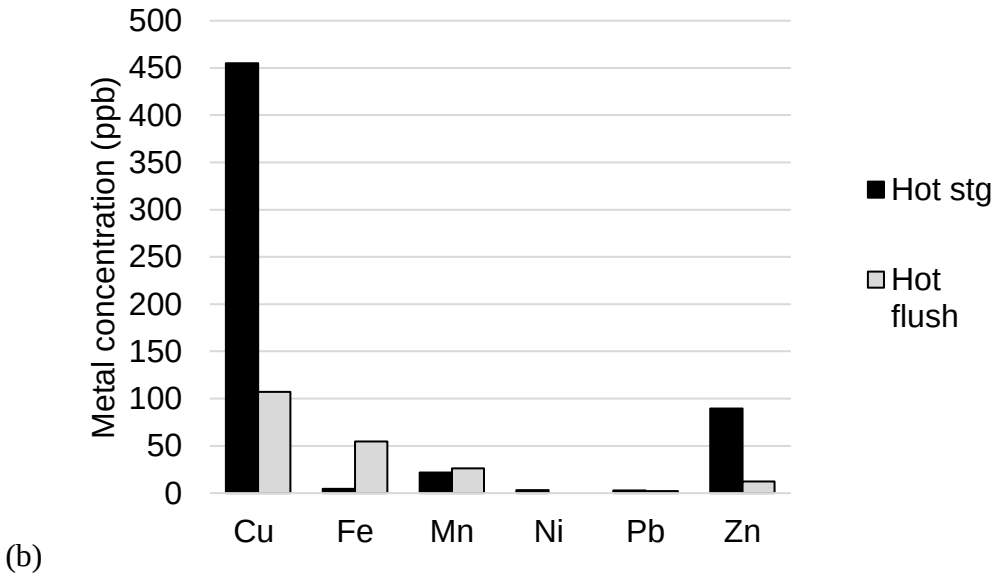
Table SI.3-2. Water quality measurements before and after flushing

Parameter and Building		First draw									After flushing*					
		Drinking water fountains (n=4/4)			Other Cold water (n=15/19)			Hot water (n=14/19)			Cold water (n=12/19)			Hot water (n=12/19)		
		Min	$\bar{x}$	Max	Min	$\bar{x}$	Max	Min	$\bar{x}$	Max	Min	$\bar{x}$	Max	Min	$\bar{x}$	Max
pH	A	7.17	7.17	7.17	7.51	7.62	7.68	7.55	7.65	7.83	7.67	7.73	7.79	7.67	7.72	7.77
	B	7.77	7.77	7.77	7.85	7.99	8.21	7.79	7.81	7.98	7.69	7.70	7.73	7.67	7.72	7.78
	C	7.63	7.63	7.63	7.55	7.60	7.96	7.72	7.77	7.82	7.72	7.78	7.86	7.71	7.78	7.90
Total chlorine (mg/L)	A	nd	nd	nd	nd	0.02	0.03	nd	0.02	0.23	1.18	1.20	1.24	0.97	1.17	1.41
	B	nd	nd	nd	nd	0.01	0.07	0.02	0.12	0.20	nd	0.84	1.29	1.15	1.17	1.18
	C	nd	nd	nd	0.02	0.03	0.19	nd	nd	nd	0.96	1.15	1.28	nd	0.86	1.24
Temperature (℃)	A	12.6	17.6	22.5	21.8	22.6	23.3	22.0	22.8	24.3	19.3	19.5	19.8	27.3	28.3	29.6
	B	13.4	13.4	13.4	22.4	22.5	22.6	21.9	22.5	23.4	19.1	20.0	20.7	22.2	24.9	28.4
	C	13.9	13.9	13.9	20.8	21.1	21.5	19.9	19.9	19.9	14.2	16.6	17.6	20.3	25.5	32.0
Dissolved oxygen (mg/L)	A	3.71	5.53	7.34	3.31	6.31	7.35	3.49	4.65	8.48	9.47	9.60	9.78	8.25	8.58	9.06
	B	9.27	9.27	9.27	9.37	9.45	9.51	9.36	9.42	9.45	9.46	9.52	9.62	8.22	8.67	8.92
	C	5.89	5.89	5.89	4.88	6.13	7.38	8.34	8.54	8.73	9.67	9.78	9.89	7.20	8.63	9.31

*Flushing started at the kitchen sinks or janitor sink for 10 to 12 minutes, and then each fixture was flushed for 2 minutes. Data were recorded only at selected locations at cold and hot water fixtures. In this table, last recording data during the flushing duration was reported.



(a)



(b)

Figure SI.3-3. Average heavy metal concentration for before and after flushing at (a) cold and (b) hot fixtures. Cold and hot stg means stagnated water samples collected at first draw, and flush means samples collected after flushing.

Table SI.3-3. First draw water quality measurement after 2 weeks

Parameter and Building		First draw								
		Drinking water fountains (n=4/4)			Other cold water (n=9/19)			Hot water (11/19)		
		Min	$\bar{x}$	Max	Min	$\bar{x}$	Max	Min	$\bar{x}$	Max
pH	A	7.01	7.20	7.38	7.57	7.63	7.75	7.71	7.79	7.84
	B	7.42	7.42	7.42	7.48	7.59	7.70	7.70	7.75	7.84
	C	7.66	7.66	7.66	7.55	7.64	7.72	7.75	7.82	7.88
Total chlorine (mg/L)	A	nd	nd	nd	nd	nd	nd	nd	nd	nd
	B	nd	nd	nd	nd	nd	0.08	nd	0.12	0.25
	C	nd	nd	nd	nd	0.02	0.03	nd	nd	nd
Temperature (°C)	A	13.2	18.1	23.0	22.2	22.4	24.8	22.7	23.1	24.1
	B	12.9	12.9	12.9	22.6	22.8	22.9	22.1	23.1	29.2
	C	13.9	13.9	13.9	21.4	21.5	21.5	20.6	21.1	21.5
Dissolved oxygen (mg/L)	A	4.02	5.28	6.54	5.43	5.66	7.77	2.73	7.81	8.20
	B	8.97	8.97	8.97	7.24	7.80	8.35	5.99	7.71	9.01
	C	9.0	9.0	9.0	7.11	7.69	8.26	5.75	7.15	8.54

Table SI.3-4. Comparison on average heavy metal concentrations for buildings A, B, C combined.

Condition		Mean ± stdev (µg/L)					
		Cu	Fe	Mn	Ni	Pb	Zn
1st visit	Drinking stg	600 ± 314	5.99 ± 2.99	26.4 ± 13.21	1.56 ± 0.88	2.42 ± 1.41	17.1 ± 26.85
2nd visit	Drinking Stg	368 ± 164	0	0.97 ± 0.71	0.84 ± 0.57	0	11.4 ± 13.9
1st visit	Cold stg	391 ± 184	4.57 ± 1.95	2.97 ± 3.73	20.3 ± 44.4	2.37 ± 0.41	139 ± 142

	Cold flush	82.5 ± 58.9	32.6 ± 44.2	3.85 ± 5.43	0	0.36 ± 1.14	8.09 ± 4.58
2nd visit	Cold stg	476 ± 289	4.99 ± 10.6	2.94 ± 3.53	7.29 ± 16.9	0	104 ± 107
1st visit	Hot stg	455 ± 221	4.48 ± 1.90	21.8 ± 23.5	3.00 ± 2.20	2.66 ± 0.80	89.6 ± 81.25
	Hot flush	188 ± 124	107 ± 109	27.2 ± 32.9	0.43 ± 0.65	2.96 ± 4.94	14.2 ± 11.5
2nd visit	Hot stg	580 ± 273	4.42 ± 12.5	5.06 ± 7.91	3.44 ± 2.24	0.81 ± 1.43	155 ± 143

Cold and hot stg means stagnated water samples collected at first draw, and flush means samples collected after flushing.

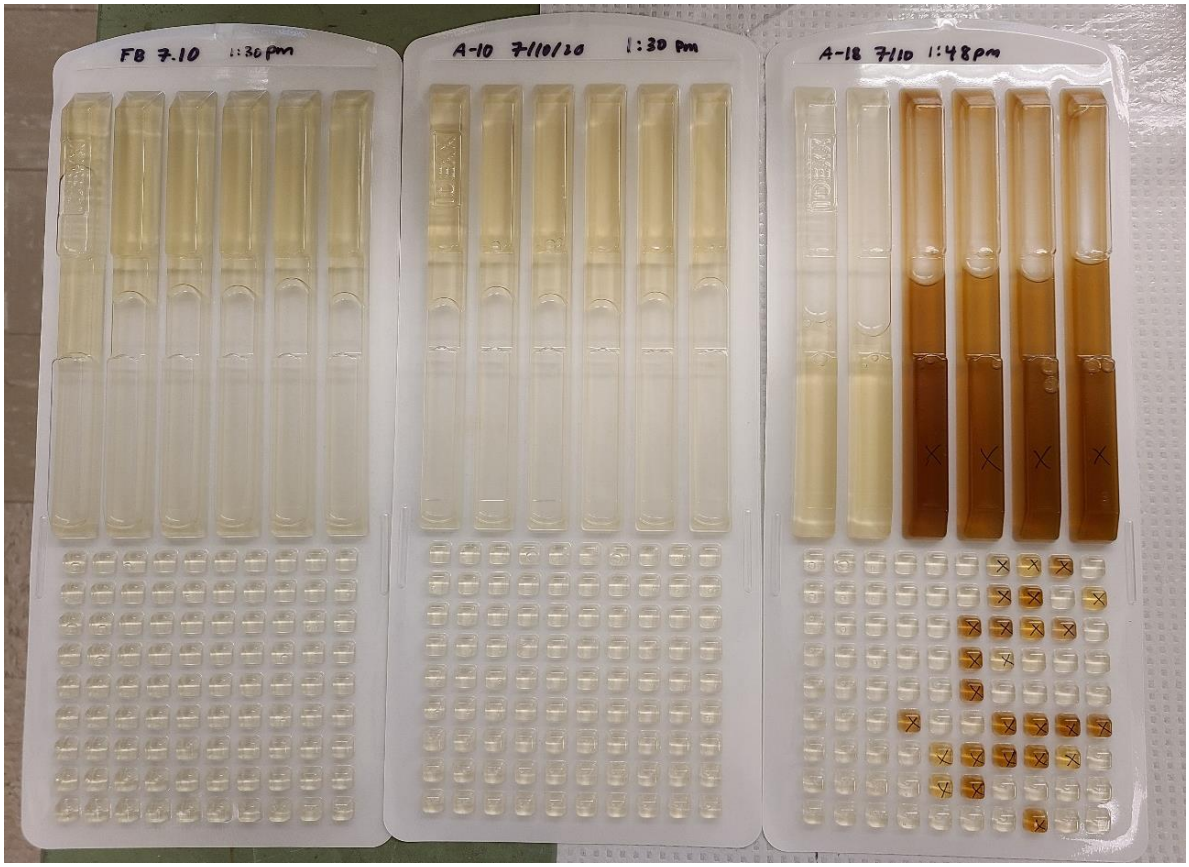


Figure SI.3-4. Example of quanti-tray by IDEXX® Legiolert for field blank, A-10, and A-18. Brown color indicates confirmed positive for *L. pneumophila.*

APPENDIX SI.4

Table SI.4-1. Summary of several recent MP detection studies in water environment

Water Type, Country	Detection /Quantification method	Size, mm	MP types reported	Abundance (MP/L)	Ref.
Drinking water	Infrared spectroscopy	>0.05	Various types	-	41
Drinking water	Raman spectroscopy	>0.02	Various types	-	15
Tap, BRA	Microscopy	0.006 – 0.05	nr	Max. 219	37
Tap, CHN	Microscopy	0.05-4.83	98.7% fiber, 2.2% film	0 – 8.6	36
Ground, USA	py-GCMS	<1.5	Only fiber (PE)	0 – 15.2	3
Surface, CHN (Lake)	μRaman spectroscopy	0.048 – 5	Fiber>fragment>pellet>foam; PP>PS>PE	0.47 – 15.0	90
Ground, DEU	μFTIR	0.05 – 0.15	PP>styrene-acrylonitrile resin>PE	0 – 7	2

Bottled, DEU	µRaman spectroscopy	<0.005	PET bottle: PET>PP>PE; glass bottle: PE>PP>styrene-butadiene-copolymer>PET	Max. in glass bottle; 35,346	41
Bottled, DEU	µRaman spectroscopy	0.005 - >0.1	PEST>PE>PP>PA	2 – 44	39
Surface, CHN (River)	µRaman spectroscopy	<0.5 – 1	Fiber>fragment>foam>pellet; PP>PE>PS	1,597 – 12,611 MPs/m^3	91
Tap, USA+	Optical microscopy	0.10 – 5	**Fiber>>fragment>film	0 – 60.9	34
Tap, DEN	µFTIR	0.01 – 0.1	Cellulose, fiber>fragment>film>PP>PS,PET	4 – 30	35
Bottled, USA++	FTIR	0.0065 – 0.1	PP>nylon fibers, particle, film	0 – 10,000	38
Surface, CAN (Lake)	SEM-XDS	>0.25	**Fiber>fragment>film>foam	52,508 – 748,027 MPs/km^2	92
Surface, NLD (River)	FTIR	0.01 – 5	**Fiber>sphere>foil	48 – 187	93

Surface, USA (River)	py-GCMS	0.3 – 4.75	**Fiber>fragment>pellet>film, foam	0.00167 – 0.01036	94
Surface, USA (River)	py-GCMS, SEM	0.33 – 4.75	**Pellet, fiber, fragment	0.00048 – 0.011	95
Surface (Ocean)	Optical microscopy, FTIR	1.93	Mainly cellulose or rayon fiber; Rayon>PE>polyamide	0 – 0.0013	96
Surface, CHE (Lake, river)	FTIR	nr	PE film>PP fragment>PS foam	790 MPs/hr for river, 91,000 MPs/km^2 for lake	97
Surface, USA (River)	SEM	0.33 – 2	**Fiber>fragment>pellet> PS foam	0.0019 – 0.018	98

nr = Not reported; Asterix (**) indicates the type of material for a MP was not reported; USA+ = samples from the USA and 14 different countries, USA++ = samples from the USA and 9 different countries; py-GCMS = pyrolysis gas chromatography mass spectrometer; SEM-XDS = Scanning electronic microscopy- X-ray energy-dispersive spectrometer; FTIR = Fourier Transform Infrared Spectroscopy.

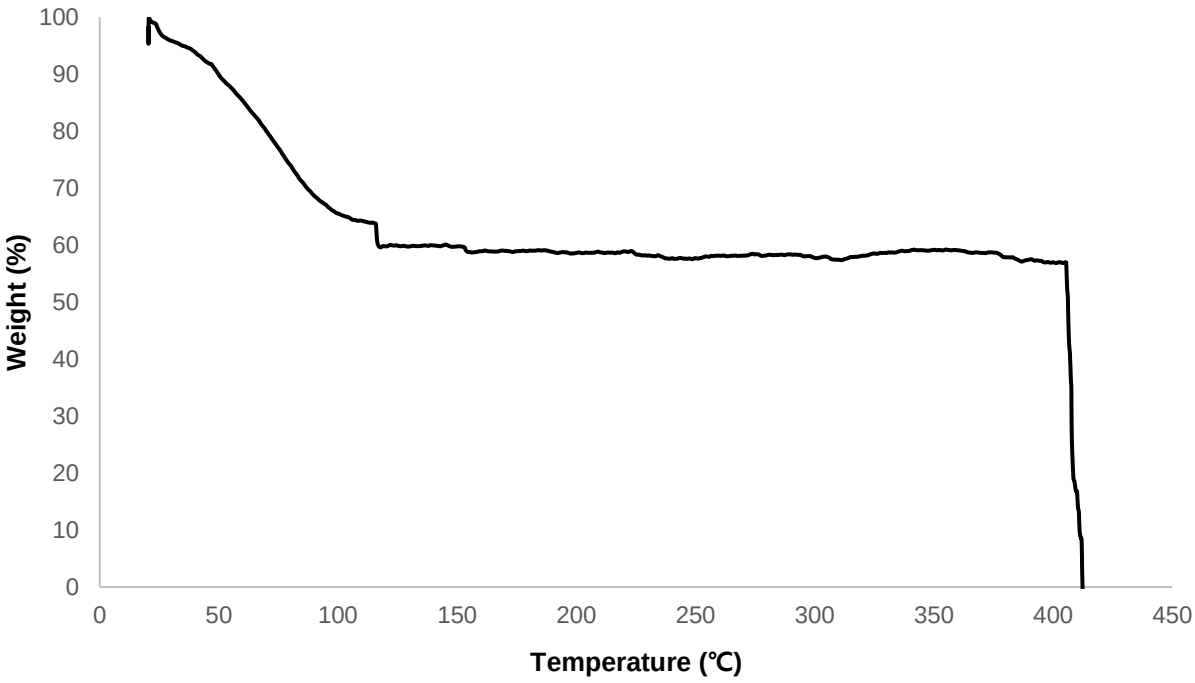


Figure SI.4-1. Thermogram of the as received water softener resin.

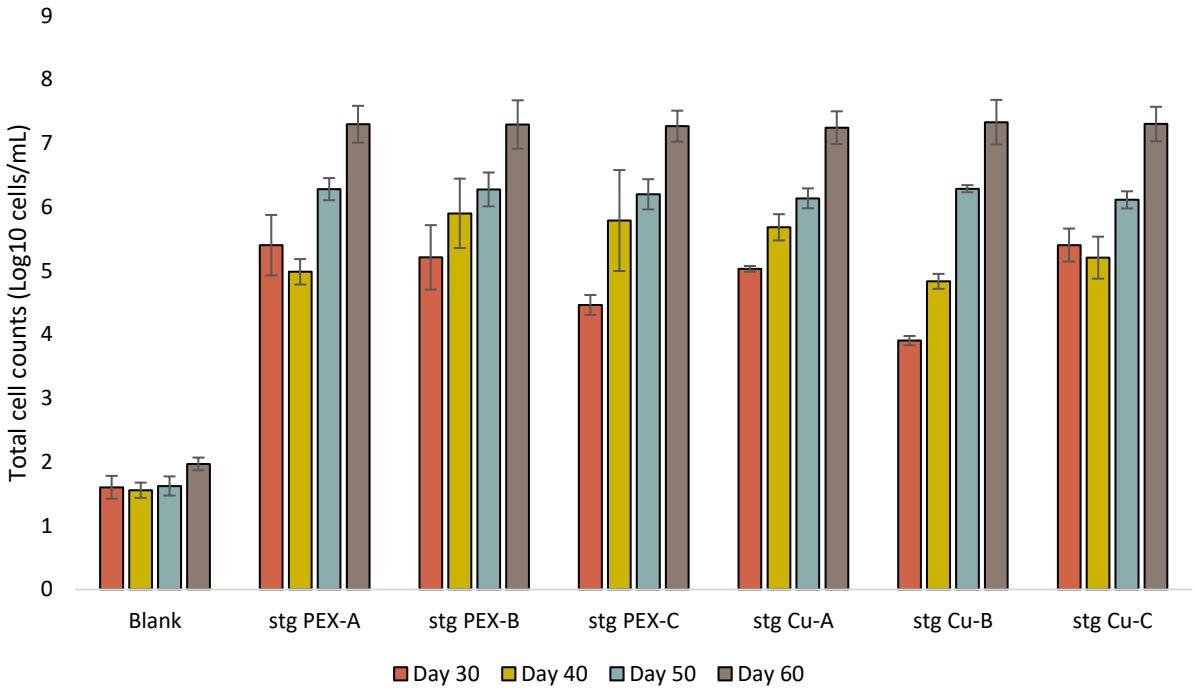


Figure SI.4-2. Total cell counts of water samples removed from aged pipes to estimate biofilm formation before microplastics were added. Three replicates for each A, B, C sets of pipes were examined.

Table SI.4-2. Total sulfur levels caused by heat treatments and for control waters

Description	Concentration, mg/L
Blank tap water	19.17 ± 0.09
Ultrapure water	0.16 ± 0.01
Treatment: 23’C in MPW	22.15 ± 4.14
Treatment: 90℃ in Air	25.29 ± 5.93
Treatment: 90℃ in MPW	25.13 ± 2.20
Treatment: 23’C in UPW	9.24 ± 4.09

MPW for municipal potable water, UPW for ultrapure water

Table SI.4-3. Total sulfur concentration for control waters and municipal water that contacted resins which were and were not exposed to superchlorinated water

Type of treatment	Control (No resin)	Shock chlorination
Blank tap water	19.67 ± 1.58	-
Ultrapure water	0.80 ± 0.97	-
Stagnation Periods the Resin was Subjected to Control Water Contact or Shock Chlorination		
#1	20.76 ± 2.19	21.89 ± 2.38
#2	19.76 ± 0.78	19.99 ± 0.91
#3	19.89 ± 0.15	20.87 ± 0.95
#4	11.87 ± 1.47	12.95 ± 2.00
#5	20.19 ± 1.77	20.57 ± 2.67
#6	12.51 ± 1.87	13.60 ± 0.65
#7	20.19 ± 0.61	20.91 ± 2.58
#8	13.71 ± 0.75	15.29 ± 0.86
#9	21.59 ± 2.67	22.45 ± 2.45
#10	12.11 ± 1.23	13.17 ± 0.13

Table SI.4-4. TOC and TS concentrations for municipal potable water removed from a 15 year old water softener

Location of Resin Sampled	TOC, mg/L	TS, mg/L
Top of the resin bed	4.06 ± 0.01	13.49 ± 0.11
2 ft below the top of the bed	271.9 ± 0.49	87.53 ± 0.73