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An investigation of spatial and temporal drinking water quality variation in green residential plumbing

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ABSTRACT

Drinking water chemical quality can deteriorate after water enters building plumbing. This study aimed to better understand seasonal and spatial water quality differences in a highly monitored net-zero energy residential building. Water flow rate and temperature were monitored for one year at the service line and at every fixture throughout the crosslinked polyethylene plumbing. Discrete water sampling events (58) were conducted at the service line, 1st floor kitchen sink, 2nd floor bathroom sink, the water heater, and 2nd floor shower. More than 2.4 billion online monitoring records were collected for fixture flow and temperature. In-building water stagnation time varied seasonally and across fixtures. Significant spatial and temporal water chemical quality variations were found. Average seasonal variability was found for service line temperature (15–23 °C) for the total chlorine residual (0.4–0.9 mg/L-Cl_2), NH_3 (<0.01–0.4 mg/L-N), NO_3^- (0.1–0.8 mg/L-N), and Cu (32–81 μg/L) concentrations. For 10.3% of the discrete water sampling events, service line water did not contain a detectable total chlorine residual. Water pH consistently and significantly increased in the plumbing system from 7.5 to 9.4, and total trihalomethane (TTHM) levels increased up to 89%. The service line total organic carbon level (0.5–0.6 mg/L) was consistent, but much greater in-building variability was found for cold (0.4–61.0 mg/L) and hot water (0.5–4.7 mg/L). Models are needed to predict chemical water quality at the faucet using service line water quality results and plumbing design and operational information. Building water sensor technology innovations are also needed.

1. Introduction

In the U.S., 283 million people receive drinking water from a public water system, and while not surveyed, it is assumed this water passes through building plumbing [1]. To reduce the chance that this water can cause disease, a patchwork of federal and state laws restrict the allowable contaminants in water distribution systems [2–5]. Water quality is not monitored at every service line, where water enters the building. Instead, systems must report their drinking water's chemical quality at the point-of-entry and select locations in the water distribution network [6–8]. Compliance with the lead and copper rule is an exception where a water sample is collected from a building faucet [9]. However, this rule does not account for water quality variability during seasons or at all buildings. Thus, information remains limited about the water quality inside these buildings, especially when the degree of water quality may seasonally and spatially differ across building fixtures.

To better understand the factors that influence in-building drinking water chemical and microbial quality, many studies have been conducted [10–17]. The time of day and season can influence service line water quality characteristics like disinfectant residual, water pH, hardness, organic carbon, disinfectant byproduct (DBP), heavy metal concentrations, NO_3^- concentrations, and microbial communities [18,19]. Seasonal changes in water temperature and organic content can also influence the rate and type of disinfection by-products (DBPs) formed. A higher water temperature during summer can accelerate DBP formation. The presence of a higher level of dissolved organic carbon (DOC) during

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summer can also prompt greater DBP levels, and DBPs include trihalomethane (THM) compounds [20,21].

Contaminants in building drinking water can be affected by plumbing materials, temperature, pH, and water flow patterns [22,23]. Temperature influences chemical reaction kinetics; An increase in temperature can increase the disinfectant decay rate, DBP formation, and plumbing component heavy metal leaching [20,21,24,25]. At higher pH values, brass and copper pipes can sometimes leach lower levels of Cu and Zn [16,26], and a greater portion of metals can be in particulate form [27]. A greater amount of THMs was found at higher pH due to the enhanced hydrolysis steps in their formation process [28,29]. The role of pH on organic leaching from plastic plumbing has gone unstudied, but polyethylene resin pellets exposed to pH 11 water released more organic carbon compared to a pH 7.8 water [30]. Changes in water pH can also influence metal precipitation onto crosslinked polyethylene (PEX) plumbing pipes [31]. In-building water stagnation can enable disinfectant residual decay and heavy metal leaching [10,32,33].

A limitation of prior studies is the lack of intensive water quality monitoring in a single building across seasons and multiple locations in the building. Online monitoring can be costly, requires skilled technicians, and collecting and analyzing water samples is labor-intensive. Online monitoring is commonly used for water source, treatment, and distribution system operations [34,35]. Many prior investigators have collected drinking water from multiple buildings and coupled this with pilot- and bench-scale experiments. To the author's knowledge, no studies have been conducted that (1) utilized online temperature and flow monitoring at every building fixture (cold and hot), with a complete plumbing system layout and accounted for all material types and sizes, and (2) conducted online water quality monitoring at the service line at the building point-of-entry to measure water quality fluctuations.

The study goal was to investigate the temporal and spatial variations of drinking water chemical quality in a highly monitored net-zero energy green building. The authors hypothesized that (1) drinking water chemical quality at the service line will vary seasonally, (2) the duration of fixture (water) stagnation will differ seasonally and spatially, and (3) in-building water temperature, pH, inorganic and organic contaminant levels will vary by season for cold and hot water. To test these hypotheses, water flow and chemical quality monitoring was conducted for an inhabited residential building and bench-scale testing was conducted.

2. Materials and methods

2.1. Water source and residential plumbing

The studied residential building had 3 bedrooms, 1.5 baths, and was located in West Lafayette, Indiana. The building was occupied by three college students and had been renovated three years earlier. The renovation included the installation of new PEX plumbing. A prior study documented water quality observations during the first four months of this PEX plumbing's startup [10].

During the present study, the building received water from a public water system that served 30,943 customers and relied on a groundwater source. Groundwater was chlorinated, aerated, filtered, chlorinated with free chlorine for secondary disinfection, and a corrosion inhibitor was added before distribution (70% orthophosphate and 30% polyphosphate). Additional information regarding the finished water chemistry can be found elsewhere [10,36]. A 1.9 cm diameter utility copper pipe delivered water to the meter and the building's 1.9 cm diameter PEX service line traveled roughly 4.3 m to the building. Water entered the building's trunk-and-branch PEX plumbing with brass ball valves. Water first passed through a point-of-entry water softener and then into cold and hot water plumbing. Design fixture flow rates (with aerators) were: kitchen faucet (6.8 LPM [1.8 GPM]), bathroom sinks (4.5 LPM [1.2 GPM]) and the shower head (7.6 LPM [2.0 GPM]). Actual fixture flows in the building under various plumbing operation conditions were reported elsewhere [37]. The hot water system included a recirculation pump, and three 409 L [108 G] glass lined hot water storage tanks in series followed by a fourth, electrically-driven water heater (151 L [40 G]). More plumbing and water flow monitoring system details have been reported in **SI-1** and elsewhere [10,37].

2.2. Water sampling and quality analysis

From October 2017 to October 2018, water samples were collected during 58 trips (at least 12 trips per season) to the building. An overview of all experimental efforts can be found in Fig. 1. More than 222,000 labor hours were dedicated to collect discrete water sampling data, not including labor for data analysis. In this study, the four seasons were defined as fall (September 21 to December 20), winter (December 21 to March 20), spring (March 21 to June 20), and summer (June 21 to September 20). During each trip, grab samples were collected from the service line and multiple in-building fixture locations during morning (0800), noon (1200), and afternoon (1500) hours. Water samples were collected in the following order: Service line (SL) before water entered the water softener, 1st floor kitchen cold (1st C), 2nd floor bath faucet cold (2nd C), water heater (WH) in the basement, 1st floor kitchen hot (1st H), 2nd floor bath faucet hot (2nd H) and the shower (2nd SH). The shower water sample involved draining the shower hose into the container and filling the rest of the sampling container with first draw water. All samples were immediately collected; no flushing was conducted. An estimated <1.8 LPM flow rate was observed during the water sampling. The number and location of grab water samples are summarized in Table SI–1.

The following water quality parameters or constituents were measured onsite in sequential order: free chlorine, total chlorine, pH, temperature, dissolved oxygen (DO), followed by water sample collection in two 125 mL HDPE bottles for metal (Al, Be, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Se, and Zn) and ion (Li^+, Na^+, NH_3, K^+, Mg^{2+}, Ca^{2+}, F^-, Cl^-, NO_2^-, Br^-, NO_3^-, PO_4^-, and SO_4^{2-}) analysis. Next, two 125 mL amber glass bottles were filled for total organic carbon (TOC), dissolved organic carbon (DOC), and alkalinity analysis, and two 10 mL glass vials were filled for TTHM analysis. Before water samples were collected, $Na_2S_2O_3$ was added to vials used for TOC/DOC and TTHM analysis. H_2SO_4 was added to plastic bottles used for metal analysis in order to preserve the samples. Field and trip blanks (controls) were also collected and analyzed. All water samples were transported less than 500 m from the building to the laboratory for analysis. Detailed analytical methods are described in the Supplementary Materials SI-2 and Tables SI-2–SI-4.

2.3. Online monitoring at the building

An online HACH® analyzer was used to characterize water quality variability of various parameters and/or constituents at the service line. This analyzer consisted of a flowmeter, a CL17 chlorine analyzer (total chlorine), pH/temperature probes, and a DB TU5300sc online laser turbidimeter with a flow sensor. Turbidity and flow rate were recorded every 1 min; water pH, temperature and total chlorine were recorded once every 5 min. Turbidity and chlorine analyzer detection limits were 0.002 NTU and 0.03 mg/L-Cl_2, respectively. This system was installed near the end of the study (September 22, 2018), which was followed by three water sampling trips. For total chlorine data, values exceeding 1.5 times the interquartile range for the entire time series were removed. The same procedure was applied for the resulting time series on hourly intervals.

To monitor water flow in the building, automated impeller flowmeters (Omega, FPR300 series) were installed on each cold and hot water supply line with 0.4 LPM accuracy. Flow meters recorded flow every 1 s. Water flow data was converted to water usage parameters, including total volume water used and average elapsed time since the last water usage event. Average elapsed time since the last event was representative of the water's stagnation at the fixture. A minimum of 3 s

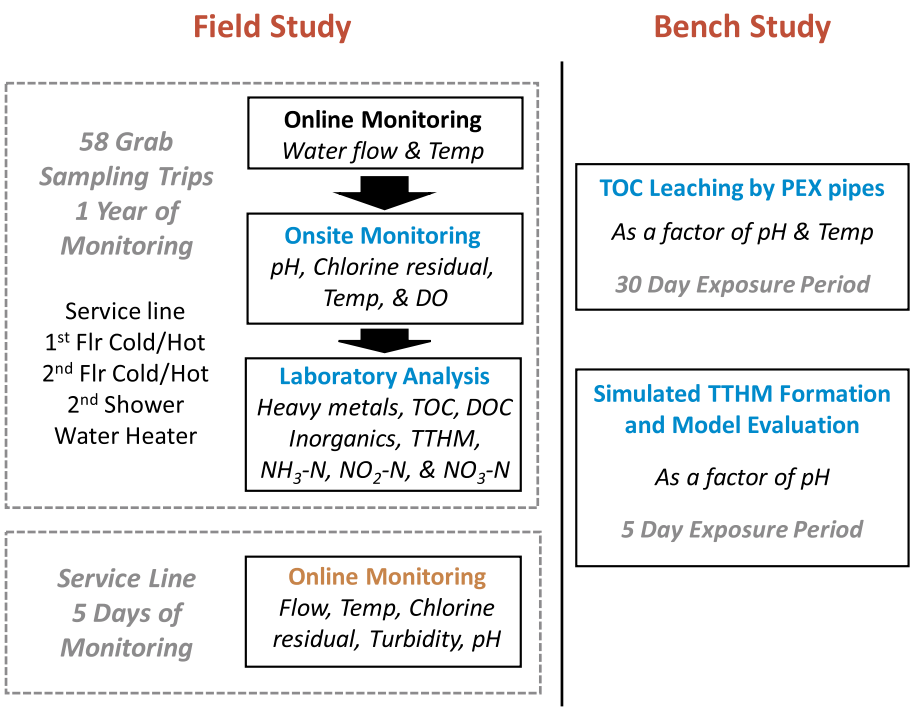


Fig. 1. Overview of experimental efforts conducted during this investigation, which included both field and bench-scale testing efforts.

was considered as elapsed time since the last event. Therefore, more than 2.4 billion online monitoring data points were collected during the present study. More information about water flow data analysis can be found in a prior study [10]. Building occupancy was also recorded. The building cost approximately $100,000 to instrument.

2.4. Bench-scale experiments

2.4.1. PEX pipe organic carbon leaching

New PEX type A (PEX-a) and type B (PEX-b) pipes were obtained as single 91.4 m coils. The PEX-a pipe was the same brand and diameter as the drinking water pipe in the residential building. Pipes were cut to 3.0 m length segments, were rinsed with municipal tap water to remove any debris, and then were disinfected with synthetic laboratory prepared drinking water [2 mg/L-Cl_2 free chlorine; pH 7.0; room temperature] in accordance with the State of California Plumbing Code [38]. After disinfection, pipes were rinsed with synthetic laboratory prepared water (no disinfectant) and were then used for water stagnation tests in accordance with methods provided by others [39]. Depending on the experiment, water pH values were adjusted to either pH 7.0 or 10.0 using NaOH and HCl. For a one-month period, the pipe sections were filled with water, and then water was removed and replaced every three days. Organic carbon concentration was measured on day 0, 3, 15, and 30. Tests were conducted at constant temperatures, 23 or 50 °C.

2.4.2. Simulated TTHM formation study

On three separate September days, amber glass bottles were filled with service line water under headspace-free conditions. Water pH was also measured, and for half of the water samples collected each day, their pH was raised to 9.0 with a borate buffer. The disinfectant residual of these samples was first measured and then neutralized either immediately (for controls) and after 6, 24, 72, and 120 h. Bottles were stored in the dark at room temperature. TTHM concentration was quantified for two replicate samples. TTHM results and other water quality data from the building, and assumptions [40–43] were then applied to evaluate the ability of existing models to predict in-building TTHM levels. Details of the model assumptions are described in the **SI-4**.

2.5. Statistical analysis

IBM SPSS Statistics 25 was used to perform statistical analysis. Water quality data were tested for normality using the Kolmogorov-Smirnov test [44]. This analysis revealed water quality data were not normally distributed, so the nonparametric analysis technique of Kruskal Wallis test followed by Dunn-Bonferroni pair-wise comparison test were applied [45]. A type I error at the significance level of 0.05 was selected for all analyses. Bivariate Pearson correlation analysis was applied to investigate the correlation between water quality parameters [46].

3. Results and discussion

3.1. Seasonal water use and in-building stagnation

Low seasonal water use (19.7–25.5 m^3/season) occurred and was likely due to the water efficient fixtures and appliances, a low number of building inhabitants, and because these inhabitants were college students (Table 1). Seasonal water use was about 70% less than the national average for a single-family building (83 m^3/season) [47]. The fall 2015 building startup study also indicated low water consumption (19 m^3) [10]. In the present study, the building's seasonal occupancy (1.5–2.8 persons/day) was lower than the average U.S. household (3.14 persons) [48]. Building water usage (0.11 m^3/person-day) was about 30% less than water use in West Lafayette, Indiana (0.38 m^3/person-day) [49]. Dodson et al. (2013) previously found that college student households used less water than a typical single-family residence (50% less use, Davis, California [50]). Outdoor climate may also have contributed to low water use [51,52].

Great differences between when fixtures were used (stagnation time: average 0.4–5.7 h) can be attributed to seasonal and outdoor temperature differences. The shower fixture utilized the most water [53], and maximum water use occurred in cold seasons (31–32% seasonally, fall and winter) compared to the warm seasons (16–24% seasonally, spring and summer). One reason this increased volume was observed may be due to the longer time needed for the water to reach the warm temperature at the point of use [51]. At the water heater, more water (67%)

Table 1
Seasonal water usage, occupancy, and fixture stagnation times.

Season (mean, max, and min Occupancy/Day) Water Use Characteristics			Fixture Locations						
			Service Line	*1st Flr Cold*	*2nd Flr Cold*	*2nd Flr Shower*	*Water Heater*	*1st Flr Hot*	*2nd Flr Hot*
Fall (2.8, 12, 0)[a]	*Total Volume, m^3/season*		25.5	0.9	0.4	8.1	8.7	1.0	3.5
	Stagnation, hr	*Mean*	0.3	1.0	2.2	2.3	0.5	1.2	1.1
		90th tile	0.0	2.2	7.3	3.6	0.9	2.0	2.5
		Max	37.5	153.0	102.7	120.0	152.0	153.0	150.2
	% time fixture was stagnant		98.9	91.7	93.5	93.5	93.7	93.5	92.6
Winter (2.2, 7, 0)[a]	*Total Volume, m^3/season*		23.6	0.8	0.4	7.3	8.3	1.0	4.8
	Stagnation, hr	*Mean*	0.3	1.1	3.2	3.4	0.4	1.0	1.1
		90th tile	0.6	2.2	9.7	9.3	0.8	2.0	2.2
		Max	16.0	99.4	69.9	72.3	50.7	72.9	72.6
	% time fixture was stagnant		87.2	88.9	90.6	90.6	90.8	90.4	89.7
Spring (1.5, 5, 0)[a]	*Total Volume, m^3/season*		19.7	0.5	0.2	4.7	5.9	0.8	2.5
	Stagnation, hr	*Mean*	0.5	2.2	5.3	4.5	0.7	1.6	1.7
		90th tile	1.0	4.1	11.6	13.8	1.1	2.8	3.0
		Max	25.8	114.1	123.1	60.7	68.9	116.2	67.0
	% time fixture was stagnant		87.7	88.9	90.2	90.1	90.2	90.0	89.5
Summer (2.7, 17, 0)[a]	*Total Volume, m^3/season*		23.8	0.9	0.2	3.7	4.3	0.7	1.0
	Stagnation, hr	*Mean*	0.1	1.3	3.9	5.7	0.7	1.6	1.7
		90th tile	0.1	2.2	7.6	15.6	1.2	2.6	3.0
		Max	47.0	118.6	145.1	79.0	95.4	142.5	65.8
	% time fixture was stagnant		96.0	98.8	99.7	99.8	99.9	99.8	99.4

[a] Average outdoor temperature: 5.4 °C (Fall), −0.7 °C (Winter), 15.6 °C (Spring), 22.6 °C (Summer), calculated using data reported at *Weather Underground*. Average daily occupancy is reported as persons/day.

was used during the cold seasons compared to the warm seasons [54,55]. During the warm seasons, hot water fixtures had longer average stagnation times compared to the cold seasons. Because stagnation can influence water chemistry and microbial growth [12,33,56–58], the authors expected water quality to differ across fixtures.

3.2. Water quality at the service line

At the service line, chlorine residual concentration and water temperature varied seasonally, while other water quality characteristics did not vary seasonally. Chlorine residual was not detected (<0.2 mg/L-Cl_2) at the service line for 10.3% of the sampling events; these events occurred in winter, spring and summer. The highest chlorine residual concentration found occurred during the spring (2.1 mg/L-Cl_2), while the greatest seasonal average concentration was found during winter (0.9 mg/L-Cl_2). For context, Indiana law requires that disinfectant residuals in water distribution systems should not be undetectable (<0.2 mg/L-Cl_2) for more than 5% of samples each month for any two consecutive months [59]. If this threshold were applied to the building's service line, noncompliance would be found: 1 of 10 trips nondetectable (10%) [May 2018], 1 of 5 nondetectable (20%) [June 2018], 3 of 9 nondetectable (33%) [July 2018].

Table 2
Seasonal variations of water chemical quality at the service line.

Parameter		Drinking Water Limits	PWS[6]	At the Residential Building Service Line[1,2]											
				Fall (n = 13)			Winter (n = 17)			Spring (n = 12)			Summer (n = 16)		
				x	10th tile	90th tile	*x*	10th tile	90th tile	*x*	10th tile	90th tile	*x*	10th tile	90th tile
General	Temp, °C	nL[3]	nr	21.6	20.5	23.3	14.6	11.7	16.6	21.1	19.8	22.0	22.9	21.9	23.6
	pH	6.5–8.5[4]	7.6	7.7	7.6	7.7	7.7	7.7	7.8	7.7	7.7	7.8	7.5	7.3	7.7
	Total Cl_2, mg/L	4.0[5]	1.2	0.4	0.3	0.6	0.9	0.5	1.1	0.6	0.1	1.3	0.4	0.1	0.8
	Free Cl_2, mg/L	nL	nr	0.3	0.3	0.4	–[8]	–[8]	–[8]	0.4	0.0	0.9	0.4	0.1	0.9
Organics	TOC, mg/L	nL	nr	0.5	0.4	0.5	0.5	0.4	0.5	0.6	0.4	0.9	0.5	0.4	0.6
	DOC, mg/L	nL	nr	0.5	0.4	0.6	0.5	0.4	0.5	0.5	0.3	0.8	0.5	0.4	0.5
	TTHM, µg/L	80[5]	19.2	<1.4	<1.4	3.8	<1.4	<1.4	1.7	2.5	<1.4	4.8	<1.4	<1.4	1.5
Heavy Metals	Pb, µg/L	–[3,7]	nd	<1.1	<1.1	2.1	<1.1	<1.1	<1.1	<1.1	<1.1	<1.1	<1.1	<1.1	2.1
	Zn, µg/L	5000[4]	nr	14.3	<0.2	40.0	14.1	<0.2	33.4	26.6	11.8	50.5	10.4	<0.2	22.6
	Cu, µg/L	1000[4]	565	81.2	16.3	177.0	75.5	18.4	161.2	72.6	21.4	121.6	32.2	15.5	55.4
	Fe, µg/L	300[4]	20	19.1	1.5	51.8	16.7	8.2	23.9	6.2	2.9	11.7	6.7	2.9	10.9
	Mn, µg/L	50[4]	20	3.1	<0.1	8.2	2.9	1.9	3.7	1.8	<0.1	3.1	2.0	0.5	4.4
Nitrogen	NH_3–N, mg/L	nL	nr	0.4	<0.01	0.7	<0.01	<0.01	0.1	<0.01	<0.01	<0.01	0.1	<0.01	0.2
	NO_3–N, mg/L	nL	0.2	0.5	0.1	0.8	0.8	0.3	1.3	0.6	0.2	1.1	0.1	0.1	0.2

National Primary and Secondary Drinking Water Standards were used for comparison; [1] x = m; nr = Not reported; nd = not detected; [2] Additional inorganic contaminant results can be found in the SI; [3]No primary or secondary maximum contaminant level;[4] Secondary Maximum Contaminant Level (SMCL); [5]Primary Maximum Contaminant Level (MCL); [6]Regulatory samples collected by water utility from different locations in the water distribution system;[7] Federal drinking water action level for Pb is 15 µg/L, but it is not a health based drinking water limit. Children should not be exposed to Pb in drinking water at levels greater than 1.0 µg/L according to the American Association of Pediatrics[92]; [8] (–) Did not measure.

The service line temperature also varied seasonally (summer: seasonal average 22.9 °C vs. winter: seasonal average 14.6 °C). Outdoor temperature likely influenced service line water temperature [55]. Alternatively, water pH (7.5–7.7) and organic carbon concentration (0.5–0.6 mg/L) did not vary by season. Seasonal TTHM levels were low to nondetectable (below the detection limit to 9.6 μg/L) (Table 2). In comparison, the public water supplier's annual average concentration in its distribution system was 19.2 μg/L [60].

The concentration of some heavy metals (Cu, Fe, Zn) at the service line differed by season while the concentration of others did not (Mn, Pb) (Table 2). A significantly lower Fe concentration was found during winter compared to spring and summer ($p < 0.05$). The lowest Cu level was found during summer ($p < 0.05$). This effect might be due to seasonal temperature fluctuations which can influence biological, chemical, and physical processes including metal corrosion [61]. During morning hours, service line water contained significantly greater amounts of Zn and Cu compared to afternoon water samples ($p < 0.05$). Overnight water stagnation in the water utility's Cu service line may have contributed to these higher metal levels. NO_3^- concentrations were the lowest during summer and had a single-day maximum of 1.8 mg/L-N in spring. No National Primary Drinking Water Regulation primary or secondary maximum contaminant levels were exceeded.

3.3. Drinking water quality fluctuations at the service line

Service line online water quality monitoring results were consistent with grab sample water quality collected during that same time period (Fig. 2). Online monitoring demonstrated an almost stable water pH (7.6 ± 0.1) and total chlorine concentration (0.2 ± 0.4 mg/L-Cl_2), similar to grab water samples (7.7 ± 0.0 and 0.3 ± 0.0 mg/L). Turbidity

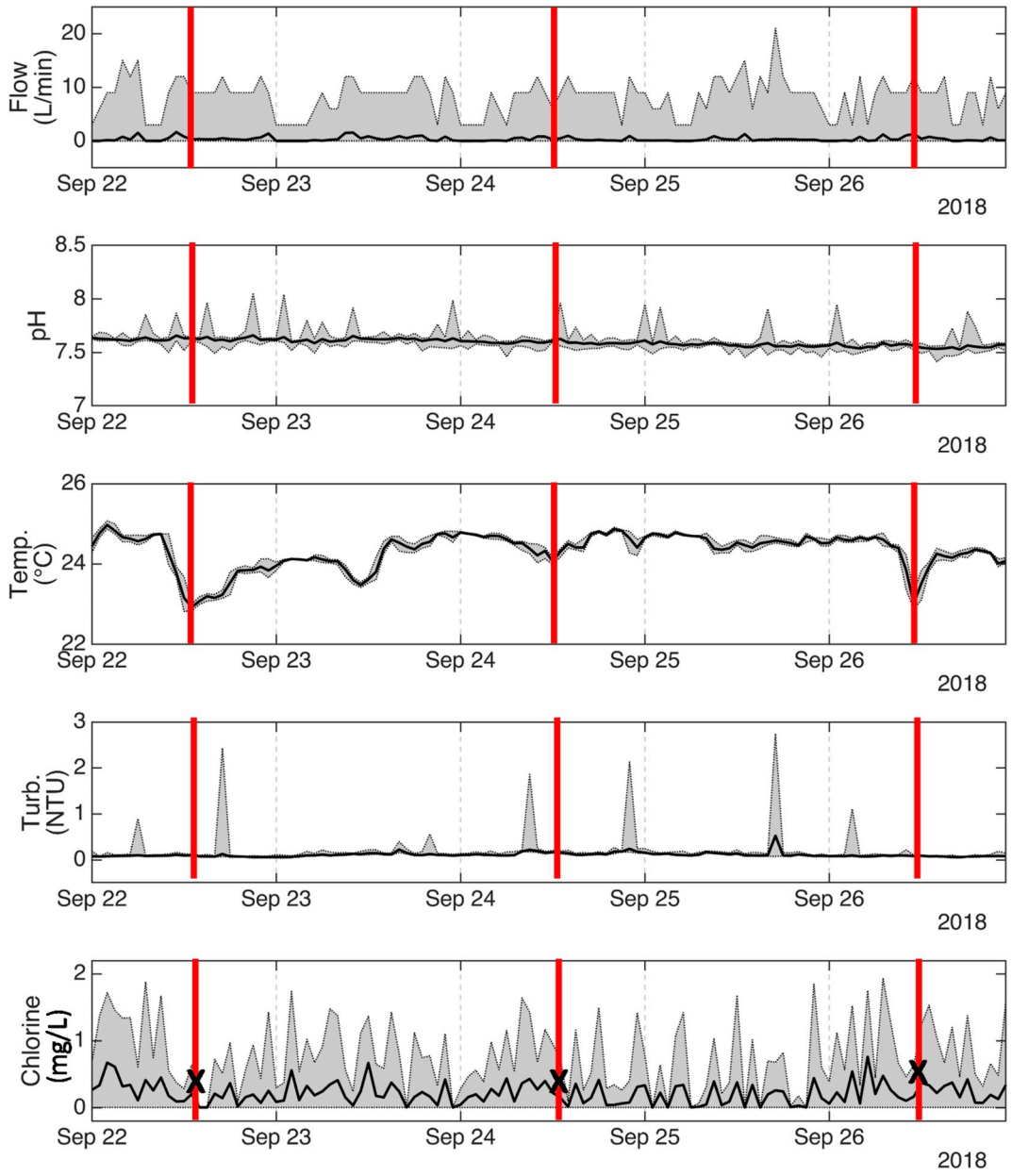


Fig. 2. Service line hourly averaged water flow, water pH**, temperature, turbidity, and total chlorine residual concentration.** Vertical red lines represent the day and time a trip was conducted to collect grab samples; X marks the day grab samples were collected. The black line (left to right) represents the average values while the gray areas show the range of variability (minimum and maximum) within the hour of observation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

was not quantified during discrete water sampling trips. Online monitoring records (n = 7200) revealed service line water had an average turbidity of 0.1 NTU with a few peaks (maximum 2.7 NTU). These peaks matched peak service line flow rates and indicated that a hydraulic event likely suspended biofilm and/or inorganic scale [62–65].

3.4. Water quality variability by fixture and time of day

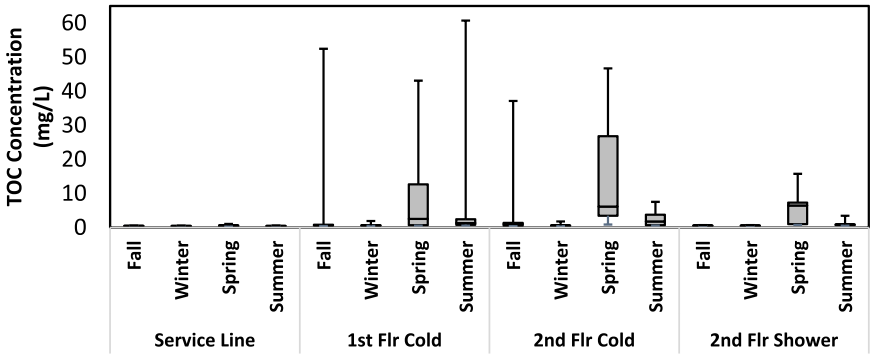
As expected, the whole house water softener reduced Ca and Mg levels and increased K and Na concentrations ($p < 0.05$) [66]. Total hardness was reduced from about 385 mg/L as $CaCO_3$ at the service line to 19 mg/L as $CaCO_3$ inside the building. The public water supplier reported 382 mg/L as $CaCO_3$ hardness at the point-of-entry to their distribution system [60]. Slight spatial and temporal differences between cold and hot water hardness were found in the building (**SI-3**). Significantly greater total hardness was found in hot water (29 mg/L as $CaCO_3$) compared to the cold water (8 mg/L as $CaCO_3$) ($p < 0.05$). This may be due to Ca and Mg scale build up in the water heater [67]. Despite the low solubility of scale constituents, Ca and Mg ion release may have caused the observed hot and cold water hardness difference ($p < 0.05$).

Water pH often significantly increased from the service line (7.2–7.8) through the building (7.2–9.4) ($p < 0.05$). The greatest water pH values were found on the 1st floor cold (7.5–9.4) and 2nd floor hot (7.7–9.0) water fixtures. About 11% of all faucet pH values exceeded the secondary maximum contaminant level of 8.5. Water pH increased within the building between 0.3 and 0.6 units, which has also been observed by others: +0.7 units [plumbing material type not reported] [68], and +0.3 pH units caused by water softeners [66,69]. As no grab sample was collected immediately after the water softener, it was not possible to distinguish its role in raising the water pH from the rest of the plumbing. As expected, water temperature increased through the building from an average of 19.6 °C, at the service line to an average of 23 °C ($p < 0.05$) in building. Both the elevated water pH and temperature changes likely impacted water chemistry.

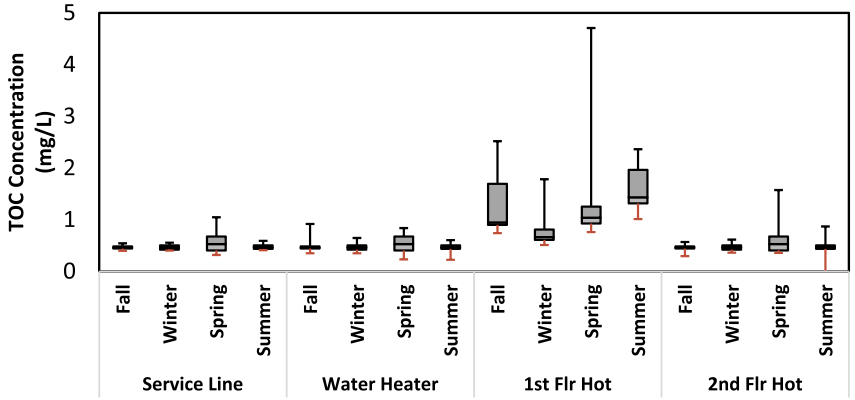
3.4.1. Organic carbon, chlorine residual, and DBP concentration variability across fixtures

Organic carbon concentrations increased significantly through the building while organic carbon levels were often greatest in the cold water samples ($p < 0.05$) (Fig. 3). A single event maximum of 60.7 mg/L was found at the 1st floor kitchen sink cold water during summer. Most organic material found was dissolved (90–98%). The observed fluctuation in the organic carbon levels might be due to PEX plumbing pipes [39], biomass release from plumbing surfaces [70–73], and transient spikes in carbon from the public water system due to hydraulic events [74–76]. For some fixtures, organic carbon levels were about 3-fold greater than levels quantified at the same building three years earlier when the plumbing was newly installed [10].

Disinfectant residual levels decreased through the building (Fig. SI-1). For more than 85% of the sampling trips, the disinfectant residual was not detected at the water heater, the 2nd floor cold, and 2nd floor shower fixture. Further, no residual was detected for 69% of the samples



(a)



(b)

Fig. 3. The box and whisker plot for spatial and seasonal total organic carbon variations at the service line and three in-building locations for (a) cold water and (b) hot water. The whiskers representing the minimum and maximum values, and the boxes show the first quartile, median, and third quartile.

at the 2nd floor hot and 1st floor cold fixtures. A significant negative correlation between temperature and disinfectant residual was found at all fixtures except the water heater tank and 2nd floor shower ($p < 0.05$). Others have also found chlorine-based disinfectants were mostly nondetectable in commercial and residential plumbing [13]. In one case, plumbing induced disinfectant decay was previously reported to be more than 144 times faster than in the water distribution system [13]. Elevated temperature likely contributed to chlorine disinfectant decay [68].

TTHM levels in the building were up to 89% greater (single event maximum 42 μg/L) than levels found at the service line (Fig. SI-1). A significant positive correlation was found between water temperature and TTHM levels for the cold water samples ($p < 0.05$). Results agreed with previous cold and hot water plumbing TTHM monitoring studies ($p < 0.05$) [22,77–79]. In-building TTHM formation may have been influenced by organic carbon [42], water stagnation [79], the water heater [68], and water pH [80,81]. A significant positive correlation between organic carbon and TTHM concentration at the service line, 1st floor hot and cold fixtures indicates that organic carbon contributed to TTHM formation. It is known that under chlorination conditions a correlation between organic carbon and TTHM concentration can exist [82].

The discovery that TTHM and pH levels were greater in building plumbing compared to the service line prompted a bench-scale experiment. The purpose of this experiment was to determine if building water pH was primarily responsible for TTHM generation. Service line water collected for TTHM formation experiments showed that disinfectant residual (0.32 ± 0.00 mg/L as Cl_2, range 0.31–0.33 mg/L as Cl_2), water pH (7.80 ± 0.04, range 7.68–7.86), and organic carbon (0.71 ± 0.27 mg/L, range 0.47–1.82 mg/L) varied. Bench-scale tests revealed raising pH to 9.0 resulted in increased TTHM generation (9–35%) compared to that same water without pH adjustment. Without any pH adjustment, the service line water TTHM concentration was 3.3 ± 0.5 μg/L after 5 days. The authors' findings are supported by literature where a higher rate of TTHM formation at elevated pH can occur since THM formation is base-catalyzed when generated within chlorinated natural and treated waters [28,83–87]. Three previously published TTHM prediction models were applied and none adequately predicted TTHM levels at the fixture studied (SI-4) [40–43].

3.4.2. PEX pipe organic carbon release was influenced by exposure time, pipe brand, water temperature, and water pH

The discovery that a greater organic carbon concentration and water pH were often found inside the building compared to the service line, prompted a bench-scale experiment. While PEX plumbing pipe sold in the U.S. can release organic carbon into drinking water [39], the role of water pH and temperature or organic contaminant release in the U.S. has gone unexplored. Chemical leaching from two brands of PEX pipes for cold and hot water at pH 7 and 10 were examined. The PEX-a pipe was the same brand present in the building. Results showed that organic carbon release was influenced by the exposure time, brand of pipe, water temperature, and water pH (Table SI–5). The highest organic carbon levels for both pipes were found during the first stagnation period and decreased with time. Notably, initial leaching (maximum 77 mg/L) was an order of magnitude larger than typical organic carbon levels in treated drinking water [88]. The large organic carbon standard deviation (15–67%) during the first stagnation period was likely due to organic carbon loading differences between the individual replicate pipe sections. Organic carbon release was greater for hot water (50 °C) compared to cold water (23 °C) for both PEX pipes ($p < 0.05$). Water pH influenced organic carbon release for PEX-a pipe, where a greater organic carbon level was found at pH 10 compared to pH 7 ($p < 0.05$). In contrast, for the PEX-b pipe, lower organic carbon levels were found at pH 10 ($p < 0.05$). The authors did not identify the specific organic compounds that had leached into the water, where only a few percent of the organic carbon leached has been previously identified [89–91]. Inorganic scale and biofilm were likely present on the PEX plumbing and may influence PEX pipe chemical leaching behavior, although this was not studied here. While bench-scale PEX-a pipe organic carbon release was significant and decreased with time, evidence suggests that organic carbon spikes might be related to the hydraulic water distribution system and plumbing events.

3.4.3. Heavy metal deposition and release from the plumbing

Differences in heavy metal concentrations suggested that Cu, Pb, and Zn leached from the plumbing while Fe and Mn deposited in the plumbing. Cu, Pb, and Zn concentrations were generally greater inside the building compared to levels at the service line. The average Pb concentration in building was 2.2 μg/L, however it was not detected at the service line. For context, the American Association of Pediatrics recommends that children should not be exposed to Pb in drinking water at levels greater than 1.0 μg/L [92]. Brass ball valves in PEX plumbing (3 for cold water, 3 for hot water) were likely partly responsible for Cu, Pb, and Zn concentrations inside the building. Compositional analysis and bench-scale testing showed that these valves contained 64.3% Cu and 34.9% Zn, and leached Cu, Pb, and Zn [93,94]. The greatest total Pb (13.2 μg/L) and total Zn (1350 μg/L) concentrations were found at the 2nd shower fixture during summer. The shower fixture was not intended for drinking water use and its long stagnation period may have deteriorated water quality [56]. Greater Cu levels were found at the water heater and 1st floor hot water samples compared to other locations but not the 2nd floor shower ($p < 0.05$). This phenomenon was also reported by others where hot water faucet Cu levels were about 33% greater than cold water [95]. Cu entered the building mostly in dissolved form (92–99%). In contrast, a greater amount of particulate Cu was found in building hot water (17–39%) compared to cold water (1–21%) samples (Fig. 4). The increase in building water pH likely caused Cu precipitation [27], though organic carbon leached from PEX plumbing can prevent Cu deposition [31].

Fe concentrations (average 12.6 ± 12.3 μg/L) were at the service line and were lower through the plumbing (1st floor hot, 6.4 ± 3.6 μg/L; 2nd floor hot fixtures, 5.3 ± 3.1 μg/L) ($p < 0.05$). Significantly lower Fe concentrations were found in hot water samples compared to the cold water samples except the cold water from the shower fixture ($p < 0.05$). The greatest Mn levels were found at the service line (2.4 ± 1.6 μg/L) and water heater compared to other locations inside the building (1.4 ± 2.6 μg/L). Three years prior to this study, it was discovered Fe and Mn had deposited onto previously installed and exhumed PEX pipes [36]. More recently, at a neighboring house, Fe and Mn were found to be major constituents on that building's PEX plumbing scale [31]. Alkalinity, hardness, chloride to sulfate mass ratio, DO, natural organic matter, and disinfectant residual may also have influenced metal species solubility [96]. A variety of other metals were detected at low levels with no significant pattern (i.e., Al, Be, Cd, Co, Cr, Ni, Se).

3.4.4. Potential seasonal nitrification

Results suggest that seasonal nitrification occurred in the hot water plumbing, although generally nitrification has been associated with chloramine residual disinfectant systems [97]. The NH_3 concentration (0.12 mg/L-N) at the service line was similar to the shower location but was lower at the 2nd hot fixture (0.02 mg/L-N). NO_2^- was not detected at the service line or cold water samples but was found during short spring and summer periods (0.02–0.05 mg/L-N) in hot water plumbing. Significantly lower NO_3^- levels were found in afternoon water samples compared to the morning or mid-day ($p < 0.05$). Other nitrification requirements (pH 7.8–8.9 [98], 25–30 °C [99]) were present. No NO_3^- spatial changes were found. SI-3 contains more information about the spatial changes of other ions.

4. Conclusion

Building water quality seasonal and spatial variations were found at

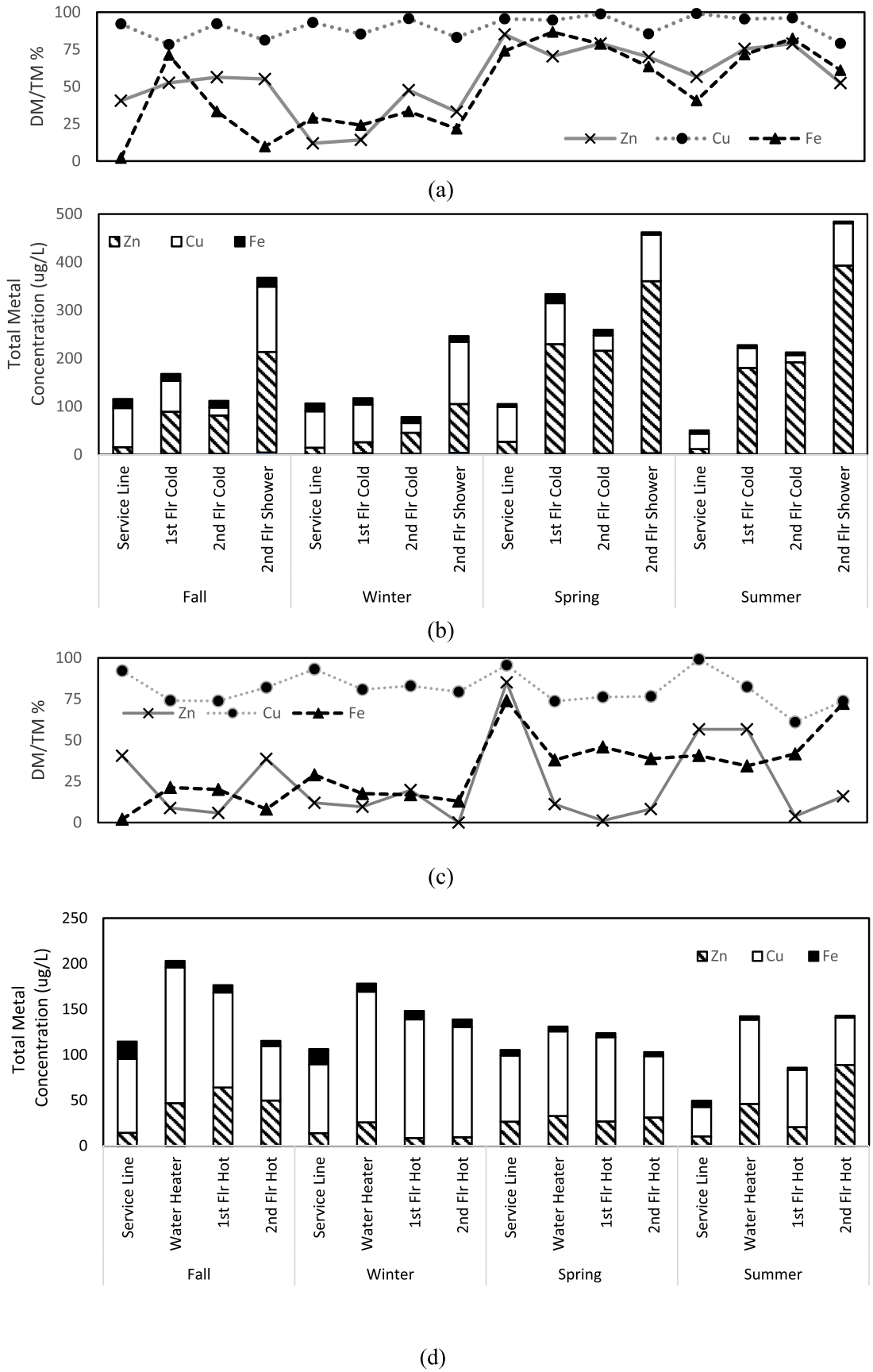


Fig. 4. Comparison of Zn, Cu and Fe concentration for cold (a,b) and hot (c,d) water fixtures by season. DM/TM % = percentage of the dissolved portion of the total metal concentration.

the service line and across fixtures. Major differences were found for pH, chlorine residual, organic carbon, TTHMs, select heavy metals, and nitrogen compounds. Reasons for these differences were determined by coupling and then interpreting 2.4 billion online water quality monitoring records and 58 discrete building water sampling events. Disparate fixture water quality can be attributed to fluctuations in drinking water quality provided by the water supplier, as well as in-building fixture water use, fixture stagnation time, hydraulic events, plumbing materials, and changes to water temperature and chemistry. To the author's knowledge, the frequency and extent of building water quality monitoring applied has not been previously reported in the literature.

Models are needed that predict drinking water chemical characteristics at building fixtures, and results show that service line water quality, as well as plumbing design and operational information are needed. Plumbing models could be used to help inform building codes, material selection, and plumbing operation decisions with the intent to limit water quality deterioration in buildings. The effectiveness of models however will largely depend upon better understanding the relationships between plumbing design and operation (flow, temperature, material), as well as material-water and bulk water chemical and microbiological processes.

Innovations in building water sensor technologies are needed to better capture water quality variability. The present study had a very high labor and financial commitment (220,000 labor hours not including data analysis; $100,000 for plumbing instrumentation and the data acquisition system). With improved sensor technology, testing costs should decrease and the monitoring of multiple buildings could be more easily conducted. During the past decade, sensor technology has enabled a better understanding of spatial and temporal drinking water quality in buried water distribution systems. Equally impactful technology advancements are needed for building water systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2019.106566.

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