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A case study on tap water quality in large buildings recommissioned after extended closure due to the COVID-19 pandemic†

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Extensive building closures due to the unprecedented COVID-19 pandemic resulted in long-term water stagnation within the plumbing of large buildings. This study examined water chemical quality deterioration in ten large buildings after prolonged stagnation caused by the closure of a university campus in response to the COVID-19 pandemic. Volume-based and constant-duration flushing protocols were implemented to replace stagnant water with fresh drinking water. The effectiveness of the developed water flushing protocols was examined by monitoring the disinfectant residuals, heavy metal concentrations and temperature for water samples collected from the buildings' point of entry (POE) and select water fixtures. More than 14 m^3 of water were flushed in all ten large buildings. The results demonstrated a significantly greater average total chlorine residual concentration in POE water samples collected after flushing (1.1 mg L^{-1}) compared to the stagnant condition (0.6 mg L^{-1}). For water samples collected from fixtures during the extended stagnation, chlorine was absent in 71% of samples from academic buildings and 69% of samples from athletic buildings. The effectiveness of flushing practices is underscored by increasing the median total chlorine concentration from <0.1 to 1.0 mg L^{-1} in academic buildings and from <0.1 to 0.75 mg L^{-1} in athletic buildings. Furthermore, the concentrations of Pb, Zn, and Cu had decreased following the water flushing, but the concentration of Fe had increased in some buildings. This study could be beneficial to prepare for prolonged water stagnation events including but not limited to pandemics.

Water impact

This study examined the water chemical quality deterioration in ten large buildings after prolonged stagnation due to the COVID-19 pandemic and evaluated the effectiveness of two different flushing practices in taking the fresh drinking water to the building plumbing. This study could be beneficial in preparation for many situations that cause stagnation events not just in pandemics but also during holidays, long weekends, long breaks due to breaks in the semester, renovation work of a building, and maybe even other emergency response situations.

Introduction

COVID-19, the severe respiratory disease caused by SARS-CoV-2, was first reported in Wuhan, China, in late 2019.[1] Within only a few months, this highly transmissible and deadly virus spread across many regions and impacted millions of people around the world as a serious global public health problem.[2] To reduce the rapid transmission of COVID-19, many countries took strict actions to encourage a significant portion of their populations to stay home.[3–5] Globally, millions of schools, office buildings, and non-essential businesses such as restaurants, music and movie theatres, clubs, and indoor sports centers were closed to an unprecedented extent and at an unprecedented speed.[3,6,7] These extensive building closures substantially impacted the water use and resulted in an extended drinking water stagnation within the plumbing of the commercial, educational, and athletic buildings.[8,9] Although some of the stay-at-home orders/advisories were lifted within several weeks, and some commercial buildings were reopened at reduced capacity, many recreational centers and school, college, and university buildings remained closed or reopened only for essential workers.[10] The zero- or reduced-occupancy in these large buildings has resulted in prolonged stagnation of drinking water in the buildings' plumbing.[11] Prolonged water stagnation within a building's plumbing raised substantial

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concerns regarding the water's microbial content and chemical quality deterioration.[12,13] The recent field studies that evaluated the water chemical quality variations due to the stagnation within the building plumbing mostly focused on the residential buildings.[12–16] Prolonged stagnation in commercial buildings yields an increased rate of disinfectant decay,[17] enhanced heavy metal leaching (*e.g.* Pb, Cu, Zn, and Fe) from metallic pipes and fittings,[13,18,19] and greater microbial growth[20] within potable water.[21]

Multiple water flushing guidelines for building recommissioning were developed by federal, state, and local agencies during the COVID-19 pandemic to mitigate the adverse impacts caused by prolonged stagnation.[22–24] These guidelines generally suggest simple flushing practices for both hot and cold water by replacing the stagnant water with fresh tap water (finished water from the distribution network).[25] However, more complex practices like shock disinfection (using elevated water temperatures and high disinfectant concentrations)[26–28] were recommended as the remediation for *Legionella* colonization. Although many of the guidelines recommend water flushing for a certain duration of time (*e.g.*, 10 min, 20 min),[29,30] additional water quality monitoring (*e.g.*, disinfectant residuals) should be conducted to ensure that the fresh tap water is replacing the stagnant water. However, no systematic studies have been conducted to evaluate the efficiency of the proposed guidelines under pandemic conditions when human resources, supplies, and access to the building information are limited. As shown in Fig. 1, following the COVID-19 disease spread in Shelby County, Tennessee (TN), in mid-March 2020, the university had extended the spring break to March 22nd, then transitioned to online instruction like thousands of other academic institutions in the U.S. After the rapid transition, only essential employees continued to work on campus until June 3, 2020. At this point, approximately 25% of the university employees were allowed to work on campus, and certain educational, recreational, and office buildings were completely closed. Only a fraction of the athletic department's staff, football staff, and football student-athletes were allowed to return to the campus for training and competition. This zero or low occupancy in university buildings raised concerns regarding the tap water quality deterioration due to prolonged water stagnation in the plumbing. Thus, as an immediate response to these concerns, an intensive water chemical quality investigation and building water plumbing recommissioning were conducted during the COVID-19 pandemic (April–June 2020) at ten large buildings on campus to ensure the safety of the tap water. In this study, recommissioning was considered as buildings' reopening after extended closure and concentrates on restoring the tap water quality to the regular water use condition.[8] The specific objectives of this study are to (1) examine the water chemical quality in the large buildings after prolonged stagnation caused by the COVID-19 pandemic, (2) implement volume-based and constant-duration flushing protocols to replace the stagnant water with fresh tap water, and (3) evaluate the effectiveness of developed water flushing protocols in promoting the water chemical quality.

Experimental

Study site, water sampling campaign, and water quality monitoring

In this study, the first draw water samples were collected during the buildings' closure or low occupancy in seven academic [B1–B7] and three athletic buildings [A1–A3] at a university campus in Tennessee, USA (Table 1). In the academic buildings, consisting mainly of classrooms and office spaces, the water fixtures were mostly faucets in restrooms and water coolers. In athletic building A1, there were offices, classrooms, a gym, and indoor courts; in A3, in addition to offices, there were some training rooms, locker rooms, equipment storage, and support rooms and a greater number of shower fixtures compared to the academic buildings; and A2 was mainly composed of athletic offices. The studied buildings were between 38 and 70 years old. The locations of the sampled buildings are shown in Fig. SI-1.† More information regarding the buildings is provided in the ESI† (SI-1).

The same municipal water treatment plant supplies groundwater that has been chlorinated, aerated, filtered, and chlorinated again with free chlorine for secondary disinfection to all target buildings. Orthophosphate was also added as a corrosion inhibitor before the water distribution. The chemical quality of finished water supplied by the local water utility is shown in Table SI-1.†[31] As buildings were locked during the study, each person needed to use an ID card to access most of the buildings. The number of access

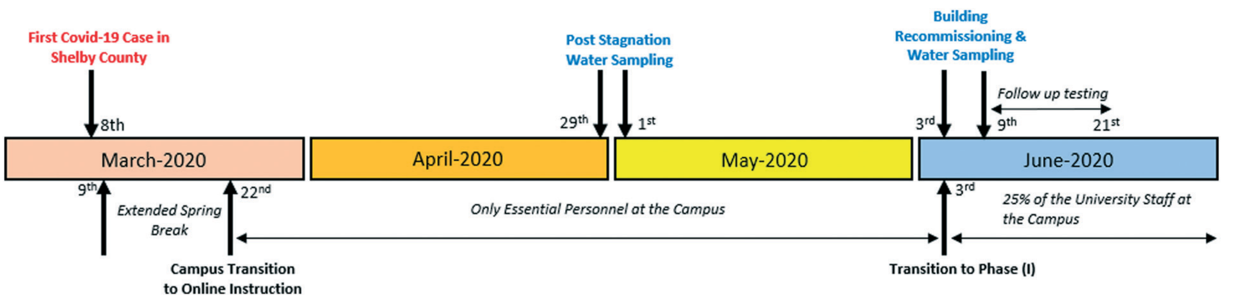

Fig. 1 The timeline demonstrating the occupancy variation, water sampling, and building recommissioning (flushing) at the university campus.

Table 1 The specifications of studied buildings

Building	Athletic			Academic						
Label	A1	A2	A3	B1	B2	B3	B4	B5	B6	B7
#Floors	3	2	2	1	4	5	4	4	2	3
Total area (m^2)	14 388	4804	7751	3883	8660	7739	7877	5750	1198	2916
Year built	1951	1983	1971	1963	1967	1973	1930	1966	1971	1958
#WHT[a]	1	2	6	2	1	1	3	1	1	1
Vol. WHT[b] (m^3)	0.1	0.3	1.5	0.2	0.3	0.8	0.2	0.2	0.2	0.2
Type of pipes	GIP[c]	CP[d]	CP	CP	CP	CP	CP	CP	GIP	GIP
#Cold water taps	23	8	37	32	41	8	8	23	10	6
#Hot water taps	3	8	15	15	11	16	6	8	5	12
#Water coolers	9	4	14	30	8	4	3	8	4	2
As-built availability	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
POE flushing duration (min)	35	10	15	45	105	10	15	80	na[e]	5
Diameter of service line (in)	2	2.5	2.5	4	4	4	3	4	2.5	2
Outlet access at POE during stagnation	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes
Outlet access at POE during flushing	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Minimum plumbing flushing duration (min)	479	186	379	342	396	239	200	195	152	188
Estimated water volume in plumbing (m^3)	2.0	0.7	3.2	1.0	1.5	1.7	ne[f]	1.0	1.1	0.7
Total collected samples	44	40	80	86	62	74	32	52	22	54

[a] Water heater tank. [b] Volume of water heater tank. [c] Galvanized iron pipe. [d] Copper pipe. [e] No access. [f] No estimation.

through the building was used as an indicator of occupancy in buildings during the extended stagnation and after flushing. The buildings' access data indicated that occupancy of the buildings was changed during the study. Although it should be noted that the building access data may show multi-entry by a single person, its overall trend could represent the variation of the buildings' occupancy during the pandemic. As shown in Table SI-2,† the number of people accessing building A1 was increased by more than three times as we conducted this building recommissioning. We have also been told that the number of people in building A3 was increased from 20 to 130 during the study. With having remote learning through the campus, the occupancy was increased more significantly in athletic buildings. We also found increased access to buildings B1, B3, B4, B6, and B7, while the access to buildings B2 and B5 had decreased slightly.

After conducting the water flushing, water samples were collected at select cold and hot water fixtures in all ten buildings to ensure the effectiveness of the flushing practices in delivering fresh drinking water into the building plumbing. The fixtures' flow rates varied from 1.5 to 2.5 LPM during water sampling. The water samples were first collected at the building point of entry (POE) and then collected sequentially at both cold and hot water fixtures along the building plumbing (as the distance from the POE increased). After extended stagnation the water samples were collected from POE outlets after 5 min to represent the water that enters the building. The water sampling was conducted by collecting 10 mL water samples from cold and hot water fixtures for on-site measurements of total chlorine residuals. Moreover, in five of these buildings [A1, A3, B3, B4, and B6], after collection of water samples for chlorine residuals, 60 mL water samples were collected for measurement of pH, temperature, and dissolved oxygen (DO), then 50 mL samples were collected in polypropylene tubes for total lead (Pb), total copper (Cu), total zinc (Zn), and total iron (Fe) quantification, and two 40 mL amber vials were filled with water from hot and cold water fixtures for total organic carbon (TOC) concentration measurements. Water pH was measured on-site using a Fisherbrand™ accumet™ XL600 pH meter. DO was measured using an Oakton DO450 Meter Kit. For preservation, the water samples were acidified to 2% by nitric acid (Fisher Chemical, technical grade) after the samples were transported to the lab. The water samples that were collected for TOC measurements were transferred in ice to the lab, where $Na_2S_2O_3$ (6 mg) was immediately added to them. Information regarding the field and trip blanks are provided in the ESI† (SI-2). The local certified analytical lab measured the Zn, Cu, Pb, and Fe *via* inductively coupled plasma mass spectrometry (ICP-MS) according to the US EPA method 200.8. The minimum detection limits (MDLs) for Zn, Cu, Pb, and Fe were 14.3 μg L^{-1}, 0.6 μg L^{-1}, 0.02 μg L^{-1}, and 20.9 μg L^{-1}, respectively. The minimum quantification limits (MQLs) for Zn, Cu, Pb, and Fe were 20 μg L^{-1}, 1.0 μg L^{-1}, 0.5 μg L^{-1}, and 100 μg L^{-1}, respectively. The TOC concentration was measured using a TOC-V CSN Shimadzu TOC analyzer in accordance with US EPA method 415.1. The instrument was calibrated from 0.0 to 25.0 mg TOC per L using HOOCC6H4COOK (r^2 0.999). A HACH® Pocket Colorimeter™ II, Chlorine instrument was used to measure the total chlorine residual using the DPD colorimetry method (MDL = 0.1 mg L^{-1}).

Water flushing procedures

The water flushing was conducted to deliver water with a sufficient level of disinfectant residuals (total chlorine residuals >0.9 mg L^{-1}) to the buildings' POE and 1st hot water fixture in the buildings. Two distinct water flushing protocols were developed to replace the stagnant water in the buildings' plumbing with fresh drinking water from the distribution system.

Water flushing at POEs

The water was flushed at the POEs of 9 buildings using the water outlet located in the buildings' utility room. We considered the service line as the pipe that connected the water distribution main to the building POE. The service lines' dimensions were identified from as-builts. The pipes used for the service line in all buildings were ductile iron. We have used the plumbing as-built drawing and the water distribution network outline to identify the dimensions. The water flow rates in the POEs were measured on-site and varied from 15 to 60 LPM. However, we have calculated the volume of water in the service line, but the concentration of the total chlorine residuals was measured on-site in the water samples collected consecutively from the buildings' POEs to ensure that fresh drinking water entered the buildings' POEs prior to conducting the water flushing inside the buildings. The water flushing at the POE was stopped when total chlorine residuals exceeded 0.9 mg L^{-1}. For building B6, that we did not have access to the POE, we have flushed the water that was stagnant in the service line using the closest cold water fixture to the building POE.

Water heater tanks

The water heater tanks (WHTs) were expected to have a large amount of sediment as they were in service for many years.[33,34] Thus, they were not drained during our building recommissioning effort. Their complete draining may have resulted in resuspension of their sediment and subsequent deposition into the hot water plumbing. Opening several hot water fixtures at the same time could have resulted in insufficient water pressure within the plumbing system. Thus, the incomplete flushing may result in redeposition of dislodged particles onto the other segments of the building plumbing.[8] Due to the lack of appropriate personal protective equipment (N-95 facemasks), the research team exited the room during flushing of the hot water fixtures and did not flush the washroom showers during this study. In lieu of draining the hot water tanks (HWTs), the hot water was flushed at the fixture closest to the HWT. The volume of water contained within the HWT and the hot water plumbing leading to the first hot water fixture was considered when calculating the minimum flushing duration (MFD_{Hot}), as shown in eqn (1), where V_{HWT} is the volume of the HWT. Despite the MFD_{Hot} estimation, the total chlorine residual in the hot water samples collected from the first hot water fixture did not increase significantly while flushing. Thus, the water flushing was continued beyond the MFD_{Hot}, and the chlorine residuals were monitored over the flushing duration until the total chlorine residual increased to greater than 0.9 mg L^{-1}. However, four buildings (A1, A3, B1 and B3) were not able to meet this condition. Flushing the hot water for more than two hours in buildings B1 and A3 only increased the total chlorine concentrations to 0.6 mg L^{-1} and 0.7 mg L^{-1}, respectively. The duration of flushing at the first hot water fixture and the total chlorine residual after flushing is shown in Table SI-3.†

$$\mathrm{MFD}_{\mathrm{Hot}} = \frac{V_{\mathrm{HWT}}\ (\mathrm{m}^3)}{q\ (\mathrm{L\ min}^{-1})} + \frac{\pi \times (d\ (\mathrm{cm}))^2 \times l\ (\mathrm{m}) \times 0.1}{4q\ (\mathrm{L\ min}^{-1})} \quad (1)$$

Volume-based flushing

The volume-based flushing procedure was applied for the nine buildings with as-built plumbing drawings available. For volume-based flushing, the minimum duration was calculated based on the time required to flush the specific volume of water that is present within the pipes between fixtures, as shown in Fig. 2. After flushing the POE and HWT, the subsequent hot and cold water fixtures were flushed individually and sequentially beginning from the fixture closest to the POE. The minimum flushing duration (MFD) was calculated according to eqn (2)[32] using the length (l) and diameter (d) of the water pipe and the water flow rate (Q).[32] The faucet's water flow rate was measured before the flushing. Prior to flushing, the fixtures' aerators were removed and cleaned where possible. The shear forces applied during water flushing could resuspend some particulate matter and detach the biofilm from the pipe surface. These contaminants may accumulate in the aerator and gradually release the heavy metals (*e.g.*, Pb, Cu) and cause microbial contamination of tap water. To prevent this contamination, the aerators were removed before flushing and cleaned and returned to the faucets after flushing. The pipe diameter and length were identified using the plumbing as-built drawings. The fixtures' flow rates varied from 1.5 to

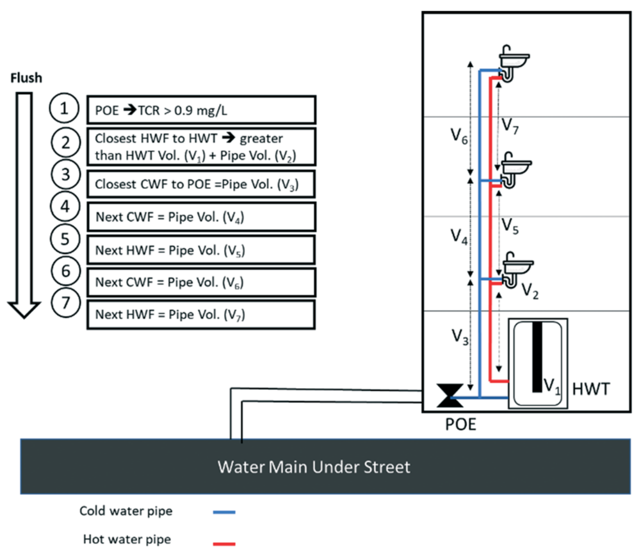

Fig. 2 The schematic demonstrating the water flushing sequence. POE: point of entry, CWF: cold water fixture, HWF: hot water fixture, HWT: hot water tank, Vol: volume, TCR: total chlorine residual concentration.

7.5 LPM. The water coolers were flushed for a constant duration of 5 min.

$$\mathrm{MFD\ (min)} = \frac{\mathrm{Volume}}{\mathrm{Flow\ rate}} = \frac{\pi \times (d\ (\mathrm{cm}))^2 \times l\ (\mathrm{m}) \times 0.1}{4Q\ (\mathrm{L\ min^{-1}})} \quad (2)$$

The level of disinfectant residuals was monitored in select cold and hot water fixtures at buildings A1, A3, and B7 for up to 12 days after flushing to identify the disinfectant residual decay behaviour under low water use condition.

Constant duration flushing

Constant-duration flushing was applied for the academic building (B4) without an as-built drawing. The water heater tank was flushed for 60 min and the total chlorine residual was increased from 0.4 mg L^{-1} to 1.0 mg L^{-1}. The cold and hot water fixtures located on the first and second floors [closer to the POE] were flushed for 5 min, and the cold and hot water fixtures on the third and fourth floors [farther from the POE] were flushed for 10 minutes.[35] The water coolers were flushed for a constant duration of 5 min.

Statistical analysis

The IBM SPSS software, version 26, was used for the statistical analysis. The normality of water quality data was examined using the Kolmogorov–Smirnov test.[36,37] The paired t-test and the non-parametric test of independent-samples median test were applied to identify the significant differences between the water quality data with the normal distributed and non-normal distributed water quality parameters, respectively. A type I error of 0.05 was selected as the significance level for all tests.

Results and discussion

Water chemical quality at the buildings' point of entry (POE)

In this study we monitored the total chlorine residuals as an indicator of the water quality. The average total chlorine residual concentration in the water samples collected from the buildings' POEs during extended stagnation was 0.6 mg L^{-1}. It should be noted that there was no access to the POE of building B1 during stagnation and also no access to the POE of building B6 during both stagnation and flushing. The POEs at all other buildings were accessible. This implies that despite the low water use due to the low occupancy, the water mains present on campus delivered relatively fresh drinking water to the buildings. However, the very small distance (0.3 miles) of the campus to the water treatment plant may have resulted in a lower water age at this campus compared to the other parts of the distribution system, and therefore the chlorine concentrations might be higher as they have not decayed in the distribution system over time. This average concentration of total chlorine residual was increased to 1.1 mg L^{-1} after flushing (p-value <0.05). The POE flushing durations varied from 5 min to 105 min. This significant increase in the total chlorine residual concentration underscores the success of the flushing protocols in conveying the fresh drinking water from adjacent water mains into the buildings' POEs. We have also monitored the variations of total chlorine residuals as a function of flushing duration at POEs in seven buildings. As shown in Fig. 3, the initial total chlorine residual concentration was greater than 0.6 mg L^{-1} in buildings B2, B3, B7, and A2. Thus, after a relatively short duration of water flushing (<15 min), the total chlorine residual concentration exceeded 1.0 mg L^{-1}. For building B2, the initial total chlorine concentration of 0.9 mg L^{-1} increased to 1.0 mg L^{-1} after 15 min, which remained almost constant after flushing for 90 min, and eventually reached the maximum value of 1.3 mg L^{-1} after 105 min of water flushing. No total chlorine residuals were found in samples collected initially at buildings B1 and B5; it took 45 min and 80 min to reach the 1.0 mg L^{-1} threshold level of total chlorine residuals in these buildings' POEs. The buildings' occupancy, service line dimensions and flow rates, outline, dimensions of water mains around the buildings, and rate of water consumption in surrounding buildings connected to the same water main may have influenced the rate of delivering the fresh water to the buildings' POE.

Monitoring the DO and TOC concentration at the POEs of four buildings (A1, A3, B3 and B4) revealed no significant difference due to the flushing. The Pb concentration in water samples collected during the extended stagnation period from POEs at buildings A1 and A3 exceeded the United States Environmental Protection Agency (US EPA) action level of 15 μg L^{-1}. The POE access line was absent in these two

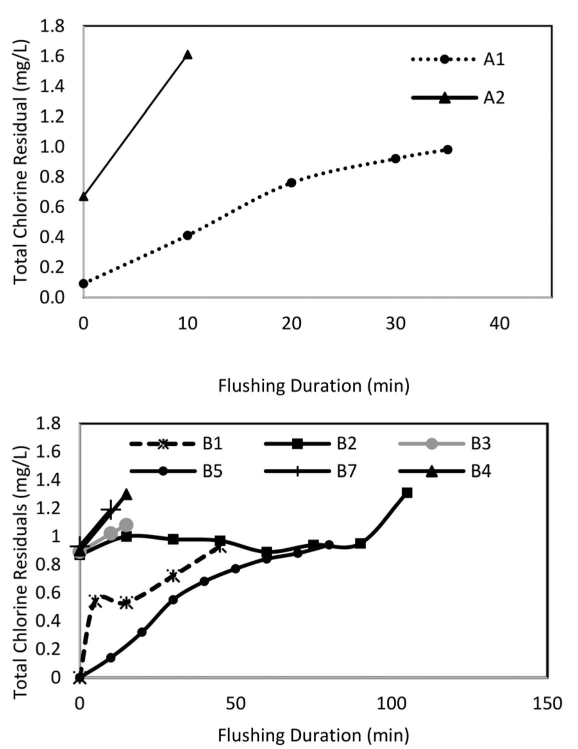

Fig. 3 The variation of total chlorine residuals at the academic and athletic buildings' POEs over time (MDL = 0.1 mg L^{-1}).

buildings, so the water outlets used to collect these water samples were hose bibs and might have contributed to this lead release. No label was found on the water outlets indicating the National Sanitation Foundation (NSF) International certification or lead-free features.[13] Greater Pb [1.5–27.5 μg L^{-1}], Zn [40.0–348.0 μg L^{-1}], Fe [226.0–2160.0 μg L^{-1}], and Cu [58.8–814.0 μg L^{-1}] concentrations were found in the water samples collected from POEs during the extended water stagnation period compared to after flushing. The Pb [0.7–10.3 μg L^{-1}], Zn [<14.3–17.5], Fe [42.6–213.0], and Cu [7.1–24.7] concentrations were reduced after flushing the POEs. Following the buildings' closure, the Fe concentration in the POE water samples from buildings A3 and B3 exceeded the US EPA Secondary Maximum Contaminant Level (SMCL) of 300 μg L^{-1}. These buildings had ductile iron service lines and had a maximum iron concentration of 2160 μg L^{-1}. However, following the water flushing, no water samples exceeded this limit. The summary of water chemical quality at the POEs is shown in Table 2.

Impacts of water flushing on disinfectant residuals inside the buildings

The results demonstrated the absence of total chlorine residuals (<0.1 mg L^{-1}) in 69% and 71% of first draw water samples collected during the extended water stagnation from the academic and athletic buildings, respectively. According to the Tennessee Department of Environment of Conservation, the residual free chlorine concentration should not be less than 0.2 mg L^{-1} in more than 5% of samples collected each month for two consecutive months for public water systems.[38] In this study we have not measured the free chlorine residuals, but when the total chlorine residuals is less than 0.2 mg L^{-1}, the free chlorine should be less than this limit. As reported in the literature, several chemical reactions that occur within the bulk water and pipe wall result in chlorine decay. Water stagnation within the building plumbing could accelerate the disinfectant residual decay as the pipe materials, biofilm, corrosion deposits, inorganic scale, and natural organic matter present in the plumbing system consume the chlorine residuals.[39,40] After conducting the buildings' recommissioning, the total chlorine residuals were below the detection limit in one hot water sample (faucet) that was flushed according to the volume-based method and underscores its limitation. Moreover, one cold water sample that was collected from a cooler in building A3 after 5 min of flushing also showed the absence of chlorine residuals, which shows that sometimes the constant duration of flushing does not replace the stagnant water with fresh tap water. The renovations in the buildings' plumbing which have not been marked in as-built drawings may result in a discrepancy between the estimated volume of water and the actual volume of water in the pipes. Despite this minor limitation, conducting the flushing practices has increased the median total chlorine concentration from <0.1 to 1.0 mg L^{-1} in academic buildings, and from <0.1 to 0.75 mg L^{-1} in athletic buildings (p-value <0.05). This finding confirms the effectiveness of developing detailed flushing protocols despite their minor limitations. The constant-duration flushing in building B4 has significantly increased the median total chlorine concentration from <0.1 to 1.0 mg L^{-1}, which was similar to that of the other academic buildings that were flushed according to the volume-based procedure. As shown in Fig. 4, the total chlorine residual concentration was greater in water entering the buildings at the POEs than in the water at the fixtures inside the athletic and academic buildings. The small-diameter plumbing within the building provided a large surface area-to-volume ratio as compared to the POE and increased the rate of chlorine decay within the building.[41] The median total chlorine residual concentration in cold water samples collected from academic buildings during the extended water stagnation period was significantly greater than that of the hot water samples (p-value <0.05). Flushing yielded 23% and 37% greater total chlorine residual in the cold water samples compared to the hot water samples in academic and athletic buildings (p-value <0.05) because elevated temperatures in hot water tanks accelerated the chlorine decay.[41] After flushing, the median chlorine residual concentrations for both cold (p-value <0.05) and hot water samples (p-value >0.05) were lower in the athletic buildings compared to the academic buildings. The majority of buildings remained at low occupancy even after

Table 2 The summary of water chemical quality at the buildings' POE

Water quality parameter / Statistical parameter		pH	DO (%)	Temp (°C)	Total chlorine (mg L^{-1})	TOC (mg L^{-1})	Zn (μg L^{-1})	Fe (μg L^{-1})	Cu (μg L^{-1})	Pb (μg L^{-1})
Before recommissioning	Mean	6.9	31.8	20.6	0.7	5.2	125.7	949.5	289.1	14.7
	STD	0.5	17.0	0.5	0.4	0.3	148.5	906.8	360.4	14.7
	Minimum	6.5	17.0	19.8	0.3	5.0	40.0	226.0	47.6	1.5
	Maximum	7.7	55.2	20.9	1.3	5.6	348.0	2160.0	814.0	27.5
After recommissioning	Mean	7.1	34.5	21.8	1.1	5.6	4.4	104.4	19.8	3.2
	STD	0.3	3.4	1.5	0.2	0.4	8.8	78.0	15.5	4.7
	Minimum	6.7	31.0	20.4	0.9	5.3	0.0	42.6	7.1	0.7
	Maximum	7.3	38.2	24.0	1.6	6.1	17.5	213.0	39.5	10.3
Num. of buildings		4.0	4.0	4.0	9.0[a]	4.0	4.0	4.0	4.0	4.0
% Change of mean		2%	8%	6%	57%	8%	−96%	−89%	−93%	−78%

[a] Samples collected from 8 POEs during the extended stagnation.

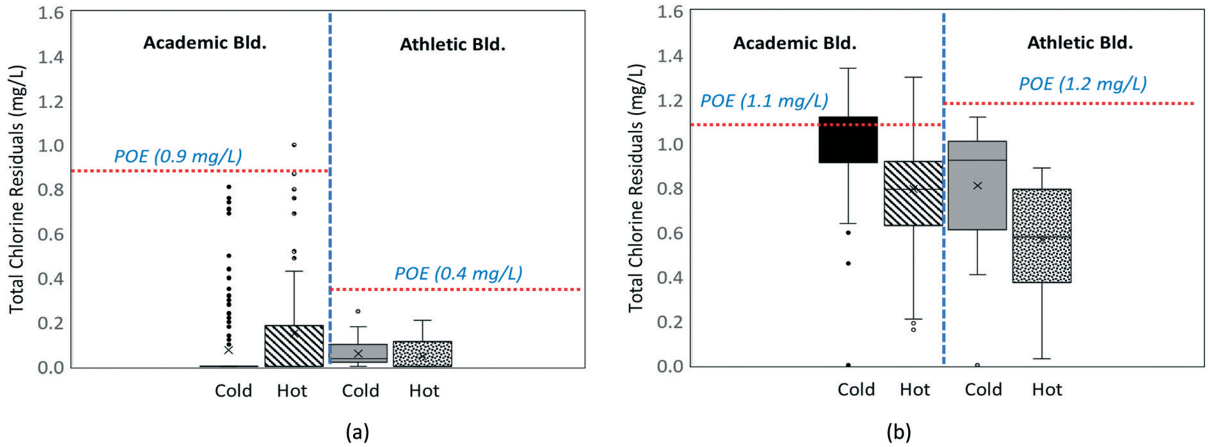

Fig. 4 Total chlorine residuals in cold and hot water samples collected from seven academic and three athletic buildings (a) after extended stagnation and (b) after water flushing. Red dotted line represents the median total chlorine concentration at buildings' POEs; within each box, horizontal black lines denote the median values, boxes extend from the first to the third quartile of each group distribution, x represents the mean, the whiskers extended from min to maximum, dots denote the outlier data (MDL = 0.1 mg L^{-1}).

recommissioning. According to the buildings' access information and our survey, the occupancy was increased significantly in buildings A1 and A3 which were athletic facilities. Thus, as shown in Fig. 5, follow-up disinfectant residual monitoring was conducted in multiple cold and hot water fixtures in select buildings to identify the disinfectant decay behaviour under limited occupancy conditions. Twelve days after recommissioning building B7, the total chlorine residual concentration was 0.2 mg L^{-1} in one of the cold water fixtures despite its low occupancy (38 access per month). On the other hand, although building A3 maintained significant occupancy (130 people), the total chlorine residuals had depleted to below the detection limit (0.1 mg L^{-1}) in less than 4 days. In general, the chlorine residuals dissipated more rapidly in the hot water fixtures compared to the cold water fixtures.[42] Despite, the increased occupancy in buildings A1 and A3, the total chlorine residual was depleted to below the detection limit as early as one day after recommissioning in the hot water fixtures. Thus, as suggested in the literature, routine water flushing could be used as an effective tool to better maintain the drinking water quality within the large buildings.[11] The plumbing materials were galvanized iron pipe (GIP) in buildings A1 and B7; however, they were copper (CP) in building A3. Although the literature suggested a faster chlorine decay in GIP compared to CP,[41] due to the complexity of building plumbing and variation in building occupancy, this trend was not observed herein.

Water pH, temperature, DO level and TOC concentrations

For the two academic buildings with CP plumbing (B3 and B4), the average pH values were lower (p-value <0.05) during the extended water stagnation (6.9 and 7.4) than they were after flushing (7.4 and 7.8). Low pH increases the potential for heavy metals to be released into the water.[43] However, the average pH for the academic building with GIP plumbing (B6) decreased from 8.1 to 7.8 following the flushing (p-value <0.05). The cathodic and anodic reactions that occur within the metallic water pipes have been identified as the reasons

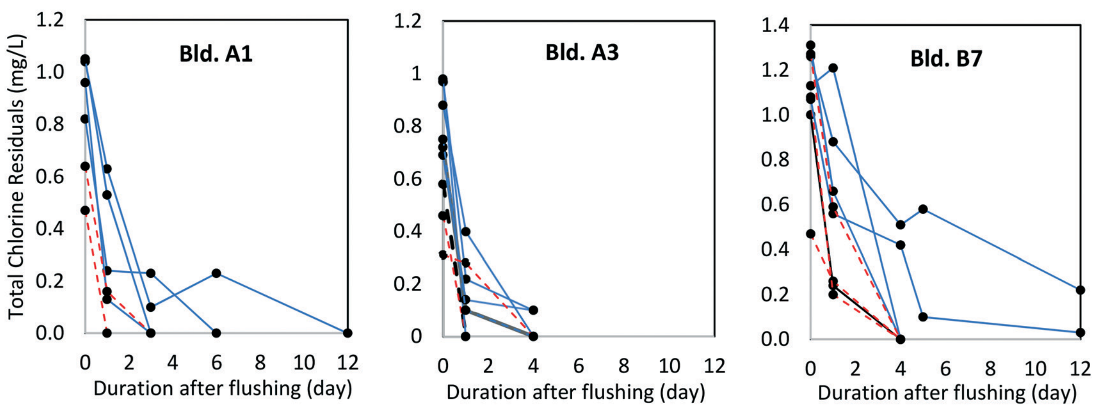

Fig. 5 The total chlorine residual concentration (mg L^{-1}) over time after buildings' (A1, A3, and B7) recommissioning. Blue line represents cold water and red line represents hot water. Each dot represents one water sampling event (MDL = 0.1 mg L^{-1}).

behind the pH variations under stagnant condition.[44] Previous authors have reported an increase in pH up to 2.3 units as water had stagnated in old iron pipes.[45–47] No significant change was found in the pH levels of water samples collected from athletic buildings after implementing the flushing practices. Among the buildings with copper plumbing, the median pH value for water samples collected in building B4 was significantly greater than the median pH value for water samples collected in building B3 after extended stagnation (p-value <0.05) and in building A3 after flushing (p-value <0.05). As was expected, the median temperature of hot water samples increased to 41.2 °C and 36.3 °C in both academic and athletic buildings due to the water flushing (p-value <0.05). The constant-duration flushing in building B4 has increased the median temperature for hot water samples by 17 C° (22 °C → 39 °C); however, the temperature was increased by 19 °C (22 °C → 41 °C) for other academic buildings that were recommissioned according to the volume-based protocol. As shown in Fig. 6, the median values of DO% in academic and athletic buildings increased significantly from 29% and 11% to 37% and 39%, respectively, after conducting the water flushing practices (p-value <0.05). The median DO% in building B4 was increased from 19% to 39% after conducting the constant-duration flushing; however, it was increased from 30% to 37% in water samples collected from other academic buildings that were flushed according to the volume-based procedure. The constant-duration flushing in building B4 has increased the median temperature for hot water samples by 17 C° (22 °C → 39 °C); however, the temperature was increased by 19 °C (22 °C → 41 °C) for other academic buildings that were recommissioned according to the volume-based procedure. The median TOC concentration slightly increased from 5.2 mg L^{-1} to 5.5 mg L^{-1} in water samples collected from academic buildings and increased from 5.3 mg L^{-1} to 5.8 mg L^{-1} in water samples collected from athletic buildings due to the buildings' recommissioning (p-value <0.05). The increased shear forces experienced during flushing may have dislodged any biofilms that had accumulated on the inner pipe surface.[12]

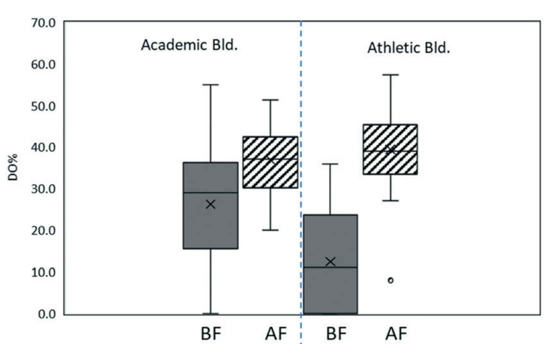

Fig. 6 DO% at academic (B3, B4, B6) and athletic buildings (A1 and A3) before flushing (BF) and after flushing (AF). Within each box horizontal black lines denote the median values, boxes extend from the first to the third quartile of each group distribution, x represents the mean, the whiskers extend from min to maximum, dots denote the outlier data.

Heavy metal concentrations

The total Pb, Cu, Zn, and Fe concentrations were monitored in the water samples collected from cold and hot water fixtures in three academic buildings [B3, B4 and B6] and two athletic buildings [A1 and A3]. The median Pb concentration in water samples collected from water fixtures in both academic and athletic buildings during the extended water stagnation and after flushing were significantly low (<1.0 μg L^{-1}). Of the 116 water samples that were collected in the buildings during the extended water stagnation period, only four water samples exceeded the US EPA action level for Pb (ranging from 15.2 μg L^{-1} to 129.0 μg L^{-1}). However, after the buildings' recommissioning, only one water sample (60.3 μg L^{-1}) exceeded the Pb limit. This sample was collected after flushing the water; however, this fixture had a very low Pb concentration (1.4 μg L^{-1}) during the extended stagnation. Thus, this quantified Pb might be the particles released from upstream plumbing due to the shear forces applied during the flushing practices. Since these buildings were originally constructed (1930–1973) several years before issuing the original Lead Contamination and Control Act (LCCA),[48] it is reasonable to assume that there might be some lead-containing plumbing components present within the building. Furthermore, the GIP plumbing present in buildings B6 and A1 might have contributed to the Pb release into the water.[49] The zinc used during the galvanizing process typically contains a minimum of 0.5% lead, and this lead could be released into the water over a long-term basis.[50–52] The lead levels that were identified in this study during both extended stagnation and after flushing were significantly smaller than the values reported for some U.S. schools (up to 18 800 μg L^{-1})[49] and Canadian large administrative and training buildings (up to 23 000 μg L^{-1}),[53] elementary schools, day cares, and other large buildings (up to 13 200 μg L^{-1}).[54] As shown in Fig. 7(a and b), the median concentration of Cu in the water samples collected from cold (362 μg L^{-1}) fixtures in athletic buildings during extended stagnation were significantly greater than cold (179 μg L^{-1}) water samples collected in the academic buildings (p-value <0.05). Three water samples in one of the athletic buildings (A3) with CP plumbing exceeded the US EPA SMCL for Cu (1.0 mg L^{-1}). None of the collected water samples exceeded the US EPA SMCL limit for Zn (5.0 mg L^{-1}). The maximum Zn concentrations in water samples collected from academic and athletic buildings after extended stagnation duration were found as 3290 μg L^{-1} (cold water) and 4260 μg L^{-1} (cold water), respectively. However, following implementation of flushing practices the maximum Zn concentration reduced to 254 μg L^{-1} (hot water) and 1100 μg L^{-1} (hot water), in the academic and athletic buildings, respectively. Occurrence of these maximum values in hot water following the flushing practices demonstrates the possible resuspension of metals from the hot water tank into the tap water. The constant-duration flushing in building B4 has

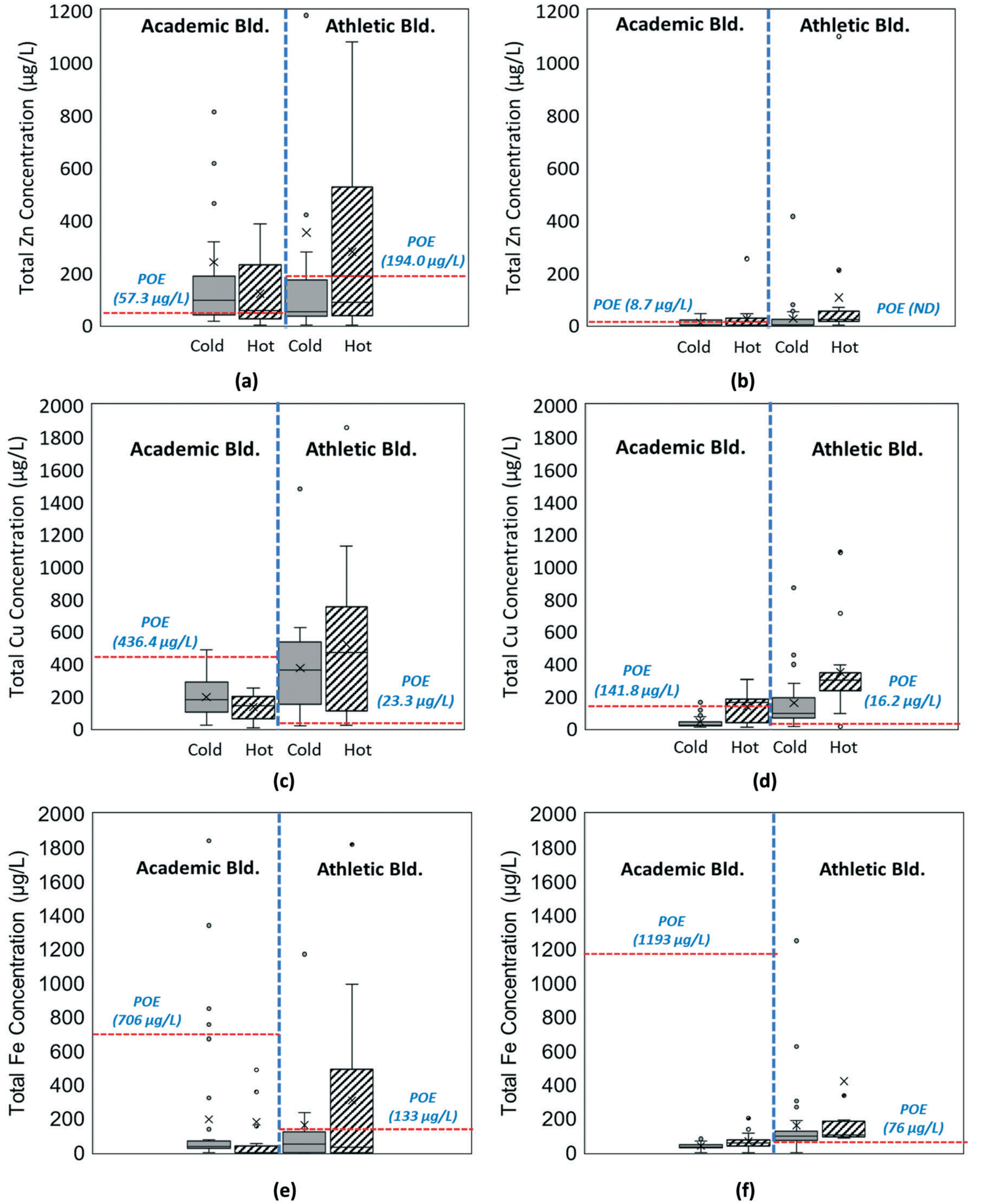

Fig. 7 Box and whisker plots for total Cu, Zn, and Fe concentrations in water samples collected after extended stagnation (a, c and e) and after buildings recommissioning (b, d and f) from academic (B3, B4 and B6) and athletic buildings (A1 and A3), outliers are not shown, within each box horizontal black lines denote the median values, boxes extend from the first to the third quartile of each group distribution, x represents the mean, the whiskers extend from min to maximum, dots denote the outlier data.

decreased the median Cu concentration from 65 μg L^{-1} to 41 μg L^{-1}, and the volume-based flushing reduced it from 186 μg L^{-1} to 23 μg L^{-1} in other sampled academic buildings (B3 and B6). As shown in Fig. 7(c and d), the median Zn concentrations in hot and cold water samples collected from academic and cold water in athletic buildings were reduced significantly due to the building recommissioning (p-value <0.05). The constant-duration flushing in building B4 has decreased the median Zn concentration from 115 μg L^{-1} to 15 μg L^{-1}, and the volume-based flushing reduced it from 75 μg L^{-1} to <14 μg L^{-1} in other sampled academic buildings (B3 and B6). As shown in Fig. 7(e and f), 14.8% of water samples collected in the buildings during the extended water stagnation period exceeded the US EPA SMCL of 300 μg L^{-1} for iron. Furthermore, the maximum Fe concentrations in academic and athletic buildings were 3590 μg L^{-1} (hot water) and 2610 μg L^{-1} (cold water), respectively. However, after building recommissioning, the Fe concentration in only 4.7% of collected water samples exceeded the SMCL limit. The constant-duration flushing in building B4 has increased the median Fe concentration from 31 μg L^{-1} to 47 μg L^{-1}, and the volume-based flushing increased it from 30 μg L^{-1} to 43 μg L^{-1} in other sampled academic buildings (B3 and B6). The maximum Fe concentration reduced to 204 μg L^{-1} (hot water) in academic buildings, but it increased to 4450 μg L^{-1} (hot water) in an athletic building (A1) with GIP plumbing. This elevated Fe concentration might have originated from particulate Fe dislodged from the corroded surface of GIP pipes due to the shear forces applied during the water flushing.[55]

The flow regime, dissolved oxygen, and disinfectant residuals are critical parameters influencing the metal scale stability and consequently the metal release behavior.[40,56] The dissolved oxygen and free chlorine residuals are the predominant oxidants present within the potable water system. Under stagnant or low flow conditions, the corroded metal surfaces rapidly consume the dissolved oxygen and free chlorines that are present in the water adjacent to the pipe surface.[56] Depletion of oxidants in water creates a reducing environment, where the scale's stability is decreasing and a more porous scale surface is formed which promotes releasing the dissolved metals to the bulk water.[45] Inversely, under high flow condition, a sufficient level of oxidants are delivered to the metallic scale which enhances their oxidation and formation of stable denser shells.[45,57,58] The Kuch reactions result in ferrous iron release from the pipe scale under reducing conditions.[45] These reactions are shown in Fig. 8. Furthermore, the flowing water provided by the municipal water treatment plant continuously supplies the orthophosphate inhibitors (1 mg L^{-1}) to the pipe scale, promoting the protective film which reduced the metal release to the water. However, the extended water stagnation within the plumbing enhances the consumption of inhibitor residuals and reduces their effectiveness.[59,60] The water pH and alkalinity are significant factors influencing the metal leaching from plumbing components.[61]The supplied water had a low alkalinity (53 mg L^{-1} as $CaCO_3$) and relatively neutral pH (7.2). Its pH was changed drastically (6.6–9.9) as water was conveyed through the building plumbing system. Prior studies that investigated the metal release under short-term stagnation periods revealed that alkalinity up to 75 mg L^{-1} as $CaCO_3$ and increased pH values reduced the corrosion.[62] However, systematic investigations should be conducted to identify the interrelated influence of water chemistry parameters on heavy metal leaching from plumbing materials under prolonged water stagnation.

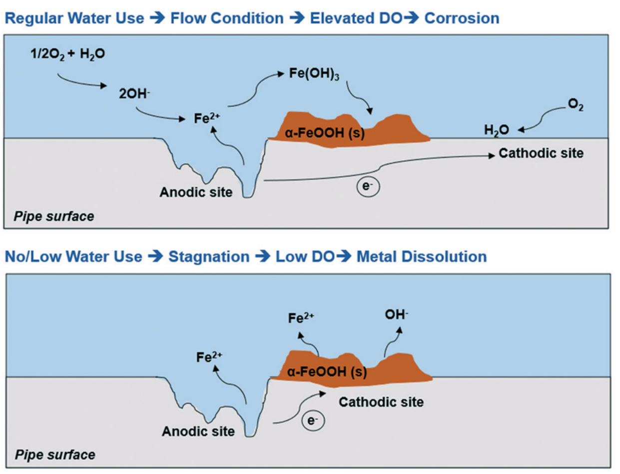

Fig. 8 Schematic demonstrating the galvanic cell reactions occur under regular water use and no water use conditions.

No/low water use condition

$$Fe(s) \leftrightarrow Fe^{2+} + 2e^- \text{ (anodic reaction)}$$

$$2FeOOH(s) + 2H^+ + 2e^- \leftrightarrow 2Fe^{2+} + 4OH^- \text{ (cathodic reaction)}$$

Regular water use

$$Fe(s) \leftrightarrow Fe^{2+} + 2e^- \text{ (anodic reaction)}$$

$$O_2(g) + 4H^+(aq) + 4e^- \leftrightarrow 2H_2O(l) \text{ (cathodic reaction)}$$

Evaluation of the efficiency of buildings' flushing practices

Although the US EPA recommends a flow rate of at least 3.0 LPM when flushing a fixture,[63] the first hot water outlet after the water heater tank with a low flow rate as low as 1.5 LPM resulted in a time-consuming flushing process. As our previous study demonstrated, running several water fixtures simultaneously results in a lower flow rate or zero flow rate in some fixtures and reduces the effectiveness of water flushing.[63] With flushing only one cold and one hot water fixture at a time, we maximized the water flow rate and promoted the effectiveness of water flushing. We have considered the total chlorine concentration of 0.2 mg L^{-1} as our threshold to evaluate the effectiveness of applied flushing protocols. However, it should be mentioned that the complexity of the building plumbing and the various occupancies in these buildings makes the comparison of these flushing protocols challenging. The percentage of water samples with total chlorine residuals less than 0.2 mg L^{-1} collected during the extended stagnation was compared with those values after conducting the flushing practices (Fig. 9a). The total chlorine residual during the extended stagnation period was less than 0.2 mg L^{-1} in 58% to 100% of water samples collected from the target buildings. However, by conducting the volume-based flushing practices, these percentages were reduced to 0% to 4.5% in the target buildings. For building B4, which was flushed according to the constant-duration approach, this percentage was reduced from 73% to 8.3%. This study showed that both flushing protocols increased the chlorine residuals in tap water

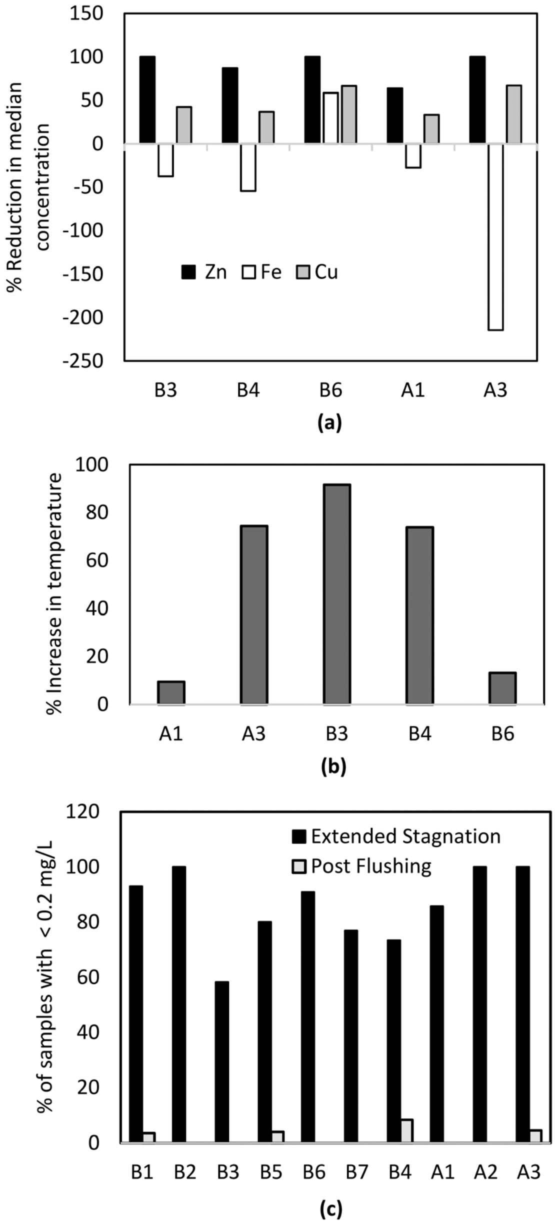

Fig. 9 (a) % reduction of median metal concentrations. (b) % increase of median temperature, and (c) % water samples with total chlorine residuals <0.2 mg L^{-1} due to building recommissioning.

significantly. However, comparison of two methods is challenging as only one building was flushed according to the constant-duration protocol. The constant-duration flushing procedure may not replace the stagnant water completely due to the various building types, the plumbing's complexity, and the range of the fixtures' flow rates. On the other hand, developing the volume-based flushing protocols is time-consuming and requires some background knowledge to read the plumbing as-built drawing and calculate the minimum duration of flushing. The percent increase in temperature of hot water samples due to the water flushing was calculated for the water samples collected from both academic and athletic buildings. As shown in Fig. 9b, the greatest temperature increase (>90%) was found for hot water samples collected from building B3. This could imply the success of the implemented flushing practice in removing the stagnant water from taps as was also confirmed by the chlorine measurements. It should be noted that in some buildings like A1 and B4, there were several point-of-use instant water heaters that impacted the water temperature during flushing that hot water taps. Future investigations should be conducted to identify the effective flushing practices for instant water heaters. As shown in Fig. 9c, the concentrations of Zn and Cu decreased in all five buildings. However, in four of these buildings, the Fe concentrations increased by 27% to 214%. This finding underscores the possible incomplete water flushing in these buildings as the particulate Fe species that separated from the plumbing components were not fully removed from the plumbing system during the flushing. The potable water pipes in three of these buildings were CP, whereas the other building had GIP pipes. Thus, the Fe could have originated from the GIP plumbing, the service line, or the finished water. The metallic deposits that had loosely adhered to the plumbing walls before flushing had been scoured out of the plumbing surfaces during flushing and may have redeposited in the low flow sections of the plumbing (*e.g.* dead ends) *via* gravitational settling.[64,65] Thus, appropriate water velocity during flushing should be maintained to retain a suspension of the particulates which later will be released to the drain. However, an elevated water velocity during the flushing also poses the risk of scouring off of the protective scale from the metallic pipe surfaces.

Conclusion

This study was conducted to examine the influence of building recommissioning on the chemical quality of drinking water in ten large buildings after prolonged water stagnation caused by zero occupancy or low occupancy in response to the COVID-19 pandemic. The results demonstrated extensive absence of disinfectant residuals, low DO levels, and elevated heavy metals in water samples collected during the extended water stagnation. The buildings' recommissioning was conducted by flushing the fire hydrants, POEs, and water fixtures according to the volume-based and constant-duration flushing protocols. The results highlighted the success of the implemented flushing protocols by increasing the disinfectant residual content of the tap water and reducing the Zn, Cu, and Pb concentrations in the water samples. However, for a few buildings, the Fe concentrations increased as the shear forces resulting from water flushing might have scoured the loose iron corrosion products out of the pipe surface. This study only focused on flushing the water fixtures such as faucets and coolers, whereas building recommissioning might be more effective if the toilets, showers, and outside spigots were also flushed. It should be noted that volume estimations may not represent the real volume of water in the plumbing, as this estimation relies on the original plumbing as-built drawing. However, the large buildings may have gone through multiple renovations and maintenance operations that could have altered the plumbing configurations and dimensions. Thus, a water quality monitoring parameter, such as measuring the disinfectant residual concentration following the flushing, should be conducted to confirm the presence of fresh drinking water in the fixtures.

Author contributions

Maryam Salehi: investigation, analysis, writing the original draft, reviewing and editing, visualization, and supervision; Dave DeSimone: investigation, reviewing and editing; Khashayar Aghilinasrollahabadi: investigation; Tanvir Ahamed: investigation.

Conflicts of interest

There are no conflicts to declare.

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References

1 Z. L. Chen, Q. Zhang, Y. Lu, Z. Guo, X. Zhang, W. J. Zhang, C. Guo, C. Liao, Q. L. Li, X. H. Han and J. H. Lu, Distribution of the COVID-19 epidemic and correlation with population emigration from Wuhan, China, *Chin. Med. J.*, 2020, **133**(9), 1044–1050, DOI: 10.1097/CM9.0000000000000782.

2 B. Blocken, T. van Druenen, T. van Hooff, P. A. Verstappen, T. Marchal and L. C. Marr, Can indoor sports centers be allowed to re-open during the COVID-19 pandemic based on a certificate of equivalence?, *Build Environ.*, 2020, **180**, 107022, DOI: 10.1016/j.buildenv.2020.107022.

3 J. Cohen and K. Kupferschmidt, Countries test tactics in "war" against COVID-19, *Science*, 2020, **367**(6484), 1287–1288, DOI: 10.1126/science.367.6484.1287.

4 M. Nicola, Z. Alsafi, C. Sohrabi, A. Kerwan, A. Al-Jabir, C. Iosifidis, M. Agha and R. Agha, The socio-economic implications of the coronavirus pandemic (COVID-19): A review, *Int. J. Surg.*, 2020, **78**, 185–193, DOI: 10.1016/j.ijsu.2020.04.018.

5 A. U. M. Shah, S. N. A. Safri and R. Thevadas, *et al.* COVID-19 outbreak in Malaysia: Actions taken by the Malaysian government, *Int. J. Infect. Dis.*, 2020, **97**, 108–116, DOI: 10.1016/j.ijid.2020.05.093.

6 M. Douglas, S. V. Katikireddi, M. Taulbut, M. McKee and G. McCartney, Mitigating the wider health effects of covid-19 pandemic response, *BMJ*, 2020, **369**, 1–6, DOI: 10.1136/bmj.m1557.

7 A. R. Masonbrink and E. Hurley, Advocating for children during the COVID-19 school closures, *Pediatrics.*, 2020, **146**(3), e20201440, DOI: 10.1542/peds.2020-1440.

8 C. R. Proctor, W. J. Rhoads and T. Keane, *et al.* Considerations for large building water quality after extended stagnation, *AWWA Water Sci.*, 2020, **2**(4), e1186, DOI: 10.1002/aws2.1186.

9 T. Keane, COVID-19 and Legionella-preparations to consider for municipal and building potable water systems. Published 2020. Accessed December 6, 2021, https://legionellae.org/wp-content/uploads/COVID-19-and-Legionella-Preparations-to-Consider-4-23-2020.pdf.

10 H. Melnick, Darling-hammond L. Reopening schools in the context of COVID-19: health and safety guidelines from other countries selected countries with open schools March/April 2020. Published 2020. Accessed December 6, 2021, https://learningpolicyinstitute.org/product/reopening-schools-covid-19-brief.

11 F. Abigail and A. J. Cantor, Routine building maintenance improves drinking water quality, *Opflow.*, 2020, 26–29, DOI: 10.1002/opfl.1398.

12 M. Salehi, T. Odimayomi and K. Ra, *et al.* An investigation of spatial and temporal drinking water quality variation in green residential plumbing, *Build Environ.*, 2019, **169**, 106566.

13 M. Salehi, M. Abouali and M. Wang, *et al.* Case study: Fixture water use and drinking water quality in a new residential green building, *Chemosphere*, 2018, **195**, 80–89, DOI: 10.1016/j.chemosphere.2017.11.070.

14 K. M. Kelley, A. C. Stenson, R. Dey and A. J. Whelton, Release of drinking water contaminants and odor impacts caused by green building cross-linked polyethylene (PEX) plumbing systems, *Water Res.*, 2014, **67**, 19–32, DOI: 10.1016/j.watres.2014.08.051.

15 M. J. Lehtola, I. T. Miettinen, A. Hirvonen, T. Vartiainen and P. J. Martikainen, Estimates of microbial quality and concentration of copper in distributed drinking water are highly dependent on sampling strategy, *Int. J. Hyg. Environ. Health*, 2007, **210**(6), 725–732, DOI: 10.1016/j.ijheh.2006.11.011.

16 B. P. Zietz, K. Richter, J. Laß, R. Suchenwirth and R. Huppmann, Release of metals from different sections of domestic drinking water installations, *Water Qual., Exposure Health*, 2015, **7**(2), 193–204, DOI: 10.1007/s12403-014-0140-8.

17 W. J. Rhoads, A. Pruden and M. A. Edwards, Survey of green building water systems reveals elevated water age and water quality concerns, *Environ. Sci.: Water Res. Technol.*, 2016, **2**(1), 164–173, DOI: 10.1039/C5EW00221D.

18 S. Masters, J. Parks, A. Atassi and M. Edwards, Distribution system water age can create premise plumbing corrosion hotspots, *Environ. Monit. Assess.*, 2015, **187**(9), 559, DOI: 10.1007/s10661-015-4747-4.

19 K. Lautenschlager, N. Boon, Y. Wang, T. Egli and F. Hammes, Overnight stagnation of drinking water in household taps induces microbial growth and changes in community composition, *Water Res.*, 2010, **44**(17), 4868–4877, DOI: 10.1016/j.watres.2010.07.032.

20 E. Bédard, C. Laferrière, E. Déziel and M. Prévost, Impact of stagnation and sampling volume on water microbial quality monitoring in large buildings, *PLoS One*, 2018, **13**(6), 1–15, DOI: 10.1371/journal.pone.0199429.

21 C. J. Ley, C. R. Proctor and G. Singh, *et al.* Drinking water microbiology in a water-efficient building: stagnation, seasonality, and physicochemical effects on opportunistic pathogen and total bacteria proliferation, *Environ. Sci.: Water Res. Technol.*, 2020, **6**(10), 2902–2913, DOI: 10.1039/d0ew00334d.

22 CDC. Guidance for Reopening Buildings After Prolonged Shutdown or Reduced Operation. Published 2020. Accessed December 6, 2021, https://www.cdc.gov/coronavirus/2019-ncov/php/building-water-system.html.

23 AWWA. Responding to water stagnation in buildings with reduced or no water use: A framework for building managers. Published 2020. Accessed December 6, 2021, https://www.awwa.org/Resources-Tools/Resource-Topics/Coronavirus.

24 USEPA. Information on maintaining or restoring water quality in buildings with low or no use. Accessed December 6, 2021, https://www.epa.gov/coronavirus/information-maintaining-or-restoring-water-quality-buildings-low-or-no-use.

25 L. Ragain, S. Masters, T. A. Bartrand, J. L. Clancy and A. J. Whelton, Analysis of building plumbing system flushing practices and communications, *J. Water Health*, 2019, **17**(2), 196–203, DOI: 10.2166/wh.2019.024.

26 AWWA. (2014) ANSI/AWWA C651-14. AWWA Standard Disinfecting Water Mains.

27 American Water Works Association, DOI: 10.12999/AWWA.C651.14.

28 International Code Council (ICC). (2018) International Plumbing Code. Washington, D.C.

29 D. Cunliffe, J. Bartram and E. Briand, *et al. Water Safety in Buildings*, World Health Organization, 2011.

30 T. Bartrand, S. Masters, J. Clancy, L. Ragain and A. J. Whelton, *Casteloes K. Flushing Guidance for Premise Plumbing and Service Lines to Avoid or Address a Drinking Water Advisory*, Water Research Foundation, Alexandria, VA, 2016.

31 MLGW Water Quality Report 2020, Accessed on Aug 6, 2021, retrieved from https://www.mlgw.com/images/content/files/pdf/WQR%202020_v10links.pdf.

32 G. A. Burlingame, C. W. Wiggins and C. H. Ogino, Responding to contamination: where do I sample?, *Opflow*, 2012, **38**(3), 10–13, DOI: 10.5991/opf.2012.38.0014.

33 R. H. Brazeau and M. A. Edwards, Role of Hot Water System Design on Factors Influential to Pathogen Regrowth: Temperature, Chlorine Residual, Hydrogen Evolution, and Sediment, *Environ. Eng. Sci.*, 2013, **30**(10), 617–627, DOI: 10.1089/ees.2012.0514.

34 W. J. Rhoads, T. N. Bradley and A. Mantha, *et al.* Residential water heater cleaning and occurrence of Legionella in Flint MI, *Water Res.*, 2020, **171**, 115439, DOI: 10.1016/j.watres.2019.115439.

35 P. Demarco, Rehabilitating stagnant building water systems-A timely reminder from the IAPMO group. Published 2020. Accessed December 6, 2021, https://constructionlinks.ca/news/rehabilitating-stagnant-building-water-systems-a-timely-reminder-from-the-iapmo-group/.

36 A. Ullah, M. Arshad, H. Kächele, A. Khan, N. Mahmood and K. Müller, Information asymmetry, input markets, adoption of innovations and agricultural land use in Khyber Pakhtunkhwa Pakistan, *Land use policy*, 2020, **90**, 104261, DOI: 10.1016/j.landusepol.2019.104261.

37 M. Salehi, K. Aghilinasrollahabad and M. Salehi Esfandarani, An Investigation of Stormwater Quality Variation within an Industry Sector Using the Self-Reported Data Collected under the Stormwater Monitoring Program, USA, *Water*, 2020, **12**, 3185, DOI: 10.3390/w12113185.

38 Rules of Tennessee Department of Environment and Conservation, Public Water Systems, 2016.

39 H. M. Ramos, D. Loureiro and A. Lopes, *et al.* Evaluation of chlorine decay in drinking water systems for different flow conditions: From theory to practice, *Water Resour. Manage. Ser.*, 2010, **24**(4), 815–834, DOI: 10.1007/s11269-009-9472-8.

40 T. Ahamed, S. P. Brown and M. Salehi, Investigate the role of biofilm and water chemistry on lead deposition onto and release from polyethylene: an implication for potable water pipes, *J. Hazard. Mater.*, 2020, **400**, 123253, DOI: 10.1016/j.jhazmat.2020.123253.

41 M. Zheng, Factors contributing to chlorine decay and microbial presence in drinking water following stagnation in premise plumbing. Published online 2013, https://trace.tennessee.edu/utk_gradthes/2485.

42 B. Liu, D. A. Reckhow and Y. Li, A two-site chlorine decay model for the combined effects of pH, water distribution temperature and in-home heating profiles using differential evolution, *Water Res.*, 2014, **53**(2013), 47–57, DOI: 10.1016/j.watres.2014.01.010.

43 S. Rahman, B. C. McDonald and G. A. Gagnon, Impact of secondary disinfectants on copper corrosion under stagnation conditions, *J. Environ. Eng.*, 2007, **133**(2), 180–185, DOI: 10.1061/(asce)0733-9372(2007)133:2(180).

44 R. A. Pisigan and J. E. Singley, Influence of buffer capacity, chlorine resdiuals, and flow rate on corrosion of mild steel and copper, *J. - Am. Water Works Assoc.*, 1987, **79**(2), 62–70, DOI: 10.1002/j.1551-8833.1987.tb02801.x.

45 P. Sarin, V. L. Snoeyink and J. Bebee, *et al.* Iron release from corroded iron pipes in drinking water distribution systems: Effect of dissolved oxygen, *Water Res.*, 2004, **38**(5), 1259–1269, DOI: 10.1016/j.watres.2003.11.022.

46 L. S. McNeil and M. Edwards, Phosphate inhibitors and red water in stagnant iron pipes, *J. Environ. Eng.*, 2000, **126**(12), 1096–1102.

47 M. Salehi, C. T. Jafvert, J. A. Howarter and A. J. Whelton, Investigation of the factors that influence lead accumulation onto polyethylene: Implication for potable water plumbing pipes, *J. Hazard. Mater.*, 2018, **347**, 242–251, DOI: 10.1016/j.jhazmat.2017.12.066.

48 H.R.4939-Lead Contamination Control Act of 1988; United States Congress: Washington, DC, USA, 1988.

49 D. DeSimone, D. Sharafoddinzadeh and M. Salehi, Prediction of children's blood lead levels from exposure to lead in schools' drinking water- A case study in Tennessee USA, *Water*, 2020, **12**(6), 1826, DOI: 10.3390/w12061826.

50 B. N. Clark, S. V. Masters and M. A. Edwards, Lead release to drinking water from galvanized steel pipe coatings, *Environ. Eng. Sci.*, 2015, **32**(8), 713–721, DOI: 10.1089/ees.2015.0073.

51 M. McFadden, R. Giani, P. Kwan and S. H. Reiber, Contributions to drinking water lead from galvanized iron corrosion scales, *J. - Am. Water Works Assoc.*, 2011, **103**(4), 76–89, DOI: 10.1002/j.1551-8833.2011.tb11437.x.

52 M. Salehi, X. Li and A. J. Whelton, Metal accumulation in representative plastic drinking water plumbing systems, *J. - Am. Water Works Assoc.*, 2017, **109**(11), E479–E493, DOI: 10.5942/jawwa.2017.109.0117.

53 E. Deshommes, S. Nour, B. Richer, C. Cartier and M. Prévost, POU devices in large buildings: Lead removal and water quality, *J. - Am. Water Works Assoc.*, 2012, **104**(4), 75–76, DOI: 10.5942/jawwa.2012.104.0058.

54 E. Deshommes, R. C. Andrews and G. Gagnon, *et al.* Evaluation of exposure to lead from drinking water in large buildings, *Water Res.*, 2016, **99**, 46–55, DOI: 10.1016/j.watres.2016.04.050.

55 L. S. McNeill and M. Edwards, Review of iron pipe corrosion in drinking water distribution systems, *J. - Am. Water Works Assoc.*, 2001, **93**(7), 88–100.

56 M. Fabbricino and G. V. Korshin, Changes of the corrosion potential of iron in stagnation and flow conditions and their relationship with metal release, *Water Res.*, 2014, **62**, 136–146, DOI: 10.1016/j.watres.2014.05.053.

57 M. Li, Z. Liu and Y. Chen, Physico-chemical characteristics of corrosion scales from different pipes in drinkingwater distribution systems, *Water.*, 2018, **10**(7), 19–21, DOI: 10.3390/w10070931.

58 Y. S. Kim and J. G. Kim, Corrosion behavior of pipeline carbon steel under different iron oxide deposits in the district heating system, *Metals*, 2017, **7**(5), 1–19, DOI: 10.3390/met7050182.

59 O. Rice, Corrosion control with Calgon, *J. - Am. Water Works Assoc.*, 1947, **39**(6), 552–560.

60 L. S. McNeill and M. Edwards, Phosphate inhibitors and red water in stagnant iron pipes, *J. Environ. Eng.*, 2000, **126**(12), 1096–1102, DOI: 10.1061/(ASCE)0733-9372(2000)126:12(1096).

61 Y. Zhang and M. Edwards, Effects of pH, chloride, bicarbonate, and phosphate on brass dezincification, *J. - Am. Water Works Assoc.*, 2011, **103**(4), 90–102.

62 Y. S. Tam and P. Elefsiniotis, Corrosion control in water supply systems: Effect of pH, alkalinity, and orthophosphate on lead and copper leaching from brass plumbing, *J. Environ. Sci. Health, Part A: Toxic/Hazard. Subst. Environ. Eng.*, 2009, **44**(12), 1251–1260, DOI: 10.1080/10934520903140009To add.

63 J. K. Hawes, E. A. Conkling, K. S. Casteloes, R. H. Brazeau, M. Salehi and A. J. Whelton, Predicting contaminated water removal from residential water heaters under various flushing scenarios, *J. - Am. Water Works Assoc.*, 2017, **109**(8), DOI: 10.5942/jawwa.2017.109.0085.

64 M. Li, Z. Liu, Y. Chen and M. Zhang, Identifying effects of pipe material, hydraulic condition, and water composition on elemental accumulation in pipe corrosion scales, *Environ. Sci. Pollut. Res.*, 2019, **26**(19), 19906–19914, DOI: 10.1007/s11356-019-05401-w.

65 A. S. Benson, Evaluation of iron corrosion release models for water distribution systems, *Master Sci.*, Virginia Polytechnic Institute and State University, 2009, https://vtechworks.lib.vt.edu/bitstream/handle/10919/32271/FINAL_THESIS_ABenson.pdf?sequence=1.

