Preventing another lead (Pb) in drinking water crisis: Lessons from the Washington D.C. and Flint MI contamination events
Siddhartha Roy and Marc A. Edwards

Abstract
Two high profile lead (Pb) contamination of drinking water events of the 21st century, namely Washington DC (2001–04) and Flint Michigan (2014–16), represent a tip of the “water lead” iceberg with millions of Americans potentially drinking contaminated tap water. In light of the U.S. Environmental Protection Agency declaring a “war on lead” in 2018, we review our current understanding of infrastructure, scientific/operational and regulatory factors that contribute to lead in water disasters. This includes the role of water chemistry, corrosion control treatment, sampling methodologies, federal and state regulations, unethical behavior and public education efforts. General prescriptions are offered to help avoid such manmade crises in the future.

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Introduction
“A long running environmental and public health catastrophe” — Werner Troesken, on rampant and misguided installation of lead pipes across US and Europe [1].

“Water […] seems to be made injurious by lead” — Vitruvius, first-century BC [2].

Lead is a potent neurotoxin, harmful to multiple organ systems, but especially damaging to developing brains and central nervous systems in fetuses and children below six years of age. For centuries, lead exposure was primarily occupation-specific (e.g., painters and potters), but the metal’s prolific industrial uses beginning in the 1800s included gasoline, paint and water pipes increased human exposure leading to deaths and disease [3]. Since 2012, it has been official U.S. Centers for Disease Control and Prevention (CDC) policy, to claim that there is “no safe level of lead exposure” due to the absence of a blood lead level (BLL) threshold for deleterious effects of lead exposure [4].

The phase-out of lead from gasoline and paint were major public health success stories of the late 20th century [5]. However, as percentage human lead exposure from the sources of food, paint, soil and dust declined, that from drinking water is believed to have increased even as BLLs of health concern have decreased [6,7]. The first two high profile lead-related public health crises of the 21st century, specifically the Washington DC (2000–04) and the Flint MI (2014–16) water crises (“DC&FWC”), have garnered widespread national and international attention. It is important to recognize that first and foremost, the DC&FWC were both crises of confidence, spawned from a betrayal of the public trust and disregard for the Safe Drinking Water Act by government agencies [8,9]. Each case involved scientific misconduct, failure to properly implement legally mandated corrosion controls, and efforts to withhold information about elevated lead in water from the public. While other public health crises involved more public health harm and deaths, the DC&FWC fiascos (Table 1) have gained an infamy akin to the Tuskegee syphilis experiments [9].

But there were also noteworthy scientific and engineering issues, which contributed to the DC&FWC. It starts with an underlying philosophical problem, in that while “there is no safe level of lead exposure,” even modern plumbing systems designed to meet stringent standards effective January 2014 can sometimes contribute up to 5 μg/L lead to potable water [10,11]. Because tap water that contacts lead-bearing plumbing is virtually guaranteed to have some lead (i.e., 0.0001, 0.001, 0.01, 0.1 μg/L) after stagnation — it implies that all tap water cannot be “safe” according to official government definitions. Herein, we also review current understanding of lead in water, relying on field and...
Table 1

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<td><strong>Primary Technical Cause</strong></td>
<td>Disinfectant switch from free chlorine to chloramine in November 2000. Chlorine had been inhibiting lead release to water.</td>
<td>Water source switch from Lake Huron (orthophosphate corrosion control; low CSMR) to Flint River (no orthophosphate, high CSMR) in April 2014</td>
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<td><strong>Responsible agencies</strong></td>
<td>DC Water (water distributor), Washington Aqueduct (water treatment); USEPA (government primacy and oversight agency); DC DOH (health department); CDC (federal health agency)</td>
<td>MDEQ (primacy agency with direct oversight); USEPA Region V (federal oversight); City of Flint, MI Council and Emergency Managers; MDHHS (health department)</td>
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<td><strong>Water Lead Levels (City meets federal LCR if 90th percentile WLL ≤ 15 μg/L)</strong></td>
<td>• Exceeded LAL in 2001–04 (e.g.: over 2/3rd of 6000 + homes tested in 2003 had WLLs &gt; 15 μg/L) • WLLs = 79 μg/L (illustrative 90th percentile in 2001), 48,000 μg/L (highest reported)</td>
<td>• Retrospective analysis suggests sharp spike in water lead in Summer 2014 that decreased thereafter; water lead stayed elevated relative to action levels until 2016 • WLLs = 28.6 μg/L (90th percentile from citizen sampling in August 2015), &gt;20,000 μg/L (highest reported)</td>
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<td><strong>Estimated Health Impacts</strong></td>
<td>• ~42,000 children (&lt;2 years) exposed • Possible increase in miscarriage and fetal death rates (~2000 miscarriages and ~200 fetal deaths)</td>
<td>• Doubling of % of Flint children with EBL (~200 confirmed cases) • Effects on adverse pregnancy outcomes under study • One of the largest Legionnaire’s Disease outbreaks in the U.S. (91 cases; 12 deaths)</td>
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<td><strong>Estimated # of lead pipes (current)</strong></td>
<td>Over 20,082 &quot;identified&quot; lead pipes (full and partial); 16,276 lines are still categorized as &quot;unknown&quot;</td>
<td>Flint residents in collaboration with Flint Water Study team, ACLU-Michigan and others in August–September 2015 following the leaking of a scientific memo by USEPA’s Miguel Del Toral describing high WLLs in resident LeeAnne Walters’ home and lack of CCT in Flint’s water</td>
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<td><strong>Exposed by</strong></td>
<td>Whistleblowers within D.C. Water, Citizens and then the Washington Post in January 2004</td>
<td>Switchback to Lake Huron water in October 2015 and tripling of orthophosphate CCT dose</td>
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<td><strong>Resolution</strong></td>
<td>• Addition of orthophosphate CCT began in August 2004 • Public education efforts, free lead filters, blood tests • Over 15,000 partial lead pipe replacements that caused lead spike and possibly increased EBL during 2007–2009</td>
<td>• Flint has been meeting federal LCR since late 2016 • Federal emergency declaration and over $600 million in relief (bottled water, lead filters, water bill credits, water testing, healthcare, nutrition and education services, capacity building, etc.) • Replacement of all lead and galvanized iron pipes as part of settlement by 2020</td>
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<td><strong>Unethical behavior and accountability</strong></td>
<td>• High WLL results dropped from sampling data a few months after switch, initiating multi-year cover-up of high water lead • Several peer-reviewed agency papers/reports with allegedly falsified data that downplayed harm to public health and derailed efforts to hold bad actors accountable • Several whistleblowers fired and received legal settlements • Class action lawsuit dismissed • Settlement packages for only five children in 2016 (12 – 16 years after exposure)</td>
<td>• “Cheats” used in sampling that allowed claims that Flint was meeting action level • USEPA silenced whistleblower Miguel Del Toral • Criminal charges against 15 civil servants at City of Flint, Emergency Managers under MI Governor, MDEQ and MDHHS • Heads of MDEQ and USEPA Region V amongst resignations • Dozens of ongoing lawsuits • Two environmental companies sued</td>
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<td><strong>Perspective on crisis</strong></td>
<td>“I think the jury is still out [if high lead in water harmed DC residents]” – George Hawkins, DC Water chief (2016)</td>
<td>“Failure of government at all levels [in Flint]” – Rick Snyder, MI Governor (2016)</td>
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<tr>
<td><strong>References</strong></td>
<td>[8,12–18]</td>
<td>[8,19–26]</td>
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Abbreviations: CCT = Corrosion Control Treatment; CDC = Centers for Disease Control and Prevention; CSMR = Chloride-to-Sulfate Mass Ratio; DC DOH = DC Department of Health; EBL = Elevated Blood Lead (≥5 μg/dL); LAL = Lead Action Level (15 μg/L); LCR = Lead and Copper Rule; MDEQ: Michigan Department of Environmental Quality; Michigan Department of Health and Human Services; WLL = Water Lead Level.
laboratory studies from the past decade, to offer scientific, regulatory and practical advice on how to avoid the high societal and financial costs of a future water lead crisis.

**Factors responsible for lead in drinking water crises**

The DC&FWC are now widely acknowledged to represent just a tip of a “water lead” iceberg in the United States. Tied to the scientific challenges of reducing water lead exposure are questions of environmental injustice and water infrastructure inequality [27]. Millions of Americans are increasingly aware that their water may have lead in excess of 15 μg/L [28]. While tap water in the U.S. may very well be relatively safe for most Americans, public perception to the contrary is creating fear, anxiety and a surge in sales of bottled water and filtration systems [29,30].

The CDC’s blood lead level (BLL) of concern has decreased from 60 μg/dL in 1960 to 5 μg/dL (“reference value”) in 2012, and a further decrease to 3.5 μg/dL is under discussion [31]. Decades ago it was estimated that 20% of lead ingested by children was from water, but for infants using reconstituted formula the percentage of exposure was estimated at 85% or higher [6]. WLLs of 11 μg/L can cause corresponding BLLs of 5 μg/dL in 10% of such exposed formula-fed infants based on estimates from the Integrated Exposure Uptake Biokinetic (IEUBK) model [32]. Children at or above 5 μg/dL BLL will, on average, experience a loss of several IQ points [33]. WLLs of 60 μg/L can increase maternal BLL of pregnant women to 5 μg/dL per the International Commission of Radiological Protection (ICRP) biokinetic model, markedly increasing miscarriage risk according to some research [33,60,88]. A comprehensive review on lead in water as it affects lead in blood is available elsewhere [34].

This review focuses on the United States, but several countries in the E.U., Australasia and Asia are also facing challenges of legacy lead pipes and/or unregulated lead in modern water infrastructure (e.g., imported leaded brass components or plastic pipes with lead-based stabilizers) or lack of lead in water regulations [35–38]. These countries have also had scandals, including lead poisonings resulting from illegal use of lead solder in multi-story buildings [39–41], but government agency misconduct has not been as prevalent. This is in large part, because countries such as Australia never assumed any public responsibility for protecting consumers from lead [42] — that is, they never instituted the equivalent of the 1991 Lead and Copper Rule (LCR) in the U.S. that gave utilities some responsibility for monitoring and reporting the problem to consumers [43]. The relevant infrastructure, operational, and regulatory factors contributing to lead in water problems are summarized in the following sections.

**Aging water infrastructure**

When present, pure lead service lines (LSLs) and lead goosenecks are estimated to be responsible for 50–75% of water lead at the tap [34]. Lead solder (~50 weight percent Pb), galvanized iron pipes (Pb impurities in coating), and leaded brass components including meters, faucets, valves, and other fittings are also important sources of water lead (Figure 1) [34]. Lead pipe or lead added to alloys, allows for manufacture of reliable and low cost plumbing devices, but its health harm to consumers was generally overlooked for many decades. There are an estimated 6.1–10.2 million LSLs across America [44], with Chicago IL and its suburbs having the greatest number and highest density of water lead pipe [45]. These LSLs are present in many larger U.S. cities because they were often required by law or plumbing code. Lead service lines are the only government “owned” (legally and morally) lead source that directly affects a product (tap water) intended for human consumption, creating a potential government conflict of interest relative to control of other lead sources such as paint, food, dust or gasoline. This inherent conflict of interest spans centuries and has created denial and occasional cover-ups of health problems in many countries with LSLs including England, Scotland and several EU countries [1].

Only two cities, Lansing MI and Madison WI assumed 100% legal responsibility for replacing their LSLs [21]. Flint MI is projected to replace all lead and galvanized iron pipes by 2020 with State and Federal government funding as part of a legal settlement [22]. At the other extreme, some cities ascribe full responsibility of LSLs to homeowners (e.g., Denver CO), and still others have a system of “shared ownership” of lead pipes between homeowner and water utility [34]. Houses with partial LSL replacements (i.e., direct LSL-copper connections) can witness galvanic corrosion and post-replacement lead scale disturbance causing higher lead release and an increased likelihood of childhood lead poisoning, as was seen in Washington D.C. during 2007–09 [17]. Poor recordkeeping and lack of an LSL inventory led to large errors in detecting lead pipes in Washington D.C. and Flint MI, and caused massive confusion in public health messaging and allocation of resources for pipe replacements [46,47,89]. Voluntary efforts towards replacing full LSLs are increasingly discussed in communities nationwide. Flint events led the Journal of Chemical Education to conclude that “aging water infrastructure, particularly lead pipes, solder, and faucets, represents a community health hazard of enduring significance” [48].

**Water chemistry and corrosion control**

There is typically very low lead (i.e., <0.1 or < 1 μg/L) in the water leaving the treatment plant, but its corrosive nature and/or factors such as weather, distribution
system changes, or water usage pattern can cause or exacerbate release of lead from plumbing (Table 2). Lead release can be dissolved (e.g., free lead ions, carbonates, phosphate or hydroxide aqueous complexes) and/or particulates originating from pipe scale, solder, brass, or sediment [34]. Lead particles dominated total lead concentrations at taps during the DC&FWC due to destabilization of lead scale [14,23]. Desktop and pilot scale feasibility studies are carried out to determine changes to pH, alkalinity and choice of corrosion inhibitors to reduce lead, copper and iron release (called, optimal corrosion control treatment or OCCT) as described in the LCR. Treatment measures are overseen and approved by a state government environmental agency [43]. Water distribution systems with “good” OCCT form stable and protective insoluble scale over time comprised of lead hydroxycarbonates, hydroxides, phosphates and other compounds, the specific mineralogy and protective nature varying with the water chemistry and history of system [49].

Unbeknownst to the water industry, free chlorine was acting as a highly effective corrosion inhibitor in Washington D.C. and other communities with lead pipe, and a switch to chloramine which lacked the ability to form and maintain protective [Pb(IV)] pipe scale triggered massive release of lead in water starting late 2000 [13,49]. In contrast, the switch to Flint River water (with high chloride levels) and interruption of orthophosphate corrosion inhibitor dosing in Flint triggered the FWC. After switching back to Lake Huron water after the problems were acknowledged, the orthophosphate dose was tripled (compared to finished water received from Detroit) resulting in drastically reduced lead levels in Flint [50,51]. However, phosphate CCT in most U.S. water systems tends to be suboptimal, especially when compared to England where doses average about two to three times higher than those typically used in the U.S [52–55]. Optimized CCT dosing, though effective in reducing lead while consumers wait and wait for lead pipe replacement, has been occasionally resisted on “philosophical and environmental grounds” in the EU [37] and now in the US.

To elaborate, there are obvious limitations to “optimizing” CCT (i.e., reducing 90th percentile below 5 µg/L) based on water quality in certain geographies. For example, high CSMR (>0.5) water increases lead
release from brass and lead solder or lead pipe galvanically connected to copper, but does not attack lead pipe alone [56]. Therefore, switching to a sulfate-based coagulant might reduce CSMR, but not if the CSMR is too high to begin with. Secondly, chloride concentrations in source waters nationwide are rising due to salt application for road deicing during snow events [57], which is making water more corrosive and can suddenly trigger lead release problems. Similarly, abrupt changes in chlorine residual levels (i.e., oxidation/reduction potential or ORP) can alter solubility of pipe scale [e.g., Pb (II) to Pb (IV)], disrupt equilibrium, and increase mobilization of scale particles and dissolution of solids (Table 2) [58]. For certain water quality conditions such as high CSMR water when lead solder is present, there is really no “optimized” CCT yet proven to control lead, but studies to develop better corrosion control strategies for these situations are ongoing (e.g., [59]).

**Lead monitoring and sampling**

The current federally mandated sampling methodology (i.e., collection of one 1 L sample at full flow — “first draw” — from a location dispensing water intended for human consumption after 6 + hours of stagnation with no water use whatsoever) was largely undermined until 2016 by using “cheats” that minimize the likelihood of accurately identifying lead release hazards. Illustrative cheats include: pre-stagnation flushing, use of small-mouthed bottles, sampling at low flow, and removal of aerator before sampling [8]. Pre-Flint, the USEPA was complicit in allowing such practices, claiming that the agency lacked authority to stop such practices. Post—Flint, the agency provided “recommendations” to discontinue the cheats, but claimed they had no legal mandate to stop them completely [63]. Dogged reporting, public outcry or even the fear of public backlash has led some water utilities to voluntarily change their practices. For example, Philadelphia Water Department vigorously defended their sampling methods using three “cheats,” but decided to comply after confronted with a class action lawsuit [64].

Recent studies on profile sampling (i.e., collection of sequential water samples) in the laboratory, private wells and public water systems [61,65—67] have revealed the erratic nature of lead release and possible limitations of flushing to clean pipes of lead. In several homes of Chicago and its suburbs, even 5—10 min of cumulative flushing does not reduce WLLs to below 5 μg/L [61,68]. The 3-bottle sampling method (first draw, 45-s flushed sample “second draw” and 2-min flushed sample “third draw”) used to reveal the FWC is far more likely to accurately detect WLLs than first draw alone as was seen in New Orleans [69]. Many utilities (e.g., Chicago) are now giving out 2—3 bottles in their sampling kits to capture lead in first draw and flushed water samples, even though only first draw “counts” for regulatory purposes except for the new Michigan LCR [70]. An industry study suggested that if second draw lead service line samples were collected and counted for determination of the USEPA action level, 70% of cities that have lead pipes, would suddenly fail to meet the 15 μg/L LCR lead action level [71].

Finally, current sample preservation practices (adding 0.15% v/v HNO₃ for acid digestion) can sometimes underestimate WLLs, because particulate lead settles to the bottom and is not adequately dissolved. Higher acid concentrations (2% v/v HNO₃), adequate mixing and longer holding times have been found to resolve this discrepancy [72].

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<tr>
<th>Factors</th>
<th>Decreases Pb</th>
<th>Possibly increases Pb</th>
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<tr>
<td>Utilities adding less chlorine</td>
<td>X</td>
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<td>Chloramine instead of chlorine</td>
<td>X</td>
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<tr>
<td>Increasing chloride levels in source water and/or use of chloride-based coagulants that raises CSMR above 0.5</td>
<td>X</td>
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<tr>
<td>Decrease phosphate doses to “optimize” CCT and save money</td>
<td>X</td>
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<tr>
<td>Creating millions of disturbed (due to general construction, digging and other projects) and partially replaced LSLs</td>
<td>X</td>
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<td>More exposed iron pipe in mains → More Fe₂⁺ less Cl⁻ → More Pb</td>
<td>X</td>
<td></td>
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<tr>
<td>More accumulated Pb scale, more Pb particulates from corrosion control and older LSLs</td>
<td>X</td>
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<td>Higher water temperatures (summertime)</td>
<td>X</td>
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<td>Aggressive water conservation, low use brass faucets, and/or water age spanning several days (i.e., increased stagnation)</td>
<td>X</td>
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Table 2

Changing water chemistry and other externalities that occasionally increase water lead release in some systems, contrary to conventional wisdom that water lead will decrease with time (modified from Edwards 2014 [60]).

Abbreviations: CCT = Corrosion Control Treatment; CSMR = Chloride to Sulfate Mass Ratio; LSL = Lead Service Line.

References: 57,60–62.
<table>
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<th>Criteria</th>
<th>USEPA Lead and Copper Rule</th>
<th>Michigan Department of Environmental Quality (MDEQ) Lead and Copper Rule</th>
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<tr>
<td>Year promulgated and in effect Applicable to</td>
<td>1991; 1997 68,000 CWS serving 300 million Americans + all NTNCWS</td>
<td>2018; 2020 1390 CWS serving 7.4 million Michiganders + all NTNCWS</td>
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| Schools/day cares coverage | • Only 10% schools/day cares that are also NTNCWS  
• LCR is not binding for ~90% schools/day cares that may rely on the non-enforceable Lead Contamination Control Act of 1988 for guidance on reducing lead exposure | MDEQ does not have rulemaking authority for schools and day cares. |
| Water Quality Parameters (WQP) monitored | pH, alkalinity, calcium, conductivity, temperature, CCT inhibitor/residual | All WQPs under USEPA LCR + CSMR; pH, alkalinity and CCT at taps. Monitored annually without exception. |
| LSL inventory | Complete LSL inventory for sample site selection. No mandate to submit inventory to state agency/USEPA. | Preliminary and verified inventories of LSLs by CWS due Jan 2020 and Jan 2025 respectively. Residents owning an LSL will be notified. |
| Lead Action Level (LAL) | 15 μg/L 1 L cold water sample (“first draw”) after 6 + hours of stagnation at kitchen or bathroom taps | 12 μg/L (starting Jan 1, 2025) First draw and fifth draw (1 L sample). No established “cheats” allowed. |
| Sampling pool | Designed to capture worst lead; Number of homes depends on system size; At least 50% of homes with lead pipe, if lead pipe is present. | Review current list of worst case homes in sampling pool and update by Jan 2020. |
| Exceedance criteria | 90th percentile of WLLs from sampled homes > LAL | |
| Remediation measures: | | |
| a) Optimizing CCT | System serving population: >50,000 = Need OCCT <50,000 = Need OCCT, unless system is meeting lead and copper action levels | All systems require OCCT |
| b) LSL replacements | Only if LAL exceeded post-implementation of OCCT. | • Mandatory statewide. Replacements (of both public and privately owned portions) to begin in Jan 2021 and should be completed within 20 years at 5% or more of total LSLs per year irrespective of LAL exceedance.  
• Full cost to be borne by water utilities.  
• Targets ~450,000 lead and galvanized iron pipes statewide.  
• Banned; unless part of emergency repairs Beyond those under USEPA LCR:  
• Revised language regarding lead release, lead particles, filters in public education materials  
• Formation of Advisory Councils (for Large systems and State-level) for generating lead public awareness campaigns and distribution of materials  
• Put educational materials online if CWS serves > 1000 people |
| Partial LSL replacements | Allowed | |
| c) Public education | • Report lead advisory on water bills, press releases, online and to vulnerable populations (children, pregnant women) through local health agencies within 60 days.  
• Send lead/copper results within 30 days to homeowners who got their water tested. | |
| Annual Consumer Confidence Report (CCR) | LCR monitoring results and educational statements on lead in water in CCR. | All content under USEPA LCR + LSL replacement status for every CWS. |

Abbreviations: CCR = consumer confidence report; CSMR = Chloride to Sulfate Mass Ratio; CWS = Community Water Supplies (Year-round service to 25 + people or 15 + living units); LAL = Lead Action Level; LSL = Lead Service Lime; OCCT = Optimal Corrosion Control Treatment; NTNCWS = Non-Transient Non-community Water Supplies (Serves 25 + of the same people for 6 + months; schools, daycares, workplaces); WLL = Water Lead Level; WQP = Water Quality Parameter, CWS system sizes: Small = < 3, 300 people, Medium = 3, 301–50,000 people, Large = > 50,000 people. References: 43,70.
Federal regulations and enforcement
To combat lead in tap water, the USEPA promulgated the LCR in 1991 (Table 3). It was always known to regulators that simply meeting the LCR does not imply, let alone guarantee, that the water is “safe” in a given home. Frank appraisals of weaknesses in the LCR are available elsewhere [73,74]. To illustrate, Flint was “officially” meeting the LCR at the height of FWC. If Flint MI had followed the LCR, by sampling worst case homes with lead pipe, not used “cheat” instructions that artificially lower water lead, and not dropped results with high lead samples from the sampling pool, the city would have exceeded the USEPA lead action level (LAL) [19]. Flint consumers would have then been informed that their city water was over the action level, educated on health protective measures, and the FWC would have never become infamous. Instead, when the problem was exposed by a collaboration between citizens and outsiders, the magnitude and malevolence of the cover-up created a media and legal firestorm. Nationwide, over 5300 water systems serving 18 million Americans failed to meet the LCR for lead in 2016. In 90% of LCR violations, the USEPA or state agencies took no formal enforcement action [28]. In the aftermath of Flint and impatient with the failure of USEPA to update the LCR on schedule, the State of Michigan has implemented its own stringent water lead regulation that fixes many loopholes (Table 3).

There are no federal regulations for 90% of schools and daycares [75], which often have serious water lead problems as witnessed in Baltimore MD, Detroit MI, Newark NJ, Portland OR and many other cities. Only eight states require testing by schools, and a 2016 national survey found only 43% of school districts had tested their water for lead and over a third of these districts had WLLs above the LAL [76]. Indoor plumbing containing traces of lead is pervasive nationwide, and it is therefore practically impossible to meet the very ambitious American Academy of Pediatrics’ goal of 1 μg/L even in water with new plumbing systems without use of lead filters [11]. Finally, there are also no regulations covering private well-water systems serving 15% of Americans, where sampling has revealed elevated WLLs that are virtually indistinguishable from that present during the height of the FWC [38].

Institutional scientific misconduct, oversight and whistleblowing
The lead industry and water utilities have unfortunately engaged in widespread deceit and denial regarding dangers of lead in water [1,2]. In recent years, civil servants at

Table 4

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<th>No.</th>
<th>Lead avoidance strategy</th>
<th>Rationale and additional details</th>
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| 1   | Lead pipe replacements (long term) | * Applies to pre-1986 homes.  
* These can be prohibitively expensive ($1000–15,000). LSL replacements do not guarantee lead-free water because indoor plumbing can still contribute lead to water.  
* Partial LSL replacements occasionally increase WLLs and should be avoided. |
| 2   | Bottled water | Expensive and environmental concerns with packaging, distribution and recycling |
| 3   | Lead filters (faucet or pitcher style) | * Relatively inexpensive (starting at $30 for filters; ~$10 per replacement cartridge; ~100 gallons or 379 L filtration capacity per cartridge)  
* These are National Sanitation Foundation (NSF) certified to remove ~99.9% lead and reduce WLLs below FDA’s bottled water standard of 5 μg/L, even with high influent WLLs as was proven in Flint MI.  
* Cities including Washington DC, Flint MI, Pittsburgh PA, and St. Joseph’s LA, are distributing (or, have distributed) free lead filters and cartridges in response to elevated water lead. |
| 4   | Water testing | Homeowners can get their water tested through their water utility, a certified water laboratory or non-profits like Healthy Babies Bright Futures (www.hbbf.org)*  
* Analyzed at Virginia Tech. |
| 5   | Remedial flushing guidelines (typically, 30 s to 2 min before using water for drinking and cooking) | Flushing has been found to be somewhat effective, but does “not consistently reduce WLLs” and in some cases, even increases WLLs as seen in Cicero, IL and New Orleans, LA. |
| 6   | Avoiding consumption of hot water from tap | * Heating water might concentrate lead through evaporation.  
* Water from hot tap should never be used for drinking, cooking meals, making infant formula and other consumption practices. |

Abbreviations: LSL = Lead Service Line; WLL = Water Lead Level.  
* Analyzed at Virginia Tech.  
Select references: 68–69, 85–86.
government agencies causing the DC&FWC (Table 1) committed institutional scientific misconduct [8,77], were promoted and awarded in one case (Washington DC), and faced criminal indictments in another (Flint MI). In the aftermath of USEPA’s embarrassing role in the Flint fiasco, former USEPA Administrator Gina McCarthy promulgated new whistleblowing directives: asserting that employees should not be satisfied with “simple technical compliance, when a broader perspective would suggest that a larger public health or environmental issue is at stake” or if “there appears to be a substantial threat to public health” [78]. Yet McCarthy repeatedly refused to accept any blame for USEPA’s negligence and failure to act in congressional testimony—an assertion vigorously disputed by one of the authors [8]. Following a two year probe, the USEPA Office of Inspector General admitted that USEPA Region V failed to exercise its oversight authority under federal law to intervene to protect the public and “completely abdicated its responsibility to warn” Flint residents [26,79]. Unprecedented accountability of civil servants in the form of criminal indictments, resignations and class actions lawsuits in Flint may have sent a message nationally to water utilities and government agencies to actively reduce WLLs at tap and vigorously enforce (and update) water lead regulations.

**Public education, lead avoidance and protection measures**

Property owners who fail to disclose lead-based paint hazards to tenants face hefty penalties and even incarceration per federal law Title X [80], but similar legal protections do not exist for lead exposure from water even in light of LCR exceedances. For example, Pittsburgh PA currently insists its water “meets or exceeds all” requirements even though it exceeds the LAL, as is allowed under the LCR [81]. Similarly, WLLs are routinely encountered in U.S. households and schools that would trigger fines and recalls if found in children’s toys [75,82]. Homeowners are also usually not aware of their “shared responsibility” for controlling dangers of lead pipes with their water utility. The inadequate annual consumer confidence reports [83,84] with lead warnings and generic flushing advice continue to provide mixed messages: the water meets all standards but, if there is lead, you, the consumer, are responsible for managing your WLLs. And meeting the LCR does not guarantee safe water in the first place. Public education efforts should emphasize these facts to allow residents to protect themselves and their families (Table 4).

**Conclusions**

The 2018 USEPA declaration of a “war on lead” with plans to “eradicate” lead from drinking water has increased interest in water lead issues [87]. Although this goal is admirable, it is practically impossible to achieve, given the definition that there is “no safe level of lead exposure” and the ubiquity of trace lead even in modern plumbing. In the aftermath of Flint, the State of Michigan has created a more stringent Lead and Copper Rule that includes a commitment to replace most LSLs in the next 20–30 years.

Safeguarding public health by minimizing lead exposure at the tap and preventing future water lead disasters like the DC&FWC requires every public water system to, first and foremost, honestly acknowledge the scale, complexity and health impacts of this issue. Utilities should take moral responsibility for the lead pipe problem, including proactive replacement of plumbing infrastructure, adherence to the letter and spirit of the Lead and Copper Rule, worst-case sampling procedures, and candid public education efforts. Adherence to the law and upholding the public trust will prevent another Flint or Washington DC lead in water disaster.

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**Conflict of interest statement**

Aside from our work exposing the water crisis in the first place, our data and testimony have been subpoenaed in several Flint water-related lawsuits. We are not party to any of the lawsuits. Dr. Edwards has been subpoenaed as a fact witness in many of the lawsuits, but he has refused all financial compensation for time spent on those activities. Previously, Dr. Edwards served as a fact witness in lawsuits pertaining to Washington DC lead-in-drinking water crisis, but these lawsuits have ended.

**References**

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest


Drinking water contaminants and health effects Beyond Buy and Dry: the Aftermath of Cowley County, Colorado


Summary of government misconduct and unethical practices that led to Washington DC and Flint Water Crises.


First paper to definitely link high water lead levels during the Washington DC lead in water crisis to elevated blood lead in DC young children. Won the ES&T Best Paper award.


First paper to definitely link high water lead levels during the Flint water crisis to elevated blood lead in Flint children.


In-depth analysis of water lead levels during and after the Flint Water Crisis, specifically the effects of enhanced corrosion inhibitor doses and citywide flushing programs.


Review of the effects of elevated blood lead in young children and recommended target water lead levels in schools from the American Academy of Pediatrics.


Comprehensive review on lead in drinking water and corresponding health effects due to elevated blood lead.


59. Bradley TN: Evaluation of zinc orthophosphate to control lead solder corrosion in waters with high chloride to sulfate mass ratio.


