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RESEARCH ARTICLE

Over the weekend: Water stagnation and contaminant exceedances in a green office building

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Abstract

The role of water stagnation (~60 hours) in a 2-story commercial office building on building water quality was studied (January to February 2020) for three weekends. Chemical and biological parameters including pH, total chlorine, metals concentrations, *Legionella* spp. and total cell count were analyzed to understand the differences in water quality at the building entry point, and at eleven fixtures within the building's copper plumbing. Consistently, the total chlorine concentration decreased over the weekend ($p < 0.05$), was greatest at the building entry point (maximum 0.8 mg/L), and was lowest within the plumbing (maximum 0.28 mg/L). As expected, total cell count levels were much greater on Monday compared to Friday ($p < 0.05$) at every sampling point. *Legionella* spp. was found to be highest at the fixture with no use recorded during sampling. Throughout the building, copper and lead levels increased over the weekend ($p < 0.05$). Copper exceedances above the federal health-based drinking water limit (1.3 mg/L) were localized to four fixtures, branched from the same riser, that shared a pattern of variable use. Flushing was conducted at one location with consistent copper exceedances but 54 minutes were required to reach the public water supply. Flushing was not a viable copper remediation method as it would need to be repeated every 19 hours or require discarding more than 50 gallons before use. No prior water testing was conducted in the buildings' life. The results suggest that water quality varies significantly over the week. This has implications for water testing plans and interpretation of data collected from buildings.

Introduction

As of 2018, there were more than 5.9 million commercial buildings in the U.S. and roughly 972,000 were office buildings [1]. In 2019, more than 100,000 buildings had green

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certifications or projects with the United States Green Building Council (USGBC) [2]. Green buildings are designed to conserve water or reduce the total volume water used compared to conventional buildings. Amongst other goals, green buildings' plumbing is designed by using water efficient fixtures and alternative water supplies. Over the past decade however, some green buildings have been associated with drinking water safety issues [3–8]. Many office buildings have consistently decreased occupancy during weekends and holidays, which regularly increases water residence time in plumbing [9]. This longer residence time increases the likelihood of bacterial growth and greater amounts of heavy metals accumulating in the water as they leach from plumbing components. The combination of lower building water use and routine low occupancy periods may enable water quality deterioration.

Water stagnation in plumbing can affect the water's chemical and microbiological quality, and may increase public health risks [9]. Common stagnation consequences include decreased disinfectant residual, accumulation of heavy metal and organic compounds due to leaching from the pipes and scaling, and an increase in bacterial concentrations including opportunistic pathogens [10–26]. The consequences of stagnation are highly dependent on total stagnation time, as reactions are likely to plateau over time (e.g., saturation, depletion of nutrients to eventually limit growth). While there is no regulated amount of disinfectant residual or bacteria concentration in building water systems, copper has a health-based safe drinking water limit of 1.3 mg/L and the American Academy of Pediatrics recommends that no lead greater than 1 μg/L lead is safe for consumption [27, 28]. To prepare plumbing to code, water chemical and microbiological testing is not required or recommended [29].

Few studies were found that described water quality and stagnation in commercial buildings. In an institutional building, Lipphaus et. al. (2014) found total cell counts (TCC) and intact cell counts (ICC) increased over one weekend and even more so during a 14-day stagnation period due to a winter holiday shutdown. TCCs and ICCs differed 100-fold between plumbing fixtures [30]. After flushing was applied as a remedial method, TCC reductions occurred at cold water taps, but reductions were not as consistent at hot water taps [30]. In another study, TCC increased after a 6 day stagnation in an Illinois institutional building (2018) [12]. Water use at different fixtures (e.g., showers, faucets) differed substantially and this may have contributed to the differential water quality at each location. In a new green institutional building in Arizona, as building occupancy increased, observed copper levels decreased [19]. Chlorine levels were also undetectable in 95% of the first and second draw samples collected [19].

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

Materials and methods

Water sampling was conducted in January and February 2020 in a 10-year-old, 3-story LEED certified office building (20,200 ft^2), in Indiana. The sampling effort was approved by the building manager and owners. A regulated public water system (PWS) that applied chloramines as its residual disinfectant delivered water to the property through a building service line (Fig 1). The buried service line consisted of three pipe segments (a 7.62 m [25 ft] galvanized pipe, and two copper pipes, 5.94 m [19.5 ft] and 22.1 m [72.5 ft]) and held 118.5 L [31.5 G]. Once the water entered the building, all water traveled through soldered copper piping, a

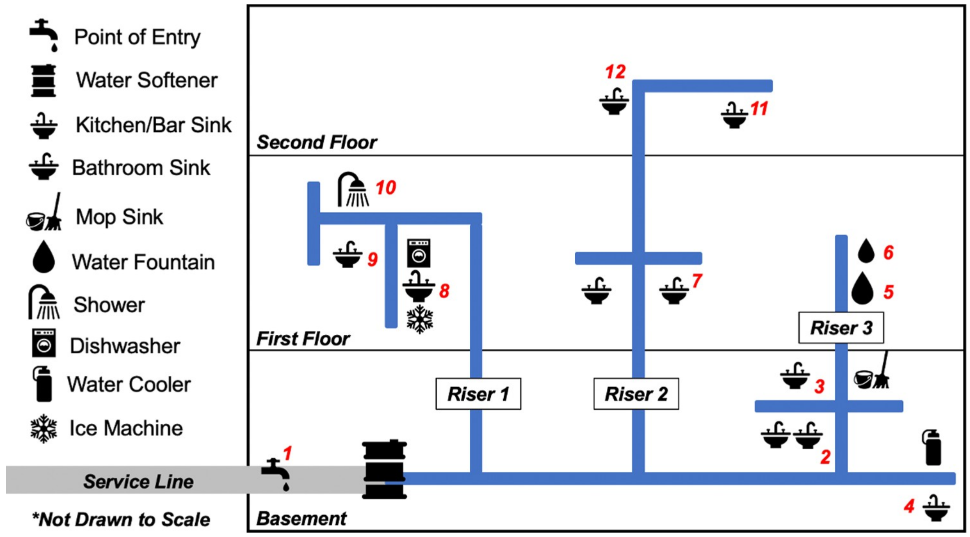

Fig 1. The building water system, including service line, based on drawings and experience. Fire systems, irrigation systems (rainwater), and toilets (rainwater/separate piping system) are not included. Pipes should only be considered vertical when they cross a floor line (i.e., horizontal physical space is necessarily using a vertical schematic representation here). On-demand water heaters are used, so cold water lines provide water almost all the way to sinks.

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59.7 L (16 G) water softener (maximum flow 20 GPM), and then entered trunk and branch plumbing with multiple risers to different fixtures. PWS water was used for drinking, appliances, and cleaning, while rainwater was collected and piped separately for toilet flushing and irrigation. Hot water was created at each fixture with on-demand water heaters (EEMAX Model: SP4208 and EX1608TC). At fixtures where these heaters were located, thermostatic mixing valves (TMV) were present, and at the bathroom sinks (Locations 2, 3, 7, 10 and 12) there was no control over water temperature (i.e., a single supplied temperature vs. a lever to control temperature at kitchen and bar sinks and the shower).

Twelve locations, including 11 of 18 total water use locations and the utility room POE, were sampled (Fig 1). A description of all water use locations can be found in Table 1. The type (cold, on-demand hot, or variable cold/hot) is identified according to temperature sampled. "On-demand hot" refers to the bathroom sinks that had motion sensors and only drew water from the thermostatic, on-demand water heaters during use (i.e., no temperature choice). Other locations (bar sink, kitchen sink, shower) also had on-demand water heaters, but temperature control was possible (cold or variable in Table 1). Water for drinking was consumed from kitchen sinks and water fountains. A water cooler (WS 7000 Water Cooler by Wellsys) connected to potable cold water copper piping (by crosslinked polyethylene tubing) was not sampled routinely, but was sampled once after copper levels greater than 1.3 mg/L were found at other locations.

Fixture monitoring

The time of day that each fixture was used was recorded on a weekly log sheet by the user. The fixtures were self-monitored from one week before the first sampling event through the end of the study. The timeline in Table 2 specifies when self-recording and sampling took place.

Water sampling and analysis

Sampling occurred on Friday evenings and Monday mornings for three weekends (Table 2). The order of sample collection for the building began at the POE and proceeded through the building (Table 1). Water analysis methods were adapted from Ra et. al. (2020) [7]. In total, approximately 2 L of water was collected during each sampling event, with sequential collection for each parameter. Sequential collection prioritized quantification of chlorine residual and total metals in the first flush (to which consumers are often exposed), to avoid potential dilution of these parameters over the 2L collected. Each time a fixture was sampled, 200 to 400 mL beaker was used to collect the first draw sample for analysis of chlorine residual with a HACH 131 Pocket Colorimeter (DPD Free and total chlorine) and pH probe. Next, two 100 mL high density polyethylene (HDPE) bottles, one holding 0.05 mL of 0.0025 N H_2SO_4 for preservation, were used to collect samples for metals and ions analysis. Metals (Al, As, Be, Cd Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, Zn) were analyzed using an iCAP 7400 Duo inductively coupled plasma- optical emission spectroscopy (ICP-OES) (Thermo Scientific) with an autosampler ASX-280 (CETAC Teledyne). Limits of detection and quantification are reported in SI-A Table in S1 File. Ions (Br^-, Cl^-, F^-, NO_3^-, NO_2^-, PO_4^{3-}, SO_4^{2-}, NH_4^+, Ca^{2+}, Li^+, Mg^{2+}, K^+, Na^+) were analyzed using an An Metrohm 940 Professional IC Vario with a 850 Professional Sample Processor. Total organic carbon (TOC) and dissolved organic carbon (DOC) samples were collected next using a 250 mL amber glass bottle. For preservation 1 mL of HCl was added after collection for TOC/DOC samples. TOC/DOC concentrations were analyzed using a Shimadzu TOC-L CPH/CPN following USEPA method 415.1 [31]. A 250 mL amber glass bottle was used to collect a sample for alkalinity analysis. Alkalinity was analyzed by an acid base titration of 50 mL of sample with 0.0025 N H_2SO_4. The TCC samples were collected using 15 mL falcon tubes and were analyzed using flow cytometry (FCM) by using SYBR Green I dye (SwissResearch method 366.1). Analysis was conducted using a Beckman Coulter CytoFlex 4 with APD detectors, highly sensitive for fluorescence, and lasers 488 nm, 405nm, 532 nm, and 640 nm. Finally, a sample was collected for qPCR in a 1 L high-density polyethylene (HDPE) bottle (with 5 mL of sodium thiosulfate for preservation).

Table 1. Locations sampled, with numbers corresponding to sample order and other figures.

Locations Sampled					
Number	**Floor**	**Riser**	**Description**	**Type**	**Volume to Water Main (G)[5]**
1	B	1	Point-of-entry (POE) (Not a water use point)	Cold	31.3
2	B	3	Men's bathroom sink	On-demand hot[1]	52.0
3	B	3	Women's bathroom sink	On-demand hot[1]	52.0
4	B	3	Kitchen sink (double lever)	Cold[2]	52.4
5	1	3	Drinking water fountain (48" tall)	Cold	52.2
6	1	3	Drinking water fountain (36" tall)	Cold	52.2
7	1	2	Bathroom sink	On-demand hot	51.9
8	1	1	Kitchen sink (double lever)	Cold[2]	49.5
9	1	1	Bathroom sink	On-demand hot[1]	49.9
10	1	1	Shower	Variable temperature–hot[3]	49.8
11	2	2	Bar sink (Single lever)	Variable temperature–cold[4]	c.a. 52.2[6]
12	2	2	Bathroom sink	On-demand hot[1]	52.0

[1] On-demand water heater with a single set (warm) temperature and flowrate.
[2] Cold and hot available, cold sampled.
[3] On-demand water heater with single lever variable temperature–warm sampled.
[4] On-demand water heater with single lever variable temperature–cold sampled.
[5] Volumes in gallons were determined by examining as-built drawings.
[6] This was an addition not included in the original building plans, and is thus an estimate.

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Table 2. Timeline of the study sampling.

Sampling Day	Sampling Detail
Monday, January 13	New week of monitoring fixture use
Monday, January 20	New week of monitoring fixture use
Friday, January 24	Sample Event 1–5:15 PM
Monday, January 27	Sample Event 2–6:30 AM
	New week of monitoring fixture use
Friday, January 31	Sample Event 3–5:30 PM
Monday, February 3	Sample Event 4–6:30 AM
	New week of monitoring fixture use
Friday, February 7	Sample Event 5–5:30 PM
Monday, February 10	Sample Event 6–6:40 AM
	Flushing sampling—7:56 AM

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For qPCR analysis, approximately one liter of the final water sample was filtered through polycarbonate filters (Milipore #HTTP047) with 47 mm diameter, and 0.4 μm pore size. DNA extractions were performed as described in EPA Method 1611 [32]. Filters were transferred to a 2 mL semi-conical screw-top microcentrifuge tube with 0.3 g of acid-washed, 212 to 300 glass beads (Sigma-Aldrich, #G-1277) and 600 mL AE buffer (Qiagen, Valencis, CA, USA) were added. The tubes were sealed, bead milled at 5,000 reciprocations/minute for 60 seconds and centrifuged at 12,000 x g for one minute to pellet. The supernatants were transferred to clean, low retention, UV treated microcentrifuge tubes, and centrifuged for an additional five minutes. The supernatants were transferred to another clean, low retention micro-centrifuge tubes and stored at -80˚C until qPCR analysis. The 23s rRNA of *Legionella* spp., and *mip* genes of *Legionella pneumophila* were enumerated by qPCR using previously published method [33] (primers in SI-B Table in S1 File). The qPCR assays were performed using the StepOne Plus™ real-time PCR System (Applied Biosystems, Foster City, CA). Each assay had six 10-fold diluted standard curve points consisting of genomic *L*. *pneumophila* strain Philadelphia-1 (ATCC 152D-5) DNA, a non-template control (sterile reagent water), and DNA extracts from water samples; each sample was tested in triplicate. The duplex *Legionella* spp. and *Legionella pneumophila* qPCR assays were amplified using a 25uL reaction mixture, with five μL template DNA, five μL of 5 X Perfecta Multiplex qPCR ToughMix (QuentaBio), 500 μM of each primer, and 200 nM of each probe. The thermal cycling protocol was as follows: denaturation for 15 minutes at 95˚C, followed by, 45 cycles of 15 seconds at 95˚C and 60 seconds at 60˚C. The qPCR efficiencies for sample events 1–6 for *Legionella* 23S rRNA and *L*. *pneumophila mip* genes were as follows, 90.906, 94.447, 93.182, 94.637, 93.157, and 100.83, respectively. The correlation coefficients of the standard curves were, 0.995, 0.999, 0.992, 0.999, 0.997, and 0.998. The following quality control measures were used, such as, PCR-grade water for negative controls, UV sterilization of PCR equipment, using aerosol-resistant tips, separate work spaces for reagent and sample preparation and amplification. In this study, trip blank, field blank and DNA extraction negative controls were included for each sample event. We addressed PCR inhibition by diluting the nucleic acid extract 5-fold and 10-fold for re-analysis. The sample was considered as positive only if all the triplicate wells showed qPCR signals. The reference genomic DNA was obtained from the ATCC and quantified using fluorometer (Qubit, Invitrogen).

Following the final sample event, flushing was evaluated to remediate elevated copper levels that were found. A flush study was conducted on Location 4 by opening the faucet for 100 minutes at 2.18 L/min, and then leaving the faucet stagnant for 6 hours, with samples taken for disinfectant residual, metals, and TCC analysis as described above. This location was chosen to limit disturbance of office workers, and the rest of the building continued with normal use. Additionally, a water cooler in the basement was sampled for metals analysis.

Statistical methods

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

Results and discussion

Fixture use

During the study, total fixture use was greatest on the first floor (833 recorded uses), followed by the 2nd floor (442 recorded uses), and then the basement (174 recorded uses). Fixture use was likely affected by the total number of fixtures and persons on each floor (6 fixtures on first floor, 2 fixtures on second floor and 5 fixtures in the basement). The basement was primarily used for occasional small conferences and thus water use was irregular. Here, water use may have been under-reported by guests unfamiliar with the recording system. The fixture with the greatest number of uses per week was location 12 (second floor bathroom sink) (80 to 104 events per week) (Fig 2). Use was likely highest here due to the small number of bathrooms and high number of offices on the second floor (i.e., high demand, low supply). The users of this tap were also primarily employees familiar with the system (i.e., not visitors). The least used fixture was location 10, the fitness shower, which did not have any recorded use. The authors were told that the shower was often used seasonally by active commuters (e.g., biking), but the present study occurred in the winter. The first floor bathroom sink next to location 7 (B*, Fig 1), which the authors did not sample, was the only location with recorded weekend use (3 times total on weekends).

Use also varied by riser. Riser 2, which supplied many of the bathrooms on the 1st floor and all outlets on the 2nd floor [Locations 7, 11–12 and B*], was used the most with 923 recorded uses. Riser 1, which supplied the 1st floor kitchen sink and the bathroom with the shower

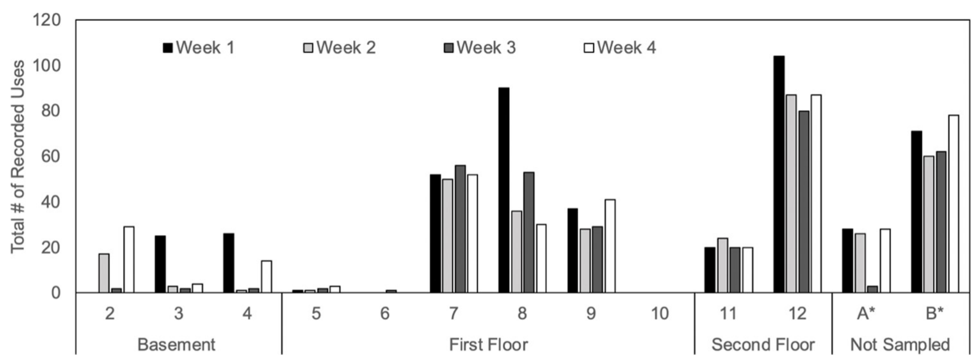

Fig 2. Usage frequency at each location throughout the study. Week 2 (starting 1/20/2020) included a government holiday on Monday. Sampling took place over the weekends following weeks 2, 3, and 4. A* is a sink with the same bathroom as Location 3, which was never sampled. B* is a sink in a bathroom next to Location 7, which was never sampled. Location 1 was the point of entry and is not shown because there is no use at this point. More location descriptions can be found in Table 1.

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[Locations 8–10], had much fewer uses at 344 recorded uses. Riser 3, which supplied the basement and 1st floor water fountains [Locations 2–6 and A*], had the fewest recorded uses with 267 recorded uses. Use of Riser 3 was also considerably variable due to the variable use in the basement described above.

Water quality variations seen at in-building locations

Water at the POE (location 1) throughout the study had pH of 7.0 to 7.5, 1.5 to 3.2 mg/L organic carbon, 0.39 to 0.8 mg/L as Cl_2, and an alkalinity of 200 to 289 mg/L as $CaCO_3$. For biological parameters, the POE had TCC of 3.72 to 4.90 (Log_{10} cells/mL) and *Legionella* spp. at 1.94 to 2.36 Log_{10} gene copy number / 100 mL (SI-C Table in S1 File). *Legionella pneumophila* was not detected in water samples in this study. Drinking water quality entering the building was comparable to the reported water quality in the utility's annual consumer confidence report and water quality monitoring station data for the PWS (SI-D and SI-E Tables in S1 File).

Some water quality differences were found amongst the three risers and individual faucets. This is likely a combined effect of the water sample's proximity to location 1 (POE), and the frequency of fixture use. Water temperature was lower at the POE compared to other sampling locations in the building. Temperatures (19 to 21˚C) were often colder before the on-demand water heaters were able to heat up fresh water (i.e., very first draw). Once this happened the temperature would increase to about 34 to 36˚C (i.e., by the end of sampling, after 1 to 2 L and at least 30 seconds had passed). Due to the sampling approach, it was difficult to determine which parameters were affected by on-demand water heating.

Within the building (locations 2 to 12), chlorine levels were nearly always lower than those at the POE (location 1) (Fig 3). The only fixtures where total chlorine was 0.2 mg/L as Cl_2 or greater were first floor cold water (locations 6 and 8) on the same Friday. While water use was not recorded directly before this measurement at location 6 (water fountain), it was recorded one hour before sampling at location 8 (first floor kitchen sink). Prior sampling at location 5 also likely affected Location 6. Although the highest levels of chlorine were detected in cold water, there was not a clear relationship between sample type (Table 2) and chlorine. Disinfectant residual decline from the POE to other observation points within the building, as well as variability amongst observation points, was expected and has been found by others [6, 8, 13, 34, 35].

Copper was found in drinking water fountains in riser 3 (Fig 1) above 1.3 mg/L (consequently, these were shut-off), but copper was not found above 1.3 mg/L in other risers. The fixtures on riser 3 (all basement fixtures or first floor water fountains) did experience less and more variable use, compared to other risers as mentioned previously. This varied use may have affected scale release and copper leaching. Additionally, due to the sampling scheme and plumbing layout, water from a riser may or may not have been captured for metals samples.

Legionella spp. was highest at locations 9 (bathroom sink) and 10 (shower), in the same bathroom on the first floor (maximum 4.25 Log_{10} gene copy number / 100 mL). Location 10 was the only fixture not used by patrons during the whole study (only used for sampling) and the sample was taken from the plastic shower hose. Shower hoses have been implicated as a unique biofilm growth niche that can support pathogens [36–39]. It should be noted that the water for qPCR was from the end of sequential sampling, and for locations with on-demand water heaters, likely was stagnant within cold lines, and had a higher temperature during sampling only due to heating seconds before.

Several water quality parameters varied within a range throughout the building. TCC (3.72 to 5.55 Log_{10} cells/mL), pH (7.2 to 7.8, SI-A Fig in S1 File), and alkalinity (171 to 278 as

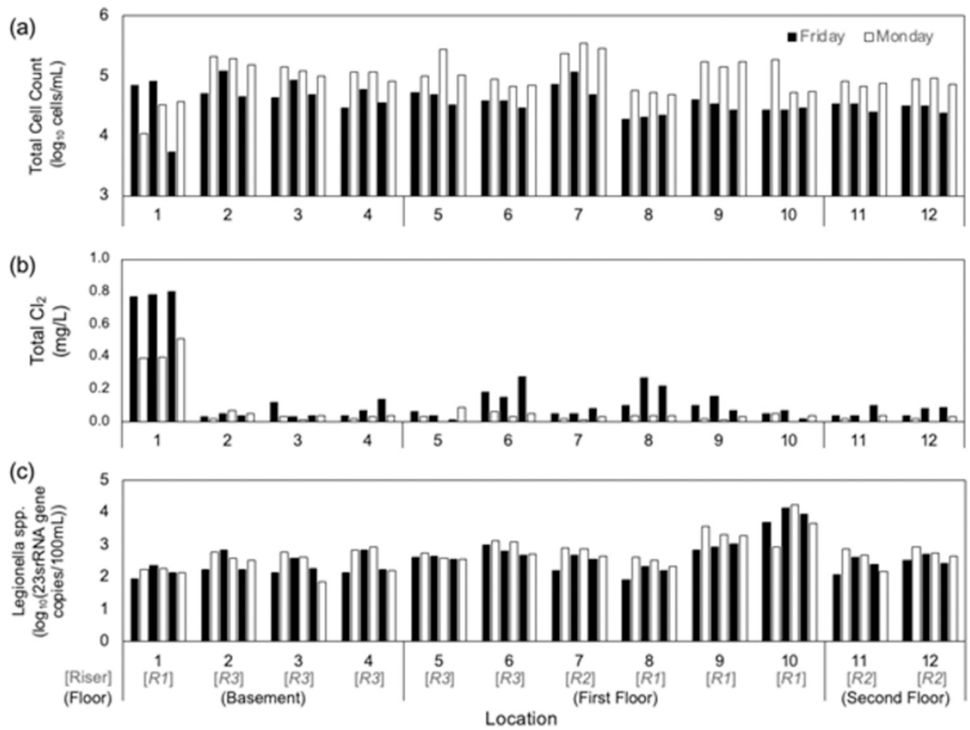

Fig 3. (a) Total cell count (TCC) concentration, (b) chlorine residual concentration, and (c) *Legionella* spp. concentration detected at each location (locations 1–12, grouped by floor) on the six days of sampling. Fridays (black) and the following Mondays (white) are presented in order. The first bar is sampling event 1 (black), then 2 (white), and so on. Riser and floor information is provided for each location and further location descriptions can be found in Table 1, and sample events are described in Table 2.

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$CaCaO_3$ mg/L) at locations inside the building were comparable to the values at the POE. While stable water chemistry was expected, an larger increase in TCC within the building was also expected (i.e., growth with stagnation at individual fixtures). For Monday samplings, locations 2–12 are consistently higher than location 1, but on Fridays, Location 1 was often higher than Locations 2–12. This may be due to the small amount of stagnant water at the sampling port. Additionally, growth may have been masked by the TCC measurement which does not differentiate between living and dead cells. The increase of *Legionella* spp. within the building does indicate that some growth occurred. Riser did not seem to affect TCC.

It is difficult to precisely identify why certain locations had differences in water quality, due to several factors. First, study design influenced observed measurements. For example, location 6 was next to location 5 (both water fountains on the first floor) with less than 2 L of water (sampling volume) within their dedicated pipes. This meant fresher water was brought to location 6 when location 5 was sampled. Due to logistical challenges, the building water sampling plan was completed and began before the as-built drawings were made available. After drawing review, it was learned that while location 3 was sampled after location 2 (basement bathrooms), location 3's pipe was upstream in the system. Sampling point 11 (second floor bar sink) was not shown on the as-built drawing so the authors estimated its location in relation to other points, but its water quality was likely influenced by its proximity to location 12 (second floor bathroom sink). Measurements of fixture use were also self-reported. Results may have been over/under reported, especially at locations where guests (rather than regular patrons) may have used use the water. Finally, our discussion of sample "type" (i.e., temperature) is somewhat limited because of the sampling method, as discussed above. Much of the sample collected, even for "hot" water samples" originated from fixture-specific or cold water piping.

Weekend stagnation affected Monday's water quality

Weekend stagnation influenced chemical and biological water quality, with clear differences in several parameters on Friday, after a week of use, and Monday, after a weekend with relatively little use. At the POE, total chlorine residual concentration was higher on Fridays than Mondays ($p < 0.05$) (Fig 3). The same trend was found at sampling points within the building ($p < 0.05$), with some exceptions. TCC levels were greater on Mondays compared to Fridays at building sampling points ($p < 0.05$). This trend did not hold true at the POE, where total chlorine detection remained higher than 0.2 mg/L as Cl_2 even on Monday morning. There was no significant difference in water temperature at the POE on Friday and Monday ($p > 0.05$). No differences were detected for *Legionella* spp., pH, TOC, and DOC between Friday and Monday sampling periods ($p > 0.05$). The U.S. EPA has a maximum contaminant level goal (MCLG) of zero *Legionella* organisms for water distribution systems, but is not enforceable [40]. It is known that *Legionella* can be introduced into a building distribution system by way of a PWS and grow within building plumbing, but a consistent spatial pattern has not been reported [41, 42].

Low fixture use frequency has previously been associated with high cell counts and pathogenic presence, where a longer stagnation time can prompt a change in temperature and loss of residual [7–15, 26, 30, 43, 44]. There were select occasions where chlorine residual measured higher on Monday than the previous Friday, contradicting what was expected of the chlorine residual during weekend stagnation. While several phenomena could explain this, this was likely due to the low water usage during the week by patrons (e.g., location 10 [shower] was not used except when sampled). The first sampling event at location 10 may have represented weeks or months of stagnation. Subsequently, the sample collected on Friday afternoon reflected stagnation from Monday to Friday (about 106 hours), while the Monday morning sample reflected only about 60 hours of stagnation (weekend). Thus, location 10 experienced 46% more stagnation time during the week than over the weekend. Several other locations also had very low weekly use (Fig 2). Interestingly, the occasions where chlorine was higher on Friday than the following Monday did not seem to have any consequences on TCC. This may be attributable to the nature of sampling, where chlorine was measured in the first 200 to 400 mL exiting the fixture, while TCC samples were taken up to 700 mL later. With small pipe diameters and many samples taken, TCC may have better represented the water further back in the pipe system than at a particular fixture or even within an on-demand water heater. Thus, total water usage on the floor, in the riser, or in the building may have had a greater influence on TCC than individual use at a tap in this study.

A brief analysis of the number of hours stagnant before use (according to recorded use by building patrons), versus chlorine (SI-B Fig in S1 File) and TCC (SI-C Fig in S1 File) did not reveal consistent trends. There was high variability in both parameters at stagnation times less than 8 hours and at hour 60 (all Monday samples were 60 hours stagnant). This could suggest failure to record usage data, but other hypotheses can also be explored in future studies. The overall stagnation patterns at each tap or in each riser likely influence water quality, regardless of last use. Moreover, this analysis did not record the volume of water used. A short low volume use, which is unlikely to completely refresh water in the tap, was recorded similarly to a longer flush. To completely model the relationships between use and water quality, a more expansive plumbing use and water quality analysis is required.

Table 3. Range of copper and lead concentrations at each fixture on Friday and Monday sampling events, with all Friday and Monday samples grouped (n = 3).

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

EX = Exceeded copper health-based limit of 1.3 mg/L.

[1] On-demand water heater with a single set (warm) temperature and flowrate.

[2] Cold and hot available, cold sampled [i.e., for drinking].

[3] On-demand water heater with single lever variable temperature–warm sampled.

[4] On-demand water heater with single lever variable temperature–cold sampled. [i.e., for drinking].

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No significant difference was found for nitrogen containing compound concentrations after stagnation. NH_4-N was consistently lower at POE than the other locations within the building (SI-C Table in S1 File). The only time NO_2-N was detected was at location 9 and 10 (first floor bathroom sink and shower), and this did not exceed the federal MCL of 10 mg/L [40].

Stagnation can allow heavy metals that leach from the plumbing scales and materials to accumulate in the water [9, 21, 45]. Copper and lead were detected at the POE, at all fixtures, and some health-based drinking water exposure limit exceedances were found (Table 3). Copper limit exceedances (22%, 8 of 36) were only found for Riser 3 (Fig 1), which fed locations 2–6. Locations 2, 3, and 4 had inconsistent use. Location 6 had consistent low use and was taken out of use when elevated copper levels were found. Three locations (Locations 2–4) contained copper at a concentration equal to or greater than the 1.3 mg/L health-based action level on both Friday and Monday sampling events. Analysis of the number of hours the fixture was stagnant (according to recorded uses) versus copper concentration (SI-D Fig in S1 File) did not indicate a strictly linear trend between copper and stagnation; fixture location and overall use in the week likely had a combined effect with stagnation. Elevated copper levels have been found in similar commercial buildings [7, 19, 20]. Lead levels found at the POE always exceeded 1 μg/L, but not 5 μg/L. Inside the building, however, 8 of the 12 fixtures had sample events where lead exceeded 5 μg/L. The office building was constructed after promulgation of the 1986 Safe Drinking Water Act, which instituted a "lead free" pipe regulation, but plumbing components were permitted to still contain lead.

Flushing only temporarily addressed copper exceedances

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

At location 4, an estimated 220 L of water was flushed. The total volume of water between the water main and location 4 was calculated to be 183 L. The regularly scheduled sample collected for sample event 6 (after weekend stagnation) had a 1.5 mg/L concentration. Copper, at the beginning of the flush, was 1.4 mg/L (a slightly lower value likely attributable to water movement during sample collection). Copper concentration then decreased during 100 minutes of flushing from 1.4 to 0.09 mg/L (Fig 4). After flushing, the fixture was not used for 6 hours, though a 125 mL sample was collected each hour for metals analysis. Copper concentration, after the first hour was 0.32 mg/L and then reached 0.61 mg/L after the sixth hour. After this 6 hour stagnation period ended, the fixture was flushed for an additional 30 minutes (65.4 L) and copper concentration subsequently decreased to 0.08 mg/L. As expected, chlorine concentration exhibited an opposite trend, where chlorine levels increased during flushing and decreased during stagnation. The copper concentration rebounded at a rate of 0.061 mg/L per hour of stagnation (Fig 4) and total chlorine decreased at a rate of 0.31 mg/L as Cl_2 per hour of stagnation. Based on these results, if the copper levels continued to rebound at the rate of 0.061 mg/L per hour, the copper level was predicted to reach 1.3 mg/L in 19 hours (starting from 0.09 mg/L, which was achieved after 100 minutes of flushing). During that same stagnation period, the total chlorine concentration would likely have decreased to less than 0.2 mg/L as Cl_2 within one hour. To avoid the 1.3 mg/L copper conditions at the faucet, if the problematic fixture had gone unused for 19 hours or longer, it would likely need to be flushed before use. However, analysis of hours stagnant (according to recorded uses) versus copper (SI-D Fig in S1 File) indicated that dynamics of copper increase rely upon multiple factors. At Location 4, a

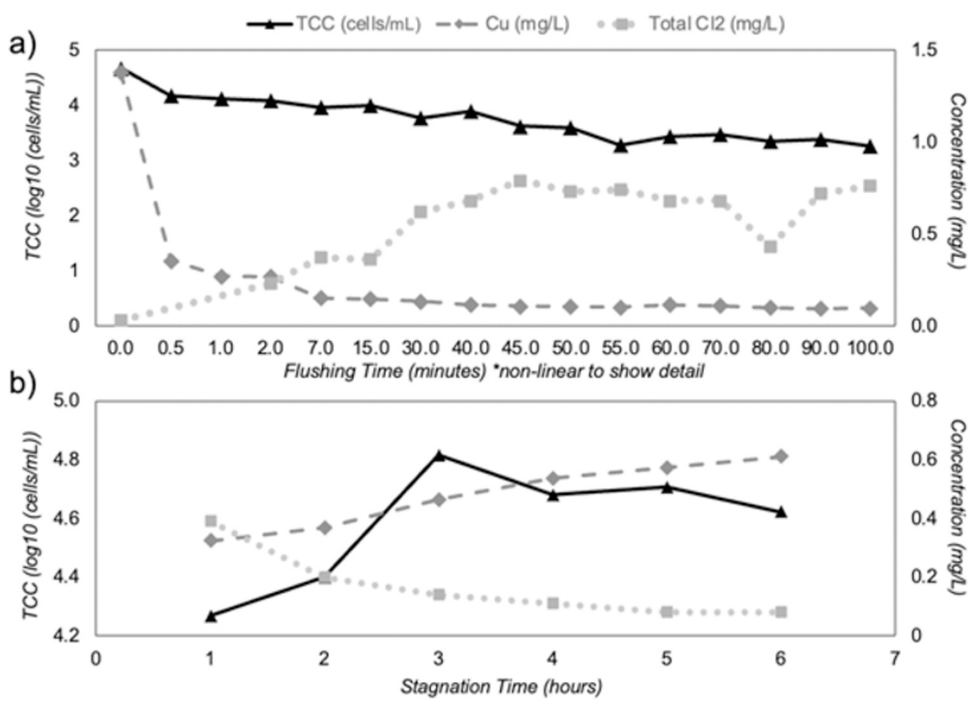

Fig 4. (a) Location 4 flushing event, copper, total chlorine and total cell count (TCC) concentrations and (b) subsequent six-hour stagnation period where copper, total chlorine and TCC concentrations were monitored each hour. Note that graphs in a and b have different scales, and that graph a has a non-linear time scale.

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sample supposedly stagnant for 25 hours had copper levels below 0.75 mg/L, while a sample stagnant for 5 hours exceeded 1.8 mg/L. In the week with 25 hours stagnation, the faucet had been used 49 times, while the day with 5 hours stagnation only had 2 total uses in the week.

Implications

The green office building studied had many features that are increasingly common in new buildings–including on-demand water heaters, TMVs to control available temperature, low-flow faucets, automatic faucets, and alternative piping systems for major water uses like toilet flushing and irrigation. These design elements can change water temperature profiles and significantly reduce the amount of water used compared to traditional office buildings, raising concerns for water quality degradation. The implications of some of these designs have been studied [4, 8, 35, 46, 47]. The water use patterns in office buildings, with consistently low to no use on weekends, raise additional water quality concerns for the first users on Monday mornings.

The loss of disinfectant residual at the building locations and during stagnation (decreasing to near non-detectable levels in about 1 hour) was expected, especially since this building uses an alternative water source for toilets, which tend to be most responsible for water use in offices [48]. This loss is a common feature since chlorine concentration can decrease due to both chemical and microbiological reactions [49–52]. Because individual faucets have variable use patterns, maintaining a disinfectant residual in first draw samples at the tap is likely an unattainable goal under current policies and practices. Despite low water use and a long dedicated service line, this building had detectable chlorine at the point-of-entry for all of the sampling dates, even on Monday morning after a weekend of little to no use. Prior work in a residential neighborhood on a different water distribution system in the state revealed that water entering a building could range from 1.3 mg/L to nondetectable chlorine levels when monitored continuously (online, not grab samples) [34]. Continuous sampling was not conducted on this office building, so more variation is possible. This building was in a busy part of town with residential, commercial, production (a brewery), and offices nearby. It would also be interesting to see if the pattern of weekend stagnation had a stronger effect on point-of-entry samples in a neighborhood with less diverse building types (e.g., a large office park).

The primary concern with loss of chlorine residual is that microbial growth will occur–particularly growth of opportunistic pathogens like *Legionella pneumophila*. In this study, an increase of TCC was observed between Friday and Monday, and flushing only marginally reduced cell counts. The most concerning measured bacteria was elevated concentrations of *Legionella* spp. in a bathroom with a seasonally used shower. Remedial measures at the beginning of the season of use may be warranted at this location, especially as showering poses a high risk of inhalation exposure. It is important to note that *Legionella pneumophila* was not detected, and presence of the genus *Legionella* does not mean pathogens are present. Detection of both the genus and species is also common in drinking water [4, 53]. In this building, on-demand water heaters were used, which (1) decreased the amount of total water stored in the building (i.e., separate hot and cold pipes throughout the building could double stored water), and (2) kept the majority of water within the building at cold to room temperature, which is lower than the preferred growth conditions of many opportunistic pathogens. A traditional hot water design may double the total water storage (i.e., both cold and hot water distribution systems plus a water heater tank). Although energy savings, rather than water safety, was the goal of these water heaters, the relative control of growth in this building may indicate a secondary benefit of the on-demand water heaters in green buildings, where other means of growth control are not available or are the energy costs are too high (e.g., high temperatures in water heaters).

Exceedances of the (acute) health-based drinking water limit for copper were found in one of the three risers, including at bathroom sinks, water fountains and kitchen sinks. Interestingly, another building that received water from the same PWS was found to also have copper exceedances (maximum 2.72 mg/L) (7). In that school building, copper levels consistently exceeded the 1.3 mg/L health-based drinking water exposure limit during the summer months (70% of samples) and even when school was in session (37% of samples) throughout the entire building. Both buildings were between 8 and 10 years old at the time of testing. Discovery that two buildings had exceedances on the same PWS does not represent a statistically representative sample size. This discovery though, coupled with water characteristics that are conductive to copper corrosion (high alkalinity), indicates that more wide-scale testing is warranted within commercial buildings served by the PWS. Testing required by the Lead and Copper Rule tends to focus on residential buildings, and thus commercial office building issues, exacerbated by stagnation patterns, will go undetected as found in the present study. When testing is conducted, it may be difficult to find problems due to highly localized variability. For example, if this office building had been targeted–only a couple of water use points would indicate a problem. Choosing points with little/variable use (i.e., the basement here), or sampling after stagnation (Monday mornings) may increase the likelihood of finding exceedances. Copper leaching can decrease over time due to passivation [54, 55], but the time-scale may be very long (7 years+) based on water quality conditions (high alkalinity, etc.).

To target copper issues, remediation by flushing was explored. To remove all plumbing influenced water and ensure exposure to only water directly from the PWS would require flushing more than 50 gallons of water at each tap (Table 1). Full building flushing (i.e., turning over all water in the building) would require flushing for 90 minutes, and to get fresh PWS water to the most distal location (Location 4) would require 54 minutes of flushing. Automatic faucets, which shut off after 20 seconds, make flushing difficult to pursue. Assuming a linear model of rebound, flushing would need be completed roughly every 19 hours in this building in order to maintain copper levels below 1.3 mg/L in the first flush at the measured tap. That said, if low levels of copper exposure (below 1.3 mg/L) are acceptable to users, it may be feasible to instruct every building user to flush for a shorter period (e.g., 1 minute, which includes a factor of safety), to reduce copper levels before collecting water for consumption. A more comprehensive study would be needed to determine the flushing time needed at each outlets—a greater flushing time might be required at other taps, for example to clear water from the entirety of riser 3. This remediation method would require significant user buy-in, as well as education for all building visitors. A passivation study as well as the installation of in-building corrosion control chemical injection, like done by others elsewhere, could be other potential follow-up options. According to the hierarchy of controls, an engineered solution, which isolates people from the hazard, is preferable to administrative control, which changes the way people work to prevent exposure [56]. Flushing, either by maintenance staff or individuals, is an administrative control and requires constant education. An engineering control, such as installing in-building corrosion control or filters, may be ultimately preferable, although even both require regular maintenance.

Conclusions

Weekend stagnation can induce chemical and microbiological water quality changes in a green office building and prompt exceedance of the acute health-based copper drinking water limit. Monday morning's water quality consistently had a low chlorine residual concentration, greater TCC, and greater levels of copper and lead compared to water found on Friday afternoons. Fixture flushing was a short-term and impractical approach to reduce elevated copper and increase disinfectant residual levels. Even after flushing, copper levels were expected to exceed 1.3 mg/L within 19 hours. In a 6 hour period, chlorine residual decayed at a rate that would have levels below 0.2 mg/L as Cl_2 within an hour.

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

Supporting information

S1 File.
(DOCX)

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