Understanding lead in water and avoidance strategies: a United States perspective for informed decision-making

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ABSTRACT

The pervasiveness of lead in drinking water poses a significant public health threat, which can be reduced by implementing preventive measures. However, the causes of elevated lead in water and the benefits of lead in water avoidance strategies are often misunderstood. Based on experiences in the United States, this paper describes an oversimplified 'lead in water equation' to explain key variables controlling the presence of lead in drinking water to better inform public health practitioners, government officials, utility personnel, and concerned residents. We illustrate the application of the equation in Flint, Michigan and explore the primary household-level water lead avoidance strategies recommended during the crisis, including flushing, filtration, bottled water use, and lead pipe removal. In addition to lead reduction, strategies are evaluated based on costs and limitations. While these lead avoidance strategies will reduce water lead to some degree, the costs, limitations, and effectiveness of these strategies will be site- and event-specific. This paper presents a simplified approach to communicate key factors which must be considered to effectively reduce waterborne lead exposures for a wide range of decision makers.

Key words | corrosion, Flint Water Crisis, lead avoidance strategies, lead in drinking water

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INTRODUCTION

The short- and long-term impacts of chronic exposure to low doses of lead from drinking water are still being investigated, but the U.S. Centers for Disease Control and Prevention (CDC) has asserted that no amount of exposure is safe. Given the bioaccumulative nature of lead, the lack of a health-based exposure threshold, and the U.S. Environmental Protection Agency's (USEPA) acknowledgement that drinking water regulations may not protect all individuals from potentially harmful lead exposures, exposure prevention is paramount (National Toxicology Program 2012). Drinking water is considered, by some, to be an underestimated source of lead, due to the corrosion of leaded drinking water infrastructure, lack of adequate treatment methods for controlling particulate lead, and sample collection methods that can undermine monitoring purposes (Schock 1990; Triantafyllidou & Edwards 2012; Edwards 2014b). Thus, instead of reacting to non-health-based regulatory triggers, public health officials should encourage vulnerable populations to take proactive precautionary measures to prevent water lead exposure and empower people with information on evidence-based strategies and technologies. Such evidence-based interventions are needed for both acute exposures such as those observed during the Flint Water Crisis and low-dose chronic exposures that are common in many Lead and Copper Rule (LCR) compliant cities with lead service lines (LSLs) (Katner *et al.* 2018; Pieper *et al.* 2018a).

While the Flint Water Crisis has elevated national concerns about water lead exposure (Hanna-Attisha *et al.*

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2016), there have been other high profile contamination events that caused serious childhood lead exposure (Edwards & Dudi 2004; Edwards & Triantafyllidou 2007; Masters & Edwards 2015). For instance, the 2001–2004 Washington DC Lead Crisis went largely unreported to the public for 4 years, caused hundreds of cases of elevated blood lead over the old CDC level of concern (10 μg/dL), and was associated with increased fetal death and miscarriage rates (Edwards *et al.* 2009; Edwards 2014b). Although a perfect comparison is not possible due to differences in sampling pools and methods, available data (Figure 1) suggest that the Washington DC first draw water lead levels (WLLs) were much higher than Flint (Edwards *et al.* 2009; Pieper *et al.* 2018a). However, it is important to note that first draw samples (i.e., samples collected after 6+ h of stagnation) do not always represent the worst-case WLLs, as these samples do not adequately characterize lead release in the particulate form or from LSLs (Edwards & Dudi 2004; Del Toral *et al.* 2013; Clark *et al.* 2014; Pieper *et al.* 2015a, 2017; Katner *et al.* 2018). Learning from these and other water lead contamination events can help avoid future problems during water crises, action level exceedances, and harmful exposures that occur in cities that meet the LCR.

The USEPA enacted the 1991 LCR to prevent widespread water lead exposure by reducing water corrosivity through corrosion control treatment (CCT) – corrosion control reduces the propensity of water to pick up lead when contacting plumbing infrastructure (U.S. EPA 1991). According to the LCR, water utilities must conduct the limited monitoring of high-risk homes under normal residential use conditions. High-risk homes are determined based on the age of structure and plumbing material composition, rather than selecting sites based on zonal variations in water corrosivity. If more than 10% of first draw samples exceed the lead action level of 15 μg/L, water utilities must optimize CCT, collect additional water samples, and notify the public. However, satisfying the LCR's action level requirements does not guarantee that a city's tap water is free of lead and is safe for all residents to consume (U.S. EPA 1991; Katner *et al.* 2016). The Natural Resources Defense Council revealed that in 2015, 5,363 water systems, serving more than 18 million US residents, had LCR health, monitoring, and/or reporting violations (Olson & Pullen Fedinick 2016). *USA Today* documented high WLLs in 350 schools and day-care centers between 2012 and 2015 (Ungar 2016), and also reported that 9,000 small water systems, serving almost 4 million rural residents, failed to test for lead in the past 6 years (Ungar & Nichols 2016). Moreover, private well users are not protected under the LCR, as private water systems (e.g., wells, springs, and cisterns) are not regulated by the USEPA (U.S. EPA 1991).

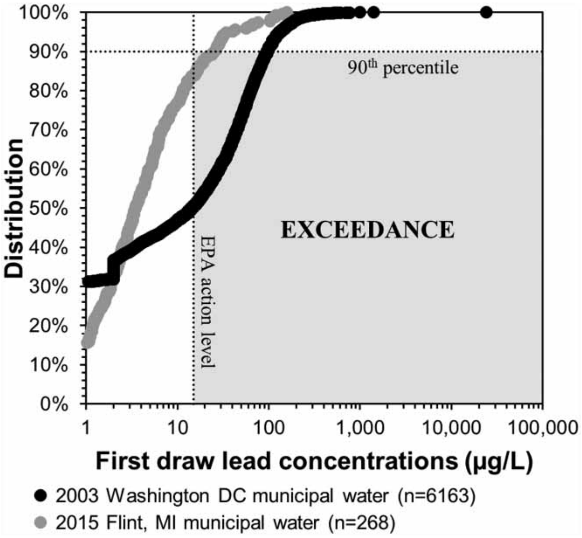

Figure 1 | Representative histogram of WLLs during the Flint and Washington DC lead in water crises (Edwards *et al.* 2009; Pieper *et al.* 2018a).

CONCEPTUAL LEAD IN WATER EQUATION

The three key variables that influence the presence of lead in drinking water at homes are: (1) lead-bearing plumbing; (2) corrosive water; and (3) ineffective CCT (Figure 2). The worst-case combination of these variables will produce the highest levels of lead in drinking water, whereas correcting one or all of these variables can potentially reduce or prevent lead in drinking water. The equation is qualitative rather than quantitative and underscores factors that must be considered when addressing lead in water issues.

Lead-Bearing Plumbing x **Corrosive Water** x **Ineffective Corrosion Control Treatment** = **Lead in Water**

Figure 2 | Oversimplified conceptual equation illustrating variables leading to lead in drinking water.

Lead-bearing plumbing

The use of lead in plumbing materials has been reduced over the years through USEPA regulations and industry best practices (Figure 3; Table S1, available with the online version of this paper). The 1986 Safe Drinking Water Act Amendments banned leaded and pure lead plumbing by requiring the installation of 'lead-free' plumbing (U.S. EPA 1989). However, 'lead-free' plumbing materials could still contain lead – up to 8% by weight until 2014 and a weighted average of 0.25% based on wetted surfaces thereafter (111th Congress 2011).

Lead-bearing service line materials

Pure lead pipes were widely used for service lines (pipe connecting premise plumbing and water main; Figure 3(a)) until the 1950s, though some cities continued to use LSLs until these pipes were banned in 1986 (Rabin 2008). LSLs are, by far, the most concentrated source of lead present in homes (100% lead) and can directly contaminate drinking water. When present, LSLs are often responsible for 50–75% of lead observed at the tap (Sandvig *et al.* 2008). Replacing LSLs as a solution to mitigate lead sources can sometimes

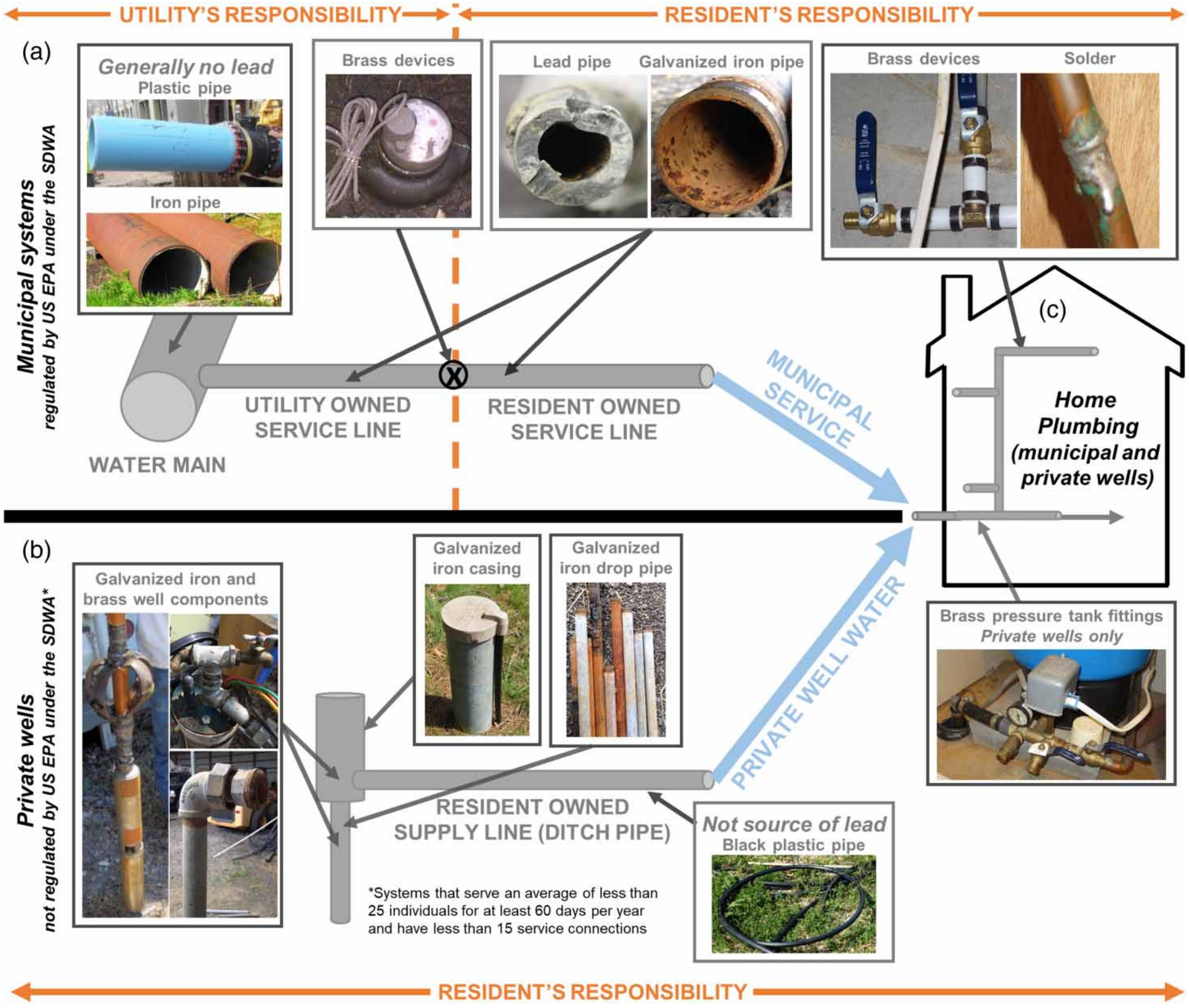

Figure 3 | Lead-bearing plumbing components potentially used within drinking water systems. (a) Municipal water systems with responsibility split between the utility and the resident; (b) private wells which are solely the responsibility of the resident; and (c) home plumbing system which are solely the responsibility of the resident.

be problematic as ownership of this pipe is split between the homeowner and water utility. When homeowners do not replace their section of the service line, only part of the lead pipe is replaced, which results in a partial lead service line replacement (PLSLR). When the utility's portion of the lead pipe is replaced with the copper pipe or brass connector fittings are installed, higher levels of lead sometimes result from accelerated corrosion of the lead pipe (Sandvig *et al.* 2008; Triantafyllidou & Edwards 2012; Cartier *et al.* 2013; St Clair *et al.* 2015) and physical disturbances of leaded scales may occur (Del Toral *et al.* 2013). As a result, occasionally PLSLRs do not reduce short- or long-term WLLs, but can even cause worse water lead issues.

Although LSLs are the primary service line material of concern, galvanized iron service lines (Figure 3(a)) and well components (Figure 3(b)) can also serve as a lead source and have been attributed to water lead problems (Sandvig *et al.* 2008; Clark *et al.* 2015; Pieper *et al.* 2017, 2018a, 2018b). A galvanized iron pipe is an iron pipe with a protective zinc–lead 'galvanized' surface coating. This galvanized coating often contained between 0.5 and 1.4% lead by weight until 2014 (Clark *et al.* 2015). Lead can leach into water from a pre-2014 galvanized iron pipe and be distributed to the tap or accumulate in iron rust layers along the interior of the pipe – creating both short- and long-term water lead problems (Clark *et al.* 2015; Pieper *et al.* 2017, 2018b). Even new post-2014 'lead-free' galvanized iron pipes (<0.25% lead in the surface coating) are still of concern due to the potential formation and remobilization of leaded rust scales (Pieper *et al.* 2016).

Lead-bearing household plumbing materials

Lead-bearing plumbing materials are still commonly used in home construction (Figure 3(c)). Leaded solders (composed of 40–50% lead) were used to connect copper plumbing until 1986 (U.S. EPA 1989; Edwards & Triantafyllidou 2007; Triantafyllidou & Edwards 2012). Several cases of childhood lead poisoning have been directly linked to the detachment of pieces of leaded solder (Edwards & Triantafyllidou 2007; Triantafyllidou *et al.* 2007). More recently, there have been concerns regarding pre-2014 'lead-free' brass (<8% lead by weight), as this lead-bearing component has been linked to several incidences of high WLLs in schools, buildings, and homes (Lytle & Schock 1996; Kimbrough 2001; Elfland *et al.* 2010; Triantafyllidou & Edwards 2012; Pieper *et al.* 2015b). Regardless of the piping material (copper or plastic), brass fittings such as ball valves, elbows, and faucet components are often present in the premise plumbing. Fortunately, 'lead-free' components containing <0.25% lead by the wetted surface (111th Congress 2011) have become available, which release lower lead in water (Pieper *et al.* 2016). However, new recommendations by the American Association of Pediatrics to reduce water lead to below 1 μg/L in school water may be difficult to achieve even with some products designed to meet the 2014 'lead-free' standard (American Academy of Pediatrics 2016; Parks *et al.* 2018).

Water corrosivity

Some waters are naturally corrosive, whereas other waters are naturally non-corrosive. There are several well-established water chemistry parameters that influence the corrosivity of drinking water such as dissolved oxygen, pH, water disinfectants, chloride-to-sulfate mass ratio, and alkalinity (Schock 1989, 1990; Triantafyllidou & Edwards 2007). These parameters are controlled and routinely monitored by the drinking water operators (see 'Ineffective CCT'). Although lead cannot typically be detected by taste, smell, or sight in water, studies note that higher water corrosivity (and resulting WLLs) can sometimes associate with certain unpleasant or undesirable characteristics of the drinking water. For example, private well users who had obvious signs of corrosion (e.g., plumbing leaks), blue-green staining on plumbing fixtures, and described the taste of water as metallic were more likely to have copper concentrations and low water pH, which were correlated with high WLLs (Pieper *et al.* 2015b). Researchers have also occasionally linked the incidence of red/rusty water reports to elevated WLLs, as the corrosion of iron pipes may indirectly result in higher WLLs (Masters & Edwards 2015; Pieper *et al.* 2017, 2018a). While the presence of red/rusty water may be an indicator of lead in some situations, that is often not always the case (Tang *et al.* 2018).

Ineffective CCT

Corrosion control by public water supplies involves the manipulation of pH, the adjustment of alkalinity, and/or the addition of corrosion inhibitors (e.g., phosphates or silicates), to reduce problems from lead pipes and other plumbing. However, residents reliant on private wells are responsible for implementing corrosion control, with associated responsibilities for monitoring and maintenance (Swistock *et al.* 2013; Pieper *et al.* 2015b). Although corrosion chemistry can be complex and dependent on plumbing materials (e.g., brass and solder), appropriate CCT can reduce lead in water through three dimensions of performance: (1) minimizing the dissolution of soluble lead and leaded scale layers by adding corrosion inhibitors to the water or increasing water pH and/or alkalinity (Figure S1(a)); (2) promoting the development of protective scale layers that reduce corrosion rates and the dissolution of soluble lead (Figure S1(b)); and (3) increasing the durability of leaded scale layers to prevent the destabilization and detachment of such layers to water (Figure S1(c)) (Figure S1 is available with the online version of this paper) (Schock 1989; Edwards & McNeill 2002). According to the LCR, any water utility serving ≥50,000 residents must have a state-approved optimized CCT plan (U.S. EPA 1991). CCT is only required in systems serving <50,000 residents when a utility exceeds the lead and/or copper action level during their required water sampling. The installation of CCT devices in private wells is limited and only corrects the water chemistry after treatment and only rarely the chemistry of water within the well plumbing (Swistock *et al.* 2013; Pieper *et al.* 2015a, 2015b).

Measuring lead in water

The LCR requires the collection of first draw samples, which was once considered the worst-case scenario as dissolved lead concentrations increase with stagnation time. This 1 L first draw sample will typically capture 7.9 m (25.9 ft) of a 6.4 mm (0.25 in.) diameter pipe, which only includes household (or premise) plumbing and not lead from the service line. Researchers have concluded that single first draw samples may not capture the worst-case water lead, which is particularly true for homes with LSLs or homes with particulate lead problems (Edwards & Dudi 2004; Renner 2008; Del Toral *et al.* 2013; Clark *et al.* 2014; Pieper *et al.* 2015a, 2017; Katner *et al.* 2018). Other factors that can result in reduced detection of lead hazards include sampling in cold weather and at low flow rates, prior removal of aerator filters, pre-flushing the night before collection, and inadequate sample processing in the laboratory (Katner *et al.* 2016). In recognition of inherent weaknesses in the LCR sampling protocol, researchers are utilizing profile sampling methods to more accurately characterize the entire plumbing network, including the premise plumbing and service lines, and its detachment in response to higher flow rates (Del Toral *et al.* 2013; Clark *et al.* 2014; Pieper *et al.* 2015a, 2017). Thus, it is imperative that proper sampling protocols be used to quantify water lead accurately.

Study objectives

The pervasiveness of lead in drinking water poses a significant public health threat, but exposure can be reduced or prevented almost completely, through the implementation of preventive measures. However, problems with monitoring, regulating, and remediating water lead have long been misunderstood due to the complexity of plumbing and corrosion control. With the USEPA's new 'war on lead' (Siegel 2018), it is imperative that simple but accurate scientific information be communicated effectively to a wide range of decision makers to reduce water lead exposures. This paper illustrates the application of an oversimplified 'lead in the water equation' to explain the key variables that control the presence of lead in water to lay audiences and presents factors to consider when selecting a household-level water lead remediation strategy. A case study methodology is used to inform practice based on the Flint Water Crisis. This work aims to provide public health practitioners, government officials, utility personnel, and concerned residents with a science-based model to inform communications, decision-making, and implementation of household-level avoidance strategies for lead from drinking water.

METHODS

The application of the lead in the water equation is demonstrated through a case study of Flint, Michigan. Published and newly collected data from Flint were applied to evaluate the four primary water lead avoidance strategies: (1) flushing, (2) bottled water, (3) lead filters, and (4) LSL replacement (Table 1). The overall approach was to evaluate

Table 1 | Comparison of the four household-level lead remediation strategies used during the Flint Water Crisis

		Reduction in WLLs (μg/L)			**Financial costs**[a]		
		Initial water lead value	**Intervention water lead value**	**Percent of samples reduced <AL**	**Cost of water per gallon**[b]	**Installation and maintenance fees**	**Non-exhaustive tangible and intangible impacts Potential impacts in Flint**
Flushing	*Home of resident zero*[c] *(1 home; 32 samples)*	First draw of 2,171 μg/L	3,550 μg/L *at 1 min* 1,412 μg/L *at 3 min* 2,542 μg/L *at 5 min* 1,742 μg/L *at 25 min*	0%	<$0.001	*Volume of water flushed* 1 min: 8.3 L (2.2 gal) 3 min: 24.9 L (6.6 gal) 5 min: 41.5 L (11.0 gal) 25 min: 207.5 L (55.0 gal) *Price of water flushed* $0.002 per 1-min flush $0.006 per 3-min flush $0.01 per 5-min flush $0.05 per 25-min flush	*Extra water use burden on water utility with morning and afternoon 3 min flush* Daily: 2.2 million L (0.6 million gal) 30 days: 65 million L (17 million gal) *Extra water use burden on household with morning and afternoon 3 min flush* Daily: $0.01 30 days: $0.35 ***Other considerations:*** - Cost of water for local utility - Water scarcity challenges - Water and wastewater treatment burden - Infrastructure impacts - Additional demand - Educating residents on the protocol - Prompting intervention adoption - Developing education materials - Perception of water safety
	Community-wide in August 2015[d] *(268 homes; 3 samples per home)*	90th percentile of 26.8 μg/L	11.3 μg/L *at 1 min* 6.6 μg/L *at 3 min*	94% 96%			
	Community-wide in March 2016[d] *(156 homes; 3 samples per home)*	90th percentile of 22.4 μg/L	9.0 μg/L *at 1 min* 3.2 μg/L *at 3 min*	96% 99%			
Bottled water (costs and water lead estimates derived from three samples from each of five brands)[e]		–	<1 μg/L	100%	$0.77–$8.32[e]	*Family of four drinking and cooking water needs* Daily: 5 L (1.3 gal) 30 day: 600 L (159 gal) *Price of bottled water* 30 day: $122.05 Save $0.14 on water bill	*Plastic bottle to solid waste* Daily: 5–40 bottles 30 days: 159–1,200 bottles ***Other considerations:*** - Ongoing cost of bottled water - Reduced water use from utility - Resident may use less water (7 gal/day compared to 100 gal/day) - Transportation to procurement/distribution of bottled water - Trash/recycle burden - Environmental and utility burden of discarded materials - Benefit of the avoidance of other contaminants and taste/odor compounds - Educating residents on bottled water use - Prompting intervention adoption - Developing education materials

(*continued*)

Table 1 | continued

		Reduction in WLLs (μg/L)			**Financial costs[a]**		
		Initial water lead value	**Intervention water lead value**	**Percent of samples reduced <AL**	**Cost of water per gallon[b]**	**Installation and maintenance fees**	**Non-exhaustive tangible and intangible impacts Potential impacts in Flint**
NSF 53 filters	*Home of Resident Zero[f] (1 unfiltered and 1 filtered sample)*	Influent of 13,200 μg/L	20 μg/L	0%	< $0.001	*Installation*: $15–50 for filter unit *Maintenance:* $10–15 per cartridge Tap-mounted: replace filters every 3–4 months Pitcher style: replace filters every 1–2 months	***Other considerations:*** - Ongoing cost of filter replacements - Burden of getting initial and replacement filters - Environmental and utility burden of discarded filters - Benefit of the avoidance of other contaminants and taste/odor compounds - Educating residents on the protocol - Prompting intervention adoption - Developing education materials - Perception of water safety - Perceived risk of microbial contamination
	Community-wide[g] (241 homes; 1 unfiltered and 1 filtered sample per home)	Unfiltered 90th percentile of 68 μg/L	Filtered 90th percentile of <1 μg/L	100%			
LSL replacement[e] *(1 house; 18 samples)*		First draw of 2,171 μg/L[c]	2.1 μg/L *first draw* <1 μg/L *at 1 min* 32.4 μg/L *at 2 min*	94%	<$0.001	Estimated $2,800 to replace 25 ft. LSL and 192 ft. galvanized iron service line	***Other considerations:*** - Perception of safety - One-time high cost to utility - Cost to consumer for full LSLR - Removal, transportation, and disposal old materials

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[a] Intervention costs (bottled water, filters, and LSL replacements) were provided to Flint residents at no cost at times during recovery.

[b] Cost of water in Flint (RFC 2016).

[c] Water lead measured in April 2015 (Pieper *et al.* 2017).

[d] Water lead measured in August 2015 and March 2016 (Pieper *et al.* 2018a).

[e] Measurements and data collected during this effort.

[f] Filter assessment at Virginia Tech in February 2016 (Edwards 2016).

[g] Filter assessment by USEPA in January 2016 (U.S. EPA 2016a).

each strategy based on costs, limitations, and reductions in lead exposure (defined as WLL reductions or by water lead avoidance).

Flushing

Data from two publications (Pieper *et al.* 2017, 2018a) were used to evaluate reductions in WLLs. Based on an average kitchen faucet water flow rate of 8.3 L/min (2.2 gal/min) (Welter 2016), the volume of water flushed was calculated at the household and city level. The price of water in Flint used in this assessment was from a 2016 Raftelis Financial Consultants (RFC) report, which was $3.30 per 14,195 L (3,740 gal) (RFC 2016). This rate was used to evaluate the increase in water bills at the household and city level.

Bottled water

To determine WLLs in bottled water, five brands distributed during the Flint Water Crisis (Deer Park, Great Value, Kroger, Member's Mark, and Nestle) were analyzed. Specifically, a 10 mL aliquot was collected from each bottle after thorough shaking, and three bottles of each brand were analyzed ($n = 15$ samples; three bottles from five brands). To evaluate bottled water costs, we reviewed popular brands available in three Virginia grocery stores in August 2018. Using reported statistics on average water use per person, it was assumed that 5 L (1.3 gal) was the volume of water used per day for all cooking and drinking purposes (U.S. Geological Survey 2016). Lastly, the savings from switching from municipal water to bottled water was calculated based on water volumes and the RFC report.

Lead filters

The USEPA published data from their in-home filter efficacy testing (U.S. EPA 2016a). For our analysis, only homes and buildings with paired unfiltered samples and filtered samples collected after the installation of a new filter were used ($n = 241$). It is important to note that unfiltered samples were not required to have 6+ h of stagnation until March 2016, and filtered samples were collected after running water through the new filter for 2 min. If multiple unfiltered samples were collected, samples were collected with the aerator removed ($n = 5$) and first draw samples ($n = 2$) were selected. Paired samples collected from the same home ($n = 20$) were used in this analysis if the samples were collected from different faucets and/or on different sampling dates with a new filter being installed. The minimum reporting limit for lead during the USEPA study was 0.5 μg/L. To evaluate filter costs, we reviewed popular brands available in four national box stores in August 2018.

LSL replacement

To evaluate WLL reduction after replacing the service line at the home of a Flint resident with high sustained WLLs (Pieper *et al.* 2017), follow-up profile samples were collected. Specifically, after 6+ h of stagnation, 18 sequential 1 L samples were collected at normal flow and shipped to Virginia Tech for analysis. All samples and aliquots were acidified with 2% (v/v) concentrated nitric acid and digested for a minimum of 16 h before analysis using inductively coupled plasma mass spectrometry (ICP-MS) per method 3125 B (American Public Health Association *et al.* 1998). For data quality assurance and quality control, blanks and spikes of known concentrations were measured every 10–15 samples. The costs of a full or partial line replacement depend strongly on site-specific considerations, such as access constraints, but cost estimates have ranged from $1,000 to $7,000 per home (Lambrinidou & Edwards 2013) to $2,500 to $8,700 per home (U.S. EPA 2016b).

Limitations of cost and cater lead estimations

There are limitations to the approaches used to estimate costs and WLL exposures. Indirect costs (e.g., increased solid waste and recycling of plastic bottles) were not included in this analysis, but they are important to identify and quantify (Wang *et al.* 2018). Also, WLLs can be highly variable, which makes realistic measurements of exposures to lead in water difficult to calculate. The focus of this paper was a case study for Flint, Michigan, and it is advisable that when this framework is applied to other locations, decisions should be based on as much site-specific data as are available. Thus, this framework aims to help communities consider and evaluate appropriate intervention strategies.

RESULTS

Using the lead in the water equation in Flint

This section presents how the lead in the water equation (Figure 2) can be applied through a case study of the lead water crisis in Flint, Michigan. In Flint, all three factors were involved, resulting in high lead in water levels.

Lead-bearing plumbing

Most housings in Flint were constructed between the 1950s and 1960s, and few homes were built after 1986, suggesting a high prevalence of LSLs and lead solder. Previously, the Michigan Department of Environmental Quality (MDEQ) estimated that at least 15,000 service connections were full or partial LSLs (MDEQ 2015). New estimates suggest that 29,100 service line connections are either lead or galvanized iron service lines (Moore 2016).

Corrosive water

The Flint River water had different water chemistry (e.g., chloride levels and pH), resulting in a drinking water supply that was more corrosive to the drinking water infrastructure than Detroit water (Del Toral 2015; Devine & Edwards 2016; Pieper *et al.* 2017). Specifically, when exposed to Flint River water, metal release into drinking water was 3.5–4.2 times higher (Devine & Edwards 2016). This increase in water corrosivity was also evident in the deterioration of water quality, as residents reported changes in taste, smell, and clarity of the water (Figure S2, available with the online version of this paper) (Felton 2014; Carmody 2015).

Ineffective CCT

When switching to treated Flint River water, city officials did not continue adding orthophosphate inhibitors (i.e., they discontinued CCT) to the finished water (Del Toral 2015; Davis *et al.* 2016; Masten *et al.* 2016; Pieper *et al.* 2017). Thus, the previously formed leaded scale layers began deteriorating and falling into the water (Pieper *et al.* 2017, 2018a). Moreover, without these protective layers, lead-bearing plumbing was in contact with the corrosive Flint River water, and the dissolution of lead from plumbing may have been occurring (Devine & Edwards 2016).

Reducing and preventing water lead exposure

The City of Flint reconnected to the less corrosive Detroit water service in October 2015 and enhanced CCT was implemented in December 2015 (Davis *et al.* 2016; Masten *et al.* 2016; Pieper *et al.* 2018a). Replacement of the 29,100 lead and galvanized iron service lines began in February 2016 and is still underway (Moore 2016). By once again reducing the corrosivity of the source water and boosting the dose of corrosion inhibitors, the city is reducing WLLs and correcting the damage done to the water infrastructure (Pieper *et al.* 2018a). In essence, the present-day Flint water has reduced all three elements of lead in the water equation (Figure 2).

EFFECTIVENESS OF LEAD IN WATER AVOIDANCE STRATEGIES

When public health officials or residents are concerned about WLLs, four household-level avoidance strategies are commonly recommended: (1) flushing water prior to consumption; (2) using bottled water; (3) installing or using a filter certified under NSF/ANSI 53 to remove lead; and (4) removing lead-bearing plumbing. This section explores WLL reduction efficacy associated with these water avoidance strategies communicated during the Flint Water Crisis and discusses some of the potential financial burdens, maintenance needs, and water conservation implications associated with these remediation strategies (Table 1).

Flushing water prior to consumption

Existing public health and utility messages suggest that residents flush water for 30 s to 2 min before consumption (Katner *et al.* 2018), as this will remove any stagnant water in contact with lead-bearing plumbing components. In homes where the primary sources of lead are brass fittings or lead-soldered joints in the premise plumbing (Figure 3(c)), short flushing protocols will often be effective (Clark *et al.* 2014; Pieper *et al.* 2015a; Katner *et al.* 2018). When partial or full LSLs are present, residents are encouraged to flush a high-volume tap (e.g., bathtub tap) for at least 5 min before flushing the kitchen tap for 1–2 min (Figure 3(a)) (U.S. CDC 2013). However, even this more extensive flushing protocol is not effective if leaded sediments and unstable scales are present within the system (Renner 2008; Del Toral *et al.* 2013; Clark *et al.* 2014; Pieper *et al.* 2015a, 2017). Thus, flushing protocols must be tailored for specific plumbing configurations and the type of lead release (Katner *et al.* 2018). Moreover, flushing is only effective when consumers follow procedures diligently and frequently, and WLLs can increase rapidly during short periods of stagnation (e.g., 50% dissolved lead after 1 h) (Schock 1990).

Resident Zero (the Flint resident who uncovered the dimensions of the crisis) was advised by city officials to flush the water for 25 min before consumption due to progressively increasing WLLs in early 2015 (Smith 2015). However, in-depth testing in April 2015 revealed that all samples collected after a 26-min flushing period (>100 L) still contained lead above 15 μg/L (217–13,200 μg/L) (Pieper *et al.* 2017). Moreover, WLLs collected after 20 min of flushing were actually increasing, demonstrating that this advice was ineffective in the midst of the water crisis. During community-wide testing in August 2015, a 3-min flush resulted in a 75% reduction in the first draw 90th percentile WLL (26.8–6.6 μg/L; $n = 268$), but 47% of residents still had detectable water lead (≥1 μg/L) (Pieper *et al.* 2018a). After switching back to Detroit water service with enhanced CCT, the city issued a lead advisory, recommending that residents flush the tap water for 5 min before consumption. Water lead samples collected in March 2016 confirmed that 3 min of flushing reduced WLLs for most homes in Flint (Pieper *et al.* 2018a). Specifically, there was an 86% reduction in the first draw 90th percentile WLL after 3 min of flushing (22.4–3.2 μg/L; $n = 156$), and 99% of samples were below 15 μg/L. However, 30% of residents still had detectable water lead, and several homes experienced spikes in lead (maximum of 69 μg/L), which were likely linked to the disruption of previously formed leaded scale layers. Thus, sole reliance on flushing as a strategy for reducing WLL exposure appeared to be inconsistently effective during the Flint Water Crisis.

While 3 min of flushing reduced WLLs for most homes in Flint, there were substantial financial burdens and water conservation implications that need to be considered (Table 1). Assuming that the water flow rate from a kitchen faucet is 8.3 L/min (2.2 gal/min) (Welter 2016), flushing for 3 min would have disposed of 24.9 L/flush (6.6 gal/flush). If all 43,404 service connections in Flint flushed twice per day (morning and after work), approximately 2.2 million L (0.6 million gal) would have been flushed daily (City of Flint 2016). Over a 30-day period, this would have amounted to 65 million L (17 million gal). As water service was largely a fixed cost operation in Flint, flushing practices would have only slightly increased water bills for residents (RFC 2016). At $3.30 per 14,195 L (3,740 gal), flushing 3 min twice daily would have cost only $0.01 or $0.35 over 30 days. Therefore, flushing was a low-cost remediation strategy for residents, but was not always effective, and may have increased water and wastewater operation costs and wasted a substantial quantity of water (Wang *et al.* 2018).

Consuming bottled water

The USEPA does not regulate bottled water quality, rather the U.S. Food and Drug Administration (FDA) is responsible for the safety and appropriate labeling of bottled water (FDA 2010). FDA's bottled water regulations do not pertain to approximately 60–70% of brands, as they are packaged and sold within the same state (Olson *et al.* 1999). There has been considerable debate regarding the health protectiveness of FDA's bottled water standards. But in terms of lead, the FDA has a lower allowable threshold than the USEPA – bottled water must contain less than 5 μg/L, which is a third of the action level (U.S. EPA 1991; FDA 2010).

To quantify WLLs in bottled water and potential bottled water lead exposure, our research team analyzed five brands distributed during the Flint Water Crisis (Deer Park, Great Value, Kroger, Member's Mark, and Nestle). All 15 samples contained non-detectable WLLs (<1 μg/L), demonstrating that these brands were safe for lead, and confirming that bottled water is a viable option that can be distributed during a water lead crisis. In addition, other corrosion-related metals (iron, copper, and zinc) were also below detectable levels (<10 μg/L). These brands differed mainly with respect to other water quality factors (e.g., sodium concentrations and water hardness) that can impact aesthetics (more information about bottled water quality and brands can be found at www.nsf.org). While bottled water provides a safe drinking water alternative in terms of lead, there are financial and environmental implications associated with its use. Moreover, the use of bottled water can impede the recovery of the system, as there will be a limited flow of distributed water with CCT in the premise plumbing and service lines.

Based on our review of popular brands available in grocery stores, a 1-gallon off the shelf container can cost between $0.77 and $1.75, while individual bottles can cost between $0.77 and $8.32 per gallon. Assuming the average person uses 5 L (1.3 gal) daily for all cooking and drinking purposes, a family of four will use 600 L (159 gal) of water over a 30-day period (U.S. Geological Survey 2016). Using the least expensive bottled water option, this family would spend $122.05 (not including tax) and only save $0.14 on water bill due to the conservation of 20 L/day (assuming $3.30 commodity charge per 14,195 L) (RFC 2016). As for waste generation, a family could generate 5–40 empty bottles daily and 159–1,200 empty plastic bottles monthly when using gallon and 16.9 ounce bottles, respectively. These estimates are consistent with a CNN profile of the Luster family in Flint (Zdanowicz 2016). Over 3 days, this family of three used approximately 4.8 gal for cooking, 3.6 gal for drinking water, and 6.9 gal for miscellaneous activities such as washing dishes and brushing teeth. While bottled water provides a safe alternative when tap water is lead-contaminated, this option may not be financially feasible or sustainable for low-income residents. Moreover, due to the inconvenience and expense, residents may use less water – the Luster family used 7 gal/day compared to an average of 100 gal/day (U.S. Geological Survey 2016).

Using a filter certified to remove lead

There are numerous treatment options available that are certified to remove specific health-related contaminants from drinking water (a consumer tool for identifying water filters certified to reduce lead can be found on the USEPA's website). NSF is one certifying body of water filters. NSF/ANSI 53 certified point-of-use (POU) filters can be a low-cost option to remediate water lead (NSF International 2015). POU filters are designed to treat water at a specific outlet, which limits the volume of water needed to be filtered. The activated carbon media sorb dissolved lead and trap particulate lead to reduce WLLs below 10 μg/L for water containing up to 150 μg/L lead (NSF International 2015). Thus, filters can be an effective remediation strategy if expired filter cartridges are regularly replaced. While POUs are available as tap-mounted, under-the-sink, and pour-through (pitcher filters) from numerous companies, tap-mounted units were recommended and distributed during the Flint Water Crisis (U.S. EPA 2016a).

At the onset of the Flint Water Crisis, there were concerns regarding POU efficacy for homes with WLLs above the NSF/ANSI 53 threshold of 150 μg/L. Our team filtered the worst water lead sample from the home of Resident Zero (sample containing 13,200 μg/L) through an NSF/ANSI 53 certified ZeroWater™ lead filter and observed that 99.85% of the water lead was removed (Edwards 2016; Pieper *et al.* 2017). Although the filtered water was still above the USEPA action level on this extreme 'worst-case' sample, this experiment illustrated that POU filters are effective in dramatically reducing WLLs even under the most extreme conditions. The USEPA conducted additional NSF/ANSI 53 POU testing to examine the efficacy of Brita™ and Pur™ brand filters under more typical 'worst-case' WLLs in Flint (the 90th WLL of the unfiltered sample population was 68 μg/L) (U.S. EPA 2016a). Based on paired data from 241 Flint homes, POU filters were capable of removing lead in exceedance of 150 μg/L (reduced 4,080 to 0.9 μg/L). Moreover, in most homes, WLLs were reduced to non-reportable levels after filtration (the 90th WLL of the filtered sample population was <0.5 μg/L; high of 1.01 μg/L). Thus, the USEPA data clearly demonstrated that POU filters could effectively reduce the lead in tap water to well below both the action level and the bottled water standard, which is consistent with prior research (Deshommes *et al.* 2010, 2012).

Although POU filters were distributed during the Flint Water Crisis at no cost to the residents (U.S. EPA 2016a), these devices are also readily available at local stores. Based on our review of popular brands available, tap-mounted POUs typically cost less than $50, with some models as low as $15. The filter capacity for most units was between 100 and 200 gal (projected to last 3–4 months), and the average cost for a replacement filter cartridge was $10–15. These POU filters cost between $25 and $35, with a replacement filter cartridge costing approximately $10–15. The pitcher style requires more frequent maintenance, as these units are only rated for 25–40 gal (projected to last 1–2 months). Over a 30-day period, the least expensive tap-mounted and pitcher style POU filters would cost only $10–15 in replacement cartridge needs, but this remediation requires an initial purchase of $15–50 for the filtration device. Thus, both POU styles provide a low-cost, effective remediation strategy for residents, but the ease of installation and filter replacement maintenance need to be considered when communicating this strategy.

Removal of partial or full LSLs

Exposure to water lead can be prevented by safely removing sources of lead. In the drinking water infrastructure, LSLs are the most concentrated source of lead and can directly contaminate drinking water. For example, assuming a family of four uses 400 gal of water per day, each foot of ¾″ lead pipe contains enough lead to raise every drop of water above the action level for more than 100 years (Edwards 2014a). Thus, replacing the LSL with a non-leaded alternative will greatly reduce water lead exposure.

As previously described, the home of Resident Zero had high WLLs over a 26-min flushing period (>100 L) – the first draw and median WLLs were 2,171 and 1,747 μg/L, respectively (Pieper *et al.* 2017). In May 2015, the 25 ft LSL and 192 ft galvanized iron service lines present at the home of Resident Zero were replaced with a non-leaded pipe. The following week, a subsequent lead profile containing 18 sequential 1-L samples was collected at this home. There was a substantial decrease in WLLs even though there was no corrosion control in the system at that point – the first draw and median WLLs were 2.1 and 1.9 μg/L, respectively. However, there was a spike of 32.4 μg/L in the 17th liter of water, which is consistent with other literature suggesting short-term incident of high WLLs even after full service line replacements (Sandvig *et al.* 2008; Cartier *et al.* 2013). In addition, this practice still leaves lead sources within the home plumbing, which after the LSL is removed, becomes the source of 100% of the lead in water and can still far exceed the lead action level (Triantafyllidou & Edwards 2007; Triantafyllidou *et al.* 2007). Indeed, during the Flint Water Crisis citizen-led sampling events, the worst-case home sampled (WLL of 1,051 μg/L) had no lead pipe, rather the lead was derived from detaching pieces of lead solder (Pieper *et al.* 2018a).

Efforts are currently underway to repair and replace the water infrastructure throughout Flint. It was estimated to take almost a decade to address all infrastructure replacement needs at the previous rate of repair, as only 224 of the 29,100 needed replacements had been completed between February and December 2016 (Derringer 2016; Moore 2016). Service line replacement can be a slow process due to its labor-intensive nature (e.g., destruction of streets and sidewalks, removal of complex landscaping, or tree root systems) (City of Flint 2016; Derringer 2016). The cost of service line replacements can also be cost prohibitive, especially for low-income communities (Katner *et al.* 2016). Additional environmental injustices can arise, as replacement decisions are at the discretion of the property owner, not renters. Through the USEPA funding, LSL and GSL replacements will be done at no cost to Flint residents (U.S. EPA 2017). However, most cities are not provided this kind of government support. Without state or federal assistance, the cost of a full line replacement ranges from $1,000 to $7,000 per home and may cost more depending on access constraints and other site-specific considerations (Lambrinidou & Edwards 2013). When residents are unable to pay for the replacement of the service line on their property, PLSLRs are conducted – a practice that disproportionately impacts low-income residents (Katner *et al.* 2016). Some water utilities are also ‘gifting’ the LSLs, which shift both the ownership and financial burden of LSL replacement to the customer (Kaplan & Hiar 2012). Removing the source of lead in drinking water infrastructure is an important step in preventing water lead exposure, but it is a time, labor, and financially intensive process.

DISCUSSION

When considering potential lead in water exposure and choosing household-level avoidance strategies, it is necessary to understand the protections afforded by regulations and public health guidance. The USEPA’s current regulatory framework attempts to account for both water chemistry and infrastructure contributions to lead release by requiring sampling at consumers' taps (U.S. EPA 1991). However, lead sampling protocols were designed to inform regulatory oversight, not to characterize exposures or public health risks. Moreover, up to 10% of homes sampled during the LCR protocol can contain substantial lead as well as homes not sampled during LCR testing campaigns. Officials are also required to promote flushing on annual consumer confidence reports, and PLSLRs are still required under some non-compliance/exceedance circumstances despite evidence of the short-term-associated risks (Katner *et al.* 2016, 2018). While USEPA regulatory officials recognize the limitations of the LCR in protecting all individuals in a city from high water lead exposures, public health officials have long misinterpreted regulatory compliance as public health assurance. The CDC's guidance for investigating the homes of lead poisoned children does not require water lead testing if other sources of lead were found or if the city is meeting the LCR action level (U.S. CDC 2002). This recommendation has omitted water lead testing in LCR-compliant cities and overlooked a potential route of low-dose chronic lead exposure. These misinterpretations have led to missed opportunities to detect water lead issues and empower people with information on strategies that would allow them to take responsibility for independently addressing potential risks.

The four household water lead avoidance strategies presented in this study reduced WLLs to some degree, but the effectiveness of these avoidance strategies will be site-specific. As explored in Flint, flushing reduced WLLs overall, but the household-level effectiveness was inconsistent. While city officials initially advised residents to flush their taps before using the water, this recommendation was replaced by using bottled water and/or an NSF/ANSI 53 lead filter. This work, along with others (U.S. EPA 2016a), have documented that both bottled water and lead filters are strategies that consistently provided safe drinking water. Although replacing the leaded plumbing removes the source of lead, as evident in Flint, this cannot be implemented at the height of a crisis.

For communities concerned about lead in drinking water, building age and knowledge of plumbing materials will help determine the appropriate avoidance strategy, as this information can indicate likely types of leaded infrastructure present. For example, homes with pre-1986 plumbing are more likely to have leaded plumbing sources, including LSLs and lead solder, and may need more intensive interventions like plumbing replacements and avoidance strategies (e.g., bottled water and NSF/ANSI 53 filters). In contrast, lower risk homes, including homes built after 1986 (no LSLs or lead solder) and homes built after 2014 (<0.25% lead in the wetted surface), may not require plumbing replacements, but rather suffice with NSF/ANSI 53 filters. Although flushing is often promoted, it is important to know the presence and location of leaded plumbing materials, as it is not effective when particulate lead and LSLs are present in the system (Del Toral *et al.* 2013; Clark *et al.* 2014; Pieper *et al.* 2015a; Katner *et al.* 2018). Lastly, other potential variables impacting the residents and the city, such as financial burden, trash and recycling needs, and water conservation implications are difficult to estimate due to poor record keeping and limited research exploring such costs (Wang *et al.* 2018).

CONCLUSION

There is a critical need for proactive interventions to prevent lead exposure from drinking water instead of relying on reactive regulatory compliance actions that may not be sufficiently protective of public health. In this study, we illustrate the application of an overly simplistic lead in water equation to help understand that worst-case WLLs result from a combination of corrosive water, leaded drinking water infrastructure, and the absence of corrosion controls. Improving any of these conditions can reduce WLLs. The water lead avoidance strategies primarily focus on interventions at the household level to reduce potential water lead, including removal of leaded plumbing, remediation strategies such as flushing and filtration, and complete avoidance by switching to bottled water consumption. The optimal strategy for a given residence will be site-specific and based on a variety of factors and considerations. Thus, engaging with residents and the community will be critical to successful implementation. This work provides public health practitioners, government officials, utility personnel, and concerned residents with science-based information for informed communication, decision-making, and implementation of household-level avoidance strategies for lead from drinking water.

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