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Water Impact Statement

Safe water is vital to child development and children spend much of their early life at schools. School building water systems can contribute to high concentrations of chemicals and microbiological contaminants that can endanger children's health. Actions needed to understand how system design and operation affect water quality in a large building are lacking.

Finding Building Water Quality Challenges in a 7-Year Old Green School: Implications for Building Design, Sampling, and Remediation

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Abstract

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

1. Introduction

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

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

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

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

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

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

2. Materials and methods

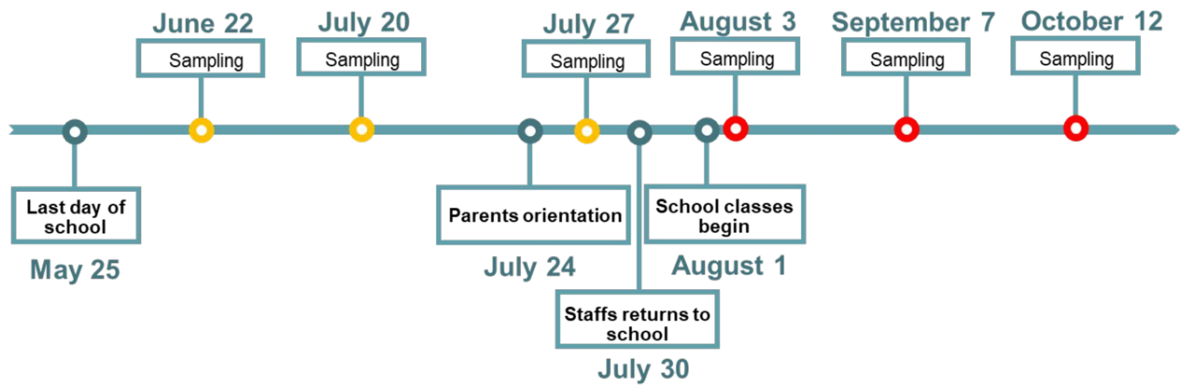
2.1 School campus water use and plumbing characteristics

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

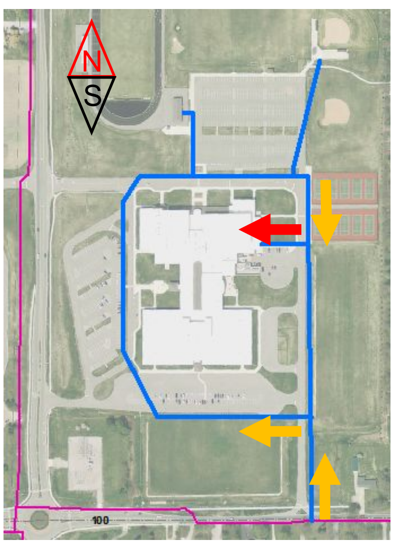
A timeline of key events at the school can be found in **Figure 1**. Six sampling events were conducted inside the building, 3 during the summer break and 3 after the school returned in session. During summer break some water use occurred in the building (**Figure SI-1**). The building's north section was used for summer camps, primarily in the auditorium, gym, and athletic fields. Every weekend, the building's north section was also used for church services, and each service had a reported capacity of up to 500 people (two church services one in the morning, one in the afternoon every Sunday all year long). Before our sampling events, the north section of the building was used the most for the summer camps: up to 250 students were in sports camps, 50 students in orchestra camps in the music room, and 200 students in a band camp. During July, one music camp was held for 100 students in the auditorium in the building's north section before the second sampling event. In contrast, the south section of the building was the "academic" classroom side. This building section was primarily unused during the summer. When classes resumed in August 2018, about 830 students staff and faculty began inhabiting the building 5 days a week thereby increasing water use on the south section of the building.

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

(a)



(b) **(c)**



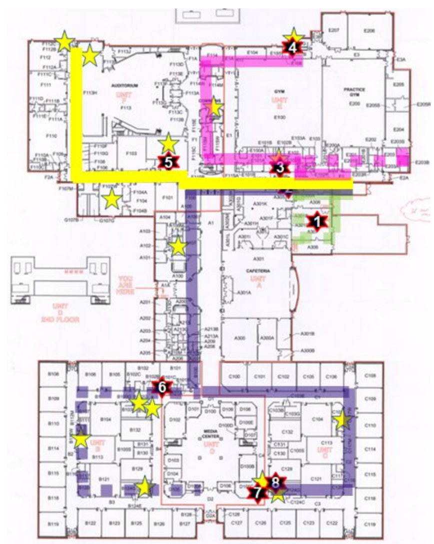


Figure 1. (a) Timeline for sampling and major school events, (b) the water service loop at school campus, the service line comes off the road to provide water from the south of the school and circles the entire school campus. Red arrow is the domestic service line that goes into the utility room, (c)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

2.2 Water Sampling Approach

Water sampling began between 7:00 am and 7:15 am on Fridays and samples were collected from 9 hot water and 9 cold water locations for 5 of the 6 events (**Figure 1, Table 1**). No students were there but a few faculty and staff members had arrived in the building before sampling. Drinking water was first collected where water entered the building (BE) and the authors proceeded to sampling locations in the north section (the most used area during summer break and closer to the entry point) and then moved to the south section (least used during summer break). No water flowrate was measured, but all the stagnant water samples were collected at a slow flowrate. Water was constantly flowing while collecting each sample but closed the tap after collection. Approximately 150 mL of water was collected for immediate analyses (pH, temperature, dissolved oxygen, total chlorine, free chlorine, free ammonia, monochloramine). Next, several samples were collected for metals [125 mL HDPE bottles with 0.05 mL acid], metals [125 mL HDPE bottles without acid], total organic carbon (TOC) [250 mL amber glass], alkalinity [250 mL amber glass], total trihalomethanes (TTHM) [two 20 mL glass vials], total cell counts (TCC) [two 15 mL falcon tubes], heterotrophic plate count (HPC)/quantitative polymerase chain reaction (qPCR) [two 1 L HDPE bottles], nitrification/denitrification [two 15 mL bottles]. Samples were kept in coolers with ice packs, transported to the laboratory a 1.5 hr drive away and were immediately analyzed. Water was screened for nitrification and denitrification processes using biological activity reaction test (BART) kits at all locations in the utility room one shower, and a bathroom sink for cold and hot. In accordance with the manufacturer's instruction, samples were evaluated for nitrification 5 days after the water was collected, and every day for 4 days for denitrification.[32] A detailed explanation of chemical and microbiological analysis methods, including equipment, instrument and method detection limits, can be found in the **SI** section.

After the first sampling event, the copper concentration in the building water system became a significant focus of this study. Initial copper results indicated building-wide copper AL exceedances. The authors then collected additional water samples for metals analysis on sampling events 2, 5, and 6. These additional water samples (same volume as the routine samples analyzed for metals) were collected after all the other water samples had been collected at each location (2.8 L later per sampling location). After finding further copper exceedances, the school, public water supplier, health department, and state drinking water primacy agency discussed the issue. Next, the school followed the state primacy agency's recommendation to flush each fixture where the authors found copper in exceedance of the AL, not implement a school-wide flushing program. Because of the author's concerns that such an action would not reduce copper concentration for other locations in the building, the authors then added an additional 19 new cold water sampling locations for the final sampling event (trip 6 of 6). To mimic the sampling approach used at other faucets the authors had previously tested during sampling events 1-5, at each new location on event 6 the first 125 mL of cold water was discarded, then a sample (125 mL) was collected for metals analysis, and then 2.8 L of cold water was discarded again before another sample (125 mL) for metals analysis was collected. This extra water sample still represents the stagnant water in different plumbing sections between fixtures (a lot of cold water pipes would store more than 3.7 L between fixtures). This approach enabled direct comparison of data collected on sampling event 6 to all other sampling events.

Table 1. Cold and hot water sampling locations included the building entry point, inside the utility room, water heaters, recirculation loops, water fountains, and sink faucets. Green shading represents a utility room location, yellow shading represents the north part of the building (most used building portion during Summer break), and orange shading indicates the south part of the building (least used building portion during Summer break).

Regular Routine Sampling Location [Room#]	Acronym	Additional New Sampling Location [Room#]	Acronym
Building entry point sampling tap [utility room]	BE	Shower room right sink faucet [E102B]	SRS
After Softener sampling tap [utility room]	AS	Shower room left sink faucet [E102B]	SLS
Before Water Heater (combined) sampling tap [utility room]	BWH	Bathroom 2 cold right sink faucet [E207J]	B2CR
Hot Water Recirculation Loop-a 120 ˚F temperature sampling tap [utility room]	HWRa	Bathroom 2 cold left sink faucet [E207J]	B2CL
Hot Water Recirculation Loop-b, 140˚F temperature sampling tap [utility room]	HWRb	Student kitchen sink faucet D [F102]	SKD
After Water Heater sampling tap [utility room]	AWH	Student kitchen sink faucet F [F102]	SKF
Bathroom outside utility room cold sink faucet [A306R]	B1C	Faculty kitchen sink faucet [A108]	FK
Bathroom outside utility room hot sink faucet [A306R]	B1H	Art room right sink faucet [F105]	ARRS
Shower head ADA compliant [E102S]	SH1	Auditorium back sink faucet [F113]	ABS
Farthest bathroom cold sink faucet [E207G]	B2C	Water fountain in coral room [F112]	WF3
Farthest bathroom hot sink faucet [E207G]	B2H	Bathroom sink faucet in office [A108M]	B9
Student's kitchen cold sink faucet [F102]	SKC	Drinking water fountain 5 [B103B]	WF5
Student's kitchen hot sink faucet [F102]	SKH	Bathroom 3 left sink faucet [C124B]	B3LS
Teacher's kitchen cold sink faucet [B102A]	TKC	Bathroom 4 next to sink 2 faucet [C124G]	B4
Teacher's kitchen hot sink faucet [B102A]	TKH	Bathroom 5 sink faucet [B103B]	B5
Men's bathroom cold sink faucet [C124B]	B3C	Bathroom 6 faucet [B124B]	B6
Men's bathroom hot sink faucet [C124B]	B3H	Staff bathroom sink faucet [B112W]	B7

Drinking water fountain [C124B]	WF1	Staff bathroom sink faucet [C112W]	B8
Drinking water fountain ADA compliant [C124B]	WF2		

2.3 Building water quality in nearby commercial buildings

Because of copper exceedances within the building, the authors collected first draw water samples at 21 nearby commercial restaurant and retail buildings from either water bubblers or bathroom sinks (**Figure SI-2**). These sites received drinking water from the same public water supplier. The sampling event was conducted on September 5, 2018 from 11:57 am to 5:50 pm. Similar methods applied at the school building were also applied for these water samples. For each sample, about 250 mL water was first collected in a glass beaker to directly measure at the site for temperature, pH, dissolved oxygen (DO), total and free chlorine, monochloramine, free ammonia measurements. Then, a 125 mL amber bottle was filled for a metal water sample and all the metal samples were transported at 4˚C in the coolers with ice packs to the laboratory for analysis.

2.4 Statistical analysis

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

3. Results and discussion

3.1. Water delivered to the campus meter and transported to the school building

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

3.2 Water quality entering the building was consistent across sampling events

Drinking water at the building entry point (BE) had different characteristics than water reported in the public water supplier's annual report. Water entering the building however did not exceed any U.S. federal primary or secondary drinking water limits.[33] The water supplier reported that the average of total chlorine concentration entering their distribution system was 1.48 mg/L-Cl_2. The water supplier changes disinfectants from chloramine to free chlorine for few weeks each year. During 4 of the 6 sampling events (3 of 5 months) total chlorine was not detected entering the building according to Indiana State law's definition of "nondetectable" [<0.2 mg/L as Cl_2] (PWS,1996): June (0.20 mg/L as Cl_2), July (0.16, 0.14 mg/L as Cl_2), August (0.43 mg/L as Cl_2), Sept (0.17 mg/L as Cl_2), Oct (BDL mg/L as Cl_2). The low disinfectant residual may be due to the long travel time from the water meter to the building. The public water supplier reported water pH ranged from 7.00 to 8.48, and a narrower range was found entering the building during the present study (7.62 to 7.87). Other organic (TTHM) and inorganic contaminants were also found entering the building but within levels reported by the water supplier (Al, Cl^-, Cr, F^-, Fe, Mn, Na, Ni, Zn, NO_3^-, NO_2^-, SO_4^{-2}, hardness) (**Table 2**, **Table SI-1**).

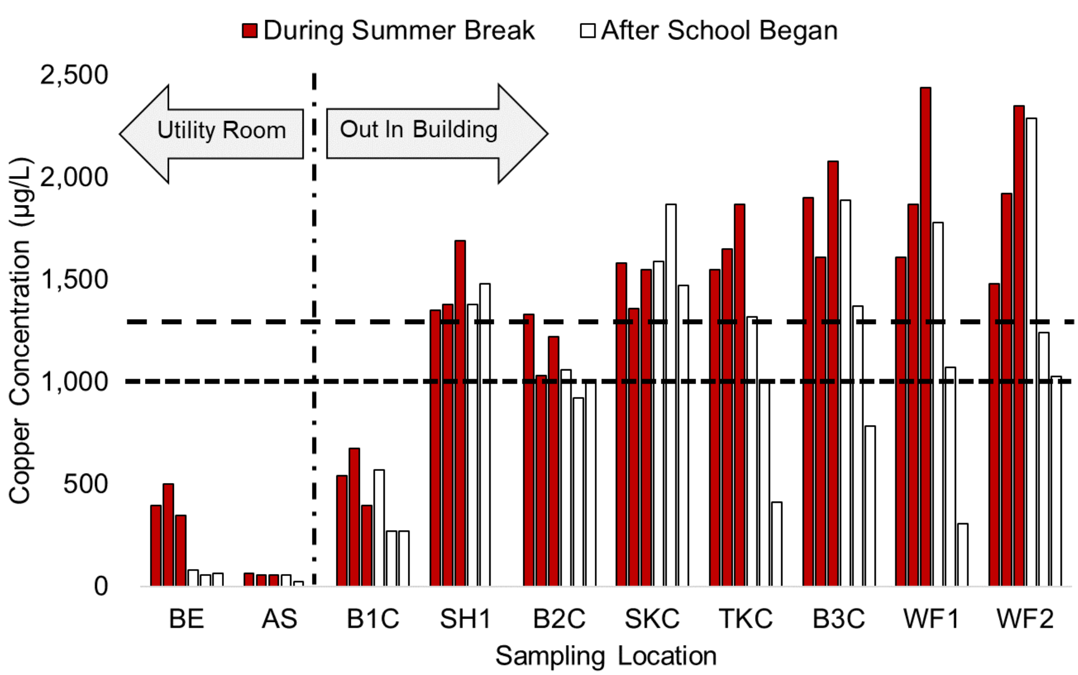
Additional water sampling was conducted at the BE location to better interpret in-building drinking water results. Slight differences were found at the building entry point throughout the sampling event for water temperature (20.4 to 27.3˚C), TOC (1.7 to 2.0 mg/L), HPC (11 to 400 CFU/100 mL), but much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

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

Water exiting the water softener never exceeded the copper AL, but the copper AL was frequently exceeded for cold water at building fixtures (**Figure 2**). More than half of the total first draw water samples [29 of 54] exceeded the copper AL. Within the building cold water, copper levels significantly reduced after the school returned to session (p=0.006) [Before 1.4 ± 0.66 mg/L (n=27); After 0.94 ± 0.57 mg/L (n=46)].

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

(a)



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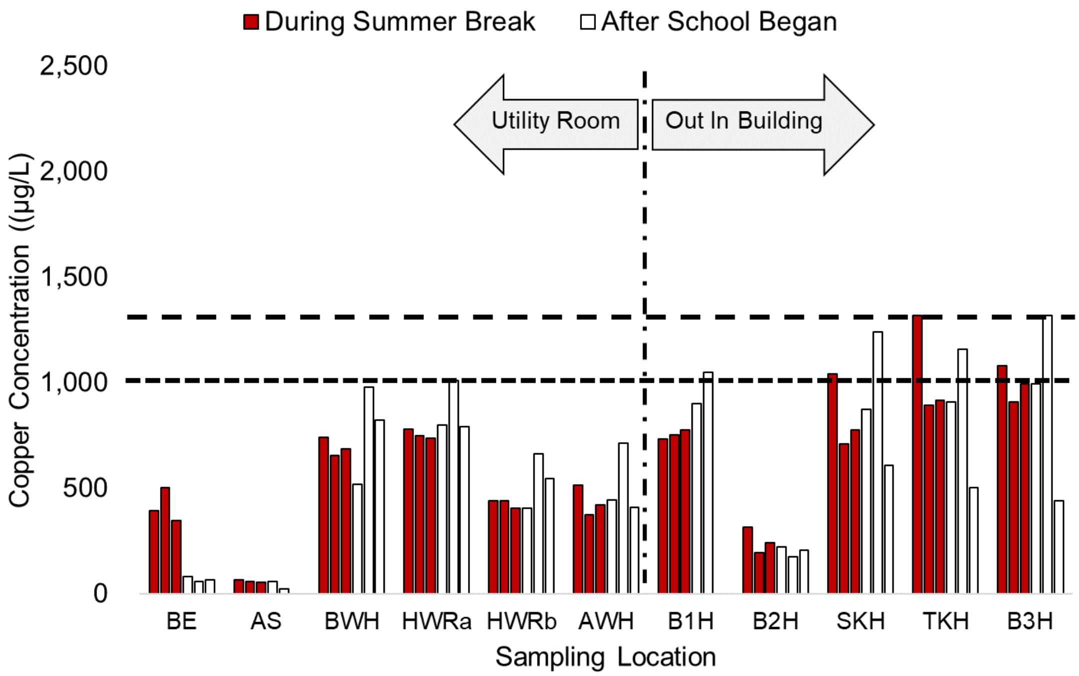
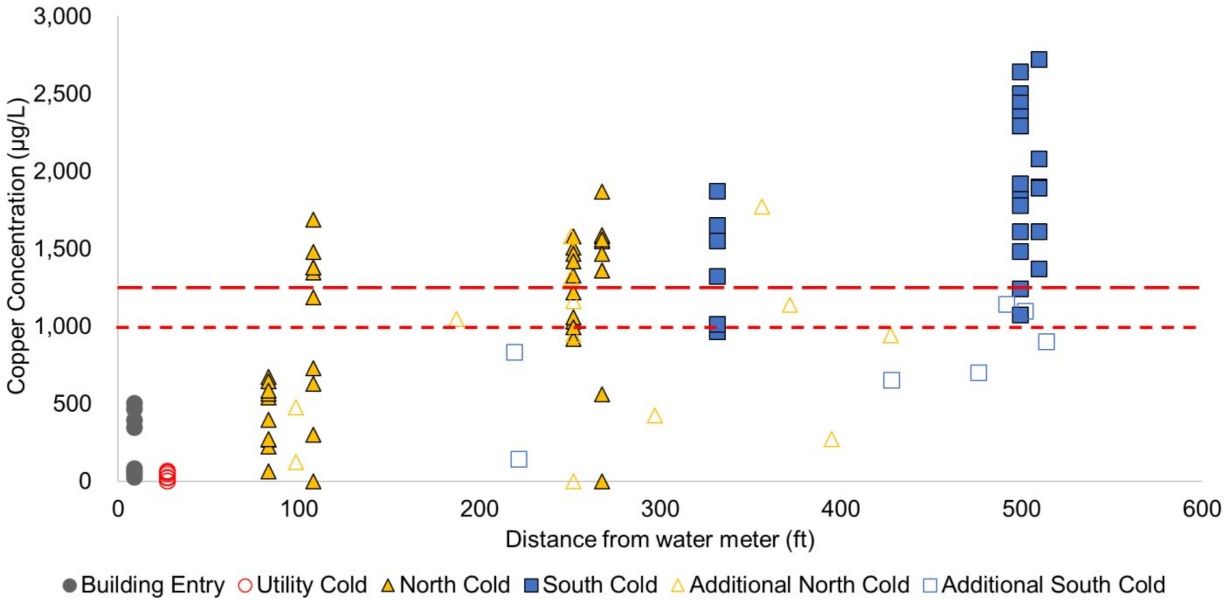


Figure 2. From June to October, 2018 total copper concentration was monitored at the building entry point (BE), water exiting the softener (AS), and (a) 8 cold water locations in the building, and (b) 4 hot water locations in the utility room and 5 hot water locations in the building. Each bar represents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

As distance from the water meter increased, the observed copper concentration increased for both cold and hot water (p<0.001) (**Figure 3**). A prior study indicated that total copper concentration increased in school plumbing as alkalinity increased and pH decreased,[8] but other variables such as DO, pH and before/after the break were also significantly correlated with copper concentration just for hot water samples (p <0.05). Unlike the prior study,[34] total chlorine, free ammonia, and alkalinity were not correlated with the observed copper concentration in the present study.

(a)



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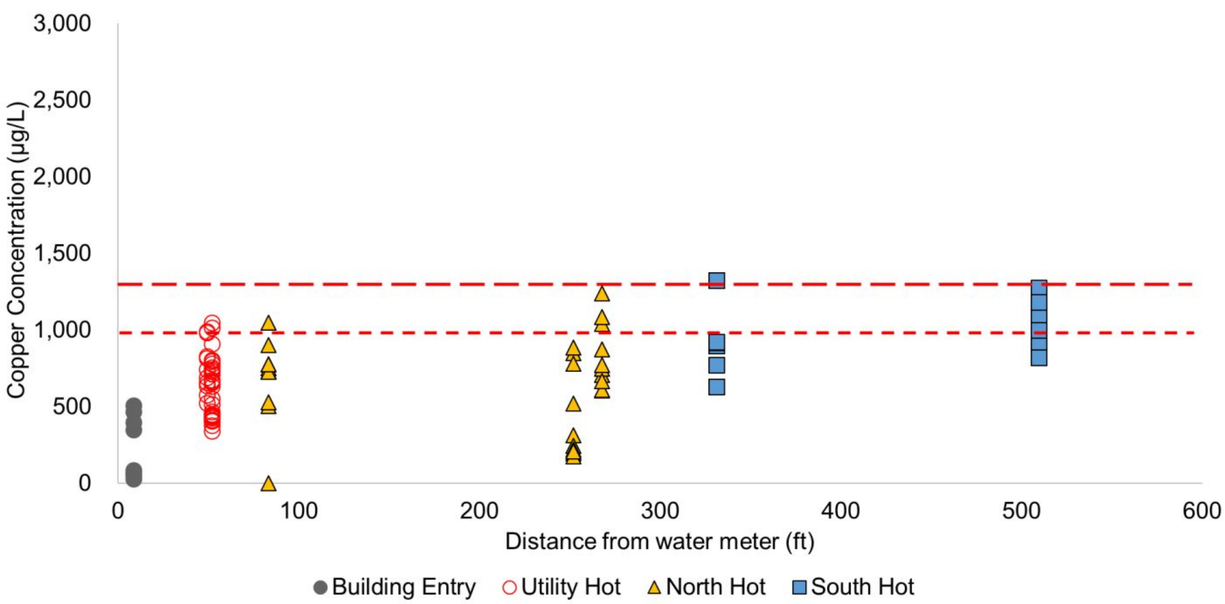


Figure 3. Total copper concentration of all collected (a) cold, (b) hot water samples compared to the faucet location's distance from the water meter. Dotted lines represent the health-based copper AL of 1,300 μg/L and aesthetic based secondary MCL of 1,000 μg/L.

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

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

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

Cold water samples always had a lower TOC concentration than hot water samples for the same location. TOC levels in cold water were not statistically different before and after school returned to session (p=0.34). Cold water TOC levels ranged from 1.5 to 6.7 mg/L (n=54) compared to hot water 1.6 to 3.4 mg/L (n=54) (**Table 2, Figure SI-5**). The greatest TOC levels were found exiting the water softener during the summer break (2.1 to 6.7 mg/L), much greater than the levels found in water entering the building and other fixtures in the building. The water's TOC concentration entering the softener was 1.9 ± 0.16 mg/L. Prior evidence indicates softeners can be sources of biological activity, providing substrate for growth and possibly leaching organic carbon to support microbial processes.[36, 37] For hot water, TOC levels were significantly reduced after school returned to session (p<0.05). TOC and other variables (pH, DO, total Cl_2, NH_3-N, alkalinity and distance from the BE location) were evaluated with linear regression. Cold water TOC level was significantly correlated with pH (p<0.05) and total Cl_2 (p<0.05), while hot water TOC level was significantly correlated with alkalinity and NH_3-N.

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

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

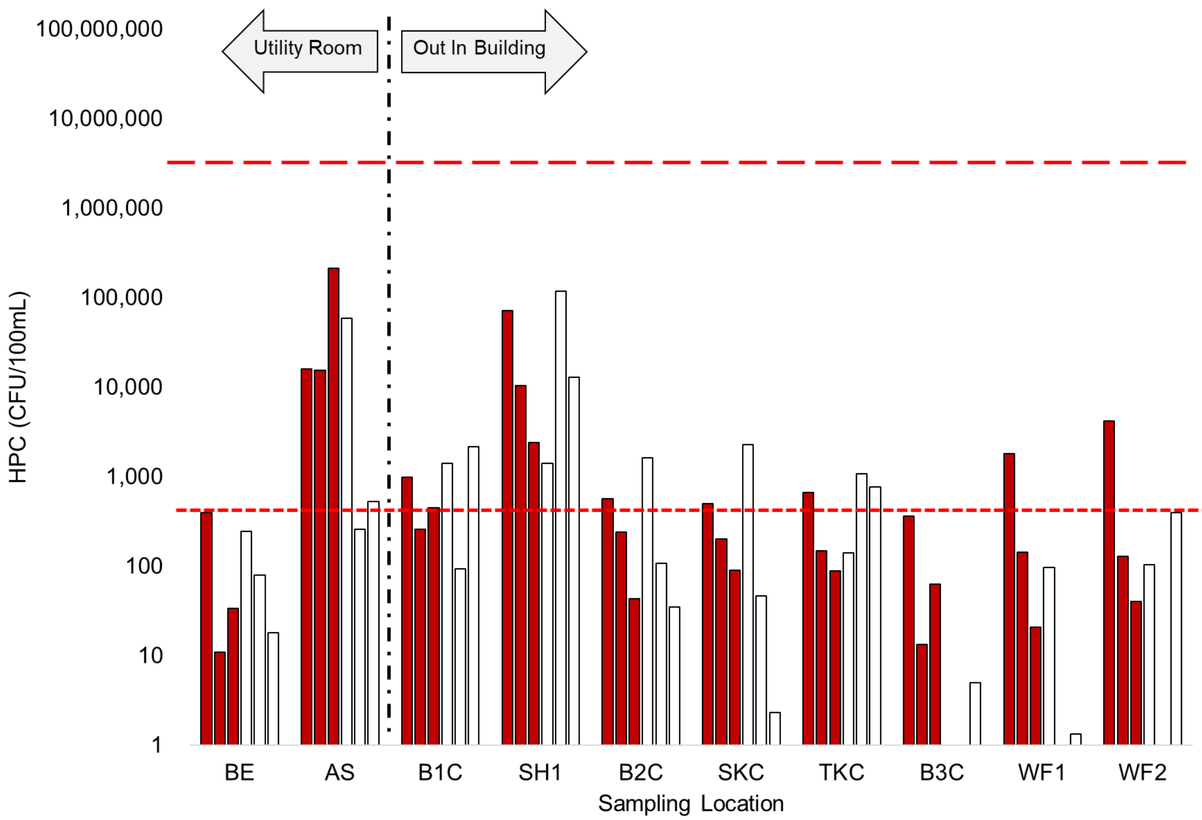
No relationship between nitrification, pH, and chloramine concentration was observed, while the literature indicates that increasing nitrification can decrease pH and chloramine residual[41]. NO_3^- and NO_2^- were detected when nitrifying bacteria were found, and regression analysis showed NO_3^- concentration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

HPCs at the BE location (11 to 400 CFU/100mL) were within the range of levels found by others at reported service lines that used free chlorine disinfectant (3,300 to 23,100 CFU/100mL)[43] and (0 to 2.1 CFU/100mL)[34]. HPC levels increased by 3 orders of magnitude in the short distance from water entering the building to the softener (about 37 ft). It was expected that HPC values would be greater inside the building than at the BE location.[44] None of the in-building cold water samples exceeded the USEPA drinking water guideline of 500,000

CFU/100mL [45,46] except for one hot water location one time during the final sampling event (**Figure 4**). No significant difference for HPC between cold and hot water samples was observed for the same location, but HPC levels gradually decreased at the heater tanks (decreased more after the tank with higher temperature), but then increased again. As expected, HPC levels at the higher temperature hot recirculation loop (60 ˚ C) was lower (1 to 4 CFU/100mL), than at the lower temperature loop (48.8˚C) (1 to 583 CFU/100mL).

A Pearson correlation analysis indicated a statistically significant correlation between HPC and TCC for cold water (p=0.01) but no relationship was found for hot water (p=0.471). HPC results were more variable across locations, temperatures and between sampling trips, while TCC results were less variable and consistent throughout the sampling trips and between locations (**Figure 4, Figure SI-6**). HPCs have been previously shown to be correlated with residence time and the presence of disinfectant residual.[43] HPCs in cold water samples were statistically correlated with distance from the water meter, while no relationship was found for HPCs in hot water to expected predictors (i.e., total chlorine, free ammonia, DO, pH, temperature, alkalinity, distance from the water meter). Past study indicated significant bacterial decline in the first 500 mL, similar level of HPC as the past study[45] were found even after collecting 2 L before HPC sample. Though, the study also indicated HPC significantly increased after only 1 hr of stagnation. Additional work should examine the relationship between HPC and presence and magnitude of pathogens like *Legionella pneumophila*, as this would be more relevant to understand building water health risks.[47,48] No other trends for microbiological parameters and the distance from the water meter were observed.

414 **(a)**


Utility Room
Out In Building
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
HPC (CFU/100mL)
BE
AS
B1C
SH1
B2C
SKC
TKC
B3C
WF1
WF2
Sampling Location

415

(b)

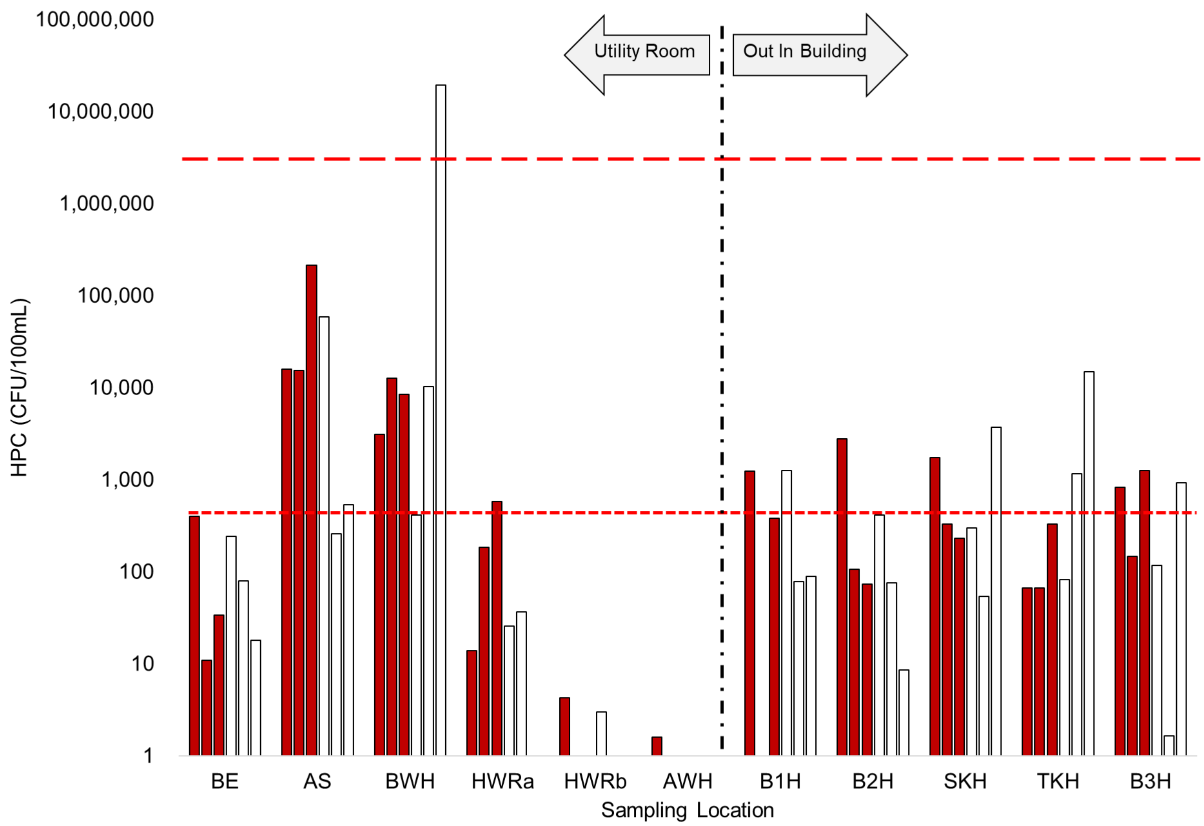


Figure 4. Heterotrophic plate count of first draw from building entry point (BE), water existing the softener (AS), and (a) 8 cold water locations in the building, and (b) 4 hot water locations in the utility room and 5 hot water locations in the building. Red dotted line is HPC drinking water guideline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

3.5 Water quality comparison to other off-campus commercial buildings

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

4. Limitations

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

Table 2. Water quality measurements of first draw samples

	Parameter	Summer									Fall								
		After meter (n=3)			Cold lines (n=27)			Hot lines (n=27)			After meter (n=3)			Cold lines (n=27)			Hot lines (n=27)		
		Min	*x*	max	min	*x*	max	min	*x*	max	min	*x*	max	min	*x*	max	min	*x*	max
General	Temp, °C	25.2	26.1	27.3	15.8	21.9	26.4	21.5	29.3	47.3	20.4	24.2	27.1	14.5	21.8	30.2	19.7	29.8	46.3
	pH	7.6	7.8	7.9	7.2	7.8	8.5	7.7	8	8.2	7.7	7.8	7.9	7.6	7.9	8.2	7.7	8	8.2
	DO, mg/L	8.9	9	9.1	2.6	6.9	10.2	3.1	5.6	8.9	7.4	8.4	9.2	4.4	7.4	9.2	3.2	6.6	9
	Total Cl_2, mg/L	0.1	0.2	0.2	0	0.1	1.4	0	0.1	1	0	0.2	0.2	0	0.03	0.3	0.01	0.03	0.13
	NH_2Cl, mg/L	0.1	0.2	0.3	0	0.08	0.5	0	0.04	0.1	0.07	0.5	0.94	0	0.07	0.41	0	0.1	0.7
	Free NH_3, mg/L	0	0.2	0.48	0	0.1	0.41	0.01	0.2	0.84	0	0.06	0.13	0	0.08	0.21	0.01	0.06	0.16
Organics	TOC, mg/L	1.7	1.9	2	1.5	2.2	6.7	2.9	3.4	3.8	1.8	2	2.2	1.5	1.9	2.3	1.6	2.3	3.4
	DOC, mg/L	1.7	1.9	2	1	2.1	6.5	2.6	3.3	3.6	1.8	2	2.1	1.4	1.9	2.2	1.7	2.2	3.3
Microbiology	HPC, cfu/100mL	11	148	400	13	12,614	214,000	0	1,284	12,667	18	114	245	0.667	7,489	117,670	0	720,894	19,430,000
	TCC, cell/mL x 10^4	3.02	20.9	35.6	4.79	23.8	62.8	54.8	81.6	116.1	5.89	80.5	43.4	6.86	19.9	32.8	15.4	34.2	79.8
Nitrogen	NH_4-N, mg/L	0.4	0.7	1.3	0.1	0.3	0.5	0.1	0.1	0.2	0.4	0.6	0.8	0.1	0.4	3.2	0.0	0.1	0.2
	NO_2-N, mg/L	-	-	-	-	-	-	0.0	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	NO_3-N, mg/L	0.8	1.5	2.8	0.8	1.9	3.0	0.9	1.3	1.7	1.2	1.4	1.5	1.0	1.5	2.6	1.0	1.3	2.2
Metal	Cu, µg/L	347	415	503	55	1,356	2,440	196	689	1,320	57	68	81	0	980	2,290	0	693	1,320
	Pb, µg/L	0	0	0	18.5	2.2	40.9	0	0	0	0	0	0	0	1.3	35.1	0	0	0

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

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

5. Conclusions and recommendations

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

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

Building water system design standards and plumbing code requirements are lacking that require an explicit consideration of source water quality, system operation, and material interactions to minimize cold and hot water quality impacts. The authors recommend both chemical and microbiological testing should be conducted before new construction is placed into service and periodically during the life of the building. Copper testing should be required for all new and renovated buildings. Water testing plans should be developed based on as-built plumbing drawings and types of the water outlets. Copper exceedances likely went undetected for 7 years because water quality testing was not conducted. Because copper leaching decreases with time, it is likely that higher copper levels were present during that 7 year period where children and other persons may have been exposed. Microbial contamination also went undetected for similar reasons. While the school building was LEED certified, and some requirements were to meet environmental regulations, standards, and focus on water efficiency [51], the plumbing caused water inside the building to exceed safe drinking water limits.

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

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