Committee on Transportation and the Environment
Chairperson Mary Cheh
Agency Performance Oversight Hearing (Fiscal Year 2020-2021)
DC Water and Washington Aqueduct

March 15, 2021

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Campaign for Lead Free Water

We appreciate the opportunity to share with the DC City Council the following information, concerns, and recommendations:

1. Background

Like many buildings in major cities across the US, thousands of District homes and commercial properties get their drinking water through lead service lines (LSLs)—pipes that bring water to each individual building from the water mains that run underneath the streets. **LSLs are typically one hundred percent lead** and are usually so durable that they have never required replacement since their installation many decades ago. The lead from these lines (like the lead from other plumbing materials in the building) can leach into the water, **potentially exposing consumers to anything from chronic low amounts to sporadic very high concentrations of lead**.

Lead is a neurotoxin so potent that scientists cannot identify any concentration at which it is safe for human consumption. It has been linked to miscarriage, stillbirth, decreased IQ, ADHD, delinquent behavior, and increased rates of arrests for violent offenses. In addition, it is associated with hematological, cardiovascular, immunological, and endocrine system harm (Hanna-Attisha 2016, Feigenbaum and Muller 2016). Since 1991, the federal Environmental Protection Agency (EPA) has had a regulation in place – the Lead and Copper Rule (LCR) – requiring water utilities to add corrosion control treatment (CCT) to their water to reduce the risk of lead leaching. CCT, however, is more of an imperfect art than a precise science. Although it can help reduce lead-in-water levels across a water distribution system, **it can never completely eliminate lead's release from plumbing**. Ultimately, as long as lead is in contact with water it will pose a significant health risk, especially to fetuses, infants, and young children.

Washington, DC has been grappling with lead-in-water contamination and documented health harm since at least the 1980s (e.g., Engel 1986, attached). **In 2001-2004, the District experienced the nation's most severe lead-in-water crisis to date**, which involved a two-and-a-half year cover up by our water utility (then named DC WASA), the DC Department of Health (DOH), and our water utility's oversight agency (EPA Region 3). The unprecedented severity and extent of the contamination was made public to all DC residents on January 31, 2004 through a historic front-page article in the *Washington Post* (Nakamura 2004, attached). Since then, peer-reviewed scientific research has shown that **DC's lead crisis resulted in over 800—and possibly up to 42,000—cases of elevated blood lead levels in young children, and that the city's fetal death rate rose by 37 percent** (Edwards, Triantafyllidou, and Best 2009, attached; Edwards 2014, attached).

In contrast to the Flint, Michigan water crisis, which:

1. **Was measurably less severe than the District's** in terms of the duration of residents' exposure, the levels of lead dispensed at city taps, and the resulting health harm, and
2. **Prompted the development of the nation's most health-protective, state-specific LCR that requires all Michigan water utilities to conduct publicly funded, proactive, and systematic full LSL replacement** (in the words of the state of Michigan, "Water supplies are required to replace an average of 5 percent of their lead service lines every year for the next 20 years unless an alternate schedule is approved…"),

Washington DC has, to date, failed to a) acknowledge the harm done, b) provide assistance to affected families, and c) implement a proactive and systematic program to fully replace all LSLs in the District with the use of public funds.

Additionally, in 2004-2008, Washington, **DC conducted the nation's most extensive to date partial LSL replacement program: at the cost of over $100 million in ratepayer money, the city partially replaced over 14,000 LSLs**. There was never any evidence, however, to suggest that this practice provides increased health protection over leaving LSLs intact**. In fact, we now know that the physical disturbance of the portion of the LSL that is left in place can actually cause significant lead release in the short- and long-term**, and that the point of contact between the old LSL and the new (usually) copper line can create a "battery effect" that under certain circumstances can accelerate lead corrosion and can cause significant lead-in-water contamination (Leonnig 2008, attached; Del Toral, Porter, and Schock 2013, attached; Triantafyllidou and Edwards 2011, attached).

Indeed, in 2011, the Centers for Disease Control and Prevention **(CDC) published a study showing that District children in homes with a partially replaced LSL were over three times as likely to have levels of lead above 10 mcg/dL (the blood lead level that was considered "elevated" at the time) as children who never had a LSL** (Brown et al. 2011, attached). Based on this finding, the *American Academy of Pediatrics* issued a call for an immediate moratorium on partial LSL replacement in a policy recommendation to EPA.

In summary, since 2001, the District's water utility has subjected DC residents to two waves of large-scale health harm: the first, during the cover-up of 2001-2004 and the second, during the city's 2004-2008 accelerated LSL replacement program that was presented to residents as a health protective gift that went above and beyond federal requirements.

2. Current state of LSL replacement in the District

In March 2020, DC Water confirmed in an email exchange with Yanna Lambrinidou that, as of December 2019 (almost 20 years following the District's historic lead-in-water crisis of 2001-2004), **the number of LSLs still in the ground was the following:**

- **In public space**

  a. 10,770 *known* LSLs,
  b. 15,886 service lines of *unknown* material.

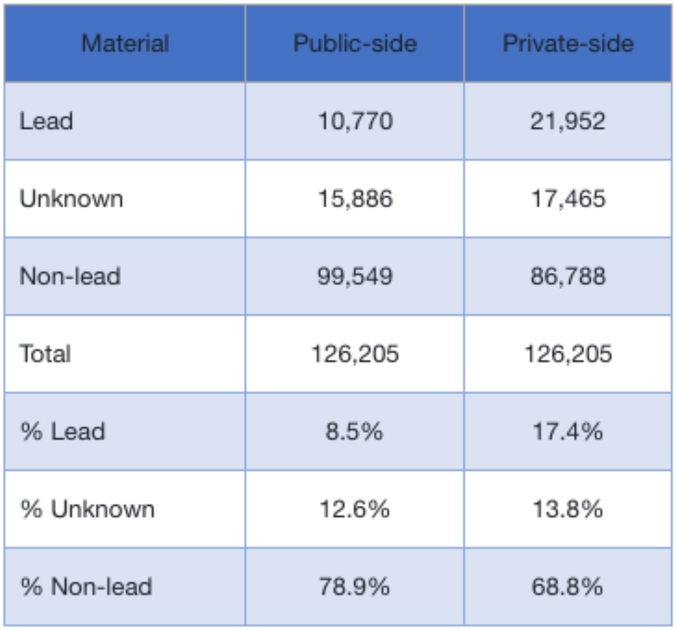
  This means that in a worst-case scenario wherein all unknown service lines in public space turned out to be lead, the District would have a maximum of 26,656 LSLs in public space.

- **In private space**

  a. 21,952 *known* LSLs (of these, 11,182 are *known* partially replaced LSLs)
  b. 17,465 service lines of *unknown* material.

  This means that in a worst-case scenario wherein all unknown service lines in private space turned out to be lead, the District would have a maximum of 39,417 LSLs in private space.

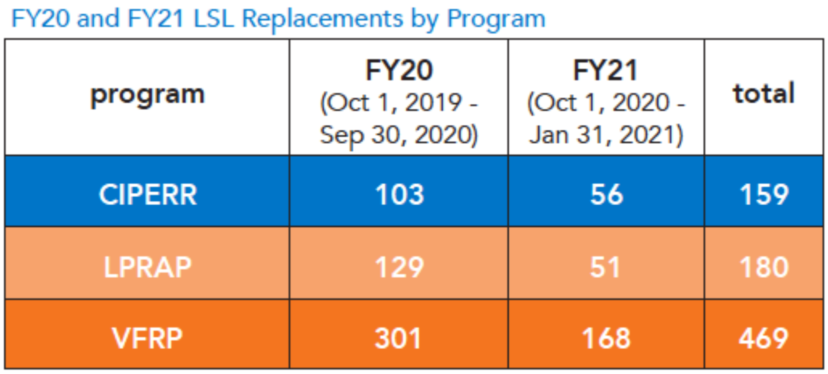
DC Water's Table



Material	Public-side	Private-side
Lead	10,770	21,952
Unknown	15,886	17,465
Non-lead	99,549	86,788
Total	126,205	126,205
% Lead	8.5%	17.4%
% Unknown	12.6%	13.8%
% Non-lead	78.9%	68.8%

While cities like Flint, Michigan; Pittsburgh, Pennsylvania; and Newark, New Jersey are implementing proactive, aggressive, and systematic programs to remove all LSLs with public funds, Washington, DC is approaching LSL replacement through a program that, although a step in the right direction, is anemic, piecemeal, confusing, user-unfriendly, cumbersome, sub-optimally effective, financially precarious, and highly unlikely to lead the District to the successful removal of all LSLs by 2030.

DC Water's own numbers (*Lead Free DC* factsheet, attached) reveal that the largest number of full LSL replacements in the last 16 months (Oct 1, 2019-Jan 31, 2021) has taken place under the Voluntary Full Replacement program (VFRP) – which requires homeowners to pay 100% of the private-side replacement costs, rather than the Capital Improvement Project and Emergency Repair Replacement (CIPERR) or the Lead Pipe Replacement Assistance Program (LPRAP) – which utilize funds from DC Water and/or the City to carry out some portion or the entire private-side LSL replacement.



FY20 and FY21 LSL Replacements by Program

program	FY20 (Oct 1, 2019 - Sep 30, 2020)	FY21 (Oct 1, 2020 - Jan 31, 2021)	total
CIPERR	103	56	159
LPRAP	129	51	180
VFRP	301	168	469

This suggests that **the District's approach to full LSL replacement relies for its success primarily on residents who have time, information, and resources to initiate and pay for private-side LSL replacement**. We are concerned that the program's multiple and, arguably, inequitable and unreasonable expectations on DC residents **set us up for failure – a problem that disadvantages us all, but even more so those among us with the least access to time, information, and resources. By extension, it also sets us up for getting blamed for the program's sub-optimal performance. This has been a longstanding and unfortunate dynamic between the District's water utility and water users, and it is visible once again in DC Water's 10.7.20 "Lead Free DC Execution Plan."**

Finally, **given the District's history of harm, DC Water's program also raises serious environmental justice concerns**. One of several examples is the following: DC Water's Lead Free DC brochure states that 314 "free" and "discounted" full LSL replacements have saved DC residents "nearly $1 million in combined costs." First, it is unclear where the 314 (in the text of the brochure) or the 307 (in Figure 1, when one adds 207 and 100) come from – what types of LSL replacements does this number represent? Table "FY20 and FY21 Replacements by Program" indicates that the total number of "free" and "discounted" full LSL replacements since October 2019 is 339 (when one adds 159 and 180). More importantly, the notion that DC residents are "saving" money by having their private-side LSL removed at no direct cost to them or at partial direct cost presumes that DC residents are the proper bearers of the financially responsibility of private-side LSLs. This presumption is based on an artificial distinction between LSLs in public versus private space, which according to a 2014 analysis by Earthjustice is legally questionable (Chavez 2014):

> **"The good news is that the popular preoccupation with private property rights is neither justified nor compelled by the prevailing legal principles. The claim that homeowners own lead service lines is highly questionable. Because those lines are integral to the water distribution system and serve no other purpose than the delivery of**

> **drinking water, service lines are legally defined as part of the public water system regulated under the LCR.**
>
> **Even assuming that lead service lines are privately owned, the hyper-focus on property lines is unjustified. It appears to grow out of a mistaken belief that the overriding purpose of private property is to enforce the owner's right to exclude non-owners from the property. To be sure, many elected officials and a few legal scholars embrace this belief. But even the most conservative scholars acknowledge – and courts agree – that government entities, and the public water utilities they own or regulate, enjoy broad authority to enter onto private property in order to protect public health" (Lambrinidou, Chavez, Schwartz 2017).**

Adding insult to injury, DC Water's latest proposal for addressing LSLs in the District involves legislative policy recommendations aiming to convince DC homeowners to take the initiative to replace the private-side of their LSL (10.7.20 "Lead Free DC Execution Plan"). Such a suggestion flies in the face of what we – and a growing number of cities across the country – know is the most efficient (in terms of time and money), effective, morally sound, and justice-centered approach to the problem of LSLs: legally mandated, publicly funded, proactive, and systematic full LSL replacement conducted by water utilities themselves.

3. Recommendation

We certainly appreciate DC Water's plan to "remove all lead service lines in the District of Columbia by 2030" (*Lead Free DC* factsheet, attached). In light of the fact, however, that currently there is neither a law requiring DC Water to execute this plan nor a commitment from DC Water to fund it, **DC Water's plan is tantamount to a hope or a dream that relies on a) non-secure and unidentified sources of funding, and b) the shouldering by DC residents of financial and bureaucratic responsibilities that stand, and will continue to stand, in the way of the program's success.**

It is worth noting that Table "FY20 and FY21 Replacements by Program" in DC Water's *Lead Free DC* factsheet (attached) indicates that in the last 16 months (Oct 1, 2019-Jan 31, 2021), DC Water – with the help of proactive DC residents who had time, information, and means – was able to complete a total of 808 full LSL replacements. Even if DC Water (with assistance from well-resourced water users) improves this rate of replacement to approximately 1,000 per year, by 2030 it will have achieved an additional 10,000 full LSL replacements. **This means that, unless there is a drastic change in how DC Water goes about LSL replacement, in ten years from now we are likely to face a yawning chasm between DC Water's current plan to remove all LSLs by 2030 and the number of LSLs that will still be in the ground (counting all intact and partially replaced LSLs as well as service lines of unknown material in public and private space).** What explanation is the District going to offer to those residents who will continue to face the risk of lead in their water or who will discover that their child was poisoned from the water three decades after their city's worst lead-in-water crisis in modern US history?

We exhort DC City Council to form a community-centered committee that will put the necessary effort into reviewing how the three LSL replacement programs currently in place (CIPERR, LPRAP, VFRP) are implemented in practice and what improvements they necessitate in order to maximize public health protection and minimize prolongation of a decades-old environmental injustice in our city. For example, we believe that a close look at DC Water's public outreach materials and programs is necessary. Equally important is an examination of environmental justice and health equity questions raised by the LPRAP and VFRP programs. Similarly, we ought to assess the protocol (if any) that DC Water uses after conducting emergency partial LSL replacements. Does the Authority go back to homeowners to inform them about the health risk of the replacement and encourage them to have the private side promptly removed? If so, what outreach process and materials does it use? We must also explore ways to improve transparency (we, ourselves, lack access to any mechanism that would keep us abreast of DC Water's latest developments vis-à-vis LSL replacements and often receive "updates" coincidentally and through hearsay). And we must figure out best ways to secure public funding. As DC Water's program stands today, 56% of the estimated cost for the full replacement of all LSLs in the District is unfunded. On the basis of historical, moral, legal, and public health reasons, we are troubled by DC Water's refusal to budget all public and private side LSL replacement costs within the CIP. DC Water must drive a systematic, fully funded, and scientifically sound approach to LSL replacement that, like the best practices in other cities, meets a proscribed timeline and is geared toward justice-oriented results and equitable outcomes. We can and must do better.

Finally, we recommend that a community-centered LSL replacement committee work on steering the District toward a legally mandated, publicly funded, proactive, and systematic full LSL replacement program. We believe that this is the only viable path forward.

Thank you.

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The Washington Post

METRO

Fear of Lead in D.C. Water Spurs Requests for Tests

Margaret Engel
Washington Post Staff Writer
657 words
6 December 1986
The Washington Post
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English

District officials have been flooded with requests by 883 households, schools and businesses to sample their water for lead after newspaper reports were published about lead problems in the drinking water of the Palisades area of Northwest Washington.

Officials of the D.C. Department of Consumer and Regulatory Affairs said yesterday that the problem could extend to thousands of houses and other structures built between 1890 and 1930 with lead water pipes. A meeting of city officials is planned this month to determine the magnitude of the problem.

Department officials said they plan to tell hundreds of families in the next few weeks whether their tap water is contaminated by dangerous amounts of lead.

According to Jacqueline Davison, administrator for the department's Housing and Environmental Regulation Administration, the mayor must decide ultimately whether the city bears responsibility for the health problem and whether the District can afford to replace the pipes or correct the problem by softening the water.

In the meantime, hundreds of District families are forgoing city tap water and paying up to $20 a week for bottled water until the results of city tests are known.

"Just about everyone we know is drinking bottled water at considerable expense," said Kate Shafer, who lives in the Palisades area. A private lab found her tap water slightly exceeds the proposed federal limit of 20 parts per billion of lead.

Lead is a potentially lethal toxin that accumulates in the body, particularly in the bones and kidneys. Large or accumulated doses can cause stunted growth and kidney problems.

A recent Environmental Protection Agency study in support of changing the federal lead standard from 50 parts per billion to 20 parts per billion found that excessive lead in public water supplies is a health hazard throughout the nation, particularly in older cities with lead water pipes and newer plumbing soldered with lead.

District water officials say that the city's water mains are constructed of concrete, but that builders of older homes used lead pipe to connect to the mains.

In the past, the city budgeted less than $2,000 a year for water testing because it received only 10 to 30 requests annually for the free service.

Last month, however, parents of 22-month-old twins publicly discussed the excessive lead in their daughters' blood that stunted their growth and described the family's yearlong effort to get city agencies to diagnose the problem. After a private lab found the water in the family's house contained nine times the proposed federal lead standard, city officials declared the problem "urgent" and deposited sample bottles on the doorsteps of 83 houses in the Palisades neighborhood.

The response of anxious residents throughout the city is causing the city to boost its water testing budget to at least $50,000, Davison said. A private lab in Rockville has been hired to test the 1,219 samples from the 883 homes and establishments.

Results from about half of the houses are complete, said James Collier, chief of the agency's water hygiene branch. Of the 83 homes tested on Sherier Place NW, the street where the twins live, lead levels in 15 percent exceed the proposed federal limit.

Collier said, however, that it may never be possible to determine what caused the twins' lead problems. "We can't determine what there was a year ago, two years ago," he said.

The twins' father, Maurice Sanders, said the city is "attempting to deny responsibility for anything." His wife, Judy Southerland, added, "The city persists in talking about lead paint as a problem. We don't believe they could breathe enough {lead paint} dust. We know they imbibed the water." CAPTION:Judy Southerland and twins Abigail and Olivia, right, drink bottled water now.

PHOTO, Judy Sutherland And Twin Daughters Abigail And olivia, Harry Naltchayan

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Search Summary

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Timestamp	14 March 2021 8:40

The Washington Post

A Section

Water in D.C. Exceeds EPA Lead Limit; Random Tests Last Summer Found High Levels in 4,000 Homes Throughout City

David Nakamura
Washington Post Staff Writer

1,605 words
31 January 2004
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Tap water in thousands of District houses has recently tested above the federal limit for lead contamination, a new phenomenon that has baffled the D.C. Water and Sewer Authority and forced the agency to begin replacing service pipes.

Two-thirds of the 6,118 residences that WASA tested last summer, or 4,075 homes, had water that exceeded the lead limit of 15 parts per billion set by the Environmental Protection Agency in 1991. This is the first time the city's water has shown significant lead contamination since the late 1980s, officials said.

WASA officials said they are not sure what has caused the spike in lead levels. They are investigating whether changes in the way water is treated at the Washington Aqueduct could have a corrosive effect on lead pipes.

Lead, which can be ingested by drinking contaminated water or inhaling lead paint fumes, can cause serious damage to the brain, nervous system, kidneys and red blood cells, particularly in children, babies and fetuses. Health officials said it is difficult to quantify how much danger lead contamination in water poses. A person whose blood has more than 10 micrograms of lead per tenth of a liter should be concerned, but how much contaminated water a person must drink to reach that level varies.

Although the extent of the water problem and its public health implications are just coming to light, WASA officials have been aware of the contamination since random tests on a small number of houses revealed a problem in 2002. Although agency officials discovered a more extensive problem last summer, they did not begin to notify homeowners about the results until November. WASA held a public meeting about the issue in December, but its advertisements did not reveal the lead problem. Instead, they simply stated that the purpose of the meeting was "to discuss and solicit public comments on WASA's Safe Drinking Water Act projects."

Tony Bullock, spokesman for Mayor Anthony A. Williams (D), said he was unaware of the lead problem and believed that the mayor had not been informed. Several D.C. Council members said they, too, were unaware.

D.C. Council member Adrian M. Fenty (D-Ward 4) said he first heard about the situation yesterday when two constituents sent his office e-mails about the lead contamination.

It is not just the number of houses that registered above the EPA limit that has alarmed experts, but also the amount of lead found in the water. Although the federal government requires that cities begin a pipe replacement program when lead levels exceed 15 parts per billion, 2,287 D.C. houses had lead levels exceeding 50 parts per billion, including 157 residences with more than 300 parts per billion.

Erik Olson, an analyst for the Natural Resources Defense Council, an environmental group that monitors public health issues, said he was shocked.

"I've never heard of anything like that. This is a really big deal," said Olson, who has surveyed the drinking water in more than 100 cities. "If schools go over 20 parts per billion, they immediately take the water out of production."

Federal authorities said it is unusual for a city that did not have lead contamination problems to suddenly exceed the level above which the EPA requires corrective action.

"The District is the only one in our region -- this is pretty rare," said George Rizzo, an environmental scientist for the EPA's mid-Atlantic office, which oversees five states and the District.

Cynthia Dougherty, head of the EPA's drinking water office, said some cities have exceeded the action level. Most of those, however, were above the limit in 1991 and are still trying to get below it, she said.

"It's shocking," said Charles Eason, whose home in Georgetown had water that registered 36 times the EPA's lead limit. "It's a particular risk for young people, and I have a 4-year-old grandson in my house regularly."

There are 130,000 water service lines for residential customers in the District. About 23,000 of those are made of lead, while the rest are made of copper, officials said. The lead pipes are spread throughout the city, mostly servicing older single-family homes.

Now that WASA has discovered widespread lead contamination, EPA guidelines require the agency to replace 7 percent of its lead pipes annually, which is estimated to cost $10 million to $20 million a year. The agency will focus on neighborhoods where lead contamination is the highest, said Michael Marcotte, WASA's chief engineer.

"Where we are aware of a situation where someone has a particular health concern and young children, we'll work with them as quickly as we can in the process," Marcotte said.

WASA is responsible only for pipes in public space. The portion of pipe that runs through private property and into a house is the responsibility of the homeowner. Thus, owners must decide whether to replace those pipes, a proposition that could cost as much as several thousand dollars, WASA officials said.

WASA recommends that residents whose water is contaminated flush their taps by allowing the water to run for 30 seconds to one minute before drinking it or using it for cooking, although that process is not always successful in clearing the lead. Residents also can purchase a home treatment device or use bottled water. Boiling the water or using a standard pitcher with a filter will not help protect against lead, officials said.

Lynette Stokes, a physician who oversees the D.C. Department of Health's lead testing program for children, said that in general, dust or lead paint poses a far greater risk than contaminated water. Parents of children younger than 6 can bring them in to have their blood tested for free, Stokes said.

"That will help us identify whether or not any of that lead in the water has dosed that child to a degree where we need to be concerned," she said. The District does not offer a screening program for adults or for children 6 and older.

WASA gets its water from the Washington Aqueduct, which also services Arlington and Falls Church. The water at the aqueduct has long been treated with chlorine to kill bacteria. But the chlorine was combining with organic materials in the pipes and creating new, harmful chemicals, officials said. Four years ago, scientists added ammonia to balance the chlorine, creating a compound known as chloramine.

It's possible, officials said, that the chloramine is more corrosive to lead pipes. Falls Church has no lead pipes; Arlington has a few but has discovered no lead contamination problems, officials said.

"It's definitely in the 'not sure' category," said Lloyd Stowe, chief of operations at the Washington Aqueduct. "The whole idea of corrosion control is more of an art than a science."

In the late 1980s, lead was found in tap water in thousands of D.C. homes, particularly in the Palisades area. The city replaced some lines, and the problem diminished in subsequent years. WASA has been conducting random sampling of water since the EPA began requiring it in 1991.

WASA first noticed problems with lead contamination during routine testing of about 50 houses from July 2001 to June 2002, Marcotte said. The agency noted the problem in its August 2002 report to the EPA and began to comply with the EPA's guidelines, which required WASA to replace lead pipes and to inform the homeowners of the dangers of lead.

Marcotte said WASA replaced 400 pipes at a cost of $3 million last year. But last summer, the agency also began conducting more widespread tests. If the sample size increased but the number of homes with lead contamination remained small, WASA would have met the EPA standard without having to replace many service lines.

Instead, the results from more than 6,000 homes last summer revealed widespread problems. WASA then began mailing results to homeowners who participated in the sampling program, Marcotte said.

"We fully disclosed, in our view, what the situation was," Marcotte said. "We let people know there was an issue."

As an independent agency, WASA is autonomous in its budgeting. But its performance is overseen by the D.C. Council's Committee on Public Works and the Environment, headed by Carol Schwartz (R-At Large). Her office knew little about the situation when contacted this week.

"Of course, I'm concerned," Schwartz said in a statement released by her office. "I hope WASA will continue the studies and rectify the problems found."

Georgetown resident Janet Stone heard about the lead contamination from her neighbor. Stone, who has two infant daughters and is pregnant, decided to spend more than $100 to have her water tested by an independent company. She also had her two daughters' blood tested for lead poisoning, even though she thinks her house has copper pipes.

"I'm concerned," said Stone, who is waiting for the results. "I'm trying not to panic."

Marilyn Lashley, whose home in Bloomingdale had water that registered 12 times the EPA's limit, put a notice about the problem on a neighborhood Internet mailing list. Cleopatra Jones, a neighborhood advisory commissioner in Bloomingdale, east of Howard University, said some neighbors played down the risks because they buy bottled water.

"I said, 'Don't you brush teeth, shower and cook?' " Jones recalled. "It's got to be alarming."

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Search Summary

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Elevated Blood Lead in Young Children Due to Lead-Contaminated Drinking Water: Washington, DC, 2001−2004

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Incidence of EBL (blood lead ≥10 μg/dL) for children aged ≤1.3 years in Washington, DC increased more than 4 times comparing 2001−2003 when lead in water was high versus 2000 when lead in water was low. The incidence of EBL was highly correlated ($R^2 = 0.81$) to 90th percentile lead in water lead levels (WLLs) from 2000 to 2007 for children aged ≤1.3 years. The risk of exposure to high water lead levels varied markedly in different neighborhoods of the city. For children aged ≤30 months there were not strong correlations between WLLs and EBL, when analyzed for the city as a whole. However, the incidence of EBL increased 2.4 times in high-risk neighborhoods, increased 1.12 times in moderate-risk neighborhoods, and decreased in low-risk neighborhoods comparing 2003 to 2000. The incidence of EBL for children aged ≤30 months also deviated from national trends in a manner that was highly correlated with 90th percentile lead in water levels from 2000 to 2007 ($R^2 = 0.83$) in the high-risk neighborhoods. These effects are consistent with predictions based on biokinetic models and prior research.

Introduction

The Washington, DC "lead in drinking water crisis" was triggered by a change in disinfectant from free chlorine to chloramine in November 2000 (*1*). The switch in disinfectant reduced the concentration of potential carcinogens (a byproduct of chlorine disinfection) to levels below those specified by the U.S. Environmental Protection Agency (EPA). However, the chloramine also altered the water chemistry and unexpectedly caused lead to leach from lead service line pipes (*1, 2*) and other plumbing materials such as leaded brass and solder (*1*). The resulting contamination affected water lead levels (WLLs) in homes throughout the city.

Two previous studies of blood lead levels (BLLs) relative to the high WLLs in Washington, DC have been published (*3, 4*). While the high WLLs appeared to have some impact on the incidence of BLLs ≥ 5 μg/dL (*3*), no evidence was found of increased incidence over the 10 μg/dL level of concern set by the Centers for Disease Control and Prevention (CDC) for children aged <6 years. Blood lead levels exceeding the CDC level of concern are termed "elevated blood lead" (EBL) in this work.

A close examination of the two prior studies reveals noteworthy limitations. Neither study focused on infants, who are most vulnerable to harm from lead in water (*5*−*7*) due to their small body weight and heavy reliance on water as a major component of their diet in the case of infants using reconstituted formula. Moreover, both studies lumped all the blood lead data for Washington, DC together, an approach that can "mask disparities among communities and camouflage pockets of high risk" relative to smaller area analysis at the neighborhood or zip code level (*8*). This research addressed these limitations.

Methodology and Data

Environmental Data. *Water Lead Data.* Measurements of "total lead (*9*)" in potable water were collected by the local water utility using EPA-approved methodology. A "first draw" sample refers to a 1 L sample collected from a tap after greater than 6 h holding time in the household plumbing. After first draw samples are collected, water is flushed for a short time period (typically 30 s to 5 min) and a 1 L "second draw" sample is collected.

Two data sets of potable water lead concentrations were used throughout this research. Data on WLLs in homes with lead pipe during 2003 were collected by the local water utility from over 6000 Washington, DC homes with lead service line pipe. The WLL EPA Monitoring Data (2000−2007) were collected by the water utility specifically for compliance with EPA regulations. Compliance is determined by using the "90th percentile lead," which is the 90th percentile of the cumulative distribution of first draw lead samples collected within a given time period. The monitoring data were reorganized into calendar year time periods for which corresponding blood lead measurements were compiled. For example, the official 2002 EPA monitoring round at the utility included water samples collected between July 1, 2001 and June 30, 2002. The samples collected between July 1, 2001 and December 31, 2001 from that round were used in calculations of the 90th percentile WLLs for the second half of 2001. The remaining water samples from that round were included in calculations of 90th percentile WLLs for calendar year 2002. Several audits have been conducted on the utility's EPA monitoring data (*10*), and trends in 90th percentile lead used in this study are not strongly impacted by remaining unresolved errors in the data.

Lead Pipes by Zip Code and other Demographic Data. The number of lead pipes in each zip code was determined using a database provided by the CDC (*3*). Demographic data within each zip code were obtained from the U.S. Census.

Identification of Sensitive Population. *Predicted Impact of WLLs on BLLs.* In April 2004 the US EPA National Center for Environmental Assessment (NCEA) modeled the impact of high WLLs on the BLLs of children in the city (See Supporting Information Reports 1−3). The NCEA results and additional assumptions were used to make predictions of EBL incidence for children who had consumed formula reconstituted with tap water during their first year of life, and children aged 1−6 years who did not consume formula but drank tap water (see Supporting Information 1). A one-year-old infant living in a Washington, DC home with lead service line pipe and consuming formula made from tap water was predicted to have a 21% likelihood of EBL in 2003. The overall prediction was that there would be 600−700 cases of EBL for children under 6 years of age in 2003 due to the high WLLs. This estimate of 600−700 cases represents only

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0.1% of the total city population and only 1.5% of the population under age 6 years.

Any attempt to correlate WLLs with incidence of EBL is also confounded by the fact that incidence of EBL in the US for children aged <6 years declined from 3.96% in 2000 to 2.0% in 2003 (*11*). This 1.96% decline is of the same order, or even higher, than the predicted 1.5% increase in Washington, DC due to the high WLLs. If the impacts of the high WLLs are to be quantified, methods that can account for the reduction in the national incidence of EBL must be considered.

For this work, additional modeling was conducted using the International Commission for Radiation Protection (ICRP) biokinetic model, to more precisely identify the population(s) most sensitive to lead in water. The ICRP biokinetic model has been successfully used to predict seasonal or weekly trends in BLLs (*12, 13*). We confirmed that the population most sensitive to EBL from high WLL is children aged ≤1 year consuming reconstituted infant formula. Moreover, the modeling indicates that some evidence of EBL due to consumption of formula in the first year of life should persist until age ≤30 months (Supporting Information 1). This result is consistent with expectations based on other research (*5*–*7*). Thus, children aged ≤1 year and children aged ≤30 months were selected as target populations for this research.

Blood Lead Data. *CDC Database.* A blood lead database from the 2004 CDC study (*3*) was obtained through the Freedom of Information Act.

Children's National Medical Center (CNMC) Blood Lead Database. A study of blood lead was reviewed and approved by the Institutional Review Board at Children's National Medical Center. The CNMC data containing >28,000 records from 1999–2007 were sorted and data for children aged ≤30 months were extracted. If there were multiple measurements of BLL for the same individual, a convention was followed in which the highest recorded blood lead for each child was retained and all other measurements were deleted (*14, 15*). This approach ensures that calculations of EBL incidence in the population are not skewed by multiple measurements from the same individual.

The 1999 CNMC data are treated differently in this work because no 1998 data are available. The convention of removing multiple blood lead measurements per child makes the 1998 data influential on the 1999 data set (children often have blood lead measurements at 1 and 2 years). Thus, with one exception, only CNMC data from 2000–2007 are used in this work.

Results

After discussing temporal trends in WLLs throughout the city from 2000 to 2007, the effects of WLLs on EBL for children aged ≤1.3 years are examined. Thereafter, a neighborhood analysis is presented for children aged ≤30 months.

Temporal Trends in WLLs in Washington, DC. The 90th percentile WLLs (Figure 1) increased after the switch to chloramine disinfectant in November 2000 (*1*). The exact point at which the WLLs began to rise after the switch in disinfectant cannot be precisely determined. Therefore, 2001 is considered a transition year and data are divided into halves (data from January to June 2001 are termed 2001a and data from July to December are termed 2001b). Other support for dividing 2001 in half is presented in Supporting Information 2. The 90th percentile WLLs remained higher than the EPA regulatory "action level" of 15 ppb from 2001 to 2004 (Figure 1) before dropping back below the action level in 2005. The drop in WLLs in 2005 is temporally linked to dosing of an orthophosphate corrosion inhibitor (from August 2004 onward) to mitigate high WLLs.

Following a January 31, 2004 front page *Washington Post* article that revealed the widespread problem with elevated WLLs, the public was eventually instructed to flush their water lines >10 min before collecting water for cooking and drinking. More than 20,000 lead filters were also mailed to homes with high risk of elevated WLLs in early 2004. Assuming these strategies were effective in largely abating human exposure to elevated WLLs, mid-2001 to early 2004 is the time period of greatest unprotected exposure to high WLLs.

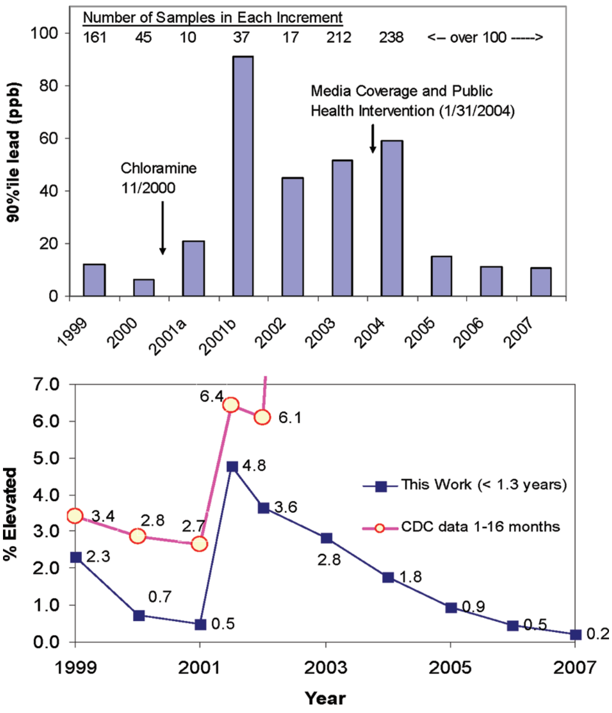

FIGURE 1. Temporal variation of lead in water (90th percentile water lead) and key events related to lead exposure in Washington, DC (top). Trends in EBL incidence for children aged ≤1.3 years (bottom).

Correlation Between EBL and WLLs for Children ≤1.3 Years of Age. Although the most highly impacted population is children aged ≤1 year there are insufficient data for this population group to support a statistically valid analysis. Only 0.62% of the overall CNMC data are for children aged ≤9 months and only 6.6% of the data are for children ≤1 year of age. The age group closest to the target population with adequate data (27% of the overall data) is children aged ≤1.3 years.

The incidence of EBL for children aged ≤1.3 years continued its decades long decline from 1999 through the first half of 2001 (Figure 1). But in the second half of 2001 the incidence of EBL abruptly increased by 9.6 times versus the first half of 2001. This 4.3% increase (from 0.5% to 4.8%) is not inconsistent with expectations presented in Supporting Information 1, especially considering that 90th percentile WLLs were higher in late 2001 than in 2003 (rough predictions in Table S1 are based on 2003 data). In 2002 and 2003, the incidence of EBL was ≥4 times higher than in 2000. In fact, EBL incidence did not return to levels observed in 2000 until about 2005, when lead in water once again met EPA standards. A proportions test in *R* (*16*) determined that the EBL incidence in the years 2001, 2002 and 2003 is greater than in 2000 with >95% confidence. A linear correlation between the incidence of EBL and the 90th percentile lead from 2000 to 2007 (see Supporting Information 5, Figure S7) is very strong (R^2 = 0.81).

The CDC database (*3*) was analyzed for the same trends. The incidence of EBL for children aged 1–16 months showed trends similar to the CNMC data (Figure 1, bottom). The absolute values of the CNMC data and the CDC data

TABLE 1. Summary Data for Neighborhoods of High, Moderate, and Low Relative Risk of Exposure to High Elevated WLLs

						% pop. above indicated WLL (ppb)		
relative exposure risk	est. lead pipes	% of total pop. in city	pop. (1000)	% pop. with lead pipe	% 1st draw over 100 ppb	1st draw >100	2nd draw >100	1st draw >400
high	10086	22	126.3	17.6	15.0	2.63	3.43	0.13
moderate	14743	55	314.3	10.3	9.4	0.97	1.59	0.02
low	1318	23	131.4	2.2	12.8	0.28	0.37	0.00

are not expected to be in agreement, because the CDC included multiple measurements of blood lead for children which tends to skew the EBL incidence higher. CDC data for 2003 are not plotted on the graph, because only 90 children were identified as age 1−16 months for that year, of which 31 had elevated blood lead (34% EBL incidence).

Data from the CDC study (*3*) were then compared to the blood lead data (>28,000 records) from CNMC. In theory, the CNMC data are a subset of the more expansive data compiled and maintained by the DC Department of Health and which were used in the CDC study. However, a comparison of records between the two databases for the year 2003 revealed an error rate of more than 50%. That is, there was less than a 50% chance that a given record in the CNMC database matched a record in the CDC data in 5 domains: sample collection date, subject age, sample recording date, zip code, and BLL. Because repeated attempts to resolve this and other discrepancies in the CDC data were not successful, only the CNMC data were used for analyses and conclusions in this work.

Correlation Between EBL and WLLs for Children Aged ≤30 Months. No strong temporal trends or correlations between EBL incidence and the varying WLLs were observed for children aged ≤30 months if the data were analyzed across the entire city (data not shown). A neighborhood analysis of the data was then conducted.

High-, Moderate-, and Low-Exposure-Risk Neighborhoods. During 2003, the local utility conducted intensive sampling in Washington, DC homes with lead service pipe. Contrary to the popular perception that lead leaching to water is a fairly reproducible phenomenon from home to home, WLLs present in the first and second draw (flushed) samples from home to home vary dramatically (*9, 17*). For instance, in homes known to have lead service line pipe the second draw samples collected from 33% of homes had WLLs below the 15 ppb EPA action level. But 17% were above 100 ppb, 1% were above 1,000 ppb, and one sample contained 48,000 ppb.

A Freedom of Information Act request of the water utility revealed that a “geographic phenomena” was identified that played a key role in the observed variability of water lead in homes throughout the city (Supporting Information 3). Specifically, certain neighborhoods were “hot spots” for high water lead. While the utility would not provide documentation of the neighborhood analysis, their 2003 lead in water data were scrutinized for geographic trends based on zip code.

The analysis demonstrated that relative risk of exposure to high lead in water was a strong function of zip code (see Supporting Information 4). To capture the risk of exposure to high WLLs for the different neighborhoods, while also pooling data to maintain sufficient statistical power, the city was demarcated into neighborhoods that had relatively high risk (22% of the population), moderate risk (55% of the population), and low risk (23% of the population). In the high-risk part of the city, 2.63% of the population had first draw WLLs above 100 ppb (Table 1). This is 9.4 times higher than the 0.28% of the population having first draw WLLs above 100 ppb in the low-risk part of the city, and 2.7 times higher than in the moderate-risk part of the city (Table 1). The population living in the high-risk neighborhoods also had much greater likelihood of exposure to second draw lead over 100 ppb or to first draw lead over 400 ppb when compared to the moderate- and low-risk neighborhoods (Table 1).

Temporal Trends in EBL. The incidence of EBL for children aged ≤30 months had strong temporal trends that differed based on neighborhood risk level (Figure 2). In the high-risk neighborhoods EBL incidence increased from 2.5% in 2000 when WLLs were low, to 6% in 2003 after WLLs had been high for a few years. Thus, the incidence of EBL cases increased 2.4 times in 2003 versus 2000 in the high risk neighborhoods. The incidence of EBL dropped rapidly in the high-risk neighborhoods beginning in 2004. In the moderate-risk part of the city the EBL incidence was higher in each of the years 2001−2003 when water lead levels were high, relative to 2000 when water lead levels were low. But in neighborhoods of the city with the lowest risk of exposure to high WLLs, the percentage of children aged ≤30 months with EBL dropped steadily from 2000 to 2007.

Comparing the high-risk part of the city to the low-risk part of the city using a proportions test in *R* shows no significant difference in EBL incidence for the year 2000 (before WLLs were high) or for 2001 ($p = 0.544$ and 0.330, respectively). But utilizing the same test in 2002, 2003, and 2004 shows a statistically higher incidence of EBL in high-risk neighborhoods relative to low-risk neighborhoods ($p = 0.024$ for 2002, 0.037 for 2003, and 0.006 for 2004). This analysis shows that the high WLLs had a very significant impact on EBL incidence for children aged ≤30 months in the neighborhoods with high WLLs.

Comparison of EBL in Washington, DC to the U.S. Trend in BLLs, 2000−2007. National trends in EBL incidence from 2000 to 2006 (*11*) are reasonably fit by an exponential decay model with an annual rate constant of −0.1867/year ($R^2 = 0.99$). Extrapolation of this trendline using the year 2000 as time = 0 provides a basis for relating the Washington, DC blood lead data to the national trend. For example, the calculated “Δ high risk 2003” (Figure 2), is the difference between the U.S. trendline and the DC data. This represents the increased incidence of EBL in the high-risk DC neighborhoods in 2003, compared to what would have occurred if the national trend had been followed.

Correlation between WLL and Deviations from National BLL Trends. The correlation between the increased incidence of EBL in DC children aged ≤30 months versus national trends, and the reported 90th percentile WLL concentrations for the city, was dependent on the neighborhood risk level (Figure 2). In neighborhoods with the highest WLLs a strong positive linear correlation was established between the increased incidence of EBL and the 90th percentile WLL concentration ($R^2 = 0.82$). In the moderate-risk section of the city the slope and correlation were slightly lower ($R^2 = 0.71$). The weak correlation ($R^2 = 0.50$) in the low-risk section of the city is to be expected, because the population in these neighborhoods had relatively low likelihood of exposure to high WLLs (Table 1). The slope of the trend-line in the highest risk part of the city is approximately double that observed

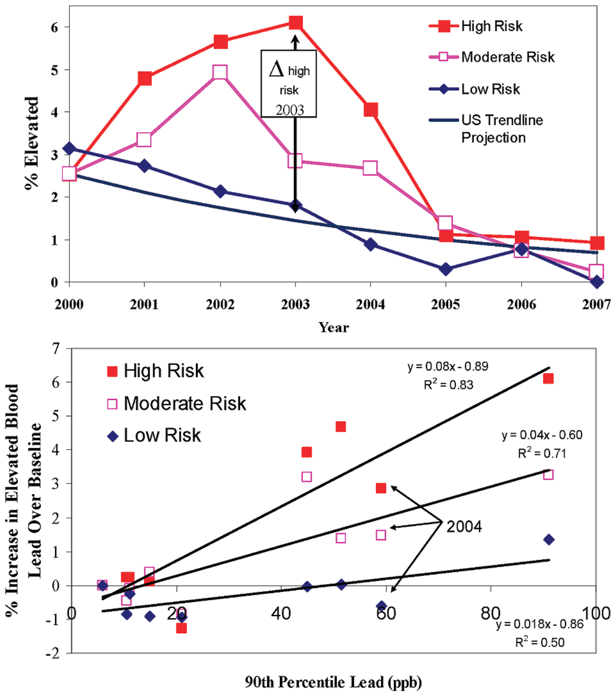

FIGURE 2. Temporal trends in incidence of EBL for children age ≤30 months. The deviation from the U.S. trendline is determined by the difference between the actual data and the projected U.S. trendline (top). Correlation between increased incidence of elevated blood lead in Washington, DC children aged ≤30 months and 90th percentile lead (bottom).

in the moderate-risk part of the city, and 4.4 times higher than in the low-risk part of the city.

If the 2001 data are not split into a first and second half, R^2 in the high-risk part of the city drops from 0.83 to 0.65, R^2 in the moderate-risk part of the city drops from 0.71 to 0.45, and R^2 in the low-risk part of the city drops from 0.50 to 0.18. (Supporting Information 5). The 2004 data also deviate significantly from the trendline (Figure 2 bottom), in that the high WLLs did not increase the percentage of children aged ≤30 months with EBL to the same extent as they did in 2001–2003. This is to be expected, since public health interventions were implemented in early 2004. If 2004 were treated as a transitional year and excluded from the analysis, R^2 would increase for the correlations (Supporting Information 5).

Discussion

EBL Cases Attributed to High WLLS Versus Predictions of Bio-Kinetic Model. The estimated number of children with EBL in Washington, DC due to the lead-contaminated water can be roughly estimated using the results of Figure 2 and the population of children aged ≤30 months in each part of the city (low-, moderate-, and high-risk neighborhoods). It is estimated from the CNMC analysis that 342 children in DC aged ≤30 months had EBL in 2003 due to high WLLs, and that 517 additional children aged ≤30 months had EBL from high WLLs in 2002. The corresponding exposure model predictions including all 1 year old, all 2 year old, and 50% of the 3 year old category (to approximate children aged ≤30 months) is for 170 cases in 2003 (Supporting Information 1). The discrepancy (342 estimated cases of EBL using the CNMC analysis vs 170 predicted for children aged ≤30 months) is not large given the model assumptions. It is not even unexpected, since the exposure model predictions did not include cases for which BLLs would be raised above 10 μg/dL from a combination of sources that include water. The most significant impacts of the high WLLs on EBL incidence probably occurred in the second half of 2001 (Figure 1, Figure 2, Supporting Information Figures S13 and S14), but calculating an increased number of EBL cases in that time period is beyond the scope of this work.

Lack of Monitoring Data for the Population Most Vulnerable to High WLLs. CDC recommends that BLL blood lead of children be screened at 1 and 2 years of age, "based on the fact that children's blood lead levels increase most rapidly at 6–12 months age and peak at 18–24 months (*18*)." These guidelines were developed from studies conducted in Cincinnati and elsewhere, where lead dust and lead paint were the predominant sources of exposure and water lead levels were low (*19*). In contrast, previous research has demonstrated that BLLs begin to rise rapidly when infant formula contains elevated lead ((*7*), see Supporting Information 2 Figure S6). Thus, when lead contaminated water is the sole or main source of lead exposure for infants, it is logical to expect that blood lead levels would tend to peak at ages much younger than 18–24 months (Supporting Information 1).

In earlier research on effects of high WLL on EBL for Washington, DC residents, it was stated that the blood lead monitoring was "focused on identifying children at highest risk for lead exposure (*3*)." This statement is correct from the perspective of lead paint and lead dust, but it is not necessarily accurate from the perspective of exposure to lead from water. Indeed, because so little blood lead data had been collected in Washington, DC for the population most vulnerable to high WLLs, no statistically valid conclusions are possible relative to incidence of EBL for children aged ≤1 year. The data presented herein for children aged ≤1.3 years (which are actually mostly data for children aged 1–1.3 years) supports the prediction that the impacts would be highly significant.

Other Considerations and Biases. A significant number of children aged ≥30 months was likely to have EBL during 2000–2003 because of exposure to high WLLs (Supporting Information 1). Moreover, even in the low-risk neighborhoods many children probably had EBL due to exposure to high WLLs. But the increased incidence of these cases cannot be readily detected in the BLL monitoring data in this work for reasons discussed previously. It is also inevitable that some misclassification of children's addresses will occur in a study of this nature, in that some children in high-risk neighborhoods would be misclassified as living in low-risk neighborhoods and vice versa. To the extent that such random bias occurred, it would tend to make the reported correlations between EBL and WLLs less significant than they actually were.

The Literature Revisited. Differences in conclusions between this work and the earlier CDC study (*3*) are mostly attributed to the type of analysis and interpretation, as opposed to discrepancies between the two databases discussed previously. In a recent discussion of the original CDC results, Levin et al. (2008) noted that the percentage of BLL measurements ≥5 μg/dL declined by 70% from 2000–2003 across the U.S., but did not decline at all in Washington, DC during the period of high WLLs (*20*). The obvious implication is that the high WLLs in Washington, DC countered the expected decline in BLLs that would have otherwise occurred, even for the general population that was analyzed in the CDC report.

Applying the Levin et al. (2008) logic to a closer examination of the CDC (2004) data suggests that the rate of decline in BLL measurements >10 μg/dL across the city was also reduced during the time period that WLLs were high. For example, the CDC study reported that from 2000 to 2003, the incidence of BLL measurements >10 μg/dL in homes with lead pipe declined by 28%, whereas incidence of EBL declined 50% nationally in the same time period (*11*). Indeed, the original CDC study did find a slight (but insignificant) increase in incidence of EBL in 2001 versus 2000 for residents living in homes with lead pipe (*3*). When the CDC 2001 data are broken into halves according to the approach of this work, the second half of 2001 has an anomalous increase in EBL incidence relative to what occurred in 1999 or 2000 for all ages tested (Figure 1; Supporting Information 6). The results for second half of 2001 are deserving of increased scrutiny in light of the very high WLLs throughout the city in July and August 2001 (Supporting Information Figures S4 and S14).

There are two other studies that examined the impact of WLLs on BLLs of DC residents. Guidotti et al. (2007) report a low incidence of EBL in a population tested well after high WLLs were front page news (*4*). Another portion of the CDC (2004) study reported no cases of EBL in 2004 for residents living in homes where second draw WLLs were over 300 ppb (*3*). In both of these studies there was a delay of months to a year between the time that consumers were first informed of hazardous WLLs and the actual measurement of their BLL (*21*). Since the half-life of lead in blood is 28−36 days, these results cannot be construed to indicate lack of harm from exposure to the lead contaminated water (*22*).

The Guidotti et al. (2007) study also erroneously identified critical dates and facts regarding the lead in water contamination event that skewed interpretations (*4*). For example the authors state that:

(1) chloramine was first added to the water supply in November 2002 [the actual date for addition of chloramines was November 2000 [see Supporting Information 7]

(2) WLLs showed an “abrupt rise” in 2003 [the WLLs had risen by the second half of 2001 as per Figure 1]

(3) the Washington, DC population had been protected by “massive public health interventions” starting in 2003 [the significant public health intervention did not begin until after the story was front page news in early 2004, see Supporting Information 7].

This may explain why the conclusions of Guidotti et al. (2007) differ from those of Miranda et al. (2006), who found a significant correlation between children’s BLLs and a switch to chloramine disinfection in North Carolina (*14*).

Overall, this research demonstrates that the experience in Washington, DC is consistent with decades of research linking elevated WLLs to higher BLL and EBL (*23, 24*). Studies in France (*25*), Scotland (*26*) and Germany (*27*) correlated WLLs to adult BLLs, even for adults drinking water after corrosion control markedly reduced water lead levels. Lanphear has also noted a correlation between BLLs and higher WLLs in a U.S. city in which no system-wide problem with WLLs was occurring (*28*). Lead in potable water is therefore a viable explanation for some of the 30% of elevated BLL cases that occur nationally for which no paint source can be found (*20*), and may even be a significant contributor to EBL in cases where lead paint is identified as a hazard in the home. Assumptions by the CDC that high WLLs are rarely the cause of EBL in children should be re-evaluated.

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Supporting Information Available

Seven supporting analyses and three reports (EPA, 2004). This material is available free of charge via the Internet at http://pubs.acs.org.

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Fetal Death and Reduced Birth Rates Associated with Exposure to Lead-Contaminated Drinking Water

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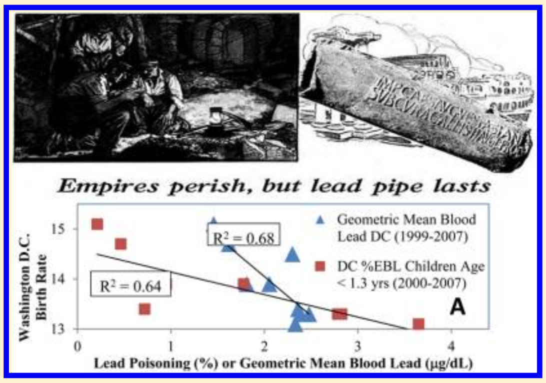
S Supporting Information

ABSTRACT: This ecologic study notes that fetal death rates (FDR) during the Washington DC drinking water "lead crisis" (2000–2004) peaked in 2001 when water lead levels (WLLs) were highest, and were minimized in 2004 after public health interventions were implemented to protect pregnant women. Changes in the DC FDR vs neighboring Baltimore City were correlated to DC WLL ($R^2 = 0.72$). Birth rates in DC also increased versus Baltimore City and versus the United States in 2004–2006, when consumers were protected from high WLLs. The increased births in DC neighborhoods comparing 2004 versus 2001 was correlated to the incidence of lead pipes ($R^2 = 0.60$). DC birth rates from 1999 to 2007 correlated with proxies for maternal blood lead including the geometric mean blood lead in DC children ($R^2 = 0.68$) and the incidence of lead poisoning in children under age 1.3 years ($R^2 = 0.64$). After public health protections were removed in 2006, DC FDR spiked in 2007–2009 versus 2004–2006 ($p < 0.05$), in a manner consistent with high WLL health risks to consumers arising from partial lead service line replacements, and DC FDR dropped to historically low levels in 2010–2011 after consumers were protected and the PSLR program was terminated. Re-evaluation of a historic construction-related miscarriage cluster in the USA Today Building (1987–1988), demonstrates that high WLLs from disturbed plumbing were a possible cause. Overall results are consistent with prior research linking increased lead exposure to higher incidence of miscarriages and fetal death, even at blood lead elevations (≈5 μg/dL) once considered relatively low.



■ INTRODUCTION

The Washington DC (DC) "lead in drinking water crisis" caused an increased incidence of elevated blood lead (EBL) in children at thresholds >5 μg/dL and also >10 μg/dL.[1−3] The "lead crisis" was inadvertently triggered in 2000 by a switch in drinking water disinfectant from chlorine to chloramine (Table 1) to reduce regulated disinfection byproducts, but the switch also caused an unintended release of lead from plumbing materials to drinking water.[1−6] Consumers had no warning of high water lead levels (WLLs) until late-2002, and the true extent of the hazard was not publicly revealed until a front page investigative Washington Post report in January 2004.[2,7] Unprecedented interventions by the DC Department of Health (DC DOH) were then implemented to protect the general public and especially sensitive populations of pregnant women including written and broadcast (radio, television) alerts to avoid tap water, use utility provided water lead filters or enhanced flushing of pipes.[1,4,7,8] These interventions dramatically reduced the incidence of childhood lead poisoning (i.e., blood lead >10 μg/dL for children under age 6) in DC from 2004 onward.[2]

Exposure to lead has been associated with spontaneous abortion, stillbirth and high rates of infant mortality.[9,10] Lead abortion pills with 32 μg lead each (256 μg Pb per day for the recommended dose of 8 pills) were used in the early 1900s, and use of new lead pipe in potable water systems for cities without corrosion control increased fetal mortality 300–400%.[9,10] On this basis a significant elevation in miscarriage and fetal death rates would be predicted in Washington, DC from late 2000 through 2003. For instance, analysis of thousands of samples collected by the District of Columbia Water and Sewer Authority (DC WASA) in 2003 from homes with lead pipe, revealed median daily consumer exposure of 70 μg Pb/day assuming 2 L tap water exposure per day from a 50:50 mixture of first draw:flushed water. The same type of analysis indicates that greater than 15% of these consumers had daily exposure exceeding that from 1900s lead abortion pills (256 μg Pb/day).[2,9,10] The presumed historical success of the lead abortion pills via acute lead exposure, highlights concerns about adverse pregnancy outcomes from short-term exposure of pregnant women in Washington, DC to elevated WLLs.

More recent research demonstrated that every 5 μg/dL increase in maternal blood lead resulted in a 180% increased

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Table 1. Demarcation of Washington DC Lead in Water Risks into Calendar Years for Consideration of Impacts on Fetal Death, Birth Rates and General Fertility

calendar year time period	consumer risk to elevated lead in water
1997−1999	**low.** low water lead when chlorine was disinfectant.
2000	**uncertain.** chloramine only dosed part of the year and no lead in water samples were taken during that time.
2001−2002	**highest.** very high lead in water and no public information of health risks until 10/2002.
2003	**high.** high lead in water and ineffective public education from 10/2002 to late 2003.
2004−2006	**low.** high lead in water, but intense public education, congressional intervention, provision of lead filters and enhanced flushing instructions protected population.
2007−2009	low general lead in water risks due to corrosion control, but high PSLR activity and removal of public health protections created **very high risk in PSLR**[a] homes.
2010−2011	**very low.** low water lead due to corrosion control, low risks in PSLR homes due to CDC health advisory issued 1/2010 and provision of lead filters.

[a] PSLR= partial service line replacement.

risk of miscarriage (defined herein as death of an embryo from pregnancy up to 20 weeks gestation).[11,12] While statistically robust records of maternal blood lead in DC are not available for analysis, it is likely that the increased incidence of childhood blood lead over thresholds of 5 and 10 μg/L (lead poisoning)[1−3] during the lead crisis is a reasonable proxy for trends in maternal blood lead, for which each 10 μg/dL increase would raise miscarriage rates by about 360%.[11,12]

While problems with elevated WLLs throughout DC were largely controlled after 2006 by dosing of an orthophosphate lead corrosion inhibitor (Table 1), more than 13 000 homes where lead pipes were disturbed had unusually high risk of elevated WLLs from 2004 to 2011.[3,7,8,13−15] Specifically, after the water utility cut lead service pipes to implement partial service line replacements (PSLR) under mandates of the U.S. Environmental Protection Agency (EPA) Lead and Copper Rule or through their own voluntary program from mid-2006 to 2009, consumer collected water samples often contained over 100 μg/L and as much as 190 000 μg/L lead.[8,13,14] The WLL remains elevated in the PSLR homes for a few months or years after cutting the pipe.[16] Although the Centers for Disease Control (CDC) identified increased risk of childhood lead poisoning risk incidence in DC PSLR homes in late 2007, the public was unaware of any problem until a Washington Post article in 2008, which revealed the serious spikes in WLLs and the utility began to scale back the PSLR program.[7,8,14] But consumers were not adequately protected from high WLLs until the CDC issued a public health advisory regarding an increased incidence of childhood lead poisoning in PSLR homes in January 2010, the utility provided consumers water lead filters, and the health risks were reinforced by congressional hearings and extensive media coverage (Table 1).[14,15,17] CDC eventually reported 330% increased incidence of childhood lead poisoning in PSLR homes versus DC homes without lead pipe.[3]

This research examines whether expectations of adverse pregnancy outcomes are evident in fetal death and birth rate data for Washington, DC from 2001 to 2003 when WLLs were elevated throughout the city and consumers were unprotected, and if there are also links between fetal death rates and PSLR activities from 2007 to 2009 before public health interventions protected the public from high WLLs (Table 1). To enhance the analysis, a general approach used in prior studies of infant mortality due to arsenic exposure in Chile drinking water was followed,[18] by comparing Washington, DC to neighboring Baltimore City, MD which had relatively low WLLs from 1997 to 2011. Baltimore City has a number of similarities to Washington, DC.(Table 2) and both cities are part of the same combined statistical area (CSA) census department designation due to social and economic ties, as well as geographical proximity.[19,20] The comparison to Baltimore City can eliminate many localized confounding factors that could impact comparisons between Washington, DC and the United States. A final phase of research applies an evolving understanding of consumer lead exposure that arises from disturbed lead plumbing, to a historic 1987−1988 Washington, DC area "USA Today Building" miscarriage cluster, where very high WLLs and proximity to renovation disturbances were initially implicated as a causal factor.[21−26]

Table 2. Representative Demographic Data for Washington DC, Baltimore City and the United States

parameter	Washington, DC	Baltimore City	United States
population	601 723	620 961	308 700 000
average family size	3.15	3.14	3.14
median household income ($)	61 835	40 00	52 762
% population in poverty	18.2	22.4	14.3
% population African American	50.7	63.7	12.6
% population women age 15−44	27.0	23.4	20.2
total housing units	296 719	296 685	131 034 946
%Pop <9th grade education	5.0	6.6	6.1

MATERIALS AND METHODS

WLL and PLSR Replacement Data. DC WLL samples collected for EPA compliance monitoring (1997−2011) were organized into calendar year time periods,[2,6] for which corresponding incidence of fetal death, live birth and other data were also compiled (Table 3). The 90th percentile (90th %) water DC WLL data from 1997 to 2000 were derived from a U.S. EPA report,[6] data from 2001 to 2007 were derived from Edwards et al.,[2] and data for 2008−2011 were obtained from DC WASA consumer confidence reports.[27] Since chloramine was only dosed in part of 2000, and no WLL data were collected for that time period (and the data were subject to revision and controversy),[6] year 2000 data was excluded from any correlations between WLLs and adverse pregnancy outcomes. DC WASA provided data on PSLRs from 2003 to 2011 (Table 3) and incidence of lead pipes by neighborhood or ward.[28] Baltimore City WLL data were obtained from consumer confidence reports (2001 onward) and from the U.S. EPA before 2001 (1997−2001).[29,30]

Blood Lead Trends for Washington, DC, Baltimore City, and the United States. Washington, DC blood leads were derived from prior published independent data due to acknowledged problems with the CDC data set and DC DOH reporting.[2,7,31] Baltimore City and U.S. data on incidence of childhood lead poisoning were compiled from Baltimore City Health Department records or CDC's lead surveillance data.[32−34]

Fetal Deaths and Live Births. Data for miscarriages <20 weeks gestation are not systematically compiled and reported in

Table 3. Lead in Water, Incidence of Elevated Blood Lead (EBL), Fetal Death Rate (FDR), Birth Rate, General Fertility Rate (GFR),@ and Partial Service Line Replacements (PSLR) in Washington D.C (DC), Baltimore City (BC) and the United States (U.S.)

	Washington, DC							Baltimore City, MD					United States			
year	DC 90th% Pb[a]	% EBL DC	% EBL DC Age <1.3 yr	PSLR	FDR DC	birth rate DC	GFR DC	BC 90th% Pb[b]	% EBL BC&	FDR BC	birth rate BC	GFR BC	% EBL U.S.&	FDR U.S.	birth rate U.S.	GFR U.S.
1997	7			na	9.7	15	61.6	13		17.1	14.1	60.0	7.6	6.8	14.2	63.6
1998	7			na	9.5	14.7	60.7	8		16.9	14.9	63.0	6.5	6.7	14.3	64.3
1999	12.5	5.5		na	7.9	14.5	59.9	10	16.7	16.9	15.4	66.0	5.0	6.7	14.2	64.4
2000	34	3.8	0.71	na	10.8	13.4	53.3	12	12.1	14	14.8	63.1	4.0	6.6	14.4	65.9
2001	79	3.2	2.78	na	12.9	13.3	52.9	11	9.5	15.2	14.1	60.7	3.0	6.5	14.1	65.1
2002	45	4.2	3.65	na	10.4	13.1	52.8	8	9.4	16.3	14.2	61.5	2.6	6.4	14	65.0
2003	51.5	3.9	2.82	373	8.9	13.3	55.1	10	6.4	13	14.4	63.0	2.3	6.3	14.1	66.1
2004	59	2.7	1.78	1745	7.1	13.9	58.3	11	6.2	13.1	14.4	64.6	1.8	6.3	14	66.4
2005	15	2.7	0.95	3210	8.2	13.9	58.4		4.8	13.3	14.4	65.1	1.5	6.2	14	66.7
2006	11	1.7	0.46	3312	7.5	14.7	58.4		4.3	11.4	15.5	69.3	1.2	6.1	14.3	68.6
2007	10.5	0.9	0.21	3430	9.9	15.1	60	7	3.4	10.9	15.5	68.8	0.9		14.3	69.3
2008	7			2442	10.1	15.4	61.4			10.3	15.6	69.5	0.7		14	68.1
2009	8			411	8.2	15.1	59.7	8		10.6	14.9	63.7	0.6		13.5	66.2
2010	5			229	7.4	15.2	56.4			10.9	14.4	61.2	0.6		13	64.1
2011	5			123	6.5	15	55.9	5[b]		10.9	14.3	61.6	0.6		12.7	63.2

[a] 90th% EPA Lead and Copper Rule data adjusted to calendar year from prior work[2,6] except for 2000, a year in which chloramine was first dosed and also includes a sampling round where high lead samples were illegally invalidated. The U.S. EPA issued a revised calculation for July 2000-June 2001 of 34 ppb.[6] [b] Baltimore has been on reduced monitoring since 2004 and only samples for lead in water every 3 years. Data in Table for Baltimore City in year 2011, is that reported in the 2012 Consumer Confidence report, to indicate trends from 2009 to 2011. [c] Fetal death rates (FDR) per thousand births are calculated for DC and Baltimore City using a standard formula [FDR = (no. fetal deaths)/(live births + fetal deaths)] × 1000; birth rates are live births per thousand population, general fertility rate (GFR) is number of live births per thousand women aged 15–44.

the U.S., but total fetal deaths (over 20 weeks gestation) and live births for Washington, DC are compiled and reported annually by the DC DOH to Vitalstats Online.[35] Total fetal deaths (over 20 weeks) in Washington, DC reported and compiled by DC DOH, were taken from Vitalstats (1997–2005) and DC DOH reports (2003–2011).[35−37] Data on Washington, DC birth rates, general fertility rates, and births by ward (neighborhood) were obtained from DC DOH reports or Vitalstats.[35−38] Fetal death rates, birth rates and general fertility rates for Baltimore City 1997–2011 were obtained from annual Maryland Vital Statistics reports,[39] and similar data for the United States were obtained from National Vital Statistics reports when available.[35,40,41]

Effects of Renovation Activity on Lead Release from Soldered Plumbing. Trends in lead release to potable water occurring as a result of vibrations during renovations were investigated experimentally. Six 0.6 m long copper pipes (1.9 cm diameter) with a single central joint and a 6″ bead of 50:50 Pb:Sn solder were created and exposed to simulated source water for the USA Today building (synthesized Potomac River water).[2] The pipes were first conditioned in a continuous recirculation mode for 3 months using a 150 L reservoir to allow development of a lead corrosion product (rust) layer, that might be mobilized to water during physical disturbances.[42] Water in the reservoir was completely changed each month throughout the study. Thereafter, baseline lead release to the recirculating reservoir was quantified for each pipe after 1 month exposure, using a representative premise plumbing flow regime of 15 s flow every 8 h at 0.66 m/sec. The pipes were then gently placed directly on a concrete pad at distances of either 3 or 15.2 m from a conventional jackhammer, weighed down with 20 kg masses to hold the pipes firmly in place, and the jackhammer was operated 30 s to generate representative vibrations that arise during renovation. The pipes were then placed back into the recirculation reservoir which was sampled (as before) at 1 and 4 months after the vibration disturbance (months 2 and 3 were not sampled).

Statistical Methods and Error Bars. Correlations, statistical testing, and upper and lower confidence intervals were calculated using a standard Microsoft EXCEL 2010 program with an assumption that data were normally distributed. All error bars in graphs represent 95% confidence intervals.

RESULTS

After reviewing temporal trends in DC fetal death rates from 1997 to 2011 as a function of WLL risk (Table 1), a similar analysis was conducted for birth rates. Results of a simulation experiment quantifying trends in lead release to water from pipes disturbed during construction renovation are then described, providing a basis for reconsidering the possible role of elevated WLLs in the USA Today miscarriage cluster.

Changes in Fetal Death Rates: Washington, DC, 1997–2011. The 90th percentile WLL in DC (Table 3) spiked over 40 μg/L from 2001 to 2004 after the switch to chloramine disinfectant, with a peak WLL of 79 μg/L in calendar year 2001.[2] Prior work indicated that during 2001, incidence of childhood lead poisoning (blood lead >10 μg/dL) increased from 0.5% up to 4.8% for children less than 1.3 years of age.[2] The DC fetal death rates declined from 9.7 down to 7.9 per thousand births in the years 1997–1999 before chloramine was dosed to water (Table 3), but increased 32–63% when WLL was high in 2001 (Figure 1A). Fetal death rates remained high in 2002, and did not drop below those of 1999 until public health interventions in 2004 decisively limited exposure of pregnant women to high WLLs.[2,7] Applying a dummy variable of 90th% lead of 10 ppb to reflect lower exposure due to the consumer public health protections from 2004 to 2006,

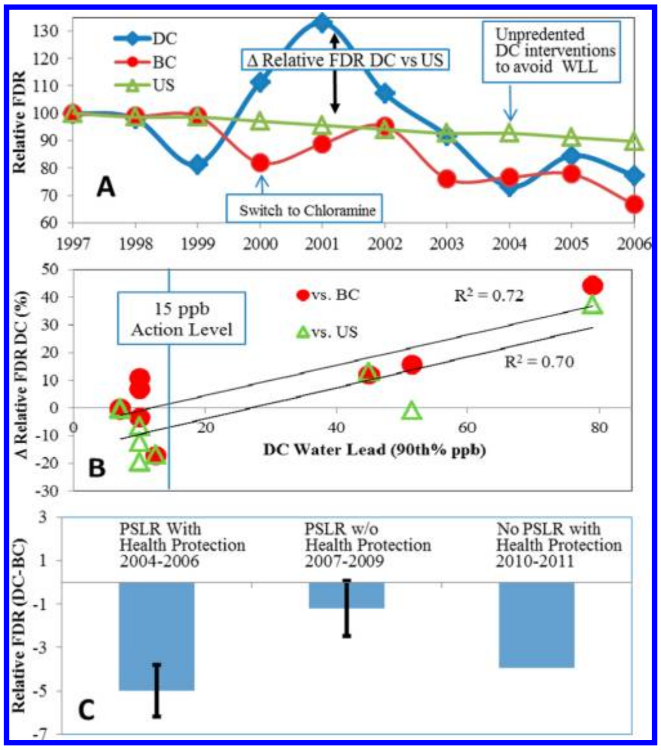

Figure 1. Relative fetal death rates (1997 = 100%) trended downward in the U.S. and in Baltimore City (BC) from 1997 to 2006, but exhibited a spike in DC around 2001 when lead in water was high (A). The change in relative fetal death rates (FDR) for DC versus BC or versus the U.S. was strongly correlated to water lead level (B; Figure excludes transition year of 2000). In years with partial lead service line replacements (PSLR) and no public health protections in 2007–2009, fetal death rates rose in DC to the point they were not statistically different from BC, before dropping back when PSLRs were discontinued and public health protections were offered residents in 2010–2011 (C).

indicates that higher WLL correlated to higher fetal death rates from 1997 to 2006 (R^2 = 0.60; data not shown excluding year 2000).

WLLs in Baltimore City (BC) declined steadily from 1997 to 2012 from 13 ppb down to 5 ppb (Table 3), along with incidence of childhood lead poisoning (16.7% in 2000 to 3.4% in 2011) and fetal death rates (17.1 down to 10.9 per thousand births). U.S. fetal death rates (6.8 to 6.1 per thousand births) and lead poisoning incidence (7.6 to 1.2%) also declined steadily from 1997 to 2006 (Table 3). After normalizing fetal death rates in DC, BC, and the U.S. by setting 1997 rates to 100% (Figure 1A), the 2000–2003 trend in DC is observed to be anomalously high. The higher rate of fetal deaths in DC versus either the U.S. or BC correlates (R^2 = 0.70–0.71) to the DC 90th% lead level (assuming 10 ppb lead as a dummy variable reflecting lower WLL exposure in 2004–2006 and excluding year 2000; Figure 1B). The correlation does not change significantly if years 2004–2006 are simply excluded from the analysis (R^2 = 0.70–0.72; data not shown). If the relative fetal death rate is calculated on an absolute rather than a percentage basis, a significant but somewhat lower correlation with DC 90th% WLL is observed (SI Figure 1; R^2 = 0.45 DC versus BC; R^2 = 0.68 DC vs U.S.). The correlation improves if years 2004–2006 are excluded from the analysis rather than using a dummy variable to reflect lower WLL exposure (R^2 = 0.62 DC versus BC; R^2 = 0.82 DC vs U.S.).

After DC experienced 3 years of relatively low fetal death rates (7.1–8.2 per thousand births) from 2004 to 2006 when the public health protections for high WLLs were in place (Table 1; Table 3), fetal death rates rose 21–42% to 9.9–10.1 per thousand births in 2007–2008 when risks of high WLLs in PSLR homes were highest and consumer public health protections were removed. DC fetal death rates declined smoothly from 2008 to 2011 as the PSLR program was phased out and public health protections were reinstituted in early 2010. During this same time period 2004–2011, fetal death rates declined or remained stable in BC. Analysis of relative fetal death rates confirm an adverse change in DC from 2007 to 2009, as DC fetal death rates rose to the point they were not statistically different from those in BC. DC fetal death rates are much lower than in BC in either 2004–2006 ($p < 0.05$) or in 2010–2011 when public health protections were in place (Figure 1C).

Changes in Birth and General Fertility Rates: Washington, DC, 1997–2006. Birth rates in DC decreased from 1997 to 1999 to 2001–2003 as WLLs rose during the lead crisis, and then increased by more than 0.6 births per thousand residents ($p < 0.05$) after public health protections were implemented from 2004 to 2006 (Table 3). Birth rates in DC continued to rise steadily from 2006 to 2009. Incidence of childhood lead poisoning and median child blood lead are possible proxies for trends in maternal blood lead (Table 3), and the DC birth rate was inversely correlated to both parameters (Figure 2A; R^2 = 0.64–0.68).

A neighborhood (ward) analysis indicated that the higher birth rates for 2004 vs 2001 in DC, were highly concentrated in the wards of the city with the highest incidence of lead pipe and WLL exposure. The presence of a lead service pipe increased

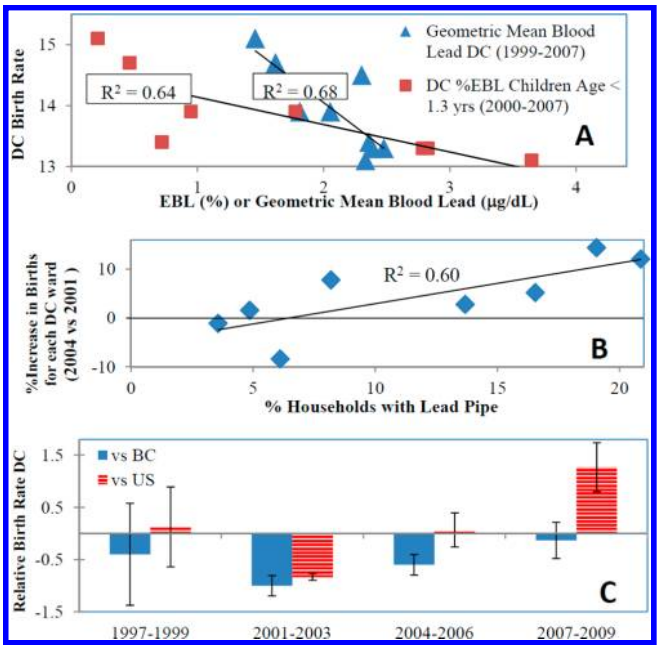

Figure 2. The birth rate in DC was inversely correlated with geometric mean blood lead and the percentage of children <1.3 years of age with blood lead over 10 μg/dL (A). Increased birth rates in each DC ward for 2004 versus 2001, was correlated to the percentage of lead pipes within each ward (B). Birth rates in Washington, DC relative to Baltimore City or the U.S., decreased during the lead crisis 2001–2003, and then increased in 2004–2006 when public health protections were implemented (C).

the likelihood of high WLLs and incidence of childhood lead poisoning during the lead crisis.[1,3,6] Specifically, the two wards with greater than 19% incidence of lead pipe observed a greater than 12% increase in births for 2004 versus 2001, whereas the three wards with less than 6% incidence of lead pipe all had less than a 1.5% increase in births (or even declining birth rate) during the same time period (Figure 2B) . The percent increase in birth rate comparing 2004 vs 2001 for each ward was correlated to the incidence of lead pipe in that ward (Figure 2B; $R^2 = 0.60$).

Birth rates nationally were relatively constant in the range of 13.5−14.7 from 1997 to 2009 (Table 3), and the national birth rate actually declined slightly to 14.0 from 14.1 in 2004 vs 2003, respectively. Birth rates were unchanged in Baltimore City from 2004 vs 2003 (Table 3). The calculated changes in birth rate for DC versus either BC or the U.S. illustrated a consistent trend, with a relative reduction in birth rates for DC in 2001−2003 when WLLs are low, and relative increases in birth rates (after 2004) when the population was protected by either public health interventions or corrosion control (Figure 2C). Taking a larger perspective using National Vital Statistics data for other U.S. states and territories,[35] the 4.8% increase in DC birth rates reported in 2004 versus 2003 was the highest among U.S. states and territories reporting more than 2000 births. Likewise, the 11% increase in DC birth rates comparing 2006 versus 2003, was matched or exceeded only in Wyoming, Thus, while the changes observed in DC are not unprecedented, they were also highly unusual compared to other states and territories.

Changes in birth rates can be a strong function of demographics; for example, if DC had a lower population of women aged 15−44 in 2004−2006 versus 2001−2003, the observed increase in birth rate starting in 2004 might have nothing to do with WLL exposure. When DC DOH trends in reported general fertility rates were examined using the same approach as for Figure 2A, DC general fertility rates were inversely correlated to both incidence of childhood lead poisoning age <1.3 years and median blood lead (SI Figure 2; $R^2 = 0.49−0.53$). Repeating the analysis of Figure 2C for changes in general fertility rates in DC versus both BC and the U.S., revealed the same trend as was observed for the birth rate (SI Figure 3). Thus, changes in demographics do not seem to be a likely explanation for the observed anomalies in DC birth rates.

There was also a reasonable inverse correlation, between DC fertility rates and DC fetal death rates (SI Figure 4; $R^2 = 0.38$). The slope of that curve implies an increase in births of 300 per year when the cases of fetal death are reduced by 30 cases per year, which roughly approximates to the actual data for DC in 2004 versus 2001 when live births increased by 308 and fetal deaths decreased by 34. If this change reflects changes in WLL exposure and its associated effect on spontaneous abortion incidence,[9−12] then decreased fetal deaths account for only about 10% of the observed increase in birth rate and the remaining 90% would be attributed to miscarriages. A ratio of 1 fetal death for every 9 miscarriages was expected based on prior research.[43] Overall, observations in DC are consistent with predictions of higher miscarriage incidence at less than 20 weeks gestation at times with high WLLs and higher maternal lead exposure, which translates to reduced birth rates as expected given the presumed successful use of 19th century lead abortion pills.[9−12]

Revisiting the 1987−1989 USA Today Miscarriage Cluster. A National Institute for Occupational Safety and Health (NIOSH) report summarized a 16-month health hazard investigation for a high profile miscarriage cluster in what was once the USA Today Building complex in Rosslyn, VA.[22] This building receives water from the same source as Washington, DC. A 100% incidence of miscarriages (eight miscarriages for eight pregnancies) was confirmed among women working on two specific floors of one building that underwent renovation during 1988, an activity which was noted to have disturbed the existing copper−lead solder plumbing system to the point that joints failed and "dripping from overhead pipes <was> common."[21] The miscarriages were associated with "working in an area under renovation during the first 20 weeks of pregnancy" (RR = 2.52; 95% CI = 1.43−4.48).[22]

Extensive testing many months after the miscarriages revealed nothing unusual except for very high WLLs (up to 1300 μg/L), with mean lead in first draw drinking water fountain samples of 100 μg/L and mean lead levels after flushing 5 min of 50 μg/L. But the two floors with the renovations and highest incidence of miscarriages had ***anomalously low*** detected WLLs (mean lead of 20 μg/L first draw and 11 μg/L after flushing), WLLs that were 80% lower than in other areas of the building with lower incidence of miscarriages ($p < 0.05$). This finding, coupled with low levels of blood lead for 39 women tested after March 1989, was used to rule out WLLs as a factor contributing to the cluster.[22,23] Expert consensus at the time was that "no matter how much water you would drink here, that by itself would not be sufficient to increase the level of lead in the body of an adult very much at all."[24]

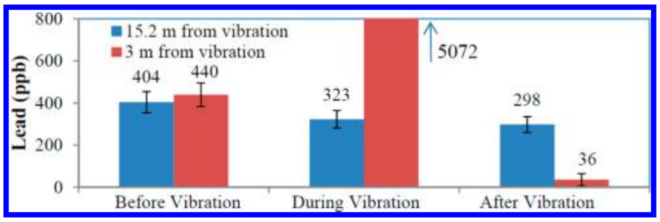

Figure 3. A simulation of construction vibration impacts for the USA Today building, illustrates massive release of lead to water for the month immediately after vibrations, and much lower water lead 2−3 months afterward for disturbed lead pipes.

Re-evaluation of the NIOSH logic and closer examination of the raw data reveals substantial uncertainty in the conclusions regarding the effect of high WLL. First, recent reports have demonstrated that physical disturbances to pure lead pipe can sometimes create massive water lead spikes over a duration of weeks to months, before eventually improving.[13−16,44] The experimental testing simulating impacts of disturbances during renovations on WLL exposure for occupants on the two floors of the USA Today building conducted for this work, revealed that before the physical disturbance lead release in the two sets of pipes were identical (Figure 3). But after just 30 s of vibrations at 3 m distance from the pipes, WLL increased over hazardous waste criteria (>5000 μg/L) for cumulative compositive samples collected for the 1 month after the disturbance. Consuming even a small amount of water containing >5000 μg/L lead would greatly exceed the dose from 1900s lead abortion pills. The same vibrations 15 m distant from the pipes had nearly no effect on WLLs (Figure 3). Importantly, three months after the vibration had ceased, the pipes closest to the vibration had 88% ***lower*** lead release than more distant pipes not impacted by the vibration ($p < 0.05$), consistent with the notion that removal of a lead rust reservoir during the prior disturbance effectively cleaned out lead from the pipes (Figure 3). Hence, the anomalously low WLLs detected on the two floors with renovation and higher miscarriages in the USA Today building months after the adverse pregnancy outcomes and renovations, is completely consistent with much higher consumer lead exposure on the same floors during the construction.

Further considering that the FOIA revealed the following: (1) only two of the reported low blood lead tests in the NIOSH report were of women on the floors where the miscarriages occurred, (2) more than seven blood lead half-lives had passed from the time of the renovation in early 1988 to the time blood lead was drawn, which would have left little trace of a spike in blood lead if it had occurred,[2,45] and (3) WLLs throughout the building are in a range known to be sufficient to cause elevated blood lead and adverse pregnancy outcomes as indicated in this report and elsewhere.[9−13] Hence, the renovation and possible exposure to the high WLLs, was a possible causal factor in the USA Today miscarriage cluster.

■ DISCUSSION

Limitations and Strengths. Inherent limitations to the ecologic study design and the data used in this work, do not allow causal relationships between WLL exposure and adverse pregnancy outcomes to be established. Further research beyond the scope of work presented herein, such as attempting to link addresses of fetal death cases to homes with lead pipe or PSLRs from 2007 to 2009, could increase the strength of the analysis and conclusions associated with this research. Such work was recently called for by an EPA Science Advisory Board, in order to more carefully examine the relationship between PLSRs and incidence of lead poisoning for DC children.[16]

On the other hand, this evaluation also has unique strengths in terms of the following: (1) widespread water lead exposure in a large city with over a half million people, for over a 3 year duration, during a time period when blood lead levels were low by modern standards and influences of other major lead sources such as leaded gas, leaded dust and lead paint were largely under control, (2) presence of a nearby comparison city with similar population and other demographic similarities to eliminate some confounding factors,[18] and (3) availability of over a decade of data synthesizing hundreds of thousands of water lead, blood lead, pregnancy outcomes, and demographic data, collected using modern instrumentation and comparable methods from both cities. The very high statistical power inherent in some aspects of this ecologic study allowed strong temporal associations to be revealed with relatively simple statistical methodology. The observed associations are also consistent with expectations based on a prospective study, which demonstrated that even relatively modest elevations in blood lead (≈5 μg/dL) would increase the likelihood of miscarriage.[11,12]

Ecologic study designs are susceptible to numerous biases and possible confounding factors. At least two are worth noting explicitly herein. First, there is no clear consensus as to the effects of chloramine versus chlorine disinfection on pregnancy outcomes. Early work suggested that a change from chlorine to chloramine would reduce miscarriage rates, whereas several recent studies have indicated that these benefits are not significant, perhaps because certain chloramine disinfection byproducts may be more toxic than previously suspected.[46−49] In Washington, DC., it is clear that hoped for improvements in pregnancy outcomes, which have been cited as a major justification for changing from chlorine to chloramine in 2000,[47] were not realized over the time period of this study. If anything the opposite trend was observed during the time WLLs were elevated. It is also possible that any possible benefits from switching to chloramine after 2000 were overwhelmed by the adverse consequences of very water high lead.

Second, the historical lows in DC fetal death rates during 2004−2006 and 2010−2011 and the rise in birth rates starting in 2004, occurred after or during periods of intense adverse publicity about tap water safety in Washington, DC (Table 1). At these times many consumers were explicitly directed to avoid tap water, use bottled water or install lead filters distributed by the water utility. Because prior research has indicated that avoiding tap water (and using bottled water) can sometimes significantly decrease risk of miscarriages,[50] this factor might confound any attribution of pregnancy outcome trends to WLL exposure alone. However, the strong correlation between maternal blood lead proxies and the measured changes in birth rate, along with the prior research establishing links between modestly elevated blood lead and higher miscarriages, supports the hypothesis that at least some of the improved pregnancy outcomes are due to reduced WLL exposure.

Implications for Policy. From a policy perspective, it is encouraging that most of the data suggest relatively small increases to fetal death rates or reduced birth rates if water was maintained below the 90th% EPA action level of 15 μg/L (Figure 1B), or if public health interventions limit consumer exposure to elevated WLLs when the lead action level was exceeded such as in 2004−2006 or 2010−2011 (Figure 1A; Figure 1C; Table 1). At the same time, the 15 μg/L EPA action level provides little or no safety factor relative to adverse pregnancy outcomes. This point was supported by biokinetic modeling of continuous exposure of 1 year olds to water lead at 7 μg/L, for which 25% of exposed children are predicted to exceed a blood lead level of 5 μg/dL.[51] A one-time acute exposure to a single 250 mL glass of water with about 2500 μg/L Pb, was predicted to increase blood lead of a typical 5 year old child from 0 to 5 μg/dL.[51] Because these trends are likely to hold for adults as well, and these types of WLL exposure occur routinely in cities with lead plumbing or after PSLRs,[44,52] public health concern over lead in tap water for pregnant women seems to be justified.[9−13] It is noteworthy that the most recent data has indicated that U.S. fetal death rates have essentially plateaued since 2003 at a level which is higher than for other industrialized countries, and that the reasons for relatively high U.S. fetal death rates are not fully understood and remain a topic of active research.[53,54]

The data presented herein suggest a very high risk for elevated lead (and by extension adverse pregnancy outcomes) in PSLR homes from 2007 to 2009. Brown et al. (2011) reported a 360% increase in lead poisoning incidence for children living in PSLR homes versus typical homes in the city using data collected from 2004 to 2006, and this was when public health protections were in place throughout DC (Table 1). After 2006 the public health protections were removed and the utility stopped collecting water samples after PSLR in consumer homes. Thus, the time period examined by Brown et al. was actually relatively low risk to consumers, compared to the 2007−2009 time period examined in this report. Further support for very high risks after 2006 was obtained during an analysis of DC DOH Freedom of Information Act (FOIA) data for 2007, which revealed that >12% of cases of lead poisoned children (>5 of 40) lived in DC PSLR homes, even though less than 1% of DC housing units had PSLRs each year.[55] The 2007 FOIA data and that from the CDC through 2006, are also dominated by analysis of children aged 1.5−6 years, whose blood lead levels are generally dominated by lead paint exposure.[2,56] Maternal blood lead can be expected to have a greater proportion of total lead exposure from water than from lead paint when compared to children age 1.5−6 years. For instance, Fertmann et al. (2004) noted that young women reduced their blood lead by 37% if tap water was completely avoided in a city with WLL exposure much lower than in DC PSLR homes.[57] The implication is that very high risk of adverse pregnancy outcomes is possible in the small subset of PSLR homes, providing a practical basis for the spiking fetal death rates in Figure 1C and Table 1 from 2007 to 2009, even when blood lead was declining rapidly and birth rates were increasing throughout the rest of the city.

This work also reinforces the basis for health concerns and warnings associated with lead spikes arising from disturbing old lead plumbing.[3,8,15,44] This evolving knowledge base parallels prior experience with lead paint remediation and renovations, during which careless disturbances created short-term lead health hazards that were ultimately regulated.[58] At present there is no requirement to even notify consumers of voluntary PLSR replacements by water utilities, which represent a majority of PLSRs occurring in practice.[16] Implementation of modest health protections for consumers in homes subject to voluntary PLSR including (1) clear notification that their pipe is being disturbed, (2) the fact that serious health hazards may be created for residents, or (3) providing relatively inexpensive (≈$30) water lead filters seems desirable. Indeed, implementation of these steps by DC Water in 2010, reinforced by the CDC health alert and heavy media coverage regarding possible health risks from PSLR during public hearings in DC and in Congress,[7,8,17] may have helped to achieve historically low fetal death rates in Washington, DC in 2011 (Table 3). Re-examination of the miscarriage cluster in the USA Today building and an associated experiment simulating lead release during renovation, extends the recent concerns with PLSRs to disturbances of lead plumbing within buildings.[44] The same procedures effectively protecting residents in PSLR homes could also be implemented to protect these consumers.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

One Table and 4 Figures providing additional analysis on fetal death and birth rates have been developed. This information is available free of charge via the Internet at http://pubs.acs.org/

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Notes

The authors declare the following competing financial interest(s): The author has been subpoenaed to testify in lawsuits of children who were lead poisoned in Washington D.C. from 2001-2004. He has received no financial compensation for his testimony. DC Water was a financial contributor to a Robert Wood Johnson Foundation grant which supported this research..

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Spikes in Lead Levels Raise Doubts About Water Line Work; Increases Followed D.C. Agency's Pipe Replacements

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Lead in tap water rose to dangerously high levels in hundreds of District homes after a city water agency replaced lead service pipes to reduce health risks, according to 2006 test results made public yesterday.

The D.C. Water and Sewer Authority launched an aggressive plan three years ago to reduce lead contamination by replacing all of the city's 35,000 lead service pipes after unprecedented, hazardous levels of lead were found in city water in 2004. But the new findings raise concerns that the $93 million effort may have at times aggravated the problem for some residents.

The WASA test results suggest that as many as 9,000 District households where lines were partially replaced in the past three years could have been exposed temporarily to tap water with elevated levels of lead, according to an analysis by Marc Edwards, a Virginia Tech professor of civil and environmental engineering and a 2007 MacArthur Fellow. He obtained the WASA test results through a freedom of information request.

The spike is blamed on disrupted lead scales and shavings, created when a service pipe is cut in half, that flow through the water lines after the replacement work.

"We've spent $93 million, we've torn up all these neighborhoods, and it appears the situation is worse than when we started," said D.C. Council member Jim Graham (D-Ward 1), who chairs the council committee that oversees WASA. "This raises serious questions about what WASA has been doing all this time, wittingly or unwittingly."

WASA officials, however, say that the addition of orthophosphate to treat the water in 2004 has dramatically reduced lead leaching and made the District's water safe to drink.

But in a council hearing yesterday, Graham proposed that the District government conduct independent testing to determine whether drinking water is safe. He said it was vital to address local activists' allegations that WASA continues to try to conceal health information from the public.

"I think it's probably needed at this point," he said. He added that it was "of great concern" to him that he learned of the spikes from an independent scientist and questioned repeatedly why WASA officials had no analysis to demonstrate the effectiveness of the partial replacement program.

D.C. WASA General Manager Jerry N. Johnson acknowledged that WASA tests show a spike in lead levels after partial replacement. But he said he believes it causes a short-term problem that is easily resolved by customers running their taps for a minute or two before drinking the water.

WASA staff said the agency has not generally retested homes months later to verify whether the problem has resolved itself, and that few customers send WASA samples for analysis, as the agency allows, to definitively answer the question.

Johnson and WASA Board Chairman Robin Martin said yesterday that they could not comment further on Edwards' analysis because they had first learned of it Thursday.

The vast majority of the 14,600 lead pipes WASA has replaced have been partial replacements. WASA made a policy decision in 2004 to replace the public portion of the lead service lines and require homeowners to pay for replacing that portion of pipe on their private property if they chose. Only 2,100 homeowners have opted to pay the $2,000 apiece to complete a pipe replacement. Another 3,400 owners had replaced the lead pipes on their private property before WASA arrived to do its work.

In Edwards's analysis of the 2006 tests, tap water drawn within a week after the agency partially replaced the lead service lines in 658 homes had average lead levels of 260 parts per billion, 17 times the amount the federal government considers unsafe in drinking water.

The lead concentrations generally fell over time, the tests show. Samples taken one to two months after the replacement in the same homes had average lead levels more than double the federal safety level of 15 parts per billion.

The findings come as WASA's management is holding public hearings to consider whether to discontinue its accelerated replacement of lead service lines.

"Partial lead service replacement has been a complete waste of money and has actually made things worse," Edwards said. "It should be stopped."

In 2004, the U.S. Environmental Protection Agency and WASA said in public statements and studies that the replacement of even half the lead pipe clearly reduced lead levels. But more recently WASA said, in brochures prepared for public meetings on reconsidering the program, that partial replacement "is not as effective as we would want," and the agency has to consider whether this is a wise use of money. None said anything about hazardous spikes of lead.

At the council hearing, environmental activists told Graham that they do not trust WASA officials who say the drinking water is safe because of their failure to alert the public to high lead levels in 2004.

The advocates said yesterday that high lead levels found in 2006 tests of D.C. school water may herald a citywide problem, but WASA officials have refused to discuss it.

"WASA is an agency that doesn't willingly share information," said Ralph Scott of the Alliance for Healthy Homes, a lead safety advocacy group. "They don't like oversight. They spin, they twist. And -- I don't say this lightly -- they don't always tell the truth. "

Johnson said WASA warned homeowners of potential spikes in lead after partial pipe replacement.

Homeowner Megan Keenan said that in 2004 she was given a flier saying lead levels would probably be reduced when WASA came to replace her service line, and only warned of potential spikes after the work was completed.

"We've told people there are spikes," Johnson said. "To suggest we haven't been giving this out to the public is incorrect."

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Detection and Evaluation of Elevated Lead Release from Service Lines: A Field Study

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S *Supporting Information*

ABSTRACT: Comparative stagnation sampling conducted in 32 homes in Chicago, Illinois with lead service lines demonstrated that the existing regulatory sampling protocol under the U.S. Lead and Copper Rule systematically misses the high lead levels and potential human exposure. Lead levels measured with sequential sampling were highest within the lead service lines, with maximum values more than four times higher than Chicago's regulatory compliance results using a first-draw sampling protocol. There was significant variability in lead values from different points within individual lead service lines and among different lead service line sites across the city. Although other factors could also influence lead levels, the highest lead results most often were associated with sites having known disturbances to the lead service lines. This study underscores the importance and interdependence of sample site selection, sampling protocol, and other factors in assessing lead levels in a public water system.

■ INTRODUCTION

Background. Most lead in drinking water comes from premise plumbing materials and lead service lines (LSLs). LSLs are generally the largest source of lead in drinking water when they are present in public water systems.[1] The 1986 Safe Drinking Water Act Amendments banned new lead pipes in the potable water network, but a legacy of millions of partial or whole LSLs remains in many public water systems.[2] Where the term "lead corrosion" is used, it refers to the corrosion of lead plumbing materials that result in the transfer of dissolved or particulate lead into the drinking water.

The Lead and Copper Rule (LCR) sampling is intended to measure the lead levels in drinking water to assess the effectiveness of corrosion control treatment utilized by public water systems (PWSs) to minimize lead in drinking water. PWSs are required to use sampling sites that are presumed to be the highest-risk sites for lead release, and to optimize corrosion control to minimize lead levels at consumers' taps. Most published sampling studies typically focus on systems having high lead levels or systems that have experienced challenges in attempting to balance LCR compliance with various other treatment or water quality objectives. Except for LCR compliance data, little published data exists or is available for systems that are considered to be operating with optimal corrosion control and meeting the lead action level (AL) in the LCR. This study focuses on a system that is considered to have optimized corrosion control using a blended phosphate, with a relatively stable water quality, and compliance results historically well below the lead AL. This situation is representative of a large percentage of systems serving 100,000 or more people that utilize orthophosphate or blended phosphates for corrosion control and the vast majority of systems are meeting the lead AL based on the current sampling protocol in the LCR. Additional information on the LCR and study is available in the Supporting Information (SI). This study focused on whether (1) the current LCR compliance sampling protocol adequately captures the peak lead levels in a water system; (2) "preflushing" (PF) results in capturing lower lead levels in samples compared to samples collected under normal household usage (NHU) conditions; (3) a first-draw sampling protocol appropriately determines the adequacy of optimal lead corrosion control in water systems with LSLs; and (4) there is seasonal variability in the sampling results using the different sampling protocols.

System Information. The Chicago Department of Water Management (CDWM) operates two similar conventional surface water filtration treatment plants serving approximately 5.4 million residents, including those in 125 suburbs. Lake Michigan is the sole water source, with relatively stable water quality leaving the treatment plants and in the distribution system (Table 1). Before the LCR, CDWM utilized pH/alkalinity adjustment for corrosion control. CDWM switched to a proprietary blended phosphate at both plants between 1993 and 1994 which is still used as the primary corrosion control treatment.

The LCR requires public water systems to collect lead samples using a first-draw (FD) sampling protocol, and samples were collected almost exclusively from single-family homes with LSLs as required by the LCR sample site selection require-

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Table 1. Water Quality Data 2011

parameter	outlets min	outlets max	distribution min	distribution max
temp (°C)	4	24	5	23
turbidity (NTU)	0.1	0.2	0.1	0.4
pH	7.5	7.8	7.7	7.8
Cl_2 residual (mg/L)	1.0	1.2	0.7	0.9
total alkalinity (mg/L as $CaCO_3$)	103	108	98	108
chloride (Cl, mg/L)	16	20	17	20
sulfate (mg/L)	29	31	29	30
Ca (mg/L)	34	39	34	39
PO_4 (mg/L)	0.4	0.6	0.5	0.5
total PO_4 (mg/L)	0.8	1.1	0.8	1.2
Al (μg/L)	34	126	29	113
Fe (μg/L)	<5	<5	<5	34
Mn (μg/L)	<3	<3	<3	<3

ments.[3] Since the initial LCR monitoring, Chicago has exceeded the lead AL only once, during July–December 1992, with an average 90th percentile compliance monitoring value between 1999 and 2010 of 6 μg/L (SI Table S2).[3]

The LCR requires 1-L, FD tap samples of water that has stood motionless in the plumbing system (i.e., has stagnated within the plumbing) for at least 6 h. The two variants of the FD sampling protocol currently used by public water systems are defined herein as the NHU first-draw sample, where water is used in a normal household manner, and then allowed to sit motionless in the plumbing for at least 6 h before the sample is collected; and the PF first-draw sample, where the water is run from the sampling tap for a specified amount of time immediately prior to the stagnation period. However, the LCR does not provide specific details on water use during the stagnation period.

Almost all PWSs in the U.S. rely on residents to collect compliance samples under the LCR and there are differences across the U.S. in how systems instruct residents not to use the water during the stagnation period prior to collecting the sample. A review of example sets of sampling instructions provided to residents by large PWSs in the U.S. found that some are instructed not to use any water *from the tap to be sampled* during the stagnation period. Others are instructed not to use *any water in the household*. Prior to 2009, CDWM used the PF first-draw sampling protocol, with a 5-min preflush preceding stagnation. Recent instructions to residents included not using water from the sampling tap or from any nearby tap until the (poststagnation) samples were collected, and to collect samples as soon as possible after the minimum required 6-h stagnation period. Regardless of the sampling protocol, resident-collected samples necessitate the use of simple instructions and make it difficult to ensure strict adherence to any sampling protocol. In addition, the diverse premise plumbing materials and configurations (SI Table S1) represent varying effects of flow rates, hydraulic flow characteristics, and possible lead sorption/particle release effects on the shapes of the lead profiles, particularly with corroded galvanized pipe locations.[4,5]

MATERIALS AND METHODS

Sampling Objectives and Protocol. Since the promulgation of the LCR, new research on lead corrosion has shown that there are many mechanisms and water quality factors involved.[1,4,6−11] Specifically, the sampling protocols used in this study were evaluated to determine if

- preflushing biases results;
- first-draw samples, with or without preflushing, capture the "worst-case" level of lead corrosion under normal use conditions; and
- seasonal variability affects lead concentrations (in this water system).

Consistent with the LCR requirements and CDWM compliance sampling, samples for this study were collected by volunteer residents from 32 single-family residences, built between 1890 and 1960, with LSLs. An additional 5 homes were sampled and determined not to have LSLs, and were therefore excluded from further sampling. All results are included in the Supporting Information, but the non-LSL sites were not used in the data analysis (SI Tables S4a, S5, S6a, S6b, and S7).

Information was requested on the specific plumbing configurations of each sampling site to a much greater extent than the regulatory requirements which simply require the plumbing material to be identified. This information, along with analyses conducted for lead, copper, iron, and zinc for each sample, facilitated a better understanding of the observed water lead levels. Residents were asked to (1) complete a plumbing profile identifying the kitchen tap and meter or internal shut-off valve, and (2) describe the internal plumbing, including any recent plumbing work (SI Figure S1). The information provided by residents along with the results of the four metals provided additional information on the sequences of plumbing materials, and the presence of in-line brass plumbing components. CDWM provided the locations of water mains, service line materials, work conducted by the city at each residence (meter installation or repair, shut-off valve repair/replacement, service line leak repair, street excavation), and monthly water use data for residences with water meters. The information provided by CDWM on water main locations was used to measure the distance from the water main to each residence, and internal plumbing information provided by residents was used along with the measured length from the water main to the residence to approximate the LSL length (SI Table S1).

Residents were provided with written sampling and reporting instructions for each sampling event (SI Figures S41−S45). One-liter, high-density polyethylene (HDPE), wide-mouth (5.5 cm, 2.2 in.) sample bottles were used to collect all samples. Residents were instructed not to remove aerators prior to sampling and not to collect samples after point-of-use or point-of-entry treatment devices.

Several prior studies have suggested that significant contributions of particulate-associated lead can be mobilized as a function of flow rate and turbulence in certain water chemistries, though studies have not developed predictive relationships to premise plumbing material, scale composition, and hydraulic flow characteristics.[6,10−15] To try to achieve the most aggressive high flow conditions under realistic field conditions, residents were instructed to collect all samples by slowly opening the cold water kitchen tap until fully open. Upon receipt, the samples were inspected by EPA for visible particulate matter prior to delivery to the laboratory.

For all first-draw samples, residents were instructed not to use any water throughout the household (i.e., no showering, washing clothes/dishes, flushing toilets, etc.) during the

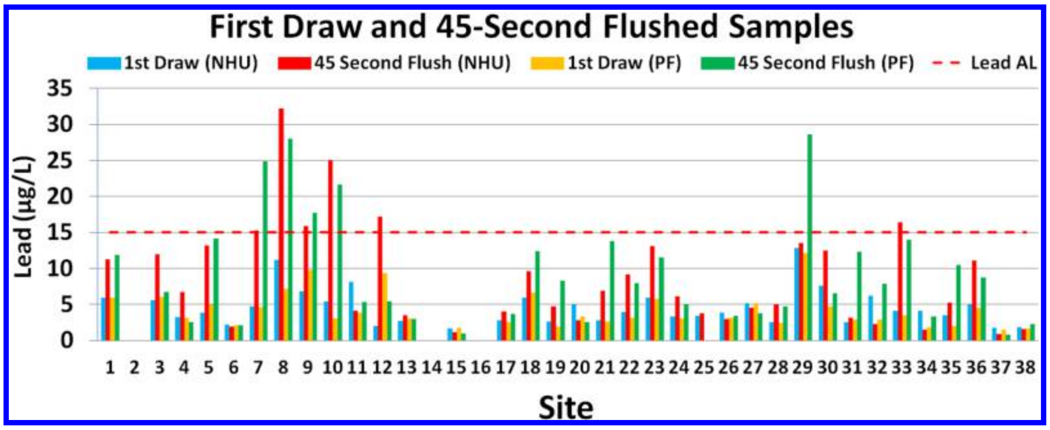

Figure 1. First round lead results for all sites.

minimum mandatory 6-h stagnation period. In this study, PF samples include a flush of at least 5 min prior to the mandatory minimum 6-h stagnation period. A NHU sample had no preflushing prior to the mandatory minimum stagnation period. Residents were instructed to allow the water to sit motionless in the household plumbing a minimum of 6 h, but not more than 24 h, and to record the dates/times the taps were flushed prior to the stagnation period, and the dates/times samples were collected following the stagnation period. First-draw samples using both variants (NHU and PF) were collected in the first and third rounds of monitoring in March/April and September/October, respectively. Additionally, 45-s flushed samples were collected in the first round to evaluate whether a second-draw sample more accurately captured the level of corrosion. Three-min, 5-min, and 7-min flushed samples were collected in the third round of sampling to provide guidance to volunteers when high lead levels were found (SI Table S7). This information can also be used to provide site-specific guidance on minimum flushing times necessary to reduce consumer exposure to lead in drinking water.

In the first round of sampling, each resident collected a NHU first-draw sample and then a second-draw (45-s flushed) sample after allowing the water to run for 45 s. On the second day, residents collected a PF first-draw sample and then a second 45-s flushed sample. EPA's current Public Notification Handbook advises[16] residents to run the water 30 s or until it turns cold before consuming, if the water has not been used for an unspecified "extended period of time", which can result in higher lead levels at the tap for consumers. It has also been previously demonstrated that in some situations, this advice can cause residents to consume the worst-case water sitting stagnant in the LSL.[17] (Figure 1)

Sites 14, 15, 16, and 37 were verified as not having LSLs and were excluded from further sampling. Site 2 was verified as not having a LSL following the June sequential sampling and was excluded from the final round of monitoring. The 45-s flushed sampling was discontinued following the March/April sampling first round due to the presence of severely corroded galvanized pipe in some of the residences (SI Figure S4) which reduced the inner pipe diameter, restricting water flow and resulting in varying volumes of water flowing through the plumbing for the same flush time.

In June 2011, each resident collected a total of twelve PF sequential samples in one day of sampling. The first PF sequential sample was also the PF first-draw sample for the data analysis. All samples were analyzed for lead, copper, zinc, and iron. The co-occurrence of the metals, along with plumbing details, was used in qualitative assessments to correlate lead results with potential sources of lead in the plumbing network (SI Figure S6).[4,10]

In September/October 2011, each resident collected a NHU first-draw sample, and a minimum of 11 PF sequential 1-L samples. Sites with high lead levels in the previous rounds collected an additional 3 or 4 PF sequential samples, and one site with a very long LSL (159 ft, 48 m) collected an additional 9 PF sequential samples. The additional PF sequential samples were collected to determine the point at which lead levels consistently dropped below the AL. All samples collected are included in the sampling summary with the numbers and types of samples collected at each site (SI Table S3).

Most stagnation times were relatively consistent across most sites at between 6 and 8.5 h, and all but two sites had stagnation times between 6 and 9 h 10 min, which facilitated unadjusted comparisons (SI Table S6c).

Additional flushed samples were collected in September/October for high lead sites in order to provide residents with guidance on minimizing lead levels in their drinking water. Recommended minimum flushing times were then estimated based on the lead levels and LSL lengths. These results are included in the Supporting Information, but not discussed here.

Sample Analyses. All samples were visually inspected for particulate matter prior to delivery to the EPA Chicago Regional Laboratory. Samples were preserved upon receipt by the laboratory using concentrated nitric acid to pH <2 and held for a minimum of 24 h prior to analysis.[18] The laboratory's Reporting Limits (RL) for lead, copper, and zinc in drinking water samples, using EPA Method 200.8, are 0.5, 1, and 10 µg/L, respectively. The laboratory's RL for iron in drinking water samples, using EPA Method 200.7, is 80 µg/L. Additional laboratory information is included in the Supporting Information.

■ RESULTS AND DISCUSSION

Both Variants of the First-Draw Protocol Significantly Underestimated Peak Lead Levels, and the NHU First-Draw Protocol Yielded Higher Results Overall than the PF First-Draw Protocol. The 90th percentile lead values for all three rounds of first-draw sampling using both variants were slightly higher than Chicago's historical compliance results, but still fell well below the lead AL (SI Table S4b). Only 2% of the total number of first-draw samples (3 of 151) exceeded the AL despite the presence of lead levels well above the lead action

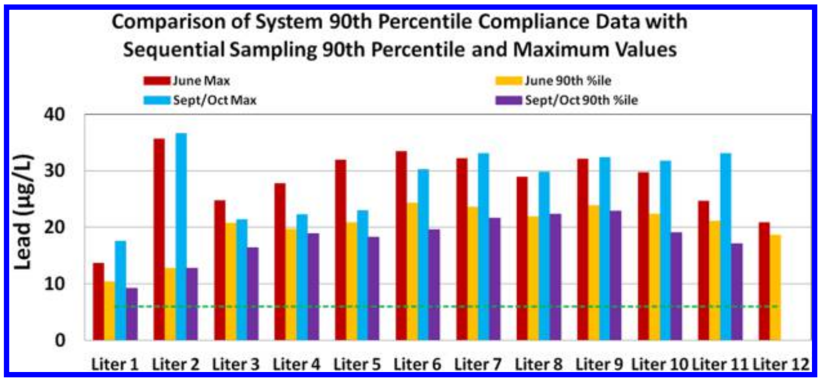

Figure 2. Comparison of 90th percentile LCR compliance data to 90th percentile values from LSL samples (across sites by liter) and maximum values from LSLs. The green dashed line indicates the average 90th percentile compliance monitoring value for Chicago between 1999 and 2010 of 6 μg/L.

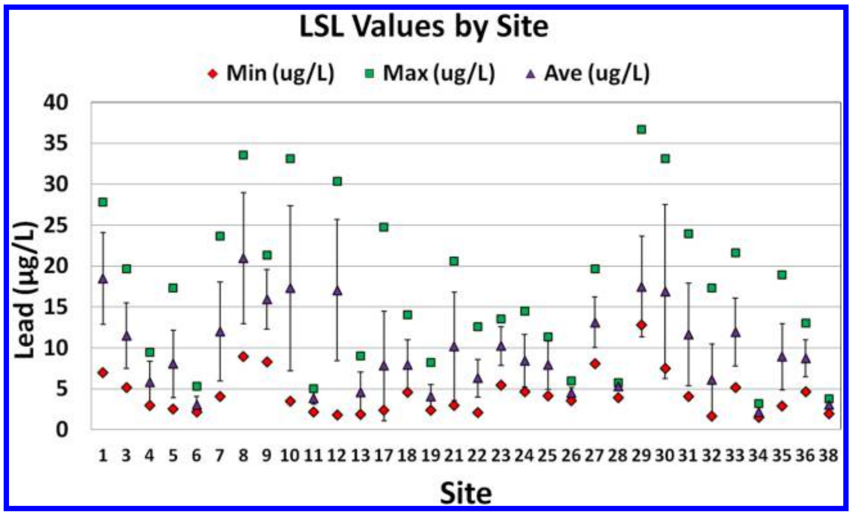

Figure 3. LSL results were highly variable within each LSL and from site to site. Error bars represent 1 standard deviation.

level within the service lines as indicated by the 45-s flushed results in the first round of monitoring and sequential sampling results in the second and third rounds.

In contrast, if the 90th percentile value of each of the successive sequential liter samples from the LSLs is computed across all sampling sites, the lead levels were up to four times higher than Chicago's average 90th percentile value using FD samples. Some peak values for each sequential liter calculated across all sampling sites were over twice the lead AL and up to six times higher than the regulatory compliance data (Figure 2). In summary, 69 of 336 (21%) of the individual sequential samples collected in June and 75 of 319 (24%) of sequential samples in September/October exceeded the lead AL, indicating that current sampling protocols will often considerably underestimate the peak lead levels and overall mobilized mass of waterborne lead in a system with lead service lines.

The NHU results were numerically higher overall than the corresponding PF values for most sites, but the differences were not statistically significant. The PF first-draw protocol produced lower individual results than NHU first-draw protocol in 23 of 32 sample pairs in March/April, and 20 of 27 sample pairs in Sept/Oct (SI Table S4a). Although NHU first-draw samples were collected without directing the residents to flush the tap prior to the stagnation period, NHU can involve showering, washing dishes, or doing laundry a short time prior to the stagnation period, which could clear the lead from the pipes similar to preflushing the tap. Thus a NHU sample can be effectively the same as a PF sample and yield similar results. Since the sequential sampling results from these same sites show that there is much higher lead present within the LSL at the same time that the NHU and PF first-draw samples were collected, it stands to reason that if the NHU activities were not undertaken, and a larger sample set were used, the NHU samples would yield results that were statistically higher than the corresponding PF samples. The distance from the kitchen tap to the beginning of the LSL was highly variable, ranging from approximately 3 to 87 feet (0.9 to 27 m), and the measured LSL lengths ranged from 43 to 159 feet (13 to 48 m). Consequently, for sites with shorter total plumbing lengths, the initial and final sequential samples would include relatively uncontaminated water from the water main following the 5-min tap preflushing. These samples would contain little to no LSL lead contribution, consistent with plumbosolvency and radial diffusion/flow principles.[5,19,20] A targeted LSL sampling protocol isolating only LSL contact water would likely yield a higher percentage of results above the lead AL for systems with Pb(II) pipe scale chemistry, but the specific location of the peak lead levels will necessarily vary with premise plumbing configurations.

Seasonal Variability. In a site-by-site comparison, lead concentrations were higher in Sept/Oct than in Mar/Apr or June, with the starkest statistical difference between first-draw

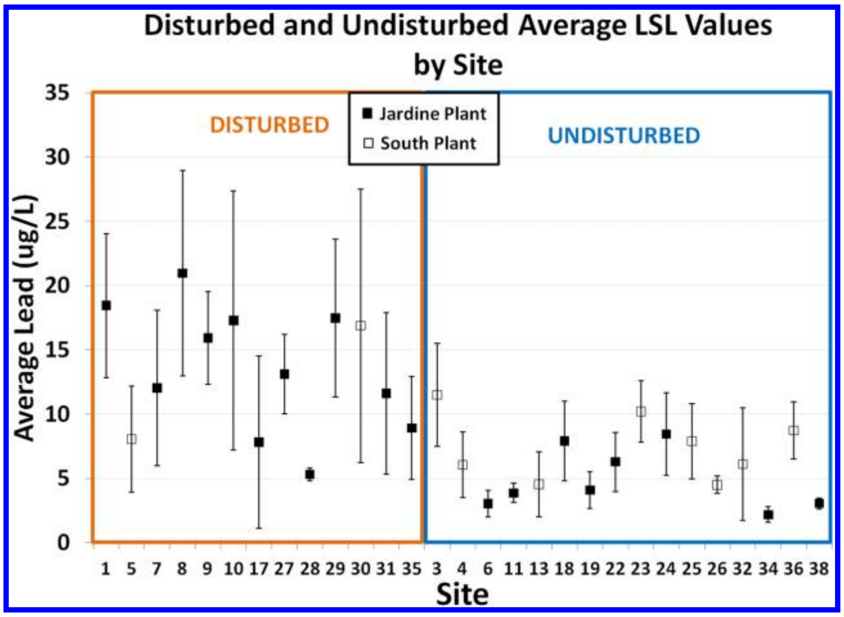

Figure 4. Average lead levels at disturbed and undisturbed sites. Error bars represent 1 standard deviation.

NHU samples collected in Mar/April and Sept/Oct ($p = 0.03$ for two-tailed paired Student's t-test). Overall, 68% and 69% of NHU and PF first-draw samples, respectively, were higher in Sept/Oct than in Mar/Apr, while 55% of paired sequential samples were higher in Sept/Oct than in June. Seasonal variation in lead levels consists of multiple contributing factors from the source water through the premise plumbing which could not be precisely isolated in this study, but the results in this study are consistent with other findings on seasonal variability (SI Table S6d).[21] Factors include (1) water temperature, (2) water chemistry variation, and (3) fluctuations in water usage for Sept/Oct versus June, which could increase or decrease lead levels.[22,23]

Lead Concentrations Vary Throughout Each Individual LSL and among Different LSLs Across the System. There was a high degree of variability in sequential sample results at most sites, some of which could include a particulate-bound component as reflected in spikes in some sequential sampling results (SI Figures S9−S40). For most sites, no individual sample result from within the LSL can *characterize* the lead concentrations at the site. Within the complete sampling profile results, lead levels at most sites ranged from well below to well above the AL (Figure 3). Under the LCR, this would mean that a system would meet the action level and have no additional regulatory requirements or would exceed the AL and be required to implement additional requirements, depending on which sample result is selected as the compliance sample. The variability within sites and between sites is similar in trend to that found in several other studies reporting sequential sampling conducted in water systems with different corrosion control strategies and chemistries from CDWM.[1,4,10,12,14,15,24−27]

Additional compliance data from a second large utility (City B) which exceeded the lead AL and conducted sampling using the temperature change LSL sampling protocol in the LCR,[3] yielded similar variability across the system (SI Figure S8 and Table S9). A total of 1975 LSL sites were sampled, with 1762 results (89%) below the lead AL; 128 results (6.5%) from 16 to 30 μg/L; 57 results (2.8%) from 31 to 50 μg/L; and 28 results (1.4%) between 51 and 580 μg/L. This LSL sampling protocol is similarly vulnerable to low biases, although many results were considerably higher than the AL (SI Figure S8).

Factors Affecting Lead Levels. The majority of high lead results occurred at sites with a documented physical disturbance of the LSL between 2005 and 2011 (Figure 4). The actual extent to which the LSL was physically disturbed is unknown for all sites, and the records of disturbances are based on information provided by CDWM and by the sampling volunteers (SI Figures S9−S40).

For the purpose of this study a physical LSL disturbance is defined as a meter installation or replacement, autometer-reader (AMR) installation, service line leak repair, external service shut-off valve repair or replacement, or significant street excavation directly in front of the home that could disturb the LSL. An "undisturbed" site is an unmetered site where neither the CDWM nor resident have a record or recollection of any disturbance, as defined above. A third category, "indeterminate", is used for three sites where CDWM has no record of any LSL disturbance, and the resident did not provide a response as to whether there has been any LSL disturbance. Cross-checking was important because information provided by volunteers in some cases contradicted CDWM records, and upon further investigation, the records were found to be incomplete and were corrected, which resulted in reclassification of the site.

Of the 13 disturbed sites, 11 sites had 3 or more sequential sampling results above the lead AL, two sites had 2 results each above the AL, and one site had no results above the AL. Of the 16 sites with no known disturbance, only three sites had any results above the lead AL. In the remaining 3 "indeterminate" sites, 30 of 81 sample results (37%) were above EPA's lead AL (Table 2).

A recent AWWA publication on the state of water infrastructure highlights the need for major infrastructure work.[28] This necessary infrastructure work will potentially increase the incidence of damage to the protective scales within LSLs as this work is performed. Inevitably, these physical LSL disturbances will continue to occur with increased frequency as part of daily routine water system maintenance and nonwater related community infrastructure work.

Table 2. Lead Results for Disturbed, Undisturbed, and Indeterminate Sites[a]

disturbed sites			undisturbed sites			indeterminate sites		
no. sites	no. samples	no. above AL	no. sites	no. samples	no. above AL	no. sites	no. samples	no. above AL
13	327	117	16	372	6	3	81	30
% samples over AL: 36%			% samples over AL: 2%			% samples over AL: 37%		

[a] Most lead results above the AL were found at sites with LSL disturbances. Additional results above the AL were also found at sites where the status of the LSL (disturbed or undisturbed) could not be confirmed. Sites without LSL disturbances had few if any results above the AL.

Possible Implications of Water Conservation and Use. Information provided by CDWM and volunteers anecdotally suggests that low water usage may also play a role in high lead levels at some sites. Of the four locations with the highest average lead levels, three (Sites 1, 29, and 10) had documented low water usage. Site 1 had average monthly water usage of 3444 gallons (13 037 L) which does not appear to be low usage. However, information provided by the resident indicates that the majority of the monthly water usage occurs during a relatively small number of days during the month when there is a high volume of water usage. Site 29 had average monthly usage of 1826 gallons (6912 L), and Site 10 had an average usage of 1438 gallons/month (5443 L/month). For comparison, the mean single-family household water usage is approximately 8582 gallons/month (32 486 L/month), with a sizable standard deviation.[29]

In two locations (Sites 17 and 5), lead levels decreased with an increase in water usage. As water usage approximately doubled at Sites 17 and 5, maximum lead levels from sequential sampling decreased from 25 to 5.5 μg/L and from 17 to 12 μg/L, respectively. Although this represents a small set of samples, these observations support the idea that higher lead levels can be associated with low water usage.[30]

Extrapolating from prior research suggests the necessity of consistent flow to deliver corrosion inhibitor effectively into passivating films,[31] and correlates increased inhibitor dosages with reduced lead release.[10,32−35] Low water usage may inhibit healing of the damaged scales, and influence the rate of galvanic corrosion. Water usage effects cannot be separated from other *seasonal* effects in this study, but prior literature and the combined sequential graphs showing entire profiles shifted up or down from the June to Sept/Oct sampling suggest further investigation is warranted (SI Figures S9−S40). As conservation efforts increase, it will become increasingly important to conduct further research on the relationship between water usage and increases in lead levels.

The results in this study also indicate that more appropriate flushing guidance must be developed, based on neighborhood and premise plumbing characteristics, and whether a home has a LSL or not. Much of the current published and web-based flushing guidance inadvertently increases the risk of exposure to elevated lead levels by clearing an insufficient amount of water volume.[17] Even fully flushing LSLs may only lower lead levels to a limiting, measurable lead level, that relates to the plumbosolvency of the water, the flow rate, the length and internal diameter of the pipe,[5−7,10,19,20] and possibly effects of prior disturbances (SI Table S7).

Risk Identification and Management. Recently, CDC issued a health alert associating higher elevated blood lead levels with partial LSL replacement,[36] and also concluded that LSLs were an independent risk factor for elevated blood lead levels even when lead levels in drinking water met the LCR lead AL of 0.015 mg/L.[37] As highlighted in this study, LSLs can contribute high lead when they are disturbed in many different ways, not just due to partial LSL replacement, and water usage may also play a role in the resultant high lead levels and potential increased human exposure. In an August 2012 update on lead in drinking water and blood lead levels, the CDC notes that *"The recent recommendations from the CDC Advisory Committee on Childhood Lead Poisoning Prevention to reduce or eliminate lead sources for children before they are exposed underscore the need to reduce lead concentrations in drinking water as much as possible"*.[38]

As the ultimate human and environmental health goal, LSLs should be completely removed where possible. The stability of the protective scales within LSLs depends on many factors which can change over time. For example, changes to water quality or treatment have resulted in high lead levels over a sustained period of time (years).[10,39−41] Under the current regulatory framework, elevated lead levels from disturbances, water quality, treatment, or water usage changes can potentially go undetected for up to 3 years between LCR compliance monitoring periods, which can result in increased public exposure over a significant period of time.

Proper selection of sampling sites, sampling protocol, and other site conditions is critical for evaluating the amount of lead corrosion and release that is occurring in the distribution system. Successful optimization of the plumbosolvency treatment depends on an accurate understanding of the corrosion mechanisms, pipe scale mineralogy and structure, and the consequences of LSL disturbances and water conservation efforts. No published studies could be found that systematically investigated the time and inhibitor doses/water quality adjustments necessary to overcome the disturbances and damage to the lead pipe scales that will be routinely occurring throughout cities across the U.S., as long as full or partial lead service lines remain in service.

Analyses of the Chicago LSL scales by EPA (to be reported elsewhere) reveal that the surface coatings on both lead service line and galvanized interior pipes from CDWM are primarily composed of amorphous aluminum, calcium, and phosphorus-rich deposits, and not crystalline lead(II) (or zinc)-orthophosphate phases that are predicted by conventional divalent lead plumbosolvency theory for orthophosphate dosing.[10,33,42] An understanding of the scales is essential to study and implement procedures and strategies for effective and timely repair of the protective scales damaged by LSL disturbances, and to minimize the public's exposure to high lead levels that can result from damaging the scales. Experimental evaluations are critical when scale compositions fall outside the scope of well-understood predictive corrosion control practices.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional background information, tabular summaries of sampling results, and graphics. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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Partial lead service line replacement with copper pipe creates a galvanic cell that can accelerate lead corrosion. Bench-scale experiments under stagnant water conditions of high chloride-to-sulfate mass ratio (CSMR) demonstrated that galvanic connections between lead pipe (new or aged) and copper pipe increased lead release into the water by 1.1 to 16 times, compared with a full length of lead pipe alone. The extent of galvanic attack was dependent on drinking water quality. Exposure to water of high CSMR increased lead release in the lead–copper rigs by 3 to 12 times, compared with a less-aggressive low CSMR water. Galvanic current also increased by 1.5 to 2 times when switching from low to high CSMR. The small area of lead pipe adjacent to the copper joint (< 0.5 ft) dissipated 90–95% of the total galvanic current and accumulated a thick (1-in.-wide) layer of lead rust (i.e., a lead-containing scale), which constituted a reservoir for semirandom particulate lead detachment into the water.

After a typical partial lead service line replacement, new copper pipe is connected to the remaining lead service line. The pipe running slantwise across the top of the photo marks the border of the property line. The pipe on the right is the lead service line left in the ground. The connection on the left shows the new copper pipe (short segment) attached to the remaining lead service line.

Galvanic corrosion after simulated small-scale partial lead service line replacements

SIMONI TRIANTAFYLLIDOU
AND MARC EDWARDS

Harmful health effects from lead (Pb) exposure through drinking water have been recognized in the United States since the 1850s. In that era, drinking water contamination by lead pipes was thought to be the main source of human-ingested lead, causing infant mortality, neurological effects, and digestive problems (Troesken, 2006). Lead service lines were the standard in many US cities through the 1950s and were occasionally installed even up to the ban of lead pipe in 1986 (Renner, 2010). As of 1990, 3.3 million lead service lines were estimated to be in service across the United States, and 6.4 million lead connections (e.g., goosenecks) were also acknowledged (Weston & EES, 1990). The actual remaining number of old lead service lines in the United States today is unknown.

BACKGROUND

Old lead service lines can contribute significant amounts of lead to water, potentially presenting health hazards to consumers. Depending on their length, diameter, water corrosivity, water use, and flow rates, old lead pipes can account for 50–75% of the lead mass measured in standing sequential samples collected at the tap (Sandvig et al, 2009). Lead in US drinking water is regulated under the Lead and Copper Rule (LCR), which may require replacement of utility-owned lead service lines if the LCR lead action level of 15 µg/L is exceeded (USEPA, 1991). Voluntary utility-owned lead service line replacement also routinely occurs during such activities as system maintenance or road repair (Renner, 2010).

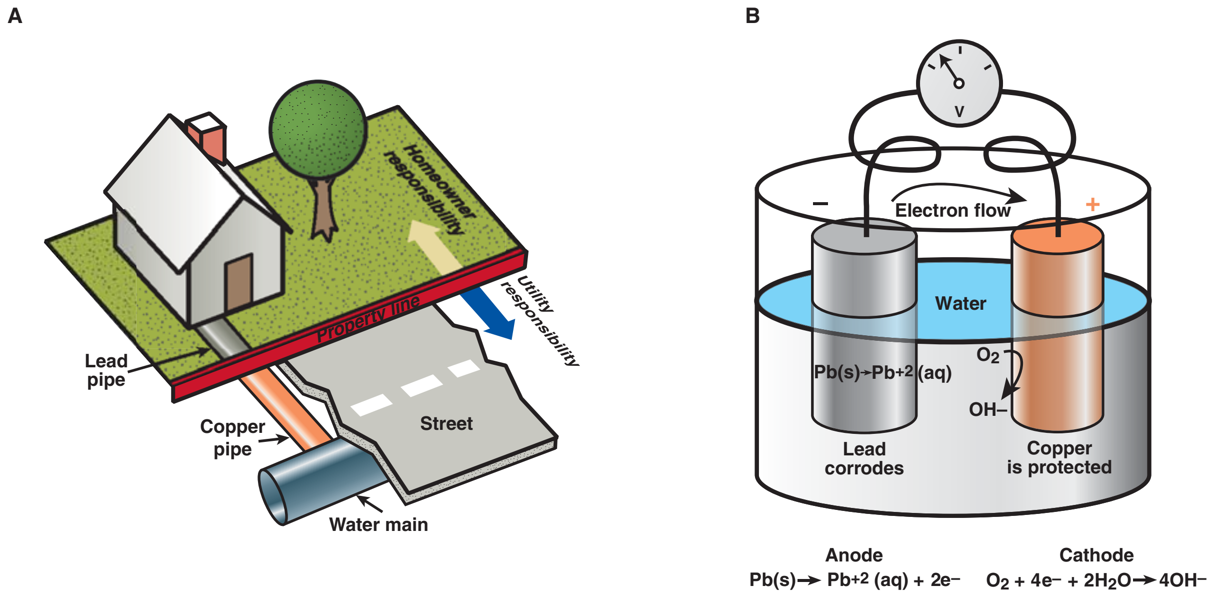
Partial lead service line replacement and its implications. If the lead service line extends onto the homeowner's property, the utility is required to replace only the portion of pipe that it owns, leaving behind the customer-owned portion of lead pipe (Figure 1, part A). The practice of partial lead service line replacement was assumed to provide health benefits because it would result in a smaller volume of water in contact with the lead pipe (USEPA, 2000). Although numbers vary dramatically from city to city and even from home to home, a national survey (Sandvig et al, 2009) indicated that the length of the typical US service line averages 55–68 ft, of which 25–27 ft (i.e., 40–45%) is under the utility's jurisdiction. Partially replacing a single lead service line can cost from $1,000 to more than $3,000 for water utilities (AWWA, 2005). Few customers voluntarily pay to replace their portion of the lead service line (Swertfeger et al, 2006).

The practice of replacing only the utility portion of lead pipe received newfound attention during implementation of the largest lead service line replacement program in US history in Washington, D.C. (Renner, 2010; Leonnig, 2008; Edwards, 2004) and then again after the Centers for Disease Control and Prevention (CDC) linked partial replacement of lead pipes to increased incidence of high blood lead levels in children living in D.C. (Frumkin, 2010). The CDC epidemiologic study found that "when lead service lines are partially replaced, children are more likely to have blood lead levels greater than or equal to 10 µg/dL, compared with children living in housing with either undisturbed lead service lines or service lines that are not made of lead" (Frumkin, 2010) or at least that "partially replacing lead service lines may not decrease the risk of elevated blood lead levels associated with lead service line exposure" (Brown et al, 2011). On the basis of this new information, some in the water industry have called for a moratorium on partial lead service line replacements (Renner, 2010).

The increased lead in water after partial lead service line replacements can arise from a variety of mechanisms and can possibly be relatively short-term (days to weeks) or longer-term (months to years) in duration (Chambers & Hitchmough, 1992). Short-term problems occur from disturbing the lead rust (i.e., scale) that has accumulated on the pipe over decades of use and/or from creating metallic lead particles when the pipe is cut (Schock et al, 1996). In the United States, these short-term mechanisms from cutting and scale disturbance have been definitively documented in laboratory experiments (Boyd et al, 2004).

Longer-term problems may arise from creation of a new electrochemical or galvanic cell if part of the old lead service line is replaced with copper pipe (Figure 1). Although the literature contains numerous warnings about the harmful effects of partial replacements because of these galvanic effects, there is a general lack of unambiguous laboratory data demonstrating whether these effects are significant (Table 1). Utilities in the United Kingdom have warned about adverse consequences of galvanic corrosion. For example, Chambers and Hitchmough (1992) noted, without citing data, that in practice, the galvanic effect between lead and copper may annul any beneficial effects of reducing the length of lead pipe in the system (Table 1). Other researchers (Breach et al, 1991) also reported on dangers from

FIGURE 1 Typical plumbing configuration after partial lead service line replacement (A) and conceptualization of galvanic corrosion caused by direct electrical connection of copper pipe to lead pipe (B)



Source: Triantafyllidou, S. and M. Edwards. **Contribution of Galvanic Corrosion to Lead in Water After Partial Lead Service Line Replacements.** ***©2010 Water Research Foundation. Reprinted with permission.***

aq—aqueons solution, Pb—lead

inserting copper pipes upstream of and electrochemically linked to lead, and earlier work (Britton & Richards, 1981) documented increased and erratic lead levels at the tap when copper–lead plumbing connections were present in front of homes (Table 1). The latter study cited extensive full-scale testing data from homes with and without partial replacements.

Recent research on galvanic corrosion indicated that any effect on lead leaching would not be significant. On the basis of surface potential measurements, Reiber and Dufresne (2006) concluded that galvanic effects were short-lived on aged and/or passivated lead service lines (Table 1). In that work, lead release to the water or the magnitude of the galvanic current was never measured. Another study (Kirmeyer et al, 2006), which also used continuous flow, concluded that galvanic coupling would not have any long-term effects on lead release (Table 1). In both of these studies, water was never allowed to stagnate inside the pipe, as occurs regularly in practice and which is known to initiate the worst-case galvanic attack because of the creation of much lower pH near the lead surface (Figure 1, part B). Previous work demonstrated that stagnation is key to initiation of galvanic corrosion problems in practice (Nguyen et al, 2010a; Dudi, 2004; Breach, 1991). More recently, DeSantis and colleagues (2009) provided clear visual and mineralogic documentation of lead galvanic corrosion in some harvested pipe connections that were excavated after 70–114 years in service (Table 1).

Galvanic corrosion of lead. The importance of this type of attack was first documented in the United Kingdom as early as 1859, when it was realized that “the solution of lead was assisted by contact with other metals” and that galvanic corrosion was “a most powerful agent in promoting the corrosive action of certain waters upon lead” (Ingleson, 1934). When copper pipe is electrically

TABLE 1 Summary of studies on galvanic corrosion between lead and copper plumbing (in chronological order)

Study	Type	Flow Rate/Frequency	Measurements	Relevant Concluding Quote
Britton & Richards, 1981	Field sampling of houses with mixed lead–copper plumbing	Real-world conditions; flow rate unknown	Lead in water; sampling details not provided	“Occasionally, the insertion of copper pipe [in lead plumbing] can produce particularly bad results, and despite pH control it might be impossible to obtain satisfactory samples.”
Breach et al, 1991	Practical experiences of a big UK company in minimizing lead at the tap	Real-world conditions; flow rate unknown	Lead in water; sampling details not provided	“Another area of possible concern that should not be overlooked is the dangers arising from inserting copper pipes or other apparatus upstream of and electrochemically linked to lead.”
Chambers & Hitchmough, 1992	Practical experiences of UK water companies on partial LSL replacements	Real-world conditions; flow rate unknown	Lead in water; sampling details not provided	“The creation of a galvanic cell, giving rise to increased and erratic levels of lead at the tap, may well annul any benefit of reducing the length of lead pipe in the system.”
Dudi, 2004	Laboratory examination of lead–copper pipe connections	No flow except during water changes	Galvanic current; lead in water	“Galvanic connections between copper and lead can dramatically worsen lead leaching under a wide range of circumstances.”
Kirmeyer et al, 2006	Laboratory examination of harvested LSLs, later connected to new copper pipe	Low flow rate of 1.3-L/min continuous flow	Lead in water	“Galvanic coupling has little relevance to accelerating metal release on the LSL and is an easily managed process.”
Reiber & Dufresne, 2006	Laboratory examination of polarization cells mounting harvested LSLs and new copper tubing	Continuous flow	Surface potential; no measurements of lead in water	“Galvanic impacts on aged and passivated LSL surfaces are minimal and in the long term, likely inconsequential.”
DeSantis et al, 2009	Examination of corrosion scales on harvested domestic lead–copper joints	Real-world conditions; flow rate unknown (> 70 years in service)	Micro/macro-characterization of scale solids; XRD	“Deep localized corrosion in the area adjacent to the pipe joints suggests a galvanic mechanism.”
Nguyen et al, 2010a	Continuation of HDR work using same apparatus	No flow except during water changes	Galvanic current; lead in water	“Clear conclusions about the effects of Pb:Cu galvanic connections on leaching of lead from lead pipe are not possible. Additional research is needed.”
Nguyen et al, 2010b	Laboratory examination of macrocells connecting copper pipe and lead wire	No flow except during water changes	Galvanic current; lead in water; chloride; sulfate; pH at anode/cathode microlayers	“Microlayer effects can explain a subset of persistent lead corrosion problems in some buildings and from lead:copper service line joints at some water utilities.”

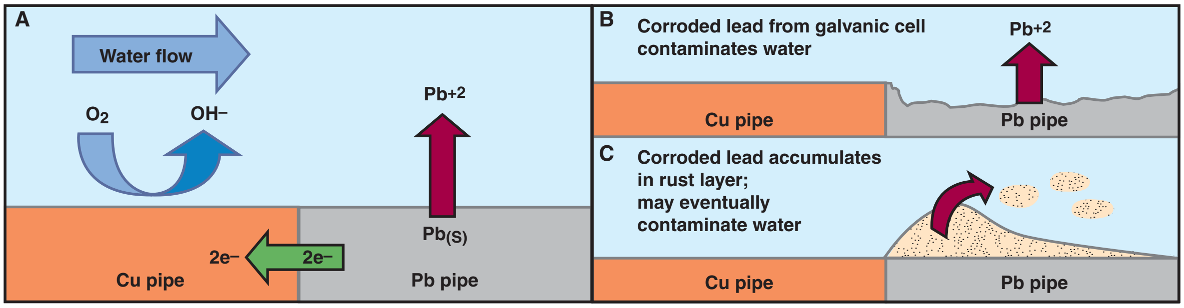
Cu—copper, LSL—lead service line, Pb—lead, UK—United Kingdom, XRD—X-ray diffraction connected to lead pipe, it can accelerate corrosion of the lead pipe by galvanic action, above and beyond corrosion that would normally occur for lead pipe alone. The drinking water in contact with these dissimilar metals serves as the electrolyte. On the basis of the galvanic series (Davis, 2000), metallic lead typically serves as the anode of this galvanic cell and is therefore oxidized (i.e., corroded) to form Pb^{+2} (Figure 2, part A). The copper pipe typically serves as the cathode, where the cathodic reaction (such as dissolved oxygen reduction) occurs over its surface (Figure 2, part A).

The production of Pb^{+2}, which is a Lewis acid, can cause a local pH drop and draw chloride ions to the lead anode surface (Nguyen et al, 2010b; Dudi, 2004). According to several studies (Edwards & Triantafyllidou, 2007; Edwards et al, 1999; Gregory, 1985; Oliphant, 1983), lead leaching to water can be increased indefinitely because of higher corrosion rate, lower pH, and higher chloride, especially in waters with a relatively high chloride-to-sulfate mass ratio (CSMR). Additional mechanistic insights that explain CSMR effects on galvanic corrosion of lead-bearing materials are presented elsewhere (Nguyen et al, 2010b).

The Pb^{+2} ions that are produced at the junction can be directly released into drinking water and contaminate it (Figure 2, part B), or they may accumulate in a lead-rust layer on the interior surface of the lead pipe (Figure 2, part C). In the latter situation, under high water flow or other disturbance, lead particles may eventually detach and contaminate drinking water with erratic "spikes" of lead (Figure 2, part C).

Deposition corrosion of lead. Another potentially important, yet unappreciated, microgalvanic phenomenon is deposition corrosion (Dudi, 2004). Deposition corrosion can occur when soluble ions from a more cathodic metal, e.g., copper, are present in the drinking water flowing through a lead pipe. Britton and Richards (1981) first noted that "each site of copper deposition [on the lead pipe] has potential to act as an individual galvanic cell" and raise the lead concentration in water. Deposition corrosion can be viewed as a two-step microgalvanic process. To illustrate, cupric ions (i.e., Cu^{+2}) released from a copper pipe installed upstream of lead pipe can be directly deposited and plated onto the lead surface (Figure 3, part A). The newly plated

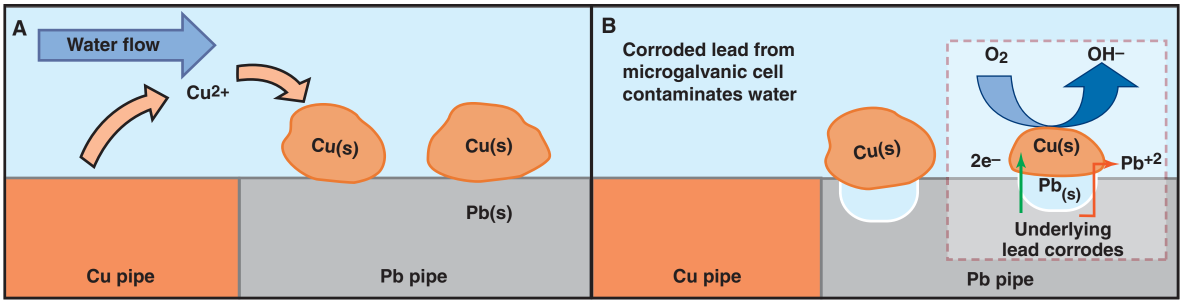
FIGURE 2 Conceptualization of galvanic corrosion and its effects



Cu—copper, Pb—lead

Galvanic corrosion can occur when copper pipe is connected to lead pipe (A), with the copper pipe typically serving as the cathode. Corroded Pb^{+2} can be released into drinking water, thereby contaminating the water (B), or can attach to the lead pipe, creating an accumulating rust layer on the interior pipe surface near the joint (C). Lead particles may eventually detach from this rust layer, causing random lead spikes in potable water (C).

FIGURE 3 Conceptualization of deposition corrosion, when a copper pipe is installed upstream of a lead pipe



Cu—copper, Pb—lead

The newly plated copper metal, in contact with the lead pipe surface (A), can form a microgalvanic cell that catalyzes oxygen reduction and causes oxidation (i.e., corrosion) of the underlying lead metal (B).

copper metal then forms a microgalvanic cell, which can catalyze corrosion of the underlying lead indefinitely (Figure 3, part B). Through this process, numerous microgalvanic cells, or "batteries," can be "turned on" at the surface of the lead pipe, accelerating corrosion of the lead pipe and contamination of the flowing drinking water (Dudi, 2004). This mechanism was recently proved to be significant for lead pipe corrosion in experiments in the presence of trace levels of Cu^{+2} ions (Nguyen et al, 2009). In those experiments, lead release increased when more Cu^{+2} was dosed to the water, whereas less than 15–50% of the initial dosed Cu^{+2} was measured in the water after exposure to the lead pipes. This suggested that the missing copper fraction had deposited onto the lead pipe (Nguyen et al, 2009).

The US Environmental Protection Agency (USEPA) has indicated a willingness to re-evaluate regulations that cover partial lead service line replacement as part of the 2012 long-term revisions to the LCR (Renner, 2010). The current work was intended to inform decision-making by conducting the first long-term study of galvanic effects on lead release into drinking water under well-defined laboratory conditions.

MATERIALS AND METHODS

The experimental apparatus was constructed to track lead leaching from simulated small-scale partial lead service line replacement with copper. The test rigs consisted of a copper pipe section—type M, ¾-in. internal diameter (ID), ⅞-in. outer diameter (OD)—that was electrically connected to lead pipe (¾-in. ID, 1-in. OD), with a total rig length of 3 ft (Figure 4). The lead and copper portions of each rig were separated by a ¼-in. insulating spacer and could be externally connected via grounding strap wires (Figure 4). If the wires were disconnected, direct galvanic corrosion between lead and copper did not occur, but if the wires were connected, the galvanic current flowed as usual (Figure 4).

The fraction of the pipe that was lead and the fraction of the pipe that was copper were systematically varied, as would occur in partial replacements with different percentages of consumer ownership of the service line. Specifically, 100% lead pipe (simulating a lead service line before replacement), 100% copper pipe (simulating full replacement), and four increments in between (i.e., 17, 50, 67, and 83% copper pipe to simulate partial replacements) were tested (Figure 4).

Four sets of rigs were constructed, using four types of lead pipe, as described here.

- New Pb pipe was lead pipe that had not yet been used in experiments.
- Aged Pb pipe A was lead pipe that was initially new but had been previously used in other short-term experiments of four months.
- Aged Pb pipe B consisted of lead pipe that was initially new but had been previously used in other longer-term experiments of one year. Each of these older lead pipes was 0.5 ft long. For the needs of this experiment, the third set of rigs was constructed by connecting together in series as many short lead pipes as needed, in order to add up to the desired lead length.
- Pb(IV) pipe was lead pipe that was exposed to recirculating water with excess chlorine to form an interior brown corrosion layer of Pb(IV) solids right before the beginning of the experiment.

The first three sets of lead pipe (new Pb pipe, aged Pb pipe A, and aged Pb pipe B) were pretreated in the same way before construction of the rigs. They were exposed to recirculating pH 2.0 water (deionized water with the addition of sulfuric acid) for 3 h in order to remove surface rust and deposits. They were subsequently rinsed with deionized water for 15 min, exposed to pH 10.0 water (deionized water with the addition of sodium hydroxide) for another 3 h, and finally rinsed with deionized water for another 15 min.

Experimental phases. The experimental period lasted more than one year and consisted of several phases.

Phase 1. During weeks 1–11, all rigs were exposed to "low-CSMR water," a synthetic tap water with a low CSMR of 0.2. This water also had an alkalinity of 15 mg/L as calcium carbonate ($CaCO_3$), monochloramine disinfectant dosed at 4.0 mg/L as Cl_2, ionic strength of 4.6 mmol/L (by addition of salts to mimic other tap water constituents), and pH of 8.0 (Table 2).

Phase 2. During weeks 12–25, after baseline results had been established in the nonaggressive water, the test water was switched to "high-CSMR water," an aggressive synthetic tap water with a high CSMR of 16. All other water parameters such as alkalinity, monochloramine, ionic strength, and pH were kept the same as in the low-CSMR water of phase 1 (Table 2).

Phase 3. For weeks 26–31, the rigs continued to be exposed to the high-CSMR water as in phase 2, but the connecting strap wires were removed so that there was no direct galvanic corrosion between the lead and copper pipes.

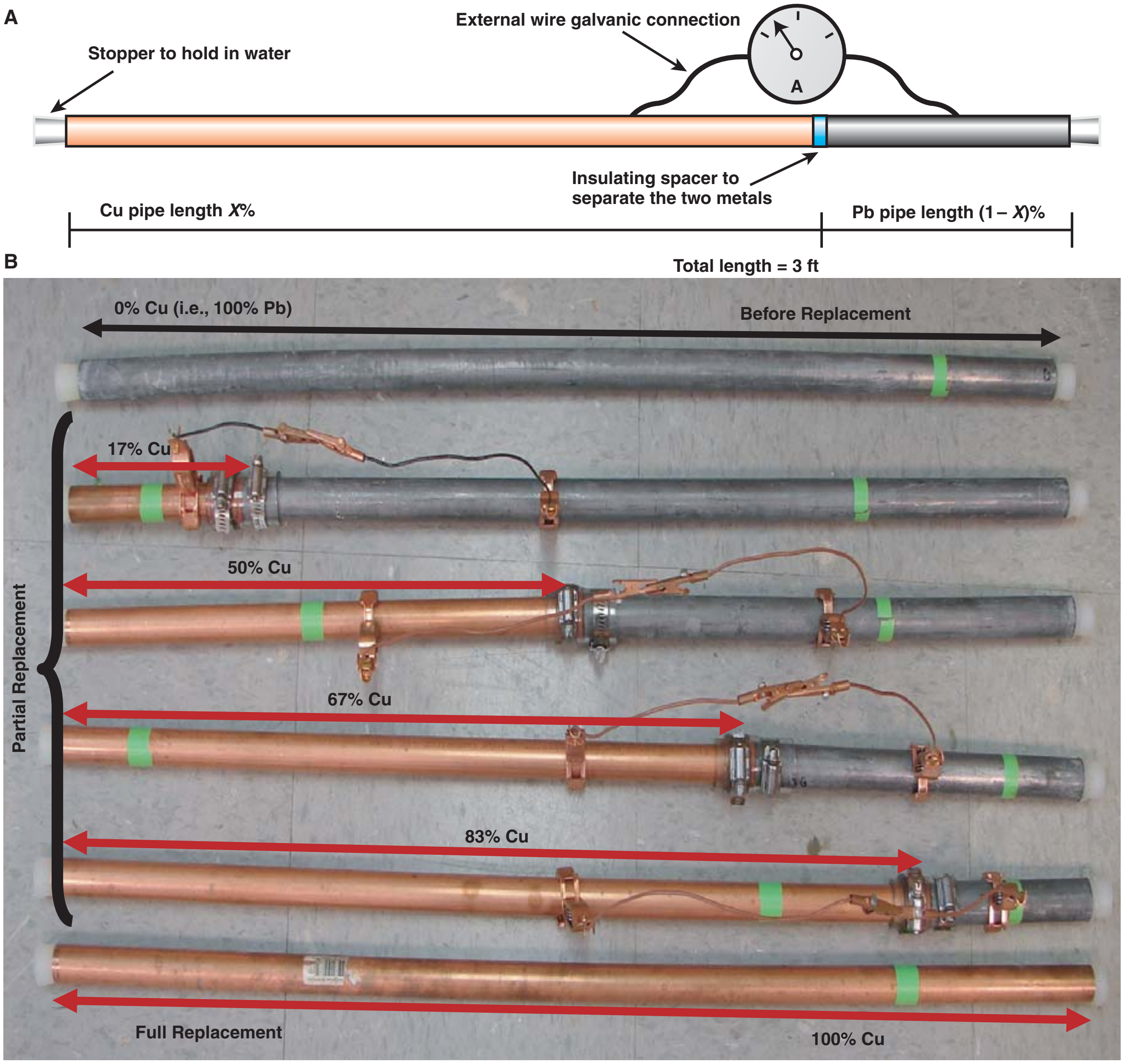
Phase 4. For weeks 32–37, the rigs continued to be exposed to the high-CSMR water as in phase 2, but the connecting strap wires between the lead and copper pipes were reconnected, thereby reactivating galvanic corrosion.

Additional experiments. Following phase 4, additional experiments were conducted. The rigs were exposed to high-CSMR water that was modified by gradually increasing the alkalinity level from 15 to 50 mg/L as $CaCO_3$ (weeks 38–41) and then from 50 to 100 mg/L as $CaCO_3$ (weeks 42–51). Alkalinity levels throughout the experiment were adjusted by adding the appropriate amount of sodium bicarbonate from a fresh stock solution to the synthetic water.

Throughout the experiment (i.e., in all phases), water was completely changed inside the pipes three times per week, using a dump-and-fill protocol. Lead release from the rigs was therefore evaluated under worst-case stagnation conditions, which are known to promote galvanic corrosion problems in practice (e.g., Dudi, 2004). These worst-case stagnation conditions represented the extremes in water use that may be encountered at schools and municipal-type buildings during weekends and/or breaks and at homes during prolonged absences. The galvanic connection's contribution—or lack thereof—to lead release was assessed by measuring total lead concentration in water and galvanic current magnitude as follows:

- One composite water sample was collected at the end of each week from each pipe by pouring the three water samples of that week into the same container. Total lead was quantified in these unfiltered composite water samples using an inductively coupled plasma/mass spectrometer[1] according to method 3125 B (*Standard Methods*, 1998). Water samples and instrument calibration standards were prepared in a matrix of 2% nitric acid by volume.
- Galvanic current between the dissimilar metals (for phases 1, 2, and 4 when the external wires were connected) was measured with a digital multimeter purchased at a retail electronics store (internal resistance determined at 100 Ω). The current flowing in each rig was measured

FIGURE 4 Generalized schematic of the experimental setup to assess the contribution of galvanic corrosion to lead in water after partial lead service line replacement (A) and depiction of the varying copper–lead ratios (B)



Source: Triantafyllidou, S. and M. Edwards. **Contribution of Galvanic Corrosion to Lead in Water After Partial Lead Service Line Replacements.** *©2010 Water Research Foundation. Reprinted with permission.*

A—ampere, Cu—copper, Pb—lead

by connecting the multimeter in line for 15 s after disconnecting the wire between the two metals.

RESULTS AND DISCUSSION

Detailed results are presented for new Pb pipe, followed by a summary of results for the other lead pipes, i.e., aged Pb pipes A and B and Pb(IV) pipe.

Temporal trends on lead release. After an initial stabilization period of the first three weeks of phase 1, lead release under exposure to low-CSMR water (weeks 4–11) became relatively low for each rig (Figure 5). The rig with pure lead pipe (i.e., 0% copper) released 120–320 µg/L of lead during that time frame. As expected, the rig with no lead pipe (i.e., 100% copper) released no lead, providing assurance that copper pipes would not release any lead and that sample contamination was not occurring. Lead leaching during exposure to low-CSMR water always increased in rigs with copper and lead galvanic connections, compared with pure lead pipe (Figure 5).

When the water was switched to high-CSMR in phase 2 (weeks 12–25), lead release from the galvanic connections dramatically increased and remained elevated throughout that time period; the high-CSMR water also increased lead release from pure lead pipe, i.e., 0% copper pipe (Figure 5). During phase 3 (weeks 26–31), when galvanic corrosion was inactivated by disconnecting the wires, lead levels plummeted even though the high CSMR water was still fed to the rigs (Figure 5). When galvanic corrosion resumed its action during phase 4 (weeks 32–37), lead release to the water immediately rose to levels previously experienced during phase 2 (Figure 5). This demonstrated the direct role of galvanic corrosion in sustaining high lead concentrations in water from the lead–copper rigs of the study.

Synthesis: Effect of galvanic corrosion and CSMR on lead release. With the exception of weeks 1–3, when lead release had not yet stabilized, results were synthesized by averaging the lead data for each experimental phase. As shown in Figure 6, all simulated partial replacements (17, 50, 67, and 83% of lead replaced by copper) released more lead to the water than did the rig consisting of pure lead (i.e., 0% copper). This was true for all three galvanic experimental phases, and results were statistically significant at the 95% confidence level (Figure 6, error bars plotted). Specifically, lead release from simulated partial replacements increased by 4–27 times (depending on the extent of replacement) during phase 1, by 2–7 times during phase 2, and by 7–20 times during phase 4, compared with a full length of lead pipe alone. Therefore, for this set of pipes, not only did the galvanic effect "annul any benefit from reducing the length of lead pipe" (Chambers & Hitchmough, 1992), but it further "exacerbated lead release" (Britton & Richards, 1981).

When the wires were connected, high-CSMR water released much more lead to the water than did low-CSMR water. In fact, Figure 6 shows that compared with lead release in low-CSMR water (phase 1), lead release in high-CSMR water (phase 2) increased by 5 times (in the case of 17% copper) to as much as 12 times (in the case of 83% copper). It is important to note, however, that the adverse effects of galvanic corrosion on lead leaching were still significant even in the water with low CSMR. Disconnecting the wires under high-CSMR water (phase 3) decreased lead release by 4–6 times in all copper–lead galvanic couples, whereas reconnecting the wires under high CSMR water (phase 4) increased lead release by 4.5–8 times (Figure 6).

During phase 3, lead release from all the deactivated galvanic rigs was not statistically higher than lead release from pure lead pipe (Figure 6). Lead release from those rigs was not statistically lower either (as would be expected because of their smaller lead surface area) compared with the pure lead pipe. This may be because other additional corrosion mechanisms were present in the lead–copper rigs during phase 3 compared with the pure lead pipe, even in the absence of galvanic connection to copper, such as copper deposition corrosion onto the lead pipe. Alternatively, it is possible that the rigs had not yet "recovered" from the previous phase (phase 2) of galvanic connection.

The extent of lead contamination was initially somewhat dependent on the extent of partial replacement. For instance, when the rigs were exposed to low-CSMR water with connected wires (phase 1), the rig consisting of 17% copper (with the remaining 83% being lead) released the highest lead. Results from the 50 and 67% copper rigs were not statistically different, and the 83% copper rig

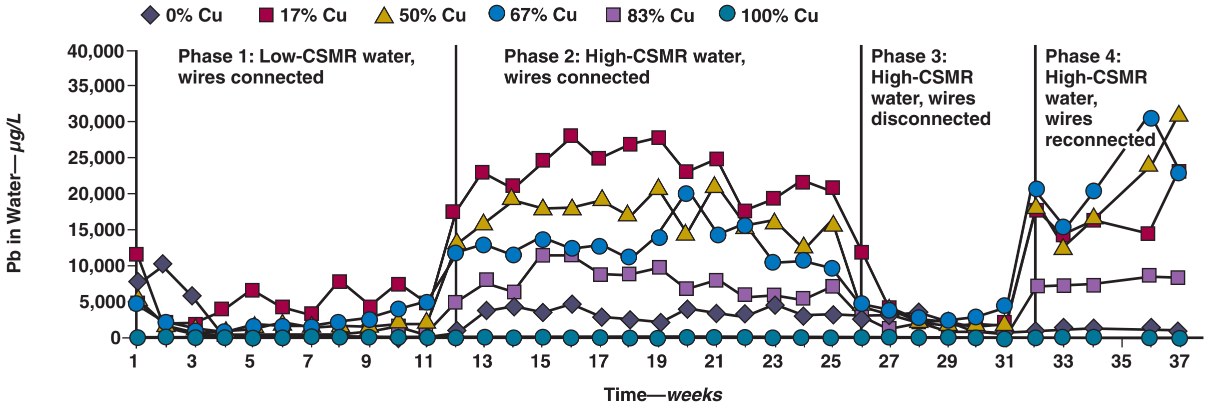
TABLE 2 Key characteristics of the synthetic waters utilized in the experiment

Water	Cl^- *mg/L*	SO_4^{-2} *mg/L*	CSMR	Alkalinity *mg/L as $CaCO_3$*	Ionic Strength *mmol/L*	NH_2Cl *mg/L as Cl_2*	pH
Low-CSMR water (phase 1)	22	112	0.2	15	4.6	4.0	8.0
High-CSMR water (phases 2, 3, 4)	129	8.0	16	15	4.4	4.0	8.0
High-CSMR water, alkalinity of 50 mg/L as $CaCO_3$ (subsequent tests)	129	8.0	16	50	5.1	4.0	8.0
High-CSMR water, alkalinity of 50 mg/L as $CaCO_3$ (subsequent tests)	129	8.0	16	100	6.1	4.0	8.0

$CaCO_3$—calcium carbonate, Cl^-—chloride, Cl_2—chlorine, CSMR—chloride-to-sulfate mass ratio, NH_2Cl—chloramine, SO_4^{-2}—sulfate released the lowest lead among the conditions representing partial pipe replacements. For the worst-case experimental condition of high CSMR and connected wires (phase 2), the rig consisting of 17% copper released the highest lead, followed by the 50, 67, and 83% copper rigs (Figure 6). In other words, less copper relative to lead worsened lead corrosion at the initial experimental phases. When the rigs were subsequently exposed to high-CSMR water with disconnected wires (phase 3), no statistically significant differences in lead release were observed among the 17, 50, 67, and 83% copper rigs (Figure 6). Similarly, during phase 4 of exposure to high CSMR water with reconnected wires, no statistically significant differences in lead release were seen among the 17, 50, and 67% copper rigs (Figure 6).

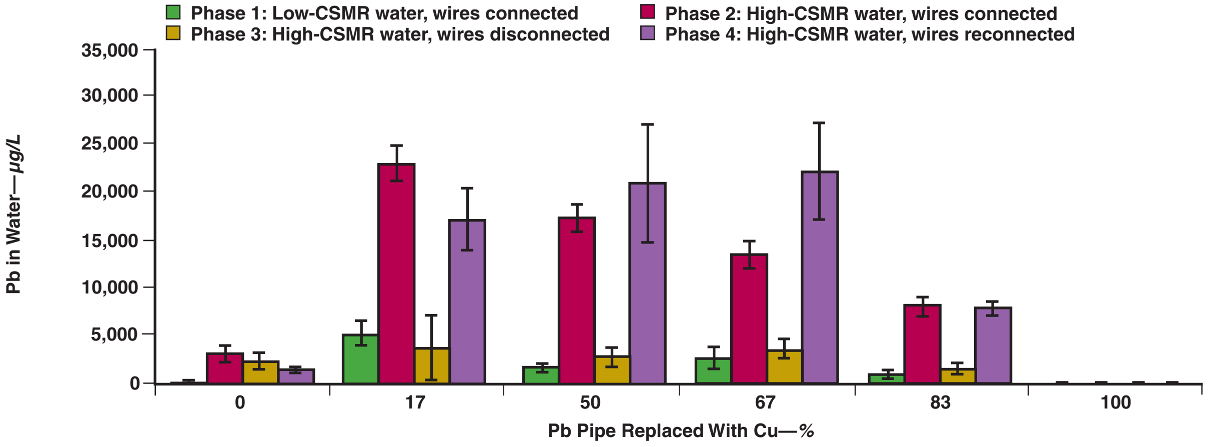
Deviation of experimental lead leaching results from conventional theory. The experimental results provided a scientific framework for evaluating extremes in behavior that might be encountered in practice. At one extreme, it is hypothetically possible that in some waters there is negligible galvanic corrosion between lead and copper pipe. In such cases, lead release from partial replacement of lead pipe with copper will follow a linear model (Figure 7). If 100% of the lead pipe is replaced, there will be no lead in water. If 50% of the lead pipe is replaced with copper, there will be 50% less lead in the water volume held in the service line than before partial replacement. In such a case, partial replacement will be beneficial after short-term problems with pipe cutting dissipate (Boyd et al, 2004), and the extent of the benefit will be proportional to the extent of replacement of the lead pipe with copper pipe. Laboratory results obtained in the current research deviated significantly from the linear model because of galvanic corrosion. For the low-CSMR water (phase 1), partial

FIGURE 5 Lead release versus time for connections of lead pipe to copper pipe



CSMR—chloride-to-sulfate mass ratio, Cu—copper, Pb—lead

FIGURE 6 Lead release versus extent of lead pipe replacement by copper



CSMR—chloride-to-sulfate mass ratio, Cu—copper, Pb—lead

Data were averaged for each experimental phase. Error bars denote 95% confidence intervals.

replacements released 18–38 times more lead to the water than the theoretical linear model suggested (Figure 7, part A). For the high-CSMR water (phase 2), partial replacements released 8–14 times more lead than the relevant linear theoretical model (Figure 7, part B).

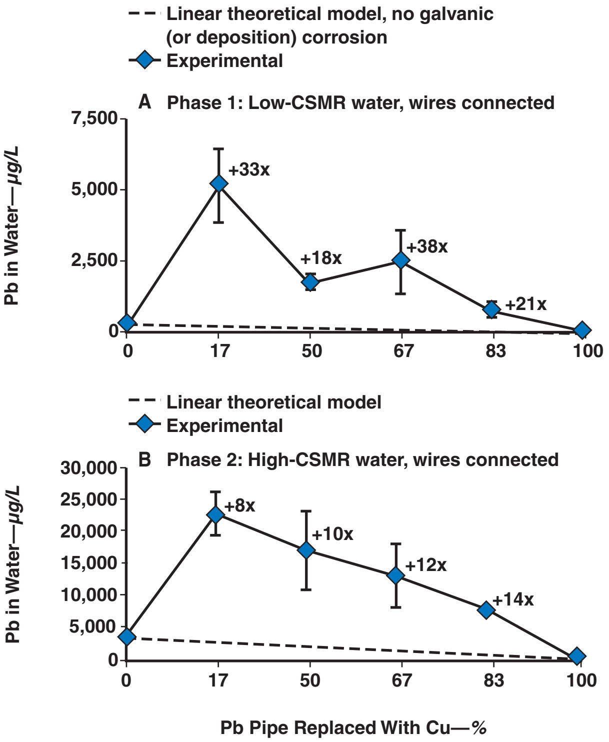
Mechanistic insights via galvanic current measurements. Measurement of the galvanic current between the lead and copper portion of the rigs can provide mechanistic insights on the observed trends for the leaching of lead. The galvanic current is a direct measure of the instantaneous rate of galvanic corrosion between the lead pipe and the copper pipe. A higher magnitude of current indicates a higher rate of galvanic corrosion.

Galvanic current measurements were taken during phases 1, 2, and 4 of the experiment when galvanic corrosion was activated. Because the wires were disconnected during phase 3, thereby blocking electron flow between the two dissimilar metals, no current measurement was obtained. Lead always behaved as the anode and copper as the cathode of each galvanic cell in all measurements undertaken in these experiments.

As shown in Figure 8, higher currents were measured when high-CSMR water was fed to the rigs (phase 2) than when low-CSMR water was fed to the rigs (phase 1). This general trend was consistent with the trend in lead leaching (Figures 5 and 6). Under the condition of high-CSMR water and connected wires (phase 2), the highest current of 87 µA was measured for the 17% copper rig, followed by successively lower current readings for the 50, 67, and 83% copper rigs (Figure 8). The ranking of the rigs with respect to the magnitude of the measured galvanic currents typically was consistent with rankings from the lead leaching results. For instance, the 17% copper rig had the highest measured current (Figure 8), and it also resulted in the highest lead-in-water concentrations (Figure 6). Under the condition of low-CSMR water and connected wires (phase 1), the highest current of 52 µA was measured for the 17% copper rig, followed by the 50, 67, and 83% copper rig (with the lowest current of 30 µA). Under the condition of high-CSMR water and reconnected wires (phase 4), the highest current of 85 µA was measured for the 17 and 50% copper rigs, followed by the 67 and 83% copper rigs (the latter having the lowest current of 57 µA).

Unlike phase 2, the ranking in terms of galvanic current magnitude during phases 1 and 4 (Figure 8) did not always agree with the ranking based on the respective results for lead leaching (Figure 6). Obviously, the galvanic current between lead and copper is a measure of galvanic corrosion only and does not account for lead release attributable to normal lead dissolution or deposition corrosion. Moreover, the corroded lead attributable to galvanic currents could also form lead rust on the pipe surface and be only partly released into the water (Figure 2, parts B and C). As shown in Figure 9, Pearson's correlation coefficient R^2 between galvanic current magnitude and lead-in-water concentration was 0.41 under

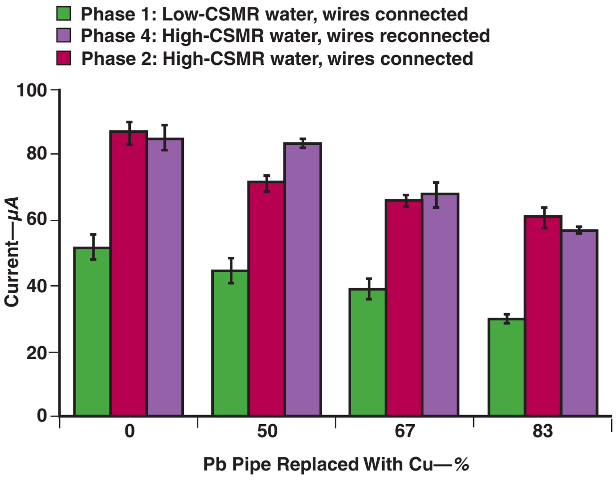
FIGURE 7 Deviation of experimental lead release results from a linear theoretical model, which assumes that lead dissolution is proportional to the length of lead pipe



CSMR—chloride-to-sulfate mass ratio, Cu—copper, Pb—lead

Error bars on experimental data points denote 95% confidence intervals.

FIGURE 8 Galvanic current versus extent of lead pipe replacement by copper



CSMR—chloride-to-sulfate mass ratio, Cu—copper, Pb—lead

Data were averaged for each experimental phase. Error bars denote 95% confidence intervals.

exposure to low-CSMR water (phase 1) and 0.71 under exposure to high-CSMR water (phase 2).

Effect of alkalinity on lead release and galvanic current. Increasing the alkalinity did not reduce either lead leaching or galvanic current magnitude for any of the partial replacements. Specifically, increasing the alkalinity from 15 to 50 mg/L and then to 100 mg/L as $CaCO_3$ resulted in statistically similar lead-in-water levels for all rigs (Figure 10, part A), and galvanic current actually increased by up to 20% (Figure 10, part B).

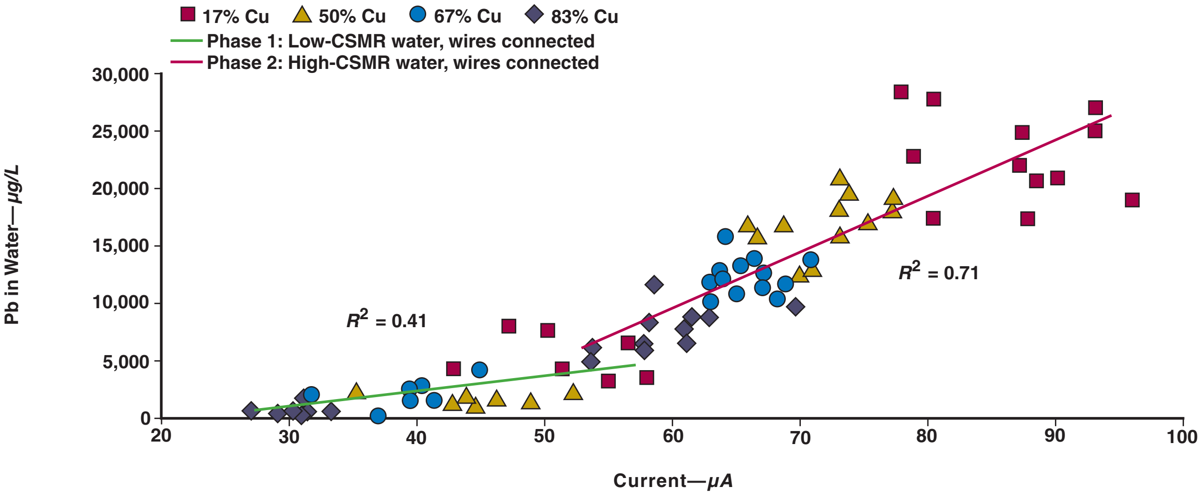
Throughout the first four phases of this study, the alkalinity of the water entering the rigs was maintained at 15 mg/L as $CaCO_3$ (Table 2). Waters with an alkalinity level this low have been described as alkalinity-deficient in terms of lead corrosion control, based on practical experiences (Edwards et al, 1999). On the basis of utility monitoring data, Edwards and co-workers (1999) identified alkalinity of 100 mg/L as $CaCO_3$ as an approximate upper bound to obtaining substantial improvements in lead release for waters with a pH below 8.5 (pH was maintained at 8.0 throughout the current study; see Table 2). It is possible that the detriments of increased conductivity for the galvanic corrosion cells (Table 2) simultaneously offset the benefits of higher dissolved inorganic carbon in reducing soluble lead (Schock et al, 1996). On the other hand, however, increasing the alkalinity did not decrease lead release from pure lead pipe either (Figure 10, part A).

In this experiment, particulate lead constituted the majority of total lead in collected water samples (70–99% of total lead was particulate; results not presented here). The ineffectiveness of alkalinity in reducing total lead leaching therefore can be explained by the abundance of particulate lead in the absence of significant soluble lead.

Area of galvanic influence and potential practical implications. One set of rigs (aged Pb pipe B) was constructed by connecting in series many short lead pipes in order to add up to the desired lead pipe length. For example, the 17% copper rig consisted of one 0.5-ft copper section, connected to five sequential 0.5-ft lead sections (Figure 11, part B). This setup facilitated measurement of the galvanic current between the copper and each section of lead pipe. The total current between the copper and lead pipe was the sum of the individual currents between the copper and each lead section.

Throughout the phases of the experiment when the wires between lead and copper were connected, the anodic galvanic current was concentrated in the lead segment that was closest to the galvanic junction. For example, during phase 1 of low-CSMR water, the current flowing between the copper and the first lead segment constituted on average 90% of the total current between lead and copper in the rig (Figure 11, part A). The second lead segment received 7% of the total current. The remaining three lead segments, i.e., those farthest away from the connection to copper pipe, accounted for only 3% of the total current (Figure 11, part A). Similarly, during phase 2 of high-CSMR water, the first lead segment received 95% of the total galvanic current, the second lead segment received 3% of the galvanic current, and the remaining three lead segments received 2% of the current (Figure 11, part A). Given that galvanic current is a direct measure of galvanic corrosion, these data suggested that the lead segment closest to the galvanic junction was by far the most affected (i.e., corroded) by the galvanic connection to copper, which was consistent with experimental results (Reiber & Dufresne, 2006) and

FIGURE 9 Correlation of galvanic current to lead release during phases 1 (green line) and 2 (red line)



CSMR—chloride-to-sulfate mass ratio, Cu—copper, Pb—lead

Phase 1 data exclude the first three weeks of stabilization.

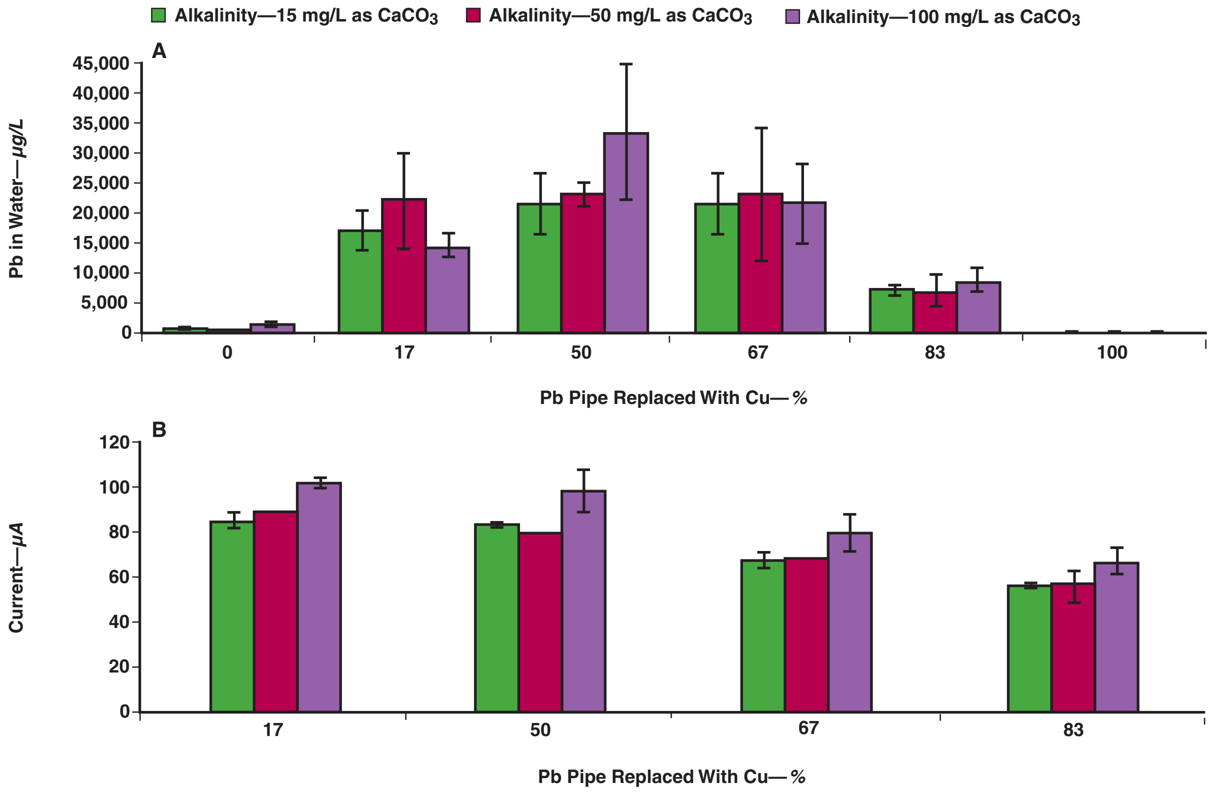
mineralogical and visual observations reported in the literature (DeSantis et al, 2009).

Translating galvanic effects to lead release and human exposure reveals serious concerns, regardless of area of galvanic influence. DeSantis and colleagues (2009) identified some failures at joints (i.e., lead pipe wall completely eaten away) caused by the depth of galvanic corrosion in the pipe wall. Simple calculations suggest that even if only a 1-in. length of lead pipe were half eaten away at the pipe wall because of galvanic corrosion, the released lead mass would equal 25 g (based on lead density of 11.3 g/cm^3, ID of ¾ in., and OD of 1 in.). This mass of lead would be sufficient to contaminate every drop of water used by a family of three for four years at a lead level above the LCR action limit of 15 µg/L (based on 300 gpd or 1,135 L/d of water use for the whole family). Thus, the limited area of attack does not translate to limited effects on public health, consistent with the extremely high levels of lead in water measured in this experiment.

The previous calculation assumes that all of the lead released through galvanic corrosion would contaminate all water equally. Cases of semirandom particle lead release, observed mostly during the latter stages of this experimental study, highlight serious potential for exposure to much higher lead doses. Specifically, by the end of this 13-month study, the lead pipe area adjacent to the junction had accumulated a thick lead-rust galvanic corrosion layer (Figure 12, part A), whereas no such thick layer was visible elsewhere on the lead surface (Figure 12, part B). Thick corrosion layers were visually observed at the joint in all lead–copper rigs tested and had a width of approximately 1 in. Toward the end of the experiment, white pieces of lead scale were occasionally detaching from the pipe galvanic corrosion layer into the collected water samples (Figure 12, part C).

After standard acid preservation of one such 260-mL water sample (collected on week 46 from the 50% copper rig), the lead concentration was quantified at 50,000 µg/L. The resulting lead dose of 13,000 µg from hypothetical consumption of just a single glass of contaminated water is equivalent to that obtained from ingesting 14 lead paint chips (Figure 12, part D), assuming the chips have a 2.6% lead content by weight (equivalent lead dose from paint chips was calculated on the basis of their measured weight on an analytical balance and their assumed lead content by weight). Clearly, such release

FIGURE 10 Effect of alkalinity on lead release (A) and galvanic current magnitude (B) during phase 4 conditions of high-CSMR water, wires reconnected



CaCO$_3$—calcium carbonate, CSMR—chloride-to-sulfate mass ratio, Cu—copper, Pb—lead

Error bars denote 95% confidence intervals.

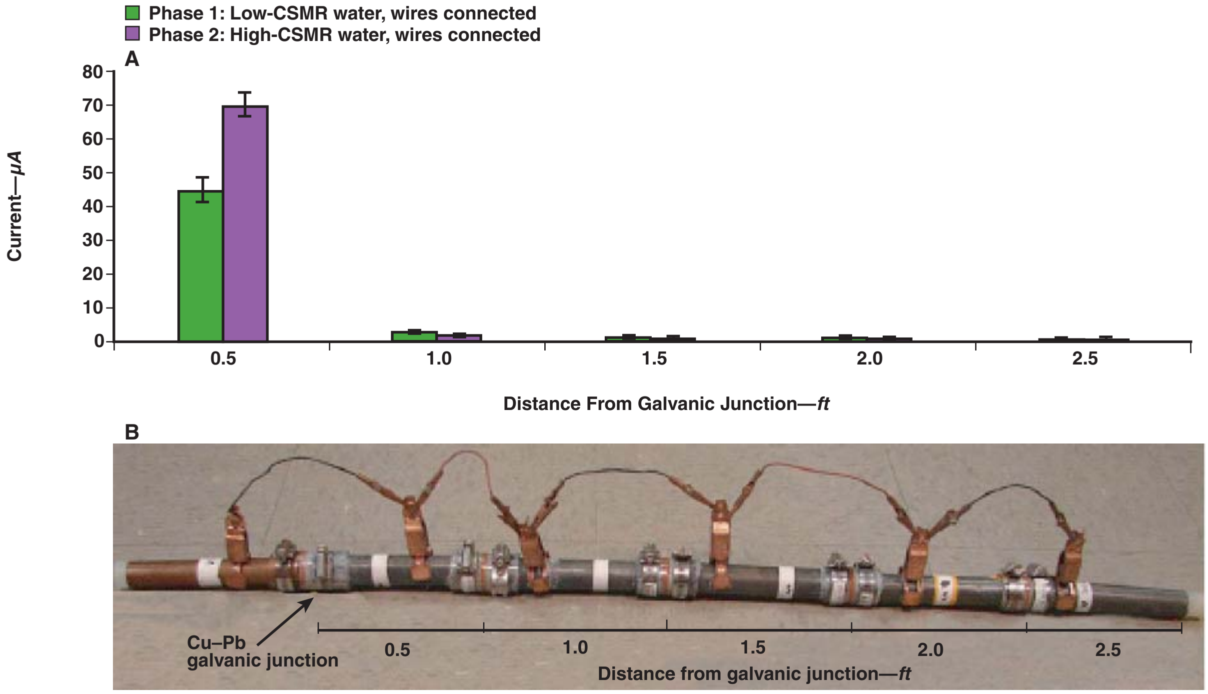
poses an acute health risk even from fairly rare exposures and also highlights obvious difficulties in detecting semirandom particulate detachment from the joint during conventional field sampling.

Summary of experimental results for other types of lead pipe tested. Overall, similar trends were observed for the other three types of lead pipe examined, i.e., aged Pb pipe A, aged Pb pipe B, and Pb(IV) pipe. In summary, partial replacements under both low- and high-CSMR water increased lead release compared with a full length of lead pipe alone, with only two exceptions: 67 and 83% copper rigs from aged Pb pipe A under low-CSMR water (Table 3). Lead release and galvanic current magnitude were higher under high-CSMR water compared with low-CSMR water, for these three types of lead pipe (Table 3). Disconnecting the wires between lead and copper decreased lead release, whereas reconnecting the wires increased lead release (Table 3). All galvanic rigs deviated from the linear theoretical model because of galvanic corrosion, and increasing the alkalinity was not able to reduce lead-leaching or galvanic current magnitude (Table 3).

Considering the increase in lead release from partial replacements compared with pure lead pipe in the vast majority of cases, the direct effect of disconnecting and reconnecting the wires on lead release into the water, and deviation from the linear theoretical model, galvanic corrosion made lead leaching worse under the experimental conditions of this study. However, the correlation between galvanic current and lead release was generally low, especially for aged lead pipes (Table 3). Aside from reasons partly explained in a previous section, strong correlations cannot be obtained when semirandom release of particles is occurring. This was especially true for aged lead pipes, where particulate lead release was more erratic. Overall, the three earlier considerations indicated that galvanic corrosion made lead leaching worse under the experimental conditions of this study, and therefore lack of a statistical correlation does not imply lack of practical association.

In an extreme case for pipes with Pb(IV) scale, there was no correlation between galvanic current and lead in water ($R^2 = 0.04$) as shown in Table 3. Because the pipes were exposed to chloraminated water, thereby causing Pb(IV) to be reduced to Pb(II) and be released into the water (Xie et al, 2010; Lin & Valentine, 2008; Switzer et al, 2006), white flakes were consistently observed in the water samples collected from the Pb(IV) galvanic pipes. Release in this set of rigs was therefore further compli-

FIGURE 11 Galvanic current magnitude as a function of lead pipe distance from the copper cathode (A) and the setup of pipe in series (B)



Source: Triantafyllidou, S. and M. Edwards. **Contribution of Galvanic Corrosion to Lead in Water After Partial Lead Service Line Replacements.** *©2010 Water Research Foundation. Reprinted with permission.*

Cu—copper, Pb—lead

Error bars (part A) represent 95% confidence intervals. As shown in part B, small segments of aged Pb pipe B were placed in series, allowing current measurements as a function of distance from the galvanic junction to copper.

cated by destabilization of the internal Pb(IV) corrosion layer, consistent with theory and prior practical experience (Xie et al, 2010; Lin & Valentine, 2008; Switzer et al, 2006; Lytle & Schock, 2005; Renner, 2004; Schock & Giani, 2004). Even so, for this set of pipes,

- lead release from simulated partial replacements increased by 10–20% compared with pure lead pipe,
- disconnecting the wires to copper decreased lead release by 5–8 times,
- reconnecting the wires to copper increased lead release by 3–4 times, and
- galvanic connections to copper increased lead release by 1.5–2.0 times compared with the linear theoretical model (Table 3), affirming that galvanic corrosion was still significant, despite the lack of correlation.

Limitations and future research. The work presented here is an important first step in understanding the implications of galvanic corrosion to lead release during partial lead service line replacement. Given the very long stagnation times and relatively short lengths of pipe used in this research, the current work can be considered "worst case" and illustrates a significant long-term concern that has been largely overlooked. More research is needed to quantify the relevant contribution of galvanic corrosion to lead release from lead service lines, compared with other mechanisms such as normal dissolution, deposition corrosion, particle detachment, and lead retention in pipe scale. Future work should examine galvanic corrosion under intermittent flow patterns, which are more representative of typical water use at homes. The effect of couplings between lead and copper pipe on galvanic corrosion (e.g., brass corporation valve or brass compression fitting, which are typically used in the field) should also be evaluated. The pipes used in this study included aged pipes with a somewhat passivated internal surface but may not reflect the behavior of pipes with decades of accumulated scale. It would be prudent to conduct testing with lead service lines harvested from the field after decades of use or additional testing of partially replaced lead pipes in the field. Finally, the effects of other water qualities on galvanic corrosion of lead (e.g., corrosion inhibitor such as phosphate added to the water) should be evaluated.

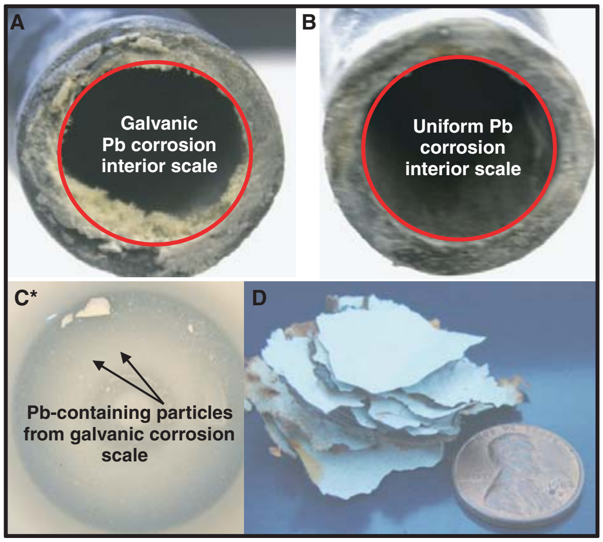
CONCLUSIONS

Controlled experiments of simulated small-scale partial lead service line replacements with copper that lasted for 13 months yielded the following conclusions.

Under stagnant water conditions galvanic connections between copper pipe and lead pipe (either new or aged) increased lead release over that seen in a full length of lead pipe alone.

- Removal of the galvanic connection between copper pipe and lead pipe decreased lead release by 2–8 times (depending on the type of lead pipe) under a high-CSMR water condition (i.e., CSMR of 16). Subsequently restarting the galvanic connection increased lead release by 2–8 times (depending on the type of lead pipe) to levels experienced before removal of the galvanic connection.
- For both new and aged lead pipes connected to copper, water with a high CSMR of 16 released 3–12 times more lead to the water than did low-CSMR water of 0.2.
- Because of galvanic (and deposition) corrosion, lead leaching from simulated partial replacements deviated from the linear theoretical model by 1.5–38 times in low-CSMR water and by 1.5–75 times in high-CSMR water.
- High, sustained galvanic currents between copper and lead pipe (up to 87 µA for new lead pipe) were measured when the CSMR was high, resulting in galvanic corrosion of the lead. When the CSMR was low, galvanic currents were lower (up to 52 µA for new lead pipe), consistent with corresponding lower results for lead leaching.
- Perfect correlations between galvanic current and lead release were neither expected nor obtained. Although galvanic current cannot be relied on to predict levels of lead in water, it is a direct measure of galvanic corrosion of lead when connected to copper pipe.
- Increasing the alkalinity from 15–50 mg/L and then to 100 mg/L as $CaCO_3$ was not able to alleviate galvanic lead corrosion, in terms of lead release into the water and galvanic current magnitude.

FIGURE 12 Lead pipe cross sections (A and B), lead-containing particles (C), and equivalent lead dose in paint chips (D)



Pb—lead

**260-mL water sample with 50,000 µg/L Pb*

Cross-sectional area of lead pipe at the end of the experiment is shown at galvanic junction to copper (A) and away from galvanic junction to copper (B). Lead-containing particles that randomly detached from the galvanic corrosion layer were visible at bottom of plastic water sampling containers (C). The lead dose quantified in such water samples (C) is equivalent to the lead dose from ingesting a number of penny-sized lead paint chips (D).

TABLE 3 Summary of experimental results for all types of lead pipe examined in this study

Lead Pipe Tested	Effect of Simulated Partial Replacement on Lead Release, Compared With Full Length of Lead Pipe Alone: Low-CSMR Water	High-CSMR Water	Effect of High-CSMR Water Compared With Low-CSMR Water: Lead Release	Galvanic Current	Effect of Galvanic Corrosion on Lead Release, Under High-CSMR Water: Wires Disconnected	Wires Reconnected	Effect of Galvanic Corrosion on Lead Release, Compared With Linear Theoretical Model: Low-CSMR Water	High-CSMR Water	Correlation R^2 Between Current and Lead Release: Low-CSMR Water	High-CSMR Water	Effect of Increasing Alkalinity, Under High-CSMR Water: Lead Release	Galvanic Current
New Pb pipe*	Increased by 4– 27 times	Increased by 2–7 times	Increased by 5–12 times	Increased by 1.6–2 times	Decreased by 4–6 times	Increased by 4.5–8 times	Increased by 18–38 times	Increased by 8–14 times	0.41	0.71	†	Increased 0–20%
Aged Pb pipe A	Changed by 0.4–2 times	Increased by 5–11 times	Increased by 5–11 times	Increased by 1.8–2 times	Decreased by 3–4 times	Increased by 6–7 times	Increased by 1.5–4 times	Increased by 12–20 times	0.64	0.44		Increased 0–40%
Aged Pb pipe B	Increased by 1–4 times	Increased by 10–16 times	Increased by 3–10 times	Increased by 1.5–2 times	Decreased by 2–4 times	Increased by 2–6 times	Increased by 3–6 times	Increased by 20–75 times	0.31	0.11		Increased 0–30%
Pb (IV) pipe	‡	Increased by 1.1–1.2 times	‡	‡	Decreased by 5–8 times	Increased by 3–4 times	‡	Increased by 1.5–2 times	‡	0.04		Increased 10–40%

CSMR—chloride-to-sulfatemass ratio, Cu—copper, Pb—lead

*Results are presented in detail in the Results and Discussion section.
†No statistically significant changes (95% confidence level)
‡Not evaluated

Ranges represent minimum and maximum results from four partial replacements of the lead pipes (with 17, 50, 67, and 83% Cu)

- On the basis of galvanic current measurements, the area of lead pipe adjacent to the copper joint (< 0.5 ft) was most affected by galvanic corrosion. The lead pipe sections that were farthest away from the copper junction (> 0.5 ft) were the least affected by the galvanic connection to the copper.
- Visual observations at the end of the experiment further defined the area of severe galvanic attack to about 1 in. of width of the lead pipe, adjacent to the junction. A distinct thick lead corrosion scale accumulated in that area, constituting a large reservoir for semirandom particulate lead detachment into the water.

Overall, these findings indicated that under worst-case stagnation conditions, galvanic corrosion was a dominant mechanism of lead release to potable water, even after more than one year following simulated small-scale partial lead service line replacements. More research is needed in order to test intermittent flow patterns, the effect of brass connections between lead and copper pipes, lead pipes harvested from the field, and other water chemistries.

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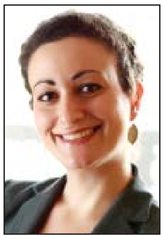

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FOOTNOTE

[1] Thermo Electron X series, Thermo Scientific, Boston, Mass.

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Association between children's blood lead levels, lead service lines, and water disinfection, Washington, DC, 1998–2006

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Drinking water
Blood lead level
Elevated blood lead levels

A B S T R A C T

Objective: Evaluate the effect of changes in the water disinfection process, and presence of lead service lines (LSLs), on children's blood lead levels (BLLs) in Washington, DC.

Methods: Three cross-sectional analyses examined the relationship of LSL and changes in water disinfectant with BLLs in children <6 years of age. The study population was derived from the DC Childhood Lead Poisoning Prevention Program blood lead surveillance system of children who were tested and whose blood lead test results were reported to the DC Health Department. The Washington, DC Water and Sewer Authority (WASA) provided information on LSLs. The final study population consisted of 63,854 children with validated addresses.

Results: Controlling for age of housing, LSL was an independent risk factor for BLLs ≥ 10 μg/dL, and ≥ 5 μg/dL even during time periods when water levels met the US Environmental Protection Agency (EPA) action level of 15 parts per billion (ppb). When chloramine alone was used to disinfect water, the risk for BLL in the highest quartile among children in homes with LSL was greater than when either chlorine or chloramine with orthophosphate was used. For children tested after LSLs in their houses were replaced, those with partially replaced LSL were >3 times as likely to have BLLs ≥ 10 μg/dL versus children who never had LSLs.

Conclusions: LSLs were a risk factor for elevated BLLs even when WASA met the EPA water action level. Changes in water disinfection can enhance the effect of LSLs and increase lead exposure. Partially replacing LSLs may not decrease the risk of elevated BLLs associated with LSL exposure.

1. Introduction

The adverse health effects of lead exposure are well known. For children, these include developmental delay, behavior disorders at low lead levels, seizures, and, in rare cases, death at very high levels. The public health impacts of lead exposure are substantial. For example, it is estimated that as BLLs increase from 0 to 10 μg/dL the fraction of individuals with an IQ >120 decreases from 9% to 3% (US EPA, 2006a). No blood lead level (BLL) threshold for adverse health effects in children has been identified (Canfield et al., 2003; Lanphear et al., 2000; Bellinger and Needleman, 2003). For adults, BLLs >1.9 but <10 μg/dL have been associated with increased risk for hypertension and increased all-cause mortality (ATSDR, 1999; Menke et al., 2006). BLLs >75 μg/dL in adults can cause poor pregnancy outcomes, intellectual impairment, and death (ATSDR, 1999). In addition, an estimate of hypertension-related risk for serious cardiovascular events indicates that a decrease in BLLs from 10 to 5 μg/dL could result in an annual decrease of 27 events per 100,000 women and 39 events per 100,000 men (US EPA, 2006a).

Although lead remains a pervasive environmental toxicant, a significant and sustained decrease in BLLs in the United States has been shown, particularly among African American and low-income children. The prevalence of BLLs of ≥ 10 μg/dL among children 1–5 years of age in the United States has decreased over time. Since 1988 percent of BLLs ≥ 10 μg/dL has decreased from 8.6% to 1.4% during 1999–2004, an 84% decline (Jones et al., 2009). In the United States, most children with BLLs ≥ 10 μg/dL have been exposed to residential lead paint hazards in older homes or lead-contaminated house dust and soil (CDC, 2002). However, lead in drinking water is known to contribute to children's BLLs and cases of childhood lead poisoning have been associated with drinking water in the United States (Shannon and Graef, 1989; Cosgrove et al., 1989; CDC, 1994). Before enactment of the Lead and Copper Rule, the US Environmental Protection Agency (US EPA, 1986) estimated that 10–20% of total exposure to lead among the general population might have come from drinking water. The contribution of water

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Abbreviations: LSL, Lead service line; WASA, District of Columbia Water and Sewer Authority; BLD, Below the Limit of Detection; BLLs, Blood lead levels; EPA, Environmental Protection Agency; CLPPP, District of Columbia Childhood Lead Poisoning Prevention Program; CDC, Centers for Disease Control and Prevention; DC, District of Columbia; DOH, Department of Health

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lead to total lead exposure would be far greater for an infant whose dietary intake is primarily infant formula mixed with lead contaminated household tap water (Shannon and Graef, 1989; CDC, 1994). In one study, an increase in drinking water lead levels from 0.5 part per billion (ppb) to 15 ppb – EPA's action level for lead in water – was estimated to increase children's BLLs an average of 1.9 μg/dL and the prevalence of BLLs ≥ 10 μg/dL by 14% (Lanphear et al., 1998).

Lead is rarely found in water at the distribution point or well head. It most commonly enters finished water through corrosion of plumbing materials containing lead (Chin and Karalekas, 1985). Three factors that influence the level of lead in drinking water are the presence of lead in plumbing materials, the pH of finished water, and the presence or absence of mineral scale in plumbing. Leaded service lines (LSL) connect homes to a central water main or run from the water meter to the home and are known to contribute to lead found in household tap water (AWWA, 1990; Schock et al., 1996). Homes built before the 1980s may have LSLs or copper pipes with lead-soldered joints. Homes built after the 1986 Safe Drinking Water Amendments have "lead-free" plumbing that may contain up to 8% lead (SDWA Amendments, 1986). Lead dissolves more readily in soft water than hard water resulting in lead leaching from lead-soldered copper water pipes or LSLs. Changes to the water supply that increase the water's pH decrease water lead levels (Goldberg et al., 1981). Mineral scale on the inner surface of older plumbing prevents lead from leaching into drinking water. However, when mineral scale is removed or has yet to develop, lead may be leached into drinking water even from "lead-free" pipes and fixtures.

In 1994, EPA proposed enhanced surface water treatment rules designed not only to protect the public from dangerous microbes in drinking water but also to limit the levels of disinfectants and disinfection byproducts that are classified as possible carcinogens (Tibbets, 1995; US EPA, 2006b). Chloramine, a chlorine–ammonia combination, produces fewer disinfection by-products than chlorine alone, thus a number of water suppliers adopted chloramine water treatment (Tibbets, 1995). In the absence of specific anticorrosive treatments such as orthophosphate, chloramine degrades accumulated mineral scale resulting in lead leaching into drinking water (Switzer et al., 2006). Increases in the average BLL of children after water disinfectant was changed from chlorine to chloramine have been reported (Miranda et al., 2007).

In Washington, DC, from November 2000 to June 2004, chloramine without orthophosphate was used as a water disinfectant. During this period, one study found that the percent of BLL test results ≥ 5 μg/dL increased above expected levels among persons living in homes with an LSL (CDC, 2004). A second study estimated that 859 D.C. children had BLLs ≥ 10 μg/dL in 2002 and 2003 because of exposures to high water-lead levels (Edwards et al., 2009).

In July 2004, WASA began adding orthophosphate in conjunction with chloramine to prevent corrosion of pipes and also began replacing LSLs. WASA was responsible for the costs of replacing lines from the street to the water meter of residences, while property owners were responsible for the costs of replacing the LSL between the water meter and the interior plumbing. In many cases, property owners declined to pay these costs, thus only the length of the line from the water main to the meter was replaced (partial replacement) rather than the entire length of line between the water meter and the residence (full replacement).

In this study, we examined BLL results among children tested for lead in Washington, DC, between 1998 and 2006. We assessed how the BLLs of tested children were affected by water disinfectant type and LSL while adjusting for the effect of housing age. We further examined the effect of both partial and no replacement of LSLs on the BLLs of children tested between 2004 and 2006.

2. Methods and materials

Three cross-sectional analyses were conducted. In this study the type of water disinfectant, the extent of LSL replacement (partial or none), and the type of service line (leaded or nonleaded) at the residence were the primary exposure variables of interest. BLL was the outcome of interest. Model 1 included LSL as the dependent variable. Model 2 included both LSL and age of housing as dependent variables. Model 2 is used to control for the potential confounding effect of age of housing, a proxy for household lead sources such as paint, house dust, and soil.

2.1. Blood lead levels

The study population was derived from the Washington, DC, Childhood Lead Poisoning Prevention Program (CLPPP) blood lead surveillance system that collected laboratory-based reports of the BLL results of individuals who were tested and whose results were reported to the CLPPP between January 1, 1998, and December 31, 2006. Blood lead tests were analyzed at various laboratories across the United States and were reported as whole numbers to the CLPPP. DC legally required that all BLLs be reported to the CLPPP beginning in 2002 (*Title XX of the Fiscal Year* 2003 *Budget Support Action of* 2002). The minimum quantitative BLL reported was 2 μg/dL. For BLLs < 2 μg/dL, we adopted the National Health and Nutritional Examination Survey (NHANES) strategy for coding laboratory results below the limit of detection. The results of tests below the limits of detection (BLD) are replaced with a value equal to the detection limit divided by the square root of 2, in this case the value 1.4 μg/dL (CDC, 2006). This method has been demonstrated to provide an accurate estimation of geometric mean and standard deviation when data are not highly skewed (Hornung and Reed, 1990).

Only one test per child was used in the analyses because repeated blood lead measures for an individual are not independent. For children with multiple tests, an algorithm consistent with CDC recommendations for follow up was used to select the most accurate result for analyses (CDC, 1997). According to this algorithm, if a child's blood lead test consisted solely of capillary samples, the lowest result was used to reduce the potential for positive bias caused by lead from skin contaminating blood when capillary tests were conducted. When the blood lead tests included venous samples, the highest venous BLL was used in analyses. Venous samples are unlikely to be contaminated. The highest test is used because subsequent tests could be influenced by efforts to reduce lead exposures. If sample type was not reported, it was presumed to be capillary. Data-cleaning included checking for duplicate observations and examining inclusion criteria, ranges of variables, and consistency of coding. A total of 67,831 unique children were identified as having been tested at least once during the study period. A categorical BLL variable based on the quartiles of the BLL distribution in the sample population was constructed with BLD as the lowest quartile and ≥ 5 μg/dL as the highest.

CDC review of CLPPP records identified that the number of tests reported in 2003 was approximately 50% lower than the number of tests reported in either 2002 or 2004. The number of tests reported in the surveillance system was otherwise consistent from 1 year to the next. These missing tests were not entered into the DC DOH lead surveillance system because laboratories did not report all BLLs during that year or tests received by DC DOH were not entered into the surveillance system.

In 2009, CDC acquired approximately 12,000 missing 2003 test results that had been unavailable in 2004 (Brown et al., 2010). We analyzed two datasets; one with and one without the missing 2003 blood lead level test data. The previously missing 2003 test results were collected using methods inconsistent with all other years. Therefore, we planned to provide results for both datasets only if the results differed. Otherwise, we provide here the results from the dataset without the missing 2003 tests.

2.2. Lead service lines

WASA provided the CLPPP and the Centers for Disease Control and Prevention (CDC) with a list of 26,155 homes presumed by WASA to have an LSL using criteria established by the Lead and Copper Rule (40 CFR Part 141). Street addresses from blood lead tests reported to CLPPP and the WASA address data were standardized using Centrus Desktop^{TM} software version 4.02 (Sagent Technology, Mountain View, CA) and matched to the complete street address. Of the 67,831 unique children with at least one BLL reported, complete street address could be found for 63,854 children who comprise our final study population. The houses of 10,859 of these 63,854 children were identified by WASA as having LSLs. The remaining houses did not appear on the WASA LSL list and were initially coded as not having an LSL.

WASA provided CDC with a list of 14,121 residential houses in which the water service line had been partially or fully replaced between 2004 and 2006. The BLL tests of 738 children were conducted after LSL was partially removed. Except as described below, these houses were coded as not having an LSL. Houses remained coded as having an LSL if the LSL replacement occurred after the blood lead test was conducted. WASA reported replacing a water service line in some homes that were not included in the original WASA data file of houses with an LSL. We recoded these houses as having had an LSL if the BLL occurred before the line was replaced.

2.3. Water disinfectant type

We designed a categorical variable, water disinfectant type coded as (1) chlorine if the BLL test was conducted between January 1, 1998, and October 31, 2000; (2) chloramine if the BLL test was conducted between November 1, 2000, and June 30, 2004; or (3) chloramine with orthophosphate if the BLL test was conducted between July 1, 2004, and December 31, 2006. These periods correspond to the dates when these types of water disinfection were used by WASA.

2.4. Study population

The final sample consisted of 63,854 uniquely identified children <6 years of age who had a BLL reported to DC DOH during the 9-year study period and a validated address.

Additional variables used in the analyses included age of housing and the child's age at the time of the BLL test. Age of housing was coded as pre-1950, 1950–1978, and post-1978. These periods coincide with changes in lead concentration in residential paint. The greatest amount of leaded paint was used pre-1950, and moderate use of leaded paint occurred from 1950 through 1978. Leaded residential paint was banned after 1978. To determine the age of houses, blood lead data were linked with tax assessor data. Data for age of houses were obtained for 37,322 (58.5%) children with validated addresses. We also categorized the child's age into ≤ 16 months of age and > 16 months -6 years of age to allow comparison to other published studies.

2.5. Data analysis

We examined the difference in distribution of children with or without validated addresses on the following variables: age, sex, blood sample type (venous, capillary, or not reported and assumed capillary), categorical BLL, and water disinfectant in use at time of the BLL test. We tested the relationship between BLL and LSL using two approaches. We used polychotomous logistic models that assumed a multinominal dependent variable. We categorized children into blood lead levels quartiles. The models estimated the risk of falling into the second, third, or fourth quartile of blood lead level compared to the lowest quartile of blood lead level given the presence or absence of a lead service line stratified by water disinfection type.

In the first approach we computed odds of BLL quartiles (BLD, 2– <3, 3– <5, and ≥ 5 μg/dL) to determine the presence of a dose–response relationship. In the second we calculated the odds of a BLL ≥ 10 μg/dL. We tested the association between BLLs and LSL for each water disinfectant type, controlling for age of housing. We further stratified these analyses by focusing on children ≤ 16 months of age. Finally, we computed odds ratios of BLL ≥ 5 μg/dL and BLL ≥ 10 μg/dL by intact or partially replaced LSL.

Logistic regression was used to model the relationship between BLL quartile, LSL, and age of housing. Standard statistical methods were used to compute odds ratios (OR) and 95% confidence intervals (CI) for all effects studied (Rothman and Greenland, 1998). The Statistical Analysis System (SAS) (SAS Institute, Cary, NC) was used for generating descriptive statistics, and regression models.

3. Results

3.1. Demographics

Among the 63,854 children in the study population 22,719 (36%) children were tested before their second birthday; 17,509 (27%) children were tested when chlorine was used to disinfect water, 23,837 (37%) when chloramine alone was used, and 22,508 (35%) when chloramine and orthophosphate were used. A total of 51,592 children (81%) had BLLs <5 μg/dL, 10,197 children (16%) had BLLs 5–9 μg/dL, and 2065 children (3%) had BLLs ≥ 10 μg/dL. As Table 1 indicates, children with a valid address were more likely than other children to have been tested by venous samples and had a slightly higher BLL distribution than children without a valid address. Of the 37,322 children in the study for whom age of housing was available, 28,238 (44%) lived in housing built before 1950. Of the children whose data were used in the analysis, 9938 (16%) lived in housing where an LSL was present and had been not replaced before the BLL test was conducted.

3.2. Stratified analyses of BLL quartile and LSLs

A relationship was observed between BLL quartile status and probability of living in a house with an LSL for every year between 1998 and 2006 including those years when WASA was in compliance with the EPA action level of 15 ppb. However, this relationship was attenuated when age of housing was entered into the models. For the period when chloramine alone was used as a water disinfectant, the adjusted odds ratio (OR) of a BLL in the highest versus the lowest quartile for children living in homes with an LSL was 2.5 (95% CI, 2.2–2.9), controlling for age of housing. The risk was greatest in 2003 when the adjusted OR of a BLL in the highest versus the lowest quartile for children living in homes with a LSL was 3.2 (95% CI 2.4, 4.4; data not shown). In models that included the nearly 6000 children whose 2003 BLLs were received in 2009, the adjusted OR of a BLL in the highest versus the lowest quartile for children living in homes with a LSL was 3.0 (95% CI 2.3, 3.8; data not shown). When chloramine with orthophosphate was used as the disinfectant (2004–2006), the odds of a BLL in the highest quartile relative to the lowest remained elevated, but these odds were somewhat lower than when chloramine was used alone (Table 2).

3.3. LSL replacement

Chloramine with orthophosphate was the water disinfectant used during the period of time when the WASA LSL replacement program was conducted. Compared to households with no LSL, partial LSL replacement was associated with elevated OR for a child's BLL 5–9 μg/dL [OR=1.9 (95% CI, 1.5–2.3)] and BLL ≥ 10 μg/dL [OR=3.3 (95% CI, 2.2–4.9)] (Table 3). Conversely no significant difference in risk was found between children in households with partially replaced LSL compared to intact LSL for either BLL ≥ 5 or 10 μg/dL (Table 3). The number of days between lead service line replacement and BLL for 921 children where LSL were replaced was unrelated to BLL (BLL <5 μg/dL, $n=769$, mean=323 days; BLL 5–9 μg/dL, $n=120$, mean=344 days; BLL ≥ 10 μg/dL, $n=32$, mean=307 days; $p=0.6$). When models where children with partially replaced LSL were removed from the analyses during the time period when chloramine and orthophosphate were used for water disinfection LSL remain strongly associated with BLL in the highest quartile [OR 1.6 (95% CI, 1.4–1.9)] for children <6 years of age and [OR 1.5 (95% CI 1.2, 2.0)] for children $\leq$ 16 months of age. These values are not significantly different from the OR estimates of models that include these children.

3.4. Age

In a subsample of 17,181 children ≤ 16 months of age, the odds of a BLL ≥ 5 μg/dL was 1.7 (95% CI, 1.1–2.6) in the period of chlorine disinfection; 3.6 (95% CI, 2.8–4.6) for the chloramine disinfection period and 1.6 (95% CI, 1.3–2.0) for the chloramine with orthophosphate period in models that controlled for age of housing (Table 4). A dose response relationship between living in a house with an LSL and BLL quartile was identified for all three disinfectant periods. Consistent with previous analyses, this relationship also was attenuated in analyses that controlled for age of housing. The risk for BLL ≥ 10 μg/dL was remarkably similar for younger and older children during the chloramine alone and chloramine with orthophosphate disinfection periods. However, for younger children the risk for BLL in the highest BLL quartile (≥ 5 μg/dL) was more than doubled in the chloramine alone period compared to either of the other disinfection periods.

When BLLs ≥ 10 μg/dL are considered, in models that control for age of housing, living in a house with an LSL was an independent risk factor for the entire study period (Table 5).

Table 1
Comparison of children < 6 years of age with validated[a] and non-validated address on blood lead variables and selected demographic characteristics, Washington, DC, 1998–2006.

Characteristic	Address validated (n=63,854)		Address not validated (n=3977)		p-value
	n	%[b]	n	%[b]	
Gender					
Male	31,534	49.4	1945	48.9	< 0.0001
Female	30,529	47.8	1820	45.8	
Not reported	1791	2.8	212	5.3	
Age					
0–11 months	8414	13.2	556	14.0	< 0.0001
12–23 months	14,305	22.4	1034	26.0	
24–35 months	13,645	21.4	747	18.8	
36–47 months	10,830	17.0	547	13.8	
48–72 months	16,660	26.1	1093	27.5	
Sample type					
Not reported, assumed capillary	12,166	19.1	2770	69.7	< 0.0001
Capillary	4183	6.6	343	8.6	
Venous	47,505	74.4	864	21.7	
Blood lead level (μg/dL)[c]					
< 5	51,592	80.8	3321	83.5	< 0.0001
5– < 10	10,197	16.0	576	14.5	
≥ 10	2065	3.2	80	2.0	
Age of housing					
Pre-1950	28,238	44.2			NA
1950–1978	7651	12.0			
Post 1978	1433	2.2			
Data not available	26,532	41.6	3977	100.0	
Lead service line (LSL)[d]					NA
Partial replacement	738	1.2			
Full replacement	183	0.3			
LSL, not replaced	9938	15.6			
No LSL	52,995	83.0			
Data not available			3977	100.0	
Water disinfectant at time of blood test					
Chlorine (1/1/1998 to 10/31/2000)	17,509	27.4	1137	28.6	< 0.0001
Chloramine only (11/1/2000–6/30/2004)	23,837	37.3	2706	68.0	
Chloramine with orthophosphate (7/1/2004–12/31/2006)	22,508	35.3	134	3.4	

[a] Address considered validated if data available for complete street address (including house number, street name, and street suffix (e.g., St., Dr., Pl).
[b] Percents may not add to 100.0% due to rounding.
[c] Service line defined as replaced only if date of replacement was before date of blood lead test.
[d] Statistics regarding age of housing and LSLs cannot be computed for non-validated addresses.

Table 2
Odds ratios (with 95% CIs) for having a LSL for BLL quartiles, relative to lowest quartile, by time periods corresponding to water disinfection type, children < 6 years of age, in Washington, DC, 1998–2006.

Blood Lead Quartile Cutpoints (μg/dL)	**Chlorine** (1/1/1998–10/31/2000)		**Chloramine** (11/1/2000–6/30/2004)		**Chloramine with Orthophosphate** (7/1/2004–12/31/2006)	
	Model 1 OR (95% CI) for LSL (n=17,509)	Model 2 OR (95% CI) for LSL, controlling for age of housing (n=9860)	Model 1 OR (95% CI) for LSL (n=23,837)	Model 2 OR (95% CI) for LSL, controlling for age of housing (n=13,898)	Model 1 OR (95% CI) for LSL (n=22,508)	Model 2 OR (95% CI) for LSL, controlling for age of housing (n=13,564)
BLD[a]	1.0	1.0	1.0	1.0	1.0	1.0
2– < 3	0.9 (0.7, 1.2)	1.0 (0.7, 1.3)	1.1 (1.0, 1.3)	1.2 (1.0 1.4)	1.0 (0.9, 1.2)	1.1 (0.9, 1.2)
3– < 5	1.0 (0.8, 1.2)	1.1 (0.8, 1.4)	1.6 (1.4, 1.8)	1.6 (1.4, 1.8)	1.4 (1.3, 1.5)	1.3 (1.1, 1.4)
≥ 5	1.6 (1.3, 2.0)	1.4 (1.1, 1.9)	3.0 (2.7, 3.4)	2.5 (2.2, 2.9)	2.1 (1.9, 2.3)	1.7 (1.5, 1.9)

[a] BLD—Below the limit of detection (1.4 μg/dL).

4. Discussion

In this study of children's BLLs in Washington, DC, LSLs were associated with increased odds of having elevated BLLs even during time periods when WASA was in compliance with the EPA action level of 15 ppb. The association was stronger when chloramine alone rather than chlorine was used as a disinfectant, particularly among younger children. Adding orthophosphate to chloramine

Table 3
Odds of having a blood lead level (BLL) 5–9 μg/dL or ≥ 10 μg/dL, comparing partial replacement[a] of lead service line (LSL) to no LSL and partial replacement to LSL not replaced when water disinfectant was chloramine with orthophosphate (7/1/2004–12/31/2006), Children < 6 years of age, Washington, DC, 2004–2006.

BLL	**Partial replacement vs. no LSL**			**Partial replacement vs. LSL not replaced**		
	Partial replacement[a]	**No LSL**	**Odds ratio (95% CI)**	**Partial replacement**[a]	**LSL Not replaced**	**Odds ratio (95% CI)**
< 5 μg/dL	598	17,029	1.0	598	2434	1.0
5–9 μg/dL	105	1592	1.9 (1.5, 2.3)	105	406	1.1 (0.8, 1.3)
≥ 10 μg/dL	27	236	3.3 (2.2, 4.9)	27	81	1.4 (0.9, 2.1)
Total	730	18,857		730	2921	

[a] Service line defined as replaced only if date of replacement was before date of blood lead test.

Table 4
Odds ratios (with 95% CIs) for having a LSL for BLL quartiles, relative to lowest quartile, by time periods corresponding to water disinfection type, children ≤ 16 months of age, in Washington, DC, 1998–2006.

Blood lead quartile cutpoints (μg/dL)	**Chlorine** (1/1/1998–10/31/2000)		**Chloramine** (11/1/2000–6/30/2004)		**Chloramine with orthophosphate** (7/1/2004–12/31/2006)	
	Model 1 OR (95% CI) for LSL ($n=3711$)	Model 2 OR (95% CI) for LSL, controlling for age of housing ($n=2180$)	Model 1 OR (95% CI) for LSL ($n=6238$)	Model 2 OR (95% CI) for LSL, controlling for age of housing ($n=3781$)	Model 1 OR (95% CI) for LSL ($n=7232$)	Model 2 OR (95% CI) for LSL, controlling for age of housing ($n=4536$)
BLD[a]	1.0	1.0	1.0	1.0	1.0	1.0
2– < 3	0.9 (0.6, 1.4)	1.0 (0.6, 1.5)	1.4 (1.2, 1.7)	1.6 (1.2, 2.0)	1.0 (0.8, 1.2)	1.0 (0.8, 1.2)
3– < 5	1.0 (0.7, 1.5)	1.1 (0.7, 1.7)	2.1 (1.7, 2.5)	2.2 (1.7, 2.7)	1.3 (1.1, 1.5)	1.2 (1.0, 1.4)
≥ 5	1.6 (1.1, 2.4)	1.7 (1.1, 2.6)	4.1 (3.4, 5.0)	3.6 (2.8, 4.6)	2.0 (1.6, 2.4)	1.6 (1.3, 2.0)

[a] BLD—below the limit of detection (1.4 μg/dL).

Table 5
Odds of having a blood lead level (BLL) ≥ 10 μg/dL, relative to a BLL of < 10 μg/dL, in presence of lead service line (LSL)[a,b] at time of blood lead test and controlling for age of housing, by water disinfectant type, children ages > 16 months to < 6 years of age and children ≤ 16 months of age, Washington, DC, 1998–2006.

Blood lead level (BLL) (μg/dL)	**Chlorine (1/1/1998—10/31/2000)**		**Chloramine only (11/1/2000–6/1/2004)**		**Chloramine with orthophosphate (7/1/2004–12/31/2006)**	
	Model 1 OR (95% CI) for LSL	Model 2 OR (95% CI) for LSL, controlling for age of housing	Model 1 OR (95% CI) for LSL	Model 2 OR (95% CI) for LSL, controlling for age of housing	Model 1 OR (95% CI) for LSL	Model 2 OR (95% CI) for LSL, controlling for age of housing
Children > 16 months to < 6 years of age	$N=13{,}798$[c]	$N=7680$[d]	$N=17{,}599$	$N=10{,}117$[d]	$N=15{,}276$[c]	$N=9028$[d]
< 10	1.0	1.0	1.0	1.0	1.0	1.0
≥ 10	2.3(2.0, 2.7)	1.5 (1.3, 1.8)	3.0 (2.6, 3.6)	2.2 (1.8, 2.7)	2.4 (1.8, 3.1)	1.7 (1.2, 2.3)
Children ≤ 16 months of age	$N=3711$[c]	$N=2180$[d]	$N=6238$[c]	$N=3781$[d]	$N=7232$[c]	$N=4536$[d]
< 10	1.0	1.0	1.0	1.0	1.0	1.0
≥ 10	3.4 (2.3, 5.0)	3.7 (2.2, 6.2)	3.1 (2.3, 4.3)	2.3 (1.6, 3.4)	2.7 (1.7, 4.2)	1.9 (1.1, 3.1)

[a] Includes children living in homes where the LSL was not replaced or where the LSL was only partially replaced prior to their BLL test.
[b] No LSL includes children living in homes where the LSL was fully replaced prior to their BLL test.
[c] *N* includes children for whom there was data on LSL.
[d] *N* includes only children for whom there were data on both LSL and age of housing.

attenuated, but did not eliminate the association. These data suggest that changes in water disinfectants that increase the leaching of lead into water can increase BLLs of children.

We also found that children living in housing where an LSL was partially replaced after 2003, were more likely to have BLLs 5–9 or ≥ 10 μg/dL than children living in housing without an LSL. The risk for BLL elevation for children living in homes with partial LSL replacement was consistent with the risk for BLL elevation among children living in homes with an intact LSL. Virtually all of the homes having lead service lines replaced were built before 1950. Continued exposure to lead in water, lead from other sources, or a combination of factors may explain these risks. However, partial LSL replacement was not effective in decreasing risk for BLL 5–9 μg/dL or ≥ 10 μg/dL.

4.1. *Limitations*

This study is subject to a number of limitations. First, we could not control for water consumption patterns at the individual level.

We have no reason to suspect that water consumption patterns at the population level changed in concert with the use of chlorine or chloramine alone until the public became aware of the high levels of lead in D.C. drinking water in January 2004. However, public health interventions such as distribution of water filters and widespread information including instructions not to drink unfiltered tap water that occurred after January 2004 may have changed drinking water habits. This public information may have partially attenuated the association we reported in the choloramine alone and with orthophosphate water disinfection time periods, although the association remained strong. We also could not evaluate the extent to which children living in houses with or without an LSL may have obtained their drinking water in other places (e.g., other houses, schools, etc.) or from bottled drinking water. Random misclassification introduced as a result of this limitation would have attenuated the estimates of an association between BLLs and LSLs.

Because BLLs were analyzed at several laboratories and reported to DOH, inter-laboratory variability may have resulted in misclassification. Measurement error in BLLs would tend to increase the standard error and result in an attenuation of the association between exposure and outcome. However, a 1998 review of commercial laboratories certified to analyze BLLs found strong reproducibility within and among laboratories, without any overall time trend or interlaboratory or intralaboratory variance (Jobanputra et al., 1998). A subsequent study of commercial laboratories found that differences in laboratory performance on blinded BLL samples were clinically insignificant (Parsons et al. 2001).

BLL surveillance data were subject to errors as well as failure to report or enter results throughout the study period. Random error would have attenuated the estimates of association reported here. Non-random error or differential misclassification can affect the odds ratio in various ways depending on the direction of the misclassification (Armstrong et al., 1992).

We assessed the impact of the 2003 missing data on the results presented here. No substantive differences were noted. For example the risk of BLL in the highest quartile compared to the lowest quartile given a LSL for the chloramine period alone without the missing data was OR=3.0 (95% CI, 2.7–3.4) versus with the missing data OR=2.9 (95% CI, 2.6–3.2).

Addresses with an LSL were derived from a list of addresses provided by WASA as highly suspected to have LSLs. Some misclassification of houses with and without LSLs is likely, given that direct inspection, which requires digging down to the LSL, is necessary to determine whether the service line is indeed made of lead. We identified that 1338 (1.5%) of the children's houses originally coded by WASA as not having LSLs were later reported by WASA as having a service line replacement and these homes were reclassified as having a LSL. Additional random misclassification of LSLs would attenuate the estimates of an association between BLLs and LSLs. Coding of the 738 children whose blood lead levels were drawn after partial replacement of LSL as having no LSL also may have introduced misclassification and attenuated the strength of the association. However, models in which these children were removed were not statistically different from those that included these children.

Control for the influence of lead exposures other than LSLs was limited to using a categorical variable for age of housing. This variable is a well established predictor of lead paint hazards in housing (CDC, 1997). We did not control for exposure to other important sources in the environment. Also, since LSLs were not perfectly assessed by WASA, age of housing may serve not only as a proxy for the presence of lead paint hazards but also for unidentified LSLs. Models controlling for age of housing may underestimate the association between LSL and BLL.

It is unlikely that lead exposure sources are distributed randomly in the population, given that children living in old, substandard housing face a variety of other lead exposure sources. Future studies that collect environmental samples, such as house dust, soil, and water would address this weakness.

4.2. *Strengths*

This study has several strengths that enhance the interpretation of these findings. First, the study uses laboratory-based reports of 63,854 children's blood lead level tests. The large number of tests facilitated our analysis of the association between BLL, LSL, and water disinfectant, enabling us to control for the effect of the temporal decline in BLL that has occurred across the United States during the study period. Secondly, the lab-based reports of BLLs included the listing of the child's address at the time of the test. These addresses could be matched to the data provided by WASA that identified housing considered most likely to be connected to drinking water mains by an LSL. Additionally, we could adjust for the potential confounding caused by leaded paint using the surrogate variable, age of housing. The correlation between elevated BLL in children and housing age is well established (CDC, 1997). Third, only 1338 homes originally considered as not having an LSL, were reclassified once information became available that an LSL had been partially or fully replaced. Finally, the analysis of children ≤ 16 months of age provided us the opportunity to evaluate how the association between BLL, LSL, and disinfectant affected very young children, thought to be the most vulnerable segment of the population.

4.3. *Comparison to previous work*

In 2004, CDC conducted a rapid assessment of reported BLL testing data in response to concerns about high concentrations of lead in water and concluded that the expected trajectory of BLLs decreasing over time was reversed for children living in houses with LSLs for BLLs ≥ 5 μg/dL, although not for BLLs ≥ 10 μg/dL, during the period when chloramine alone was used as a water disinfectant (CDC, 2004). The 2004 assessment was subject to a number of limitations including the use of multiple blood lead tests per person, the inclusion of individuals >6 years of age and not specifically investigating the effects on the youngest children. This study addressed all those limitations. We found that LSLs increased the odds of elevated BLLs during both time periods when chloramine was used as a water disinfectant, and that this finding is independent of age of housing, which is a proxy for the presence of lead paint.

Guidotti et al. (2007) found that 5.3% of children living in homes with LSL had BLL ≥ 10 μg/dL based in part, on 2342 children tested for lead between February and July 2004. In a correction to the study the authors concluded that public health measures instituted in 2004 may have prevented more frequent blood lead elevations The authors attributed the blood lead elevations to other environmental sources in the community (Guidotti et al., 2007).

In contrast, we found that LSL was a risk factor for *r* increased BLL independent of age of housing throughout the study period. The association was strongest during the period when choloramine alone was used as a water disinfectant.

Edwards et al. (2009) reported that D.C. children ≤ 16 months of age were more than four time as likely to have had BLLs ≥ 10 μg/dL during the period 2001–2003 compared to 2000. Both Edwards et al. (2009) and this study examined the association between water disinfection methods and BLLs ≥ 10 μg/dL. We found that the strength of the association (size of the odds ratio) was greater for younger children than for older children during all three time periods (Table 5). This difference was greatest during the earliest time period when chlorine was used to disinfect drinking water. The stronger associations reported for young children may reflect their intake of formula mixed with tap water and mouthing behaviors.

5. Conclusions and recommendations

In Washington, DC, between November 2000 and December 2006, children living in homes with an LSL were at increased risk of having higher BLLs than children living in homes without an LSL. This association was strongest during 2003 when chloramine alone was used for water disinfection. The association persisted after controlling for the age of housing. Finally, partial replacement of LSLs did not result in a decrease in the association between LSL and elevated BLL.

For the majority of children in the United States with elevated BLLs, lead paint and lead-contaminated house dust and soil are the primary routes of lead exposure (Levin et al., 2008). But children are exposed to multiple lead exposure sources – including water – and evidence suggests that, particularly for children with BLLs 5–10 μg/dL, no exposure source may dominate (Bernard and McGeehin, 2003). Thus the contribution of lead in drinking water to children's BLLs, particularly at BLLs <10 μg/dL may be underestimated.

The most effective strategy to reduce BLLs remains controlling or eliminating sources of lead in children's environments before they are exposed. The consequences of changes in water disinfection practices on a range of health issues including exposure to lead should be carefully considered by water utilities before they are adopted. A summary of internal corrosion control of water distribution systems concluded that appropriate corrosion control is essential in water distribution systems where lead is present (AWWA, 1996). Had appropriate corrosion control been in place in DC in 2001–2004, it would have prevented the increase in water lead concentrations seen (US EPA, 2007).

Residents of properties where plumbing work has been done, including partial replacement of LSL, should take precautions such as using bottled or filtered water until they are sure that the water lead levels are below the EPA action level of 15 ppb. Finally, given that no safe blood lead level threshold has been identified for children, and that lead in water contributes to BLLs, prompt and effective action by utilities to rapidly comply with existing drinking water standards is warranted.

Acknowldgments

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envres.2010.10.003.

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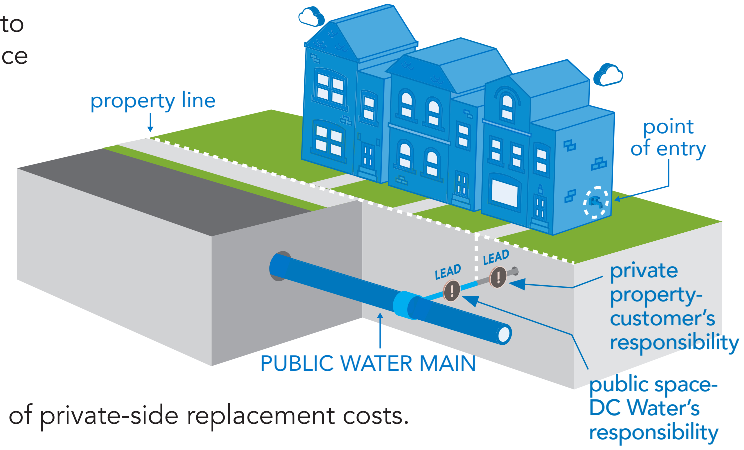
DC Water plans to remove all lead service lines in the District of Columbia by 2030

In 2019, DC Water launched the **Lead Free DC** initiative to 1) accelerate replacement of more than 25,000 lead service lines and 2) align DC Water's replacement programs to incorporate new District law.

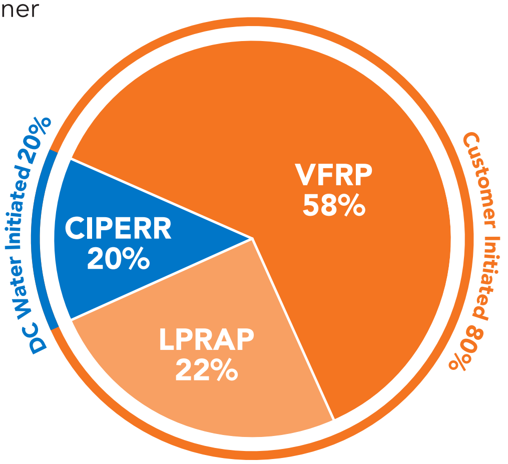
Lead Free DC comprises three lead service line (LSL) replacement programs, two of which are funded in part by the District.



- **CIPERR** **(Capital Improvement Project and Emergency Repair Replacement)** DC Water-initiated replacements during planned capital improvement work and emergency repairs. The District pays for 100% of private-side replacement costs.
- **LPRAP** (**Lead Pipe Replacement Assistance Program**) Customer-initiated replacements where only the private-side is lead. The District pays for 50-100% of private-side replacement costs.
- **VFRP** (**Voluntary Full Replacement Program**) Customer-initiated replacements where both the public-side and private-side are lead. The homeowner pays for 100% of private-side replacement costs.

FY20 and FY21 LSL Replacements by Program

program	FY20 (Oct 1, 2019 - Sep 30, 2020)	FY21 (Oct 1, 2020 - Jan 31, 2021)	total
CIPERR	103	56	159
LPRAP	129	51	180
VFRP	301	168	469



FY20 and FY21 % of Total LSL Replacements by Program

Progress

Since October 2019, DC Water has provided 314 free and discounted lead replacements that have saved customers nearly $1 million in combined costs **(figure 1)**.

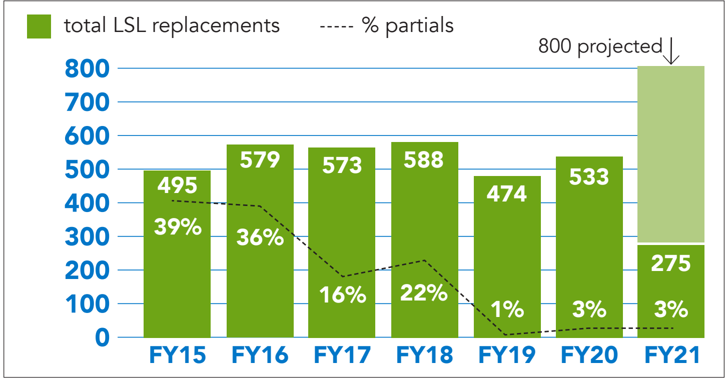
DC Water expects to complete 800 LSL replacements this fiscal year—the most of any year in the past decade **(figure 2)**.

FIGURE 1. District-Funded Lead Assistance Programs

	FY20	FY21	Total
Total (all programs)	533	275	808
Discounted LSL Replacements	207	100	314
Customer Savings	$600,000	$298,279	$958,279

DC Water is excited to break ground later this year on several capital projects that will remove 150 lead service lines from neighborhoods across wards 1, 3, 4, 5, 6, and 7. District funding to pay for private-side replacement costs has been instrumental in helping DC Water eliminate LSLs in their entirety.

FIGURE 2. Partial LSL Replacements as a % of Total LSL Replacements



For more information please visit **dcwater.com/lead**

DC Water plans to remove all lead service lines in the District of Columbia by 2030

Funding

DC Water's capital improvement plan (CIP) for water main replacement work is estimated to address 20% of known lead service lines by 2030. The current funding level for this work is **$627 million** and does not include **$22 million** needed for private-side lead service line replacement.

DC Water estimates that the remaining 80% of lead service lines will be removed on a block-by-block basis and through established customer-initiated programs. The estimated cost of this effort is **$703 million**, which is currently unfunded and not included in the approved CIP. It also does not include **$76.5 million** needed for private-side lead service line replacement.

Cost to Eliminate All LSLs in 10 Years	Cost Estimate	% of Total Cost
Public-side Replacement Costs - CIP	$627,200,000	44%
Public-side Replacement Costs - Block-by-Block	$703,200,000	49%
Private-side Replacement Costs - CIP	$22,200,000	2%
Private-side Replacement Costs - Block-by-Block	$76,500,000	5%
Public-side Subtotal	$1,330,400,000	93%
Private-side Subtotal	$98,700,000	7%
Grand Total	$1,429,100,000	100%

Currently Funded
$627,200,000 / 44%

Currently Unfunded
$801,900,000 / 56%

An Equitable Approach

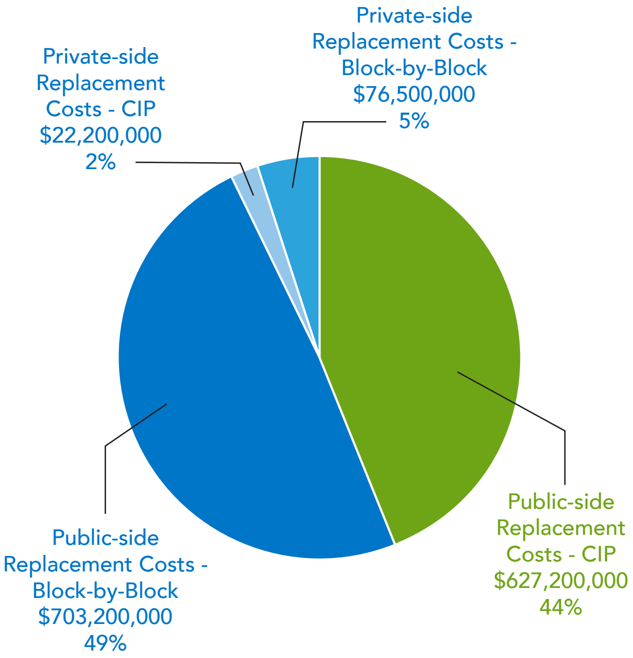
To tackle the 80% of lead lines not addressed by the current approved capital improvement plan, DC Water has developed a model to use water quality and health equity data to prioritize future lead service line replacement projects.

This approach prioritizes lead replacement for:

1. Vulnerable populations most impacted by lead exposure (children and seniors).
2. Communities that are historically underserved, and experience disproportionately poorer health outcomes compared with other parts of the city.

The model scores and ranks blocks according to the health benefit and social impact of lead service line replacement so that projects can be funded and executed equitably.

Funded and Unfunded Public-side and Private-side Costs to Eliminate All LSLs in 10 Years



For more information please visit **dcwater.com/lead**