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Original Research

Four buildings and a flush: Lessons from degraded water quality and recommendations on building water management

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ABSTRACT

A reduction in building occupancy can lead to stagnant water in plumbing, and the potential consequences for water quality have gained increasing attention. To investigate this, a study was conducted during the COVID-19 pandemic, focusing on water quality in four institutional buildings. Two of these buildings were old (>58 years) and large (>19,000 m^2), while the other two were new (>13 years) and small (<11,000 m^2). The study revealed significant decreases in water usage in the small buildings, whereas usage remained unchanged in the large buildings. Initial analysis found that residual chlorine was rarely detectable in cold/drinking water samples. Furthermore, the pH, dissolved oxygen, total organic carbon, and total cell count levels in the first draw of cold water samples were similar across all buildings. However, the ranges of heavy metal concentrations in large buildings were greater than observed in small buildings. Copper (Cu), lead (Pb), and manganese (Mn) sporadically exceeded drinking water limits at cold water fixtures, with maximum concentrations of 2.7 mg Cu L^{-1}, 45.4 μg Pb L^{-1}, 1.9 mg Mn L^{-1}. Flushing the plumbing for 5 min resulted in detectable residual at fixtures in three buildings, but even after 125 min of flushing in largest and oldest building, no residual chlorine was detected at the fixture closest to the building's point of entry. During the pandemic, the building owner conducted fixture flushing, where one to a few fixtures were operated per visit in buildings with hundreds of fixtures and multiple floors. However, further research is needed to understand the fundamental processes that control faucet water quality from the service line to the faucet. In the absence of this knowledge, building owners should create and use as-built drawings to develop flushing plans and conduct periodic water testing.

1. Introduction

During the COVID-19 pandemic, many commercial and institutional buildings were either closed or transitioned to low occupancy, which prompted drastic reductions in building water use [1]. In response, several government agencies cautioned building owners about the potential increase in chemical and microbiological health risks associated with constructing water systems [2–7]. Pre-pandemic building water system investigations have shown that lower water use and stagnation periods sometimes resulted in increased bulk water heavy metal concentrations, such as copper (Cu), iron (Fe), lead (Pb), zinc (Zn), reduced disinfectant residual concentrations, and increased microorganism concentrations (*Legionella pneumophila*, *Pseudomonas aeruginosa*,

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etc.) [8–24]. Additionally, pipe scales and biofilms were reported to influence water quality before the pandemic. Changes in water pH can influence disinfectant efficacy [18], and such changes can also shift system conditions towards precipitating metal oxides [19–23].

The present field study was begun during the pandemic when no prior low occupancy building water system data were available. Since then, several investigations into building water quality conducted during the pandemic in countries, such as Canada, China, Switzerland, and the U.S., have been published [24–36]. Across all these commercial and institutional building studies, stagnant water often had low chlorine residual levels and sometimes elevated heavy metal and microbial concentrations. Flushing fire hydrants every other day near low occupancy buildings in the U.S. resulted in reduced Cu, Pb, and Zn concentrations in building water [34]. Oversized water softeners and low water usage were found to be partly responsible for *Legionella* growth [33]. Plumbing treated with chloramine disinfectant exhibited less *Legionella* growth than those treated with free chlorine disinfectant [35–37]. For perspective, free available chlorine is the predominant disinfectant used in U.S. drinking water distribution system to limit microbial growth [38]. Comparisons across studies were complicated by the fact that buildings served by the same public water system often had different water quality, likely due to variations in plumbing design and usage [30].

To mitigate the risk of encountering unsafe water during the pandemic, numerous organizations recommended fixture flushing before reopening buildings [3,6,39]. Some organizations also recommended routine fixture flushing during the low occupancy period. However, recommended actions sometimes conflicted between organizations, such as the wide range of flushing times (ranging from a few minutes to a couple of hours per fixture) and the number and locations of recommended in-building flushing locations. Studies conducted during the pandemic revealed certain outcomes: immediate and frequent flushing temporarily increased chlorine disinfectant levels, reduced heavy metal concentrations [26,34,36], decreased bacterial cell counts [37], and decreased *Legionella* concentrations. In one case, chlorine dioxide treatment was applied to reduce *Legionella* to nondetectable levels [40]. However, some investigators found that bacteria levels (mycobacteria and *Mycobacterium avium* complex) rebounded a few days later after flushing stopped [36]. Flushing also increased the microbial activity in the plumbing system, which was hypothesized as “high shear sloughing of biofilm” and nutrient introduction [41]. Heavy metal concentrations sometimes increased after flushing, depending on the location and the type of metal [34,37]. Theories suggested that Cu, Pb, corrosion scales, and microbiological contaminants (*Legionella* species and biofilms) were released into bulk water during flushing [28]. Tempered water increased Cu concentrations during a 5-min flush, but Cu levels were also hypothesized to depend on the age and type of plumbing [30]. Various studies showed that flushing, without a detailed plan, was ineffective in resolving water quality issues due to the complexity of the plumbing.

The goal of this study was to better understand water quality, both chemically and microbiologically, in low-occupancy buildings and the impact of flushing on water quality. Water usage records were reviewed, and chemical and microbiological water analyses were conducted on four buildings served by a single public water system. The specific research objectives included: (1) characterizing the first-draw chemical and microbiological water quality in stagnated buildings, (2) conducting flushing of each building water system and monitoring changes in chemical and microbiological quality, and (3) identifying effective measures to maintain water quality during low water usage periods.

2. Materials and method

2.1. Water supply and buildings studied

Water quality was monitored within four buildings served by a public water system in Indiana, the U.S., from March to July 2020. The public water system obtained its raw water from nine wells where it added free chlorine disinfectant as residual and fluoride. A proprietary phosphate blend (ortho- and poly-phosphate) WSU 389 from Water Solutions Unlimited, Inc. (Camby, IN) was added as the corrosion inhibitor. The typical total phosphate range in the distribution system was 1.0–1.2 mg L^{-1} as P. In 2020, the total chlorine residual concentration reported in the distribution system was 0.78–1.0 mg L^{-1} as Cl_2 (Table SI1). Drinking water was provided to approximately 250 buildings and a 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 predominant material used for water mains, while a small amount (5%) of the water mains were made of 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, and buildings C and D in the Southeast service area (Fig. SI1). 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. Building A had an additional deionized water line for laboratories, and the hot water was softened before heating. Both cold water and softened cold water were used for potable water applications. Due to renovations over the past 30 years, complexity was encountered within single buildings. For example, cold water was being softened on the east side of building A, while on the west side, two softeners were empty (no resin), yet water still flowed through those tanks. Building B had the smallest water heater (151.4 L). An electric water meter was installed in buildings B, C, and D. Buildings C and D were right across the street from one another, drawing off the same water main. The distance between the service lines of the two buildings was about 198 m. Building C had a 145.9 L on-demand tankless water heater (steam heated). In building D, one water softener and water heater remained connected to the plumbing, allowing water to flow through the tanks without regenerating (Fig. SI2). No water softener was present in either building B or C, and the regeneration frequency of water softener building A prior to the pandemic was not reported to the authors.

2.2. Water sampling approach

From March to July 2020, building site visits and water sampling were conducted (Fig. 1). As part of the study, the sampling team notified the building owner before each building was visited and identified the locations to be sampled. Buildings were formally reduced to low occupancy on March 16th by the building owner. Before buildings were officially shut down, 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 and cold and hot water fixtures at the bathroom and kitchen sinks (Table SI2). A few drinking water fountains were inoperable at building D.

Generally, water sampling began around 8:30 a.m. and one building was sampled by the authors at a time. Two buildings were sampled in a day, taking around 2 h for each smaller building and

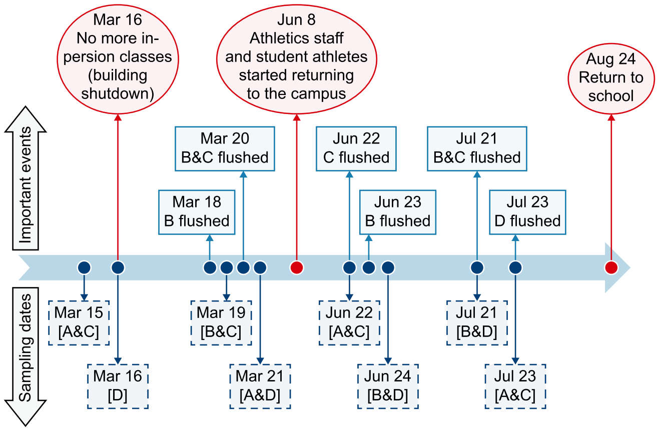

Fig. 1. Sampling timeline. Few flushing dates that were close to sampling dates or on the day of sampling were added to this timeline because flushing occurred by the school (blue square outlines) may have interrupted the stagnant sample for the study.

3–4 h for each larger building. Only about 6–8% of all fixture locations were sampled in buildings A, C, and D, and 25% were sampled in building B. Samples were transported to the laboratory within 2 h after sample collection and stored at 4 °C. 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 was collected. Hot water was collected subsequent to sampling cold water at the same kitchen sinks. At most bathroom sinks, only hot water was collected, in part due to fixed-temperature faucets. Faucets that seemed to be located closest to the service line on the lowest floor were sampled first, and samples were then collected on the upper floors. The authors tried to designate sampled fixtures by balancing spatial (e.g., longitudinal and vertical distance from the service line) and fixture type.

Approximately 1.5 L of water was collected for analysis. First, about 200 mL of water was collected in a glass beaker to measure pH, temperature, dissolved oxygen (DO), 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 the first draw sampling, additional water samples for metals and ions analysis were collected after 5 min of flushing at several same and new locations within each building. Ions in building B were not collected as it was not collected in the March sampling. All water samples were collected at a slow flow rate to minimize splashing caused by some fixtures. although the authors opened the fixtures for a slow flow rate, the water flow rate varied across different fixtures. The water flow rate was measured at several bathroom sinks of building B (5.82–7.68 L min^{-1}, 1.36 L min^{-1}) and building D (8.29 L min^{-1}, 8.98 L min^{-1}). Several fixtures in all buildings had automatic sensors that prompted water sampling difficulty (i.e., start and stop water flow automatically every 20 s).

2.3. *Total chlorine decay in plumbing*

Disinfectant chlorine residual monitoring was conducted in buildings A, B, and C at a few kitchen and bathroom sinks to quantify total chlorine residual decay. Each fixture was flushed for 20 min 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-h period by collecting small aliquots. To assess the impact of plumbing on the reduction of chlorine residual decay, control samples of 1 L each were collected at buildings A and B and measured chlorine residual over a 6-h period. To investigate this, seven fixtures across buildings A, B and C were run for 5 min and four fixtures for 30 min monthly.

2.4. *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. A few locations reported by the building owners in buildings A and D were not visually confirmed due to restricted access doors.

3. Results

3.1. *Building water systems and owner flushing activities*

More than 250 buildings were owned and operated by a single organization, and four buildings were intensively sampled in the present study. Building A and D had three water systems: (1) cold water (unsoftened) to sinks, toilets, and urinals, (2) cold water (softened) to drinking water fountains, and (3) hot water (softened) to all hot water fixtures. Building B and C only had cold and hot (unsoftened) water systems and did not have a softened water system. The building owner informed the authors that the softener in building D was empty, but the water was still flowing through the resin tank to the softened water plumbing.

The author-initiated water sampling for four buildings in March 2020, shortly after they were reduced to low occupancy. In April 2020, the building owner began a periodic cold and hot water fixture flushing program on its property without notifying the authors. If a building's water usage was less than 30% of the weekly water use collected before March 23rd, 2020, the building owner conducted fixture flushing in that building the following week. Approximately 20 staff were responsible for building water systems for all 250 buildings and visited buildings each week for two different purposes: cold water and hot water flushing. In May 2020, the authors learned of this flushing activity and requested the building owner to delay flushing the four study buildings (A, B, C, and D) until they had collected their own samples each morning. In May, the building owner placed the softener in Building A into a weekly regeneration cycle not formerly used.

The cold water flushing practices conducted by the building owner did not follow a standard operating procedure or use building-specific flushing plans. Each building owner representative personally decided: (1) the day and time of their visit to the assigned building, (2) which cold water fixture(s) they would open, and (3) the duration for which they would run those fixture(s). Discussions with the building owner indicated that sometimes only one to two fixtures were operated in buildings with varying floors (up to a maximum of 10) and fixtures (up to a maximum of 215) for various time periods. Fixtures flushed included kitchen sink faucets, bathroom sink faucets, and toilets. Fixture flushing was not conducted on all floors. During the study period, when the building owner assigned a representative to visit the same building multiple times, that person sometimes chose to open different fixtures for different durations on different floors, compared to their previous visits. Sometimes buildings that one individual visited were visited by someone else a subsequent week, and this person opened different fixtures for different durations. Fixtures were generally run for shorter durations at smaller buildings (B and C) than at larger ones (A and D). Building B had the shortest fixture flushing duration (3 min), and records indicated flushing was stopped after the representative detected a free chlorine concentration of 0.2 mg L^{-1} as Cl_2. The longest recorded single fixture flushing duration was 7.7 h in building D, and the chlorine concentration at that location at the end of flushing was 0.1 mg L^{-1} as Cl_2.

Limited onsite information was recorded by building owner representatives, and this inhibited interpretation of the author's water sampling results. Representatives recorded information, such as the name of the building visited, the date and time, but sometimes, not always, recorded the specific fixture(s) opened, the initial chlorine residual concentration, and the time they closed the fixture(s). Representatives used a SenSafe® free chlorine water test strip kit to measure the chlorine residual concentration and flushed until a chlorine residual was detected (method detection limit 0.05 mg L^{-1} as Cl_2).

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 sampling event, the building owners visited the large buildings to flush cold water systems on an average of 4.7–5.6 days and small buildings on an average of 0.6–3 days. For buildings B (July) and C (June), staff were found running fixtures inside the building while the authors were sampling that building. Hot water fixture flushing was also conducted by a separate group of building owner representatives. 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 with the hot water flushing schedule and did not provide the procedure or water quality results.

3.2. 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 1). The small buildings had a 40–75% lower monthly water use during the pandemic. Monthly water use in large buildings was similar to previous years (Fig. SI3). Based on recorded building water use data, the authors estimated flushing volumes by the building owner using a maximum fixture flushing duration. Calculations indicated 0.04–8% of the monthly water use volume during the study period was associated with building owner fixture flushing (Building B > D > C > A). Although flushing activities by the building owners were not consistently organized, flushing could have affected the present study results because the building water was not completely stagnant at some locations. For small buildings, flushing volumes did not approach monthly water use from prior years. It is well-known that water demand could depend on vacations (low occupancy), rainfall, population, etc. [42]. Decreased water demand, likely increased water age, may have impacted observed in-building pressures [43]. A study also found that water demand played a key role in building microbial communities [44]. Thus, many factors could also have indirectly influenced water quality. While improving water management strategies (outside the building) has historically been a focus, improved practices [30,42,45,45] should be applied within buildings to manage water use and lessen potential health risks at low occupancy.

For the two buildings with the lowest water use (B and C), an analysis of as-built drawings indicated that a much longer flushing duration was required to remove stagnant water than the flushing durations the building owner applied. Even for these two buildings, the total flushing durations needed to remove stagnant

Table 1
Building characteristics varied, including year built, size., flushing, and monthly water use before and during the pandemic.

Name	Year Built	Size (m^2)	Floors	Purpose	Total number of fixtures	Number of times in 17 weeks that buildings were flushed by the owner		March–July monthly water use *presented as:* Min–Max (Average) (Liters $month^{-1}$)				
						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	4639	2	Offices, research labs	32	13	14	7949–31,620 (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)[a]	167,379–229,963 (198,857)

[a] Building D in July 2017 was not measured. The average was only calculated in March–June.; Total number of fixtures of the two buildings is not 100% certain because an as-built drawing is not available and laboratory equipment is not included (eye washes, safety showers, fume hood fixtures).

Fig. 2. Various fixture conditions: a drinking water fountain bubbler in building A (**a**), a breakroom faucet in building C (**b**), a 2nd-floor bathroom faucet was flushed for 7.7 h in building D (**c**), and colored water from building D in March 2020 (**d**). After the buildings were reopened, the drinking water fountain from building A was replaced with a new drinking water fountain containing filters.

water differed significantly between these buildings (for example, Building B: 2.85 h and Building C: 14.9 h). This difference is partly due to the different plumbing component sizes and designs (Table SI3). The author's calculated flushing time did not consider draining or flushing water heaters or opening multiple faucets at once, thereby maximizing fixture flowrate or potentially depressurizing the plumbing. To have fully removed all stagnant water from the plumbing, the building owner representatives would have needed much more time and much more staff. Because updated as-built drawings for buildings A and D were not available, the authors were unable to estimate flushing durations in those buildings. A Student's *t*-test indicated that flushing durations and average water use volume were not significantly related ($p > 0.1$). Because each building has a different plumbing design (e.g., pipe diameter and length), flushing durations may be different even if the building sizes are the same.

Because building owner flushing volumes did not approach the overall monthly building water use volumes, water use was likely a function of building inhabitant activity (Fig. SI4). The author's firsthand experiences also indicate that internal building water pressure and fixture condition influenced water use. For example, several fixtures, including drinking water fountains in buildings A, C, and D, were not in good visual condition, and some water samples were discolored and turbid (Fig. 2). It has been found elsewhere that people hesitate to use drinking water fountains because of their appearance prompting water safety concerns [46]. Some drinking water fountains in building D were badly maintained, and water samples were cloudy and yellow (Fig. 2). Building D was initially constructed as a dense residential building and was subsequently renovated to be an office building, with little change in plumbing (i.e., water heaters still sized for frequent shower use). In March, on the 5th floor, one drinking water fountain had little flow, and its flow stopped a few seconds later. On the 10th floor, one drinking water fountain had no flow. Flow problems existed even on the 1st floor, where drinking water fountains were next to one another, but only one dispensed water. 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.

3.3. First draw cold and drinking water fountain quality

3.3.1. Disinfectant, pH, DO, TOC, and TCC

First draw cold water and drinking fountain water quality was similar across all buildings for chlorine residual concentration (0–0.06 mg L^{-1} as Cl_2), pH (7.0–7.7), DO (1.0–9.36 mg L^{-1}), TOC (0.33–0.83 mg L^{-1} as C), and TCC levels (3.44–5.43 Log cells mL^{-1}) (Table 2). The only locations (2 of 46) where chlorine residual was detected were both at drinking water fountains in building A. The public water system reported having a total chlorine level of 0.78–1.0 mg L^{-1} as Cl_2 entered their water distribution system [47]. Potential *L. pneumophila* was detected at building A in May and June and at buildings B, C, and D in July by the culturing method. Though, none of them was confirmed as positive for *L. pneumophila* by IDEXX® Legiolert. In July, water samples collected from the same fixture and different fixtures in the same and other locations were analyzed using IDEXX® Legiolert. None of the locations (0 of 3 drinking water fountains, 0 of 2 cold and 0 of 2 hot) were positive for *L. pneumophila*. The authors used the culturing method for confirming *L. pneumophila* because it was widely accepted in the U.S. Though, this traditional method required a longer duration for preparation and confirmation. In prior studies, researchers have found unclear results due to the "overgrowth of non-*Legionella* bacteria" [48]. Previous studies indicated that the Legiolert method could reliably quantify *L. pneumophila* [49–51], so the authors also used Legiolert to test and confirm relatively quicker than the traditional method. A few studies have detected a low amount of false-positive results on Legiolert [52–55] and "indicated Legiolert works as well or better than the traditional method" [51].

3.3.2. Heavy metals

Initial sampling for heavy metals revealed comparatively higher concentrations in larger buildings than in smaller ones. The maximum metal concentrations were always found in building D, the old residential building repurposed into an office building. Building A had a greater number of locations with high metal concentrations than the other smaller building. Cu and Pb levels sometimes exceeded the public water system's 90th percentile values in their annual water quality report (Cu_{90}: 0.529 mg L^{-1}, Pb_{90}: <1.0 μg L^{-1}) [47]. Cu exceeded the health-based drinking water limit (1.3 mg L^{-1}) at a few drinking water locations in building D (2 of 43, maximum 2.8 mg L^{-1}) and one cold water location at building A (1 of 14, maximum 2.04 mg L^{-1}). Pb levels found in drinking fountain water and cold water in buildings A, B, and C were higher than 1 μg L^{-1} but less than 5 μg L^{-1}. In building D, one drinking fountain exceeded 5 μg L^{-1} in March (45 μg L^{-1}) and May (29.5 μg L^{-1}). In June, no Pb was detected, but Pb exceeded 1 μg L^{-1} again in July at the same drinking water fountain. Manganese (Mn) was detected at all locations in all buildings, and concentrations were greater at drinking water fountains than at other cold water fixtures. In building D, drinking water fountains at the basement, 1st-floor, and 5th-floor drinking water fixtures exceeded the U.S. EPA 1-day health advisory for a child (1 mg L^{-1}) during all four visits (maximum 1.4 mg L^{-1}). The two other building

Table 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	Temperature (°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})	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^{-1})	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^{-1})	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
Microbiology	TCC (log cells mL^{-1})	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^{-1})	3.57	129	2779	101	332	508	63	373	2044	234	349	845	246	293	348	75	371	679
	Pb (μg L^{-1})	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^{-1})	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

*A detailed first draw hot water results are discussed in the SI.

D drinking water fountains were below 0.1 mg L^{-1}.

To better understand the range of heavy metal concentrations at building cold water fixtures, 15–84 additional sampling locations were visited per each building for the first draw water sample collection (A: 52, B: 15, C: 96, D: 84). Cu did not exceed the 1.3 mg L^{-1} action limit at any of these locations. In all buildings, samples with detectable Pb were more abundant in July (Mar: 0–1 buildings, May: 0–2, June: 0–3, July: 1–4). Similar to the first draw of water samples, no sample exceeded 5 μg Pb L^{-1} in buildings A, B, and C. At one cold water location in building D, the Pb reached 14.3 μg L^{-1} (May), 12.7 μg L^{-1} (June), and 24.2 μg L^{-1} (July). At the same cold water location that had a Pb exceedance also exceeded the Mn health advisory level of 1 mg L^{-1}: May (1.9 mg L^{-1}), June (1.9 mg L^{-1}), and July (1.6 mg L^{-1}). No trend was found between Cu, Pb, and Mn concentrations in the first draw water samples. Studies have revealed that sometimes, but not always, Cu, Fe, Pb, Mn, and Zn levels were greater after stagnation in school buildings located in Arizona [29], Tennessee [34,56], Massachusetts [57], and China [24]. Because these metal (Cu, Mn, Mg, Pb, and Zn) leaching are often likely from the pipe materials and scales form during stagnation [57]. Due to the varied water sources, treatment conditions, and description of water quality and water use, reasons for each observation may be due to one or more of the following: corrosion inhibitor reduced efficacy [58], metal component leaching, and scale destabilization. Results also showed building A was producing softened water, while building D, which contained a softener that was reportedly empty per the building owner, was not reducing hardness levels (Tables SI4 and SI5). Buildings C and D were across the road from each other but showed significantly different types and concentration of metals. Because of building complexity, all buildings demonstrated different water quality conditions. The water quality reports provided by the public water supply did not represent the variability found within the buildings, likely because only a few points in the same distribution system were tested, and plumbing itself prompted water quality changes.

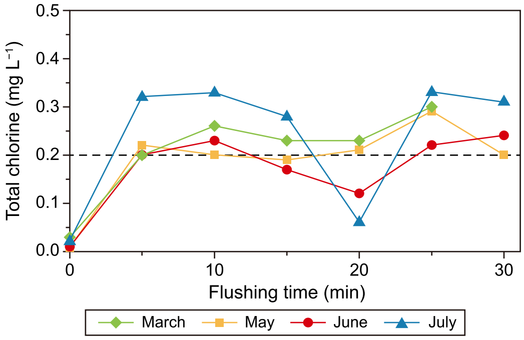

Fig. 3. Total chlorine residual concentrations (as Cl_2) varied monitoring during continuous 30 min of flushing at building A. The dashed line represents 0.2 mg L^{-1} as Cl_2, which was defined as detectable in public drinking water distribution networks. See Fig. SI5 for other buildings.

3.3.3. *Chlorine residual varied at fixtures and remained above 0.2 mg L^{-1} as Cl_2 for about 6 h during stagnation*

A detectable chlorine residual concentration was rarely found at building A, B, and C fixtures (2 of 57), and subsequent flushing of those fixtures revealed the water delivered to building faucets had variable chlorine levels. In building D, no chlorine residual was detected after 125 min of flushing, so flushing was not examined here. During flushing, chlorine residual concentration sometimes fluctuated, especially at building A (Fig. 3). Of seven different locations flushed for the first 5 min, only one location (building A) always had detectable chlorine residual during the study period. Two locations had less than 0.2 mg L^{-1} as Cl_2 after a 5-min flush. During the 30-min flush in the same location, chlorine residual decreased below 0.1 mg L^{-1} as Cl_2 at some locations (Fig. 3, Fig. SI5). During the 30-min flush, no water was found to have a chlorine concentration in the range reported by the public water system [47]. A study found antibiotic resistance gene markers and opportunistic pathogens in biofilms within the distribution system even after flushing activities and chlorinating the water in the storage tanks [59]. The present study also shows that flushing may not always solve long-term building water quality problems.

Chlorine residual decayed faster at fixtures on the upper floors than found at fixtures on the lower floors, which were closer to the water entry point in a large building (Fig. 4). The chlorine decay experiment was conducted in buildings A, B, and C when the buildings were back to normal operations (November). Generally, across most fixtures, floors, and buildings, no chlorine decay differences were observed. Concentrations remained above 0.2 mg L^{-1} as Cl_2 for 6 h when pre-stagnation concentrations were 0.4 mg L^{-1} as Cl_2 (Fig. 4). For two locations in building A, chlorine decayed to less than 0.2 mg L^{-1} as Cl_2 after only 4 h. Other investigators have found faster [12,60] and slower [34] chlorine residual decay inside healthcare, office, and university buildings.

4. Discussion

Widespread exceedances of heavy metal drinking water thresholds in building water were not found during the present study, but health-based drinking water limits were exceeded at some locations. Like prior studies in low occupancy institutional

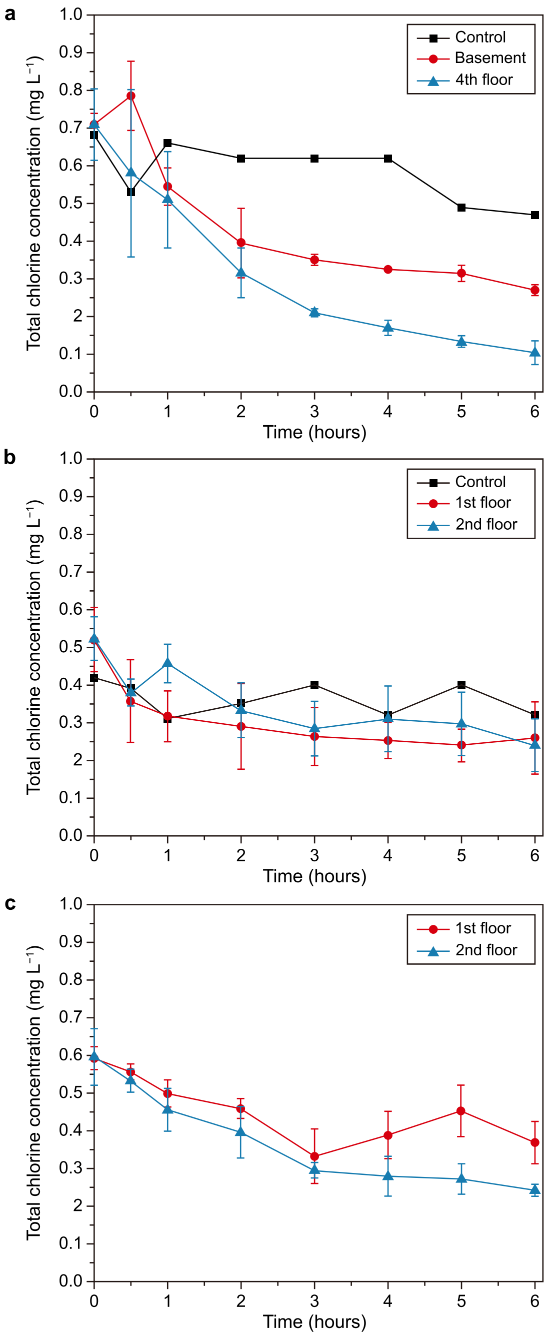

Fig. 4. Total chlorine concentration (as Cl_2) decayed over 6 h at various fixtures within building A (**a**), building B (**b**), and building C (**c**). Building D did not have detectable chlorine residual at the service line even after flushing for 2.08 h. For the control, 1 L of water was collected on the 1st floor in buildings A and B and analyzed over the same period to determine if the plumbing affected the disinfectant decay rate.

and commercial buildings, chlorine concentration was almost always not detectable in first draw samples [12,14,16,34]. This phenomenon has also been observed elsewhere during normal use periods [60,61]. In the present study, water from a few locations (including repeatedly at a single drinking water fountain) exceeded Cu, Pb, and Mn health-based drinking water limits. While the softener in building A was removing calcium and magnesium from drinking water, no trend was detected for differences in Cu, Pb, or Mn concentrations across the cold and hot water softened water systems in that building.

Despite the small number of fixtures sampled in the large buildings and the fact that the building owner flushed some fixtures without informing the authors during the study, water quality problems were still found in the buildings. The small number of buildings was studied due to the high labor requirement of sampling and analysis. Study results 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 at some locations may have prompted hydraulic transients, dislodged scales, and biofilm collected in some water samples. Building plumbing components (i.e., types, lengths, volumes) differed significantly across and even within some buildings, likely inhibiting trends from being detected. It is known that different pipe materials (e.g., ductile iron, Cu, PVC, HDPE, etc.) in public water distribution systems may cause diverse bacterial growth, corrosion, scales, and accumulation, and this may have affected water quality delivered to the service line and even within plumbing [62–66]. With competing influences such as low occupancy and building owner flushing and challenges applied by the building owner flushing activities, it was difficult to determine what impacts either condition had. Some plumbing issues (i.e., in building D) existed before the study began and persisted throughout the study. Overall, study results show that buildings with more controlled influent water quality and use conditions and a more detailed understanding of plumbing component types and locations are needed to elucidate which factors synergistically and antagonistically influenced fixture water quality.

The disparate flushing approach applied by the building owner in the present study was an echo of the approaches in publicly available guidance issued by others to building owners during the pandemic. While many guidance documents recommend that building owners should flush stagnant water before a building is reopened, as reasoned by Proctor et al. (2020), an Indiana state agency [6], and the U.S. Centers for Disease Control and Prevention (CDC) [67], there was no agreement on how flushing should be conducted. For the buildings investigated in the present study, prior to the pandemic, the public water system had directed the building owners to flush drinking water faucets for 0.5–2 min to minimize potential Pb exposure. Prior to the pandemic, the U.S. CDC also issued guidance on fixture flushing and water use for low-occupancy buildings [2]. Broadly, some pandemic building flushing guidance documents recommended continuously flushing fixtures for a minimum of 10 min and flushing all equipment connected to the water lines [5]. Prior to the pandemic, researchers reported that large buildings could have long distances between faucets that may take up to 30 min to flush for a single faucet [68]. Some pandemic-issued building water system guidance documents [4] recommend flushing each outlet for up to 30 min but do not explain how to ensure the fresh new water is at the fixture. Building owners lacked evidence-based practices for reducing health risks after long stagnation periods.

To predict health risks at institutional building faucets, research is needed to understand the relationship between chemical and microbiological levels at the point of entry, through the plumbing and at the faucet. Additional understanding of how plumbing design, materials, and operations influence fixture water quality is also needed. A single study [69] has examined this phenomenon at scale and focused on residential buildings. That study involved more than 220,000 labor hours for monitoring a single-family home with grab samples and continuous online flow and water quality monitoring. There, total chlorine residual, legionella, and heavy metal concentrations at faucets were strongly influenced by influent water quality, service line length, and water use frequency. The study also revealed that legionella concentrations were influenced by interactions between variables, such as water age, chlorine residual, DO, temperature, TOC, heterotrophic plate count (HPC), and TCC [70]. No studies have yet applied such integrative systems scrutiny to commercial or institutional buildings, but these studies are recommended [71,72].

5. Conclusion

The objective of this study was to enhance the understanding of water chemical and microbiological quality in low occupancy buildings and the role of flushing on water quality. This study examined the water quality in four institutional buildings, consisting of two old (>58 years) and large and two new (>13 years) and small institutional buildings. Initial analysis revealed that the first draw of cold/drinking water rarely contained detectable residual chlorine. During the pandemic, the building owner implemented fixture flushing, where a few fixtures were operated per visit in buildings with hundreds of fixtures and multiple floors. Flushing for 5 min by the authors often resulted in detectable residual to faucets in three buildings. However, even after 125 min of flushing in the largest and oldest building, no residual chlorine was detected at the fixture closest to the building's point of entry. During the stagnation, the chlorine residual concentration remained above 0.2 mg L^{-1} as Cl_2 for 6 h. Despite these flushing activities, certain new locations exceeded the limits for Cu (maximum 1.1 mg L^{-1} in cold water at building C, 1.5 mg L^{-1} in hot water at building A), Pb (maximum 24.2 μg L^{-1} in cold water at building D, 10.6 μg L^{-1} in hot water at building B), and Mn (maximum 1915 μg L^{-1} in cold water at building D, 153 μg L^{-1} in hot water at building B). As the present and previous studies showed, spot flushing may not consistently resolve the degraded water problems in plumbing [16,34].

To better manage water quality in low occupancy buildings where the health risks are not yet fully understood, certain actions can be implemented. First, each building should have its own plumbing operations and maintenance plan that includes a well-defined flushing procedure to be applied periodically. Routine water quality testing should include all types of devices in the building, such as water softeners, water heaters, and ice machines. Knowledge of building characteristics, such as plumbing layout, pipe size, the characteristics of the water devices, and fixture count, is important to design an effective flushing plan. As-built plumbing drawings should be created for each new building and renovation project. In the present study, the absence of as-built drawings posed challenges in designing an optimal water sampling and flushing plan, particularly for larger buildings remodeled multiple times over decades. Because water pressure fluctuations may influence flushing, the time needed to bring fresh water to the fixture may vary by fixture. Flushing activities alone may not suffice to prevent water quality issues in complex building plumbing environments. To identify and mitigate potential health risks, chemical and microbiological water testing should be conducted during building commissioning and periodically throughout its service life.

CRediT authorship contribution statement

Kyungyeon Ra: Methodology, Investigation, Data Curation, Writing - Original Draft, Visual Preparation. **Caitlin Proctor**: Methodology, Investigation, Writing - Reviewing & Editing, Supervision, Project Administration, Funding Acquisition. **Christian Ley**: Methodology, Investigation, Writing - Reviewing & Editing. **Danielle Angert**: Investigation, Data Curation. **Yoorae Noh**: Investigation, Data Curation. **Tolulope Odimayomi**: Investigation, Data Curation. **Andrew J. Whelton**: Methodology, Investigation, Writing - Reviewing & Editing, Supervision, Resources, Project Administration, Funding Acquisition.

Declaration of competing interest

There are no competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ese.2023.100314.

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