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Studying the impacts of non-routine extended schools' closure on heavy metal release into tap water†

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The extensive school closures due to the unprecedented COVID-19 pandemic resulted in prolonged water stagnation within schools' plumbing for longer durations than routine schools' holidays and summer breaks. With many of the U.S. schools suffering from problems of lead (Pb) in potable water for decades, the extended water stagnation caused by schools' closure has raised significant concerns regarding the schools' water safety. Thus, this research was conducted to evaluate the resiliency of schools' potable water plumbing toward the interruption caused by the COVID-19 pandemic. For this purpose, the impact of extended water stagnation on heavy metal release into water samples collected from fixtures with and without known lead problems in 25 schools within a school district in Tennessee was investigated. The results revealed a significant increase in the median Pb concentration due to the extended water stagnation. Furthermore, elevated levels of Fe, Zn, and Cu were released from both problematic and nonproblematic fixtures into tap water. Estimation of children's blood lead level (BLL), assuming the consumption of prolonged stagnated water, revealed an increased risk of elevated BLLs (>5 μg dL^{-1}). To better identify the potential sources of lead release within schools, a combination of plumbing investigation and sequential water sampling was conducted. The lead-containing fixtures, connecting plumbing, and interior plumbing were found as the possible sources contributing to the lead release into water. Implementation of remediation actions reduced the lead release into tap water to less than 3.4 μg L^{-1} in the target fixtures.

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Water impact

This research evaluated the resiliency of schools' potable water plumbing toward interruption caused by the COVID-19 pandemic through studying the heavy metal release. The results revealed elevated levels of lead and other heavy metals released into water after extended stagnation. The lead levels were significantly reduced by detailed investigation of schools' plumbing and implementation of mitigation plans. This investigation is informative for many schools suffering from lead issues to conduct permanent mitigation practices before allowing students to consume tap water following extended water stagnation.

Introduction

In an immediate effort to limit the spread of COVID-19, many countries have conducted preventive interventions such as limiting social interactions, restricting travels, and closure of nonessential activities, including schools to reduce virus contraction among their populations.[1,2] In many regions around the world, schools were closed rapidly. The limited space of classrooms prevented social distancing, and practicing appropriate hygiene was challenging for young children.[3,4] Moreover, despite the lower risk of severe disease and mortality among children, they may act as vectors to spread the disease to adults, such as their parents and teachers who are at a higher risk of contracting the severe disease.[5,6] As reported by UNESCO, schools' closure in the U.S. started in March 2020, followed by the summer break, and continued in many of the states through fall 2020 and spring 2021 and affected more than 77 million learners.[7] In many of these schools, only a limited number of staff, including the teachers and administrators, were present, who were directed not to drink the water, while most of the water fixtures in the schools were labeled "No Use". The literature has indicated the water stagnation within the schools' plumbing during the summer (2–3 months) as the "worst-case" resulting in release of elevated

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lead levels into water,[8] although, the schools' closure following the COVID-19 pandemic created the "extreme-case" due to the longer durations of water stagnation (>3 months). This extended water stagnation within the buildings' plumbing has created a serious concern as lead release into the schools' tap water is a prominent problem within the U.S. A recent study conducted by Cradock *et al.* (2019) reported that 12% of the total 485 152 first draw water samples collected from schools in 12 states exceeded the state's action level for lead.[9] Furthermore, several studies listed in Table 1 have quantified the lead release into the schools' tap water and developed mitigation practices. As our recent research and the published literature reported, long stagnation of water within the building plumbing results in disinfectant residual decay and reduction of dissolved oxygen (DO).[10–12] These water quality variations make a reductive environment within the plumbing system, which exacerbates the dissolution of heavy metals [*e.g.*, Pb, Zn, Fe, Cu] in water.[13] Moreover, discontinuing the daily supplement of corrosion inhibitors due to the low/no water use conditions prevents the formation of protective film onto the corroded surface of metallic plumbing components and promotes heavy metal release into water.[14] This condition is concerning as a multitude of lead sources [*e.g.*, solder, fitting, brass, galvanized iron pipes, and fixtures] might be present in schools that were built before 1986.[8,9,15–17] However, the lead release into tap water is not only limited to the schools built earlier than 1986, several studies reported the elevated Pb release in schools constructed after that.[18] Furthermore, loss of disinfectant residuals due to the extended water stagnation could promote microbial regrowth within the plumbing system.[19] The majority of the existing literature has solely investigated the impact of short-term stagnation (few hours to days) on tap water quality;[20–23] however, the water quality deterioration under extended water stagnation conditions ranging from weeks to months has received less attention.[12]

The influence of long stagnation on chlorine decay and heavy metal release into tap water in residential buildings has been reported by prior studies.[30,31] A recent study which investigated the tap water quality variations caused by water flushing in three Arizona schools after extended stagnation has revealed greater levels of disinfectant residuals and lower Cu concentrations and UV_{254} absorption for water samples collected after flushing the water fixtures. However, the target fixtures in that study did not suffer from the lead problem, and the median lead concentration in the water samples collected during stagnation was low (1.7 μg L^{-1}).[29] Our recent research demonstrated that extended water stagnation within plumbing of ten large buildings at a university campus during the COVID-19 pandemic resulted in significant loss of disinfectant residuals and elevated heavy metals in tap water.[13] However, the duration of water stagnation in plumbing of those buildings was less than two months, and building recommissioning has improved the water quality effectively.[13] The specific objectives of this study are to (1) investigate the extent of Pb, Cu, Fe, and Zn release into school tap water after extended stagnation conditions, (2) estimate the risk of elevated blood lead levels (BLLs) for students due to the consumption of prolonged stagnant tap water, and (3) identify the possible sources of Pb release into school tap water and develop an effective remediation plan.

Table 1 A summary of studies that investigated lead contamination in schools' tap water (E.S., elementary schools; M.S., middle schools, H.S., high schools)

Location	Year of testing	Number of schools	Types of building	Max Pb level (μg L^{-1})	Type of sample	Major results	Ref
Philadelphia (PA)	2000–2001	173 36 54	E.S. M.S. H.S.	>100	First draw, 30 s flush	Pb level in 57.4% of sampled schools >20 μg L^{-1}, Pb level in 28.7% of sampled school >50 μg L^{-1}	24
Missouri (MO)	1991–1992	1651	School Daycare	>20	First draw	5.7% of sampled fixtures in schools >20 μg L^{-1}, 2.4% of sampled fixtures in daycare centers >20 μg L^{-1}	25
North Carolina (NC)	2017–2018	86	Childcare	121	First draw	12.3%, 10.4%, 7.5%, and 0.9% of water samples collected from pre-1987, 1987–1990, 1991–2013, and post-2013 buildings >5 μg L^{-1}	26
Kansas (KS)	2008–2009	56	Primary schools Pre schools	>300	First draw	Pb level in 3.6% of water samples >20 μg L^{-1}	15
Washington, (DC)	2014	1	School	1800	First draw, flush	Samples with detectable Cd had an average lead concentration higher than the samples without Cd, implicating galvanized steel pipes as a significant source of Pb in this school	27
Seattle (WA)	2004	2 1 1	Schools E.S. M.S. H.S.	1600	First draw, flush	Various new end-use plumbing components contributed to the lead. The old galvanized-steel pipe, lead/tin solder, and brass components and flexible connectors contributed to Pb release	18
Los Angeles (CA)	2008–2009	601	E.S.	13 000	First draw, flush	Excessive Pb was discovered in 6% of first-draw water samples and 1% of flushed water samples	28
Arizona (AZ)	2020	45	E.S.	NA	First draw	The ages of the three schools with detectable levels of Pb in drinking water ranged from new construction to 31 y	29

Experimental

Study site

This study was conducted in a school district in Tennessee, USA, in 2020 and 2021. The school district has requested the research team to conduct this investigation aiming to prevent the lead release into tap water and protect children from lead hazard. The target schools received treated groundwater from the municipal water treatment plant. The finished water was the groundwater that has undergone chlorination for primary and secondary disinfection processes, aeration, filtration, and chlorination. Orthophosphate was added to the water as a corrosion inhibitor. The records for the Pb concentrations in the water samples collected during the regular school operation in 2017 and 2019 were acquired from the school district, in which totals of 583 and 3428 first draw 250 mL water samples were collected in 2017 and 2019, respectively. It should be noted that the water sampling by the school district in 2019 was conducted during the fall break when students were not present in school. However, the duration of water stagnation during the period was significantly lower than the conditions that occurred under the COVID-19 pandemic. To better understand the parameters that contributed to the Pb release into the schools' drinking water, the buildings' questionnaires were completed prior to the onsite visits and building investigations. Furthermore, an interactive lead service line (LSL) map provided by the local water utility was utilized to identify if a lead service line is installed in any target schools.

Water sampling campaign

(A) Water sampling after extended water stagnation. To identify the impact of extended school closure on tap water quality, first draw potable water samples (250 mL) were collected at select 14 elementary, three middle, and eight high schools within a school district in 2020 as shown in Table SI-1.† In these schools, 36 fixtures were identified as potable water fixtures with past lead issues, as the Pb levels in their first draw water samples have exceeded the USEPA action level (15 μg L^{-1}) during the 2019 water sampling. They were disconnected in September 2019. Thus, at the time of water sampling, potable water had been stagnant for almost a year. In total, 105 fixtures were sampled as the fixtures without past lead issues after approximately seven months of water stagnation due to the schools' closure following the COVID-19 pandemic and summer vacation (Fig. SI-1†).

(B) Water sampling to identify the sources of lead release into tap water and the effectiveness of remediation practices. Water sampling to identify the lead release sources was conducted at 26 schools in the target school district. As the problematic fixtures were shut down for almost a year before conducting the sequential water sampling, the fixtures were flushed for 5 min by the schools' operators and sequential water samples were collected 48 h later. Sequential water sampling was conducted according to the USEPA 3 Ts best practices to diagnose the Pb release source at the outlet, where the sampling protocol varies for water fountains, coolers, ice machines, and kitchen faucets. Thus, multiple water samples were collected at each fixture without flushing beforehand or running water between samples. Then, 24 h later, a 250 mL water sample was collected after 30 s flushing to identify any possible lead sources in the upstream plumbing. Further water samples were collected at the schools' point of entry (POE) and at the problematic water fixtures after collection of sequential water samples for pH, total chlorine residual, temperature, and DO quantification as described in SI-1.† The list of samples is shown in Table SI-2.† The statistical analysis is described in SI-2.† After implementing the remediation action, the fixture was flushed, and 48 h later, a 250 mL first draw water sample was collected and analysed by a certified laboratory for total Pb concentration.

Water quality analysis

To determine the total metal concentration in discoloured water, the samples were acidified with 2% nitric acid and 2% hydroxylamine, and then heated at 50 °C for a minimum of 24 h; however, the other samples were only acidified with 2% nitric acid for a minimum of 24 h.[32] The Cu, Zn, Fe, and Pb concentration analysis was performed *via* inductively coupled plasma-optical emission spectrometry (Agilent 5110 ICP-OES). The Pb analysis was also conducted using a Perkin Elmer AAnalyst 400 atomic absorption spectrometer attached to an HGA 900 graphite furnace. The method detection limits have been varied to be 9–16 μg L^{-1} for Cu, 6–26 μg L^{-1} for Zn, 34–143 μg L^{-1} for Fe, and 4–30 μg L^{-1} for Pb. The Pb method detection limit for samples analyzed by the analytical lab was 0.15 μg L^{-1}. The water pH was measured using a Fisherbrand accumet XL600 pH meter. Pocket Colorimeter™ II chlorine was used to measure the total chlorine residual (detection limit 0.1 mg L^{-1}).

X-ray photoelectron spectroscopy (XPS)

The XPS analysis was conducted to identify the types of Pb and Cu species present in the deposits collected from select potable water fixtures in the target schools. For this purpose, three different deposit samples collected from the select cooler, water fountain, and kitchen pot filler were analysed. The XPS analysis was performed using a Perkin Elmer model PHI 5600 electron spectrometer. The following conditions were used: monochromatic Al Kα radiation ($h\nu$ = 1486.6 eV). For all experiments, an X-ray power of 75 W at 12 kV was used with a spot size of 400 μm^2; experiments were conducted at about 1×10^{-9} mBa and room temperature. The binding energy scale of the instrument was calibrated against $Cu2p_{1/2}$ (952.35 eV), $Cu2p_{3/2}$ (932.6 eV), $Pb4f_{5/2}$ (143.1 eV), and $Pb4f_{7/2}$ (138 eV).[33,34] The "Avantage v5.995" software included with the instrument was used to accomplish the

XPS data acquisition. Curve-fitting was performed after the baseline was subtracted.

Blood lead level modeling

The Integrated Exposure Uptake Biokinetic (IEUBK) and the Bowers models were employed to evaluate the potential risks of consuming prolonged stagnant tap water by elementary and high school students, respectively.[17,35,36] Since no quantitative models depicting the lead uptake into the bloodstream for students at the middle school age level were available, blood lead level extrapolations have been made only for the elementary and high school students. Although the default values for dietary lead intake (2.22 μg per day), water consumption (0.59 L per day for IEUBK and 2.0 L per day for Bowers), and soil ingestion (0.085 g per day for IEUBK and 0.02 g per day for Bowers) were used, site-specific lead concentrations for soil (52 μg g^{-1}), household water (8.63 μg L^{-1}), and school water (data from experimental samples) were imported into the model. Likewise, the default value for the biokinetic slope factor (0.375 μg dL^{-1} per μg per day) and the previously used baseline blood lead concentration for the population of interest (1.0 μg dL^{-1}) were imported into the Bowers model. A lognormal distribution with a geometric standard deviation of 1.6 was assumed where necessary. When other data were not available, Pb concentrations in the flushed samples were estimated to be one-sixth of the Pb concentrations in the first draw samples. To ensure that the model employed data from water samples that could realistically be consumed by students, each school's median first draw and median flushed concentrations were used as model inputs. More information is described in SI-3.†

Remediation practices

Flushing is considered as a temporary solution to the problem of lead in water. One time morning water flushing may not protect the children against lead exposure throughout the whole day, so permanent solutions were applied for the problematic fixtures. The lead solder and lead-containing water bubblers were found as significant sources of lead release. The lead solder could be identified using instant lead test swabs. The permanent solution is to replace those with lead-free fixtures and pipes. After pipe replacement, the old fixtures should be disposed of properly to prevent their reuse. Despite the initial cost associated with the replacement, this practice offers a long-term solution to the lead problem. Point of use (POU) filters that were certified against NSF/ANSI Standard 53 (for lead removal) and Standard 42 (for particulate reduction) were used to remove the lead released by the interior plumbing. For this school district, due to the significant contribution of lead sources in upstream plumbing, the major remediation actions for the water fountains are identified as replacement of the connecting plumbing and installation of the bottle fill station that have POU devices to remove the dissolved and particulate lead. However, for the kitchen faucets, due to the contribution of connecting and/or upstream plumbing, the connecting plumbing was replaced, and POU devices were also installed at some schools.

Results and discussion

Investigation of the prior lead in water testing data

Analysis of lead in water data demonstrated that in 2017 and 2019, 13% and 25% of sampled schools had at least one drinking water fixture exceeding the USEPA action level (15 μg L^{-1}), respectively. According to the 2019 water sampling, 90% of the schools had at least one fixture that exceeded the American Association of Paediatrics' recommendation (1 μg L^{-1}). Of the schools reporting lead concentrations greater than 1 μg L^{-1}, over half were elementary schools (34 of 60 schools in 2017 and 90 of 145 schools in 2019). The maximum value (18 800 μg L^{-1}) was over 40% greater than the maximum concentration reported recently in Flint, Michigan (13 200 μg L^{-1} in 2015) and over 2.5 times greater than the maximum value reported in Washington D.C. (7500 μg L^{-1} in 2004). The average ages of the district's elementary, middle, and high school buildings were all greater than 50 years old; however, the amendment of Safe Drinking Water Act (SDWA) that was issued to mitigate lead in school drinking water[37] was implemented only 31 years prior to the 2019 sampling. Therefore, it is reasonable to assume that many of the schools were constructed using materials that have since been deemed inappropriate for school water distribution. The water sampling in 2019 was conducted soon after the Tennessee code was amended to require public schools constructed before 1998 to test their drinking water lead concentrations. Following the 2019 water sampling, in total 80 water fixtures were found which have released lead levels greater than 15 μg L^{-1}. Analyzing the types of these fixtures demonstrated that the majority came from water fountains (56%) and to a lesser extent from kitchen sinks (23%) and coolers (16%). Only three kitchen pot fillers (4%) and one ice maker (1%) were found with elevated lead levels (Fig. SI-2†). After the 2019 sampling, the potable water fixtures with lead concentrations greater than the USEPA action level were immediately removed from service. Thus, mandatory drinking water lead concentration testing at schools could be very significant in decreasing or preventing childhood lead exposure.

Building investigation

This investigation showed no schools with the lead service line; however, the type of service line was not identified in four schools. The average age for the target elementary, middle, and high schools was found to be 61, 56, and 68 years old, respectively. The newest building was 14 years old and the oldest was 119 years old. In 22 schools, copper was the only type of plumbing, but in 15 schools, galvanized steel pipes were utilized in combination with copper pipes for conveying the drinking water through the school buildings. The building investigations revealed that some water fixtures with elevated lead levels, indeed, were the water fixtures that have not been used for years or have been rarely used. Low water use results in longer stagnation of water within the buildings' plumbing and increases the dissolution of lead-containing corrosion products in the contact water.[10,12] A few kitchen faucets that have not been used regularly for washing and cooking were also found among the fixtures with elevated lead levels. Although aerators were absent in several kitchen faucets, some of the aerators that were removed contained deposits (Fig. SI-3†). Aside from flow control, aerators have additional benefits of capturing particles that could end up in tap water.[38,39] However, if they were not cleaned frequently, they could be a source of Pb leaching into tap water.[40,41]

The influence of non-routine prolonged water stagnation on Pb release by problematic fixtures

The total Pb concentrations in first draw water samples collected from problematic fixtures in 2019 during the regular operation of schools were compared with the Pb levels in samples collected in 2020 after extended water stagnation (Fig. 1A). The water was stagnant in problematic fixtures for almost a year after these fixtures were closed because of the release of elevated Pb levels into the water. It was significantly longer than water stagnation during the routine summer breaks (2–3 months). Some of the collected water samples were significantly discoloured and contained visible particulate matter with a maximum turbidity of 136 NTU (Fig. 2). The discoloration of tap water might be primarily due to suspended particles rather than the true color.[40] Furthermore, this discoloration might be associated with elevated Pb levels in the water.[32] The results demonstrated a significant increase (p-value < 0.05) in median Pb concentration in water samples collected from fountains after extended water stagnation (126 $\mu g\ L^{-1}$) compared to the samples collected under regular operation conditions (30 $\mu g\ L^{-1}$). The elevated Pb levels in these water samples indicate the presence of Pb containing plumbing components such as solder (Fig. 2), the valve within the water fountain, connecting pipes, or even the deposits accumulated within the bubblers.[41] The median Pb concentration for the samples collected from coolers after extended water stagnation (47 $\mu g\ L^{-1}$) was almost two times that of the samples collected under normal operation conditions (25 $\mu g\ L^{-1}$); however it was not significantly different (p-value > 0.05). The first draw water samples collected from coolers represent the water in contact with the bubbler valve and plumbing inside the cooler and its storage tank.[41] Historically, coolers as a source of Pb release into water were referred to as lead-lined storage tanks.[42] Currently, lead-lined water coolers are rarely present within the schools; however, lead-containing sediments originating from upstream plumbing could accumulate in coolers over the years and contribute to the gradual Pb release into water. The median Pb concentration for the samples collected from the kitchen faucets was increased significantly (p-value < 0.05) by greater than 13 times from 23 $\mu g\ L^{-1}$ to 319 $\mu g\ L^{-1}$. The first draw water samples collected from the kitchen faucets represent the water in contact with the faucet and connecting plumbing.[41] The drastic increase in Pb release after extended stagnation suggests the significant lead sources within the faucet and connecting plumbing. The maximum Pb concentration after extended water stagnation was found to be 9901 $\mu g\ L^{-1}$ in a water fountain. However, the Pb concentration at this fixture during the regular school operation was only 61 $\mu g\ L^{-1}$. Among studied schools, only two schools were built after the implementation of LCCA in 1986.[43] Thus, a variety of lead-containing components such as solder, fittings, faucets, and fixtures might be present within the building plumbing.[8] Lead-containing solder joints are known as the very common sources

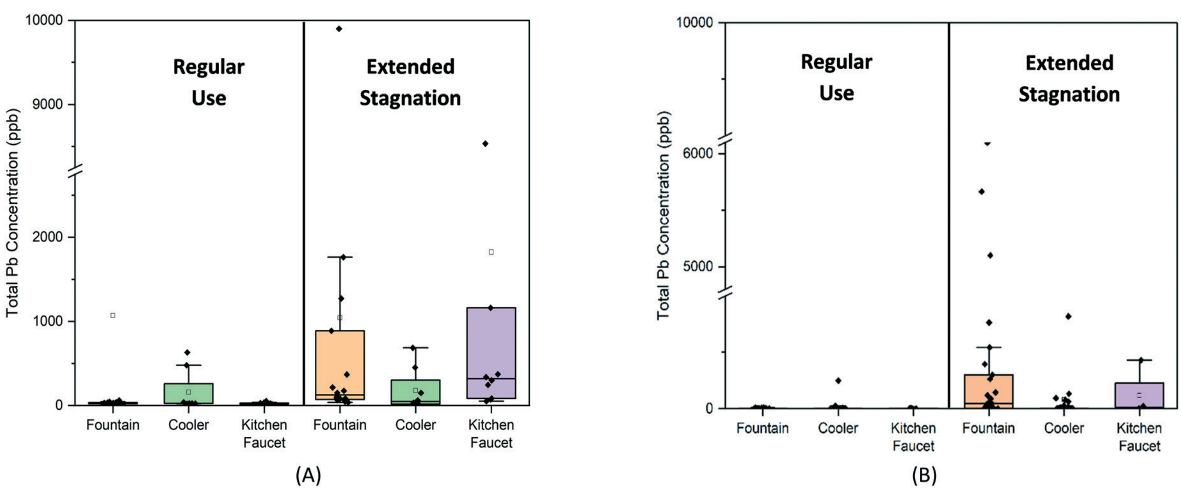

Fig. 1 The box plot charts for the total Pb level in water samples collected from (A) problematic and (B) nonproblematic fixtures during the regular operation and after extended water stagnation (single data of 18 800 $\mu g\ L^{-1}$ for a problematic fountain under regular water use conditions has not been shown), within each box horizontal black lines denote the median values, boxes extended from the first to the third quartile of each group distribution, the whiskers extended from min to maximum, and dots denote the outlier data.

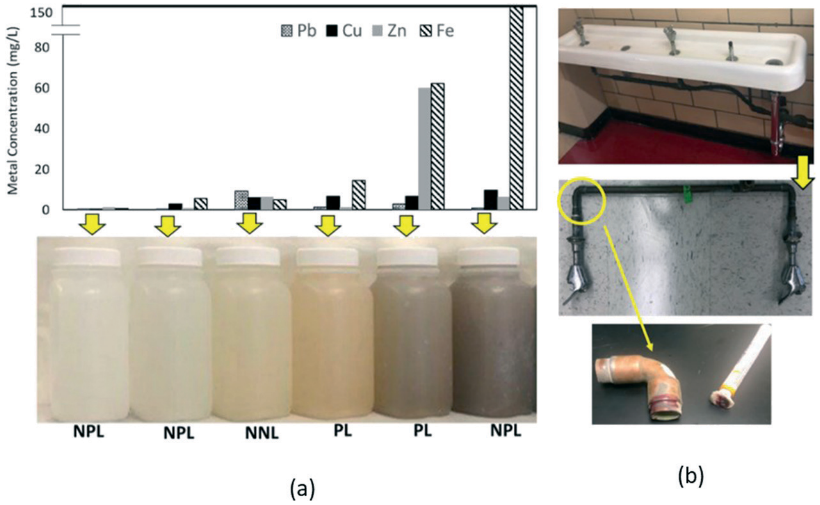

Fig. 2 (a) The discoloration of water samples from problematic (P.L.), nonproblematic (NPL), and no known lead record (NNL) fixtures collected after extended water stagnation and their heavy metal concentrations and (b) identification of lead-containing solder (red stain) in water fountain connecting plumbing using the instant lead test.

of Pb release for schools built before mandating the lead-free plumbing.[43] The solder joints could have 50–50 (tin–lead) formulation.[44] Furthermore, galvanized iron pipes (GI) in combination with copper pipes (CP) in seven schools could have contributed to the Pb release.[27,45,46]

The influence of non-routine prolonged water stagnation on Pb release by nonproblematic fixtures

Water was stagnant in nonproblematic fixtures for around seven months. As shown in Fig. 1B, the median Pb concentration in the water samples collected from fountains was increased significantly (p-value < 0.05) from 1 μg L^{-1} to 45 μg L^{-1} due to the extended water stagnation. The median Pb concentration in water samples collected from coolers was increased slightly (p-value < 0.05) from 1 μg L^{-1} to 2 μg L^{-1} after extended water stagnation. The median Pb concentration in water samples collected from kitchen faucets was increased (p-value > 0.05) from 2 μg L^{-1} to 13 μg L^{-1}. However, all 105 water samples collected from these fixtures during the regular school operation in 2019 were below the USEPA action level for Pb; after extended water stagnation, 26 water samples exceeded this limit. The maximum Pb concentration was found to be 6908 μg L^{-1} in a water fountain after extended water stagnation; however, the Pb level in this specific fixture during the regular school operation was only 3 μg L^{-1}. The median Pb level in the water samples collected from nonproblematic coolers (2 μg L^{-1}) was significantly lower (p-value < 0.05) than that from problematic coolers (47 μg L^{-1}). Despite the lower Pb levels in the samples collected from nonproblematic fountains and kitchen faucets, they were not significantly different from those for problematic fountains and kitchen faucets (p-value > 0.05). In addition to the shorter duration of water stagnation in nonproblematic fixtures (7 months) than the problematic fixtures (1 year), there might be more significant lead sources within the problematic fixtures. The disinfectant residual decay and DO reduction make a reductive environment within the plumbing, which exacerbates the dissolution of heavy metals in the water.[10–13] Moreover, discontinuing the daily supplement of corrosion inhibitors due to the low/no water use conditions prevents the formation of protective film onto the corroded surface of metallic plumbing components and promotes heavy metal release into the water.[14] This condition is concerning as a multitude of sources for Pb release might be present in schools that were built before prevention of lead-containing plumbing components.[16,24] The lead release into tap water is not only limited to the schools older than four decades, several studies reported the elevated lead release in schools constructed after that.[18]

Blood lead level modeling

To better evaluate the risk of students' exposure to lead through potable water that was stagnated extensively in schools' fixtures, the blood lead level modeling was conducted. The IEUBK model and the Bowers model were employed for elementary school and high school students, respectively.[47] Given several environmental, behavioural, and biokinetic parameters, each model predicts a population's blood lead level distribution. Each model's output can be interpreted as the probability that a single individual will have an elevated BLL (>5 μg dL^{-1}) or as the fraction of the population that will have an elevated blood lead level. Due to the model assumptions, the model outputs for each year are estimates. However, because all assumptions and inputs have been held constant (aside from the school drinking water concentrations for the year of interest), the relationship between the 2019 and the 2020 model outputs can be

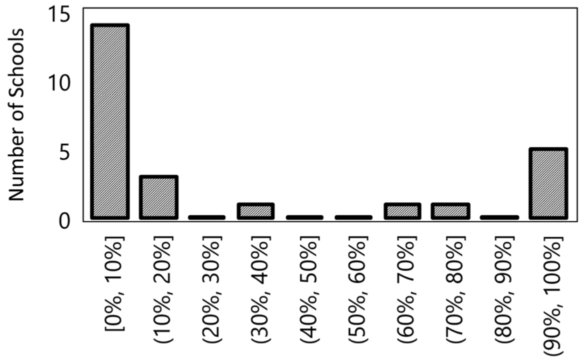

Fig. 3 Percentage increase in students at risk of elevated BLLs (>5 μg L^{-1}) due to the extended water stagnation compared to the regular water use conditions in 2019.

deduced with confidence. It's unlikely that children consume the very turbid and discoloured water samples; however it was not possible for the investigators to omit the highly discoloured water samples for the modeling purpose as no turbidity and Fe concentration information were available for the samples collected in 2019.

The distribution of percentages of at-risk elementary school students experienced a large and statistically significant (p-value < 0.05) increase from regular water use conditions (2019) to prolonged water stagnation (2020). Over the same period, the fraction of at-risk high school students increased only slightly (median high school had 0.5% of students at risk in 2019 and 0.6% at-risk in 2020), but the effect was also statistically significant (p-value < 0.05). It should be noted that the lead concentrations in 75% of first draw water samples that were collected during the 2019 sampling exceeded the 20 μg L^{-1}; however, the non-routine prolonged water stagnation enhanced the number of these fixtures by 21%. As previous authors have suggested, this difference in effects is likely attributed to young children being more susceptible to lead absorption than older populations, given similar environmental conditions.[17,44] However, since both populations were affected, the models indicate that the extended stagnation could potentially have a detrimental effect on all students' health if they drink the water that was stagnant for an extended period. The distribution of increases in at-risk students across all schools is shown in Fig. 3. As indicated by the figure, all the schools exhibited either a large (60–100%), moderate (10–40%), or negligible (≤10%) increase in at-risk student populations, but no schools exhibited a decrease. Therefore, effective recommissioning practices for both problematic and nonproblematic fixtures are recommended before reopening schools to ensure that the extended stagnation does not yield adverse health effects on students. For comparison, the models were also run assuming that no lead was present in the water. Under this ideal assumption, 0.002% of elementary school students and 0.073% of high school students would be at risk of elevated blood lead levels.

The influence of non-routine prolonged stagnation on Fe, Cu, and Zn release into tap water

The Cu, Zn, and Fe concentrations were quantified for the first draw water samples collected from the problematic and nonproblematic fixtures (Fig. 4). No data were collected regarding these heavy metals during the 2017 and 2019 water sampling. The median concentrations of Fe in the water samples collected from nonproblematic fountains, coolers, and kitchen faucets (0.37 mg L^{-1}, 0.07 mg L^{-1}, 0.07 mg L^{-1}) were lower than the median values found for problematic water fixtures (0.78 mg L^{-1}, 1.33 mg L^{-1}, 0.37 mg L^{-1}). The median concentrations of Cu in the water samples collected from nonproblematic fountains, coolers, and kitchen faucets (0.85 mg L^{-1}, 0.60 mg L^{-1}, 0.82 mg L^{-1}) were lower than the median values found for problematic water fixtures (1.33 mg L^{-1}, 1.77 mg L^{-1}, 1.63 mg L^{-1}). 53% of the water samples collected from problematic fixtures after extended water stagnation have exceeded the USEPA action level (AL) of 1.3 mg L^{-1} for Cu. The median concentrations of Zn in the water samples collected from nonproblematic fountains, coolers, and kitchen faucets (1.77 mg L^{-1}, 0.14 mg L^{-1}, 0.25 mg L^{-1}) were lower than the median values found for problematic water fixtures (3.45 mg L^{-1}, 0.73 mg L^{-1}, 0.96 mg L^{-1}). No significant difference was found between the Cu and Zn levels in the water samples collected from problematic and nonproblematic fixtures (p-value > 0.05). 25% of the water samples collected from problematic fixtures after extended water stagnation have exceeded the USEPA SMCL of 5.0 mg L^{-1}. Zn levels above 3.0 mg L^{-1} were reported to cause turbidity and unpleasant astringent taste when boiled.[48]

The Pb concentrations in the water samples collected from problematic fountains were significantly correlated with the Cu, Fe, and Zn levels (Table SI-3†). However, the significant positive correlation among Pb and Cu indicates the contribution of lead-containing solder joints used to connect copper plumbing to Pb release from the fountains in studied schools to the water. The study conducted by Murrell (1991) reported the lead content of lead–tin solder to vary from 41.9% to 73.1%.[49] The Pb, Cu, and Zn are also known as the brass elements; their significant correlation may indicate the possible contribution of brass plumbing components such as faucets.[50] Copper pipes were solely present in 14 schools, and a combination of copper pipes with GI pipes was used in the other seven schools. The elevated Zn levels could originate from the GI pipes, as iron pipes are coated with zinc in the galvanization process to prevent corrosion. Elevated Cu and Zn levels could be released from brass fittings used for copper connection or the brass faucets.[51] It should be noted that, due to our analytical limitations, we were not able to quantify Cd and Sn in the water samples, despite their importance in pinpointing the galvanized iron and lead-containing solder for lead release. The elevated heavy metal release into water due to the extended water stagnation was confirmed by previous studies that reported enhanced corrosion of metallic components under stagnation

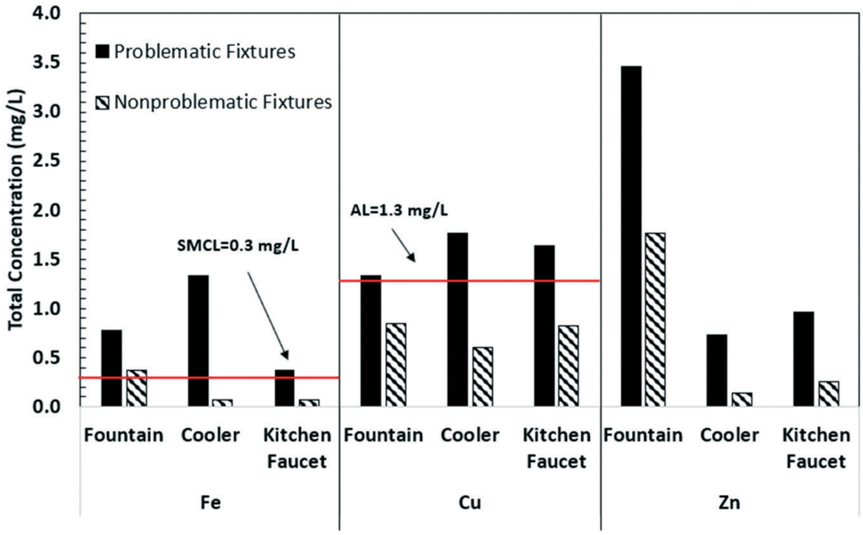

Fig. 4 The median concentrations of Fe, Cu, and Zn in the water samples collected after extended water stagnation.

conditions, which resulted in elevated Pb, Zn, Fe, and Cu release into water.[12] The presence of oxidants such as free chlorine and DO under regular water use conditions improves the stability of metallic corrosion products; however, under extended stagnation conditions, their absence or low concentration promotes the solubility of corrosion products and increases their release into water.[51–53]

Water chemical quality

The summary of water chemical quality statistics at the POE of schools is shown in Table SI-7.† The total hardness values ranged from 21.0 to 101.1 with a median value of 43.0 (mg L^{-1} as $CaCO_3$). Similarly, the alkalinity ranged from 26.3 to 100.0 with a median value of 48.8 (mg L^{-1} $CaCO_3$). The temperature and pH ranged from 16.2 to 22.8 (°C) and from 6.3 to 7.6, respectively. The total chlorine residuals and DO content ranged from <0.1 to 1.8 (mg L^{-1}) and from 4.7 to 10.9 (mg L^{-1}), respectively. These two parameters were correlated since they both decrease as the water experiences stagnation (p-value < 0.05). Therefore, it was to be expected that the schools having a low chlorine content also had a low DO content. The turbidity in the water samples collected from the POEs was very low (<0.5 NTU). As shown in Table SI-7,† compared to the buildings' POEs, the distributions for hardness and alkalinity tightened, but the median values remained relatively constant. The temperatures and pH values increased slightly compared to the POE measurements. However, the pH increase was likely the result of oxidation and reduction reactions occurring within the metallic pipe surface. The solubility of ferrous phases controls the release of iron into water; hence iron release should decrease as the pH increases. Furthermore, an increase in pH increases the rate of formation of ferric hydroxides, which are less prone to dissolve than ferrous solids.[54] The DO and total chlorine values were significantly lower for the fixtures as compared to the POE data (p-value < 0.05). The DO and chlorine contents were correlated (p-value < 0.05), but the distributions for both decreased because the water experienced stagnation while in the building. The turbidity values for the fixtures were greater than those for the water entering the schools at the POEs (p-value < 0.05). This further indicates that some inorganic deposits and/or biofilm were released from the interior plumbing while water was transported through the building. Analyzing the lead concentrations in the water samples collected from the POEs of 39 schools revealed that the lead concentrations are smaller than 15 μg L^{-1} in 36 schools. The follow up water sampling was conducted at three schools with elevated lead levels (27–31 μg L^{-1}) in their POE water samples and revealed no detectable level of lead in sequential water samples collected from the first cold water fixture after their POEs.

Identifying the types of Pb and Cu species present within the potable water fixtures

The deposits removed from select potable water fixtures were analyzed using XPS to identify the type and magnitude of Pb and Cu species present within these deposits. The atomic percentages of different Pb and Cu species identified within the deposits removed from the select water fountain, cooler, and kitchen faucet are shown in Table SI-8.† The high-resolution Pb 4f spectra for deposits removed from the select water fountain are shown in Fig. SI-4a.† The appearance of a peak at the $Pb4f_{7/2}$ binding energy of 139.4 suggests the presence of $PbCO_3$ (43.6%) as the major lead species in this sample.[33] However, studying the high-resolution Pb 4f spectra for deposits removed from the select cooler (Fig. SI-4b†) and pot filler (Fig. SI-4c†) suggests the elemental lead as the major species. The peak appeared at the 139.4 eV binding energy, indicating the presence of lead oxide (PbO) in all the studied samples. Lead oxidation generally occurs due to the reaction of lead with the free chlorine residuals present in the water.[55] Lead oxide was found as the second dominant species in the sample removed from the select cooler (30.6%) (Fig. SI-4b†). However, lead dioxide (PbO_2) was found as the second dominant species in the sample removed from the select pot filler (18.1%) as indicated by the $Pb4f_{7/2}$ peak appearing at the 136.2 binding energy (Fig. SI-4c†). The $Cu2p_{3/2}$ spectra was analyzed to identify the type and magnitude of copper species that were present within the deposits removed from the select potable water fixtures. The $Cu2p_{3/2}$ peak at the binding energy of 932.6 eV was found as the prominent feature associated with the elemental copper in the deposits removed from the select cooler, fountain, and pot filler (Fig. SI-5†). As expected, the oxidation of copper caused by free chlorine residuals present in the water resulted in formation of copper oxides in the forms of CuO and Cu_2O, as indicated by the peaks appearing at the $Cu2p_{3/2}$ binding energies of 933.6 eV and 932.4 eV, respectively.[34] However, copper carbonate ($CuCO_3$) was found in less magnitude in the deposits removed from the select cooler, fountain and kitchen faucet.

Sequential water sampling

The Pb concentrations in the sequential and 30 s flushed water samples collected from water fountains, coolers, and kitchen faucets are shown in Fig. 5. The median Pb concentration for the 1st draw water samples in water fountains was found to be 31.0 $\mu g\ L^{-1}$, which was reduced to 19.9 $\mu g\ L^{-1}$ and 9.0 $\mu g\ L^{-1}$ for the 2nd draw and 3rd draw water samples (Fig. 5a). For coolers, the maximum Pb concentration was found to be 4928 $\mu g\ L^{-1}$ for the 1st draw water sample. The Pb concentrations in the sequential and 30 s flushed water samples were compared for individual fixtures. The results demonstrated the upstream plumbing as a major source of Pb release for 17 out of 18 studied water fountains as the Pb concentration in the 3rd draw and/or 30 s flushed water samples exceeded the 5.0 $\mu g\ L^{-1}$ concentration. Furthermore, the elevated Pb levels in the 1st draw water samples indicated the additional Pb release by the fixtures' bubbler and connecting pipes in 8 out of 18 studied water fountains. The 30 s flushing was not found as an effective method to reduce the Pb levels in water fountains due to the significant sources of Pb release in upstream plumbing.

As shown in Fig. 5b, the median Pb concentration was greater in the 2nd draw (11.8 $\mu g\ L^{-1}$) samples collected from the coolers compared to that in the 1st draw (4.6 $\mu g\ L^{-1}$) water samples. The maximum Pb concentrations in the 1st draw, 2nd draw, and 30 s flushed water samples collected from the coolers were found to be 48.8 $\mu g\ L^{-1}$, 258.9 $\mu g\ L^{-1}$, and 8.5 $\mu g\ L^{-1}$, respectively. Analyzing the samples collected from individual coolers demonstrated the upstream plumbing, sediments and deposits in the coolers as the potential sources of Pb release. The 30 s flushing was found as an effective practice to decrease the Pb concentration below 5.0 $\mu g\ L^{-1}$ in 7 out of 8 coolers. For the kitchen faucets, the median lead concentration was greater in the 2nd draw (32.0 $\mu g\ L^{-1}$) compared to that in the 1st draw (24.1 $\mu g\ L^{-1}$) water samples (Fig. 5c). The Pb concentration was reduced to below the detection limit in the water samples collected from the kitchen faucets after 30 s flushing. This finding underscores the 30 s flushing as an effective practice to reduce the Pb release at the target kitchen faucets. However, the significant presence of Pb levels in the 2nd draw water samples (>5.0 $\mu g\ L^{-1}$) for 6 out of 8 studied fixtures indicates the presence of lead sources in plumbing upstream of the faucets.

Furthermore, the Fe, Cu, and Zn concentrations were quantified in the sequential water samples. The median Fe concentrations in the 1st draw water samples collected from water fountains, coolers, and kitchen faucets were found to be 557 $\mu g\ L^{-1}$, 82 $\mu g\ L^{-1}$, and 155 $\mu g\ L^{-1}$. The median Cu concentrations in the 1st draw water samples collected from water fountains, coolers, and kitchen faucets were found to be 321 $\mu g\ L^{-1}$, 331 $\mu g\ L^{-1}$, and 331 $\mu g\ L^{-1}$. The median Zn concentrations in the 1st draw water samples collected from water fountains, coolers, and kitchen faucets were found to be 205 $\mu g\ L^{-1}$, 94 $\mu g\ L^{-1}$, and 242 $\mu g\ L^{-1}$. These values were reduced in the 30 s flushed water samples as listed in Tables SI-4 to SI-6.† The first draw samples collected at water fountains exceeded the USEPA SMCL limit for Cu (1.3 mg L^{-1}), Zn (5.0 mg L^{-1}), and Fe (0.3 mg L^{-1}) at 2, 1, and 11 fixtures, respectively. However, only the 1st draw water samples that were collected at three coolers and two kitchen faucets have exceeded the USEPA limit for Fe.

Remediation practices

Integration of knowledge acquired through the building investigation, sequential and flushed water sampling, and literature review was utilized to identify the possible sources of lead release into the schools' water. The lead soldered joints (commonly used until 1987), lead-containing bubblers, faucets, and galvanized steel pipes were found as the major sources for lead release in the studied schools. Flushing is considered as a temporary solution to the problem of lead in water. One time morning water flushing may not protect the children against lead exposure throughout the whole day, so permanent solutions were applied for the problematic fixtures. Furthermore, it's recommended to not reuse the old fixtures for any plumbing work as they may contain lead. All kitchen faucets should have aerators (screens). The faucet aerators should be cleaned on a regular basis (quarterly); if a deposit build-up was observed, the aerators should be cleaned more frequently. By removing the redundant water fixtures, the water use at the other water fixtures will be enhanced, and consequently, the duration of water stagnation and possibly the lead release into water will be reduced. If the fixtures are seldom used, they can be removed permanently from service. The lead solder and lead-containing water bubblers were found as significant sources of lead release. The lead solder could be identified using instant lead test swabs. The permanent solution is to replace those with lead-free fixtures and pipes. After pipe

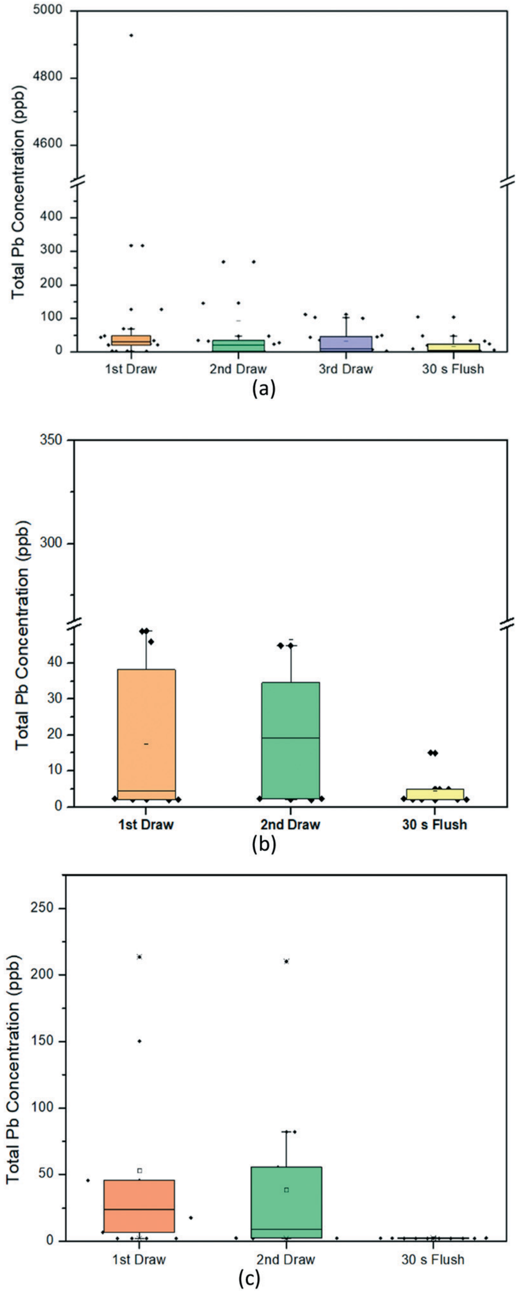

Fig. 5 The total Pb concentrations in water samples collected sequentially and after 30 s of flushing from (a) water fountains, (b) coolers, and (c) kitchen faucets, within each box horizontal black lines denote the median values, boxes extended from the first to the third quartile of each group distribution, the whiskers extended from min to maximum, dots denote the outlier data.

replacement, the old fixtures should be disposed properly to prevent their reuse. Despite the initial cost associated with the replacement, this practice offers a long-term solution to the lead problem. Point of use (POU) filters that were certified against NSF/ANSI Standard 53 (for lead removal) and Standard 42 (for particulate reduction) were used to remove the lead released by the interior plumbing. The recommended filter change cycles are mostly presented as the maximum volume of water that could be filtered and vary based on the types of filters and vendors. Additional precautions should be taken when a greater level of lead is present in water that is filtered. Appropriate filters should be installed upstream of bottle filling stations. The filters should be changed on a regular basis, and documentation should be kept updated regarding the filter changes. The bottle fillers could be installed on top of the risers to promote the water flow through the school plumbing. By having the potable water fixtures next to locations with higher water use (such as the restrooms), the water stagnation and consequently the lead leaching to the water will be reduced. Elevated temperature increases the lead leaching to water, so it's recommended to use cold water for water consumption for cooking and food preparation purposes. For this school district, due to the significant contribution of lead sources in upstream plumbing, the major remediation actions for the water fountains were identified as replacement of the connecting plumbing and installation of bottle filling stations that have POU devices to remove the dissolved and particulate lead. However, for the kitchen faucets, due to the contribution of connecting and/or upstream plumbing, the connecting plumbing was replaced, and POU devices were also installed at some schools. The results demonstrated the significant reduction of Pb levels to below 3.4 μg L^{-1} at the target fixtures as shown in Fig. 6.

As many schools were built before 1986, there are many lead-bearing plumbing materials in their buildings, which makes their complete removal impossible. However, to mediate the influence of long water stagnation in schools' plumbing on weekends, holidays, and summer, a regular flushing plan should be implemented. Automated flushers could be installed at certain water fountains to promote the water flow through the schools' plumbing. Long-term monitoring should be conducted to identify the appropriate frequency and duration of flushing practices. Automatic flushing of water in schools at certain times in the morning could be conducted by installing time-operated valves at the main water line in schools. Although this practice promotes

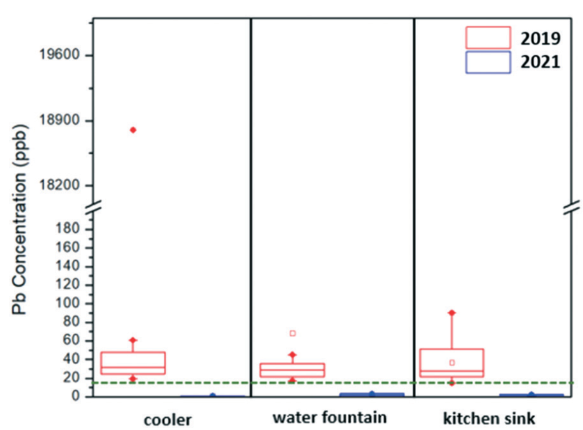

Fig. 6 Total Pb concentrations in water samples collected in 2019 and after implementation of remediation actions in 2021.

the water flow in the main upstream pipes, for the pipes connected to specific fixtures, additional flushing may need to be conducted to reduce the lead release into water. It should be noted that few school districts such as the Boston School District that employed this practice have stopped that due to the high cost associated with the system maintenance and frequent problems.[56,57]

Conclusion

The extended school closures caused by the COVID-19 pandemic resulted in prolonged water stagnation within schools' plumbing. With many of the U.S. schools suffering from issues of lead in water, concerns regarding the safety of potable water after school reopening and resumption of water use have been raised. Aside from the pandemic conditions, the water stagnation duration in schools could have increased to months considering the weekends, holidays, and summer break. Moreover, some schools are operating with a significantly lower population than their original capacities, which results in longer residence of water within the schools' plumbing. The presence of a multitude of sources of lead [*e.g.*, solder, brass, galvanized iron, *etc.*] in water plumbing in schools built before implementation of LCCA and even in more recent school buildings experiencing longer water stagnation resulted in lead release into the schools' water. Our research demonstrated that the long-term stagnation of water has intensified the lead release into water. Moreover, elevated levels of Fe, Zn, and Cu were released into tap water. We have guided the target school district to conduct efficient water flushing practices to replace the stagnant water with freshwater from the distribution system before allowing the children to consume the tap water. However, we have estimated the elevated blood lead levels assuming that the children consume the prolonged stagnant water to demonstrate the worst scenario that could happen if effective recommissioning has not been conducted. Thus, it's recommended to conduct the efficient schools' potable water plumbing recommissioning before school reopening. Conducting regular water flushing practices during the schools' normal operation could significantly promote the tap water quality and prevent exposure of children to heavy metals in tap water.

Author contributions

Shima Ghoochani: investigation, analysis, visualization; Maryam Salehi: conceptualization, methodology, writing original draft and editing, project administration, funding; Dave DeSimone: investigation, analysis; Mitra Salehi Esfandarani: investigation, Linkon Bhattacharjee: investigation

Conflicts of interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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