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

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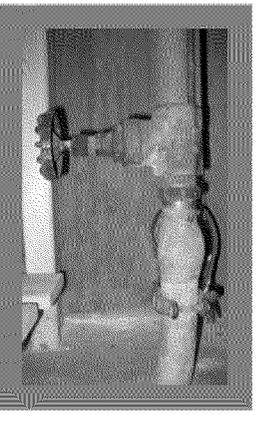
* Supporting Information

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

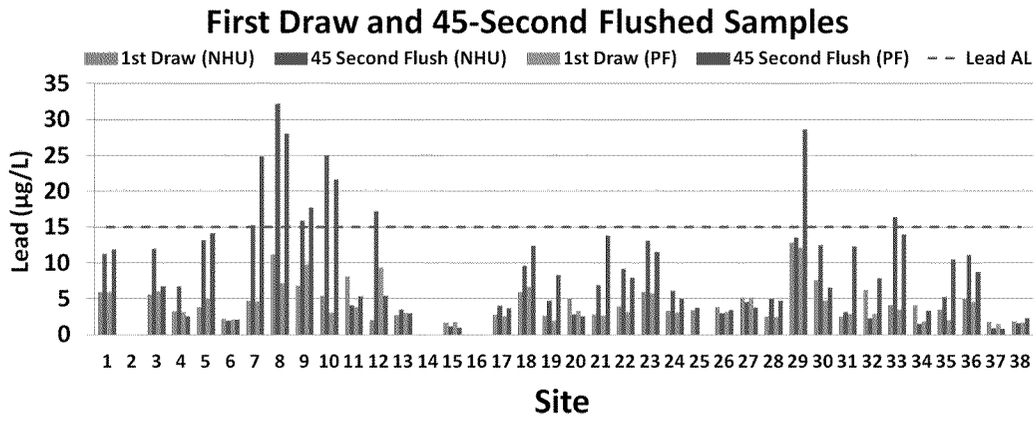

Figure 1. First round lead results for all sites.

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

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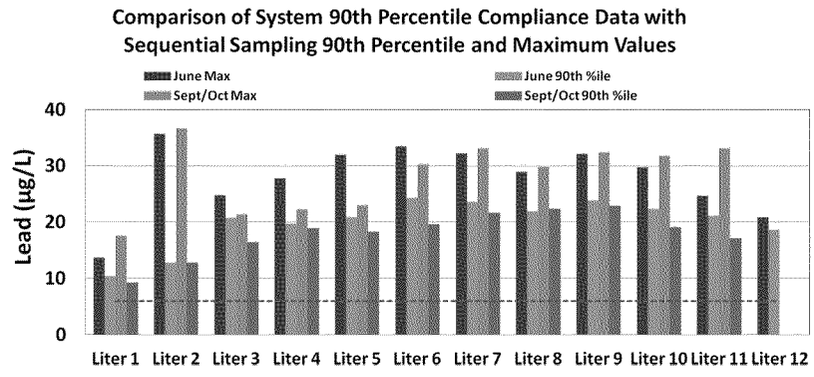

Figure 2. Comparison of 90th percentile LCR compliance data to 90th percentile values from LSL samples (across sites by liter) and maximum values from LSLs. The green dashed line indicates the average 90th percentile compliance monitoring value for Chicago between 1999 and 2010 of 6 µg/L.

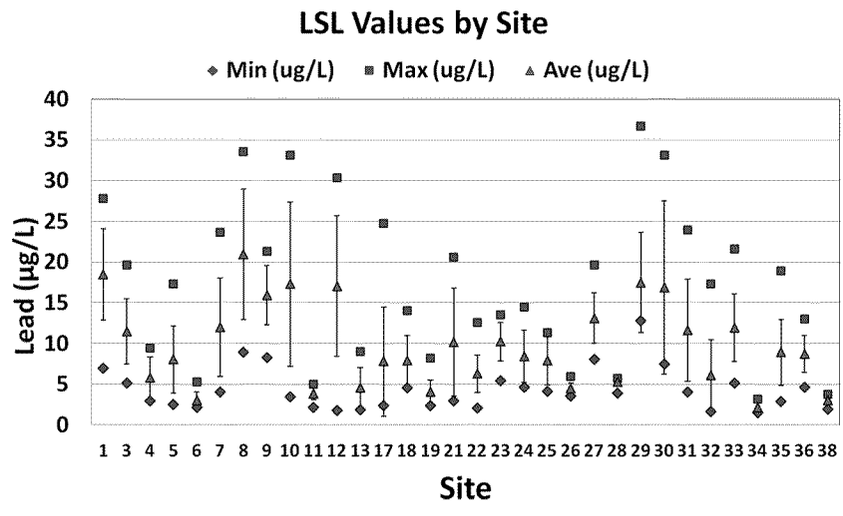

Figure 3. LSL results were highly variable within each LSL and from site to site. Error bars represent 1 standard deviation.

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

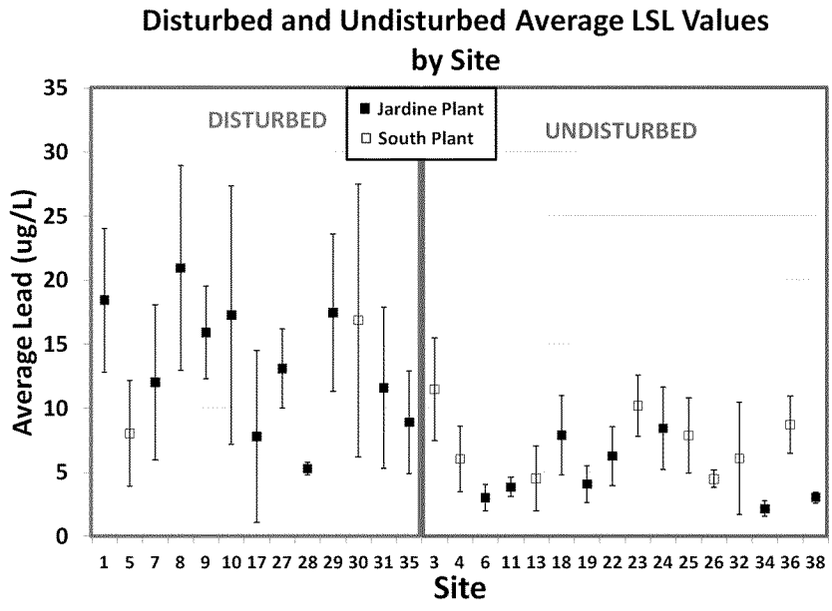

Figure 4. Average lead levels at disturbed and undisturbed sites. Error bars represent 1 standard deviation.

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.

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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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REFERENCES

(1) Sandvig, A.; Kwan, P.; Kirmeyer, G.; Maynard, B.; Mast, D.; Trussell, R. R.; Trussell, S.; Cantor, A. F.; Prescott, A. Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues; Research Report 91229; American Water Works Association Research Foundation: Denver, CO, 2008.

(2) Triantafyllidou, S.; Edwards, M. Lead (Pb) in tap water and in blood: Implications for lead exposure in the United States. Crit. Rev. Environ. Sci. Technol. 2012, 42, 1297-1352.

(3) U.S. EPA. National Primary Drinking Water Regulations, 40 CFR Part 141 Subpart I • Control of Lead and Copper, 2012.

(4) Schock, M. R.; Lemieux, F. G. Challenges in addressing variability of lead in domestic plumbing. Water Sci. Technol.: Water Supply 2010, 10 (5), 792-798.

(5) Van Der Leer, D.; Weatherill, N. P.; Sharp, R. J.; Hayes, C. R. Modelling the diffusion of lead into drinking water. Appl. Math. Modell. 2002, 26 (6), 681-699.

(6) Cartier, C.; Arnold, R. B., Jr.; Triantafyllidou, S.; Prévost, M.; Edwards, M. Effect of flow rate and lead/copper pipe sequence on lead release from service lines. Water Res. 2012, 46 (13), 4142-4152.

(7) Cartier, C.; Bannier, A.; Pirog, M.; Nour, S.; Prévost, M. A rapid method for lead service line detection. J. - Am. Water Works Assoc. 2012, 101 (11), E582-E595.

(8) Elfland, C.; Scardina, P.; Edwards, M. Lead-contaminated water from brass plumbing devices in new buildings. J. - Am. Water Works Assoc. 2010, 102 (11), 66-76.

(9) Sarver, E.; Edwards, M. Effects of flow, brass location, tube materials and temperature on corrosion of brass plumbing devices. Corros. Sci. 2011, 53 (5), 1813-1824.

(10) Schock, M. R.; Lytle, D. A. Internal corrosion and deposition control. In Water Quality and Treatment: A Handbook of Community Water Supplies, 6th ed.; McGraw-Hill, Inc.: New York, 2011.

(11) Triantafyllidou, S.; Parks, J.; Edwards, M. Lead particles in potable water. J. - Am. Water Works Assoc. 2007, 99 (6), 107-117.

(12) Britton, A.; Richards, W. N. Factors influencing plumbosolvency in Scotland. J. Inst. Water Eng. Sci. 1981, 35 (5), 349-364.

(13) Cartier, C.; Laroche, L.; Deshommes, E.; Nour, S.; Richard, G.; Edwards, M.; Prevost, M. Investigating dissolved lead at the tap using various sampling protocols. J. - Am. Water Works Assoc. 2011, 103 (3), 55-67.

(14) Clark, B.; Edwards, M. 3-D Lead profiling to characterize particulate lead risks in potable water. In Proceedings AWWA Water Quality Technology Conference, Toronto, ON, November 4-7, 2012.

(15) Hulsmann, A. D. Particulate lead in water supplies. J. Inst. Water Environ. Manage. 1990, 4 (2), 19-25.

(16) U.S. EPA. Revised Public Notification Handbook; EPA 816-R-09-013, U.S. Environmental Protection Agency, Office of Water: Washington, DC, 2010.

(17) Edwards, M.; Dudi, A. Role of chlorine and chloramine in corrosion of lead-bearing plumbing materials. J. = Am. Water Works Assoc. 2004, 96 (10), 69-81.

(18) Feldmann, C. R.; Walasek, J. B.; Lobring, L. B. Procedure for preserving lead in drinking water samples. J. - Am. Water Works Assoc. 1992, 84 (7), 89-91.

(19) Cardew, P. T. Development of a convective diffusion model for lead pipe rigs operating in laminar flow. Water Res. 2006, 40 (11), 2190-2200.

(20) Kuch, A.; Wagner, I. Mass transfer model to describe lead concentrations in drinking water. Water Res. 1983, 17 (10), 1303.

(21) Deshommes, E.; Prévost, M.; Levallois, P.; Lemieux, F.; Nour, S. Application of lead monitoring results to predict 0-7 year old children's exposure at the tap. Water Res. 2013, 47 (7), 2409-2420.

(22) Schock, M. R. Causes of temporal variability of lead in domestic plumbing systems. Environ. Monit. Assess. 1990, 15, 59-82.

(23) Karalekas, P. C., Jr.; Craun, G. F.; Hammonds, A. F.; Ryan, C. R.; Worth, D. J. Lead and other trace metals in drinking water in the Boston metropolitan area. J. N. Engl. Water Works Assoc. 1976, 90, 150-172.

(24) Deshommes, E.; Laroche, L.; Nour, S.; Cartier, C.; Prévost, M. Source and occurrence of particulate lead in tap water. Water Res. 2010, 44 (12), 3734-3744.

(25) Douglas, I.; Campbell, A.; Muylwyk, Q. Lead control in soft water: Experience from a Canadian utility. In Proceedings AWWA Annual Conference and Exhibition, Toronto, ON, June 24-28, 2007.

(26) Muylwyk, Q.; Waller, M.; Spielmacher, A.; Olesiuk, J.; Suffoletta, V. Full versus partial lead service line replacement and lead release in a well-buffered groundwater. In Proceedings AWWA Water Quality Technology Conference, Phoenix, AZ, November 13-17, 2011.

(27) Wujek, J. J. Minimizing peak lead concentrations after partial lead service line replacements. Presentation AWWA Water Quality Technology Conference, San Antonio, TX, November 14-18, 2004.

(28) American Water Works Association. Buried No Longer: Confronting America's Water Infrastructure Challenge; American Water Works Association: Denver, CO, 2012.

(29) Rockaway, T. D.; Coomes, P. A.; Rivard, J.; Kornstein, B. Residential water use trends in North America. J. - Am. Water Works Assoc. 2011, 103 (2), 76.

(30) Arnold, R. B., Jr.; Edwards, M. Potential reversal and the effects of flow pattern on galvanic corrosion of lead. Environ. Sci. Technol. 2012, 46 (20), 10941-7.

(31) American Water Works Association. Corrosion Control for Operators; American Water Works Association: Denver, CO, 1986; p 128.

(32) Colling, J. H.; Croll, B. T.; Whincup, P. A. E.; Harward, C. Plumbosolvency effects and control in hard waters. J. Inst. Water Environ. Manage. 1992, 6 (6), 259-268.

(33) Schock, M. R.; Wagner, I.; Oliphant, R. The corrosion and solubility of lead in drinking water. In Internal Corrosion of Water Distribution Systems, 2nd ed.; AWWA Research Foundation/DVGW Forschungsstelle: Denver, CO, 1996; pp 131-230.

(34) Hayes, C. R.; Hydes, O. D. UK experience in the monitoring and control of lead in drinking water. J. Water Health 2012, 10 (3), 337-348.

(35) Hayes, C. R.; Incledion, S.; Balch, M. Experience in Wales (UK) of the optimization of ortho-phosphate dosing for controlling lead in drinking water. J. Water Health 2008, 6 (2), 177-185.

(36) Triantafyllidou, S.; Edwards, M. Galvanic corrosion after simulated small-scale partial lead service line replacements. J. - Am. Water Works Assoc. 2011, 103 (9), 85-99.

(37) Brown, M. J.; Raymond, J.; Homa, D.; Kennedy, C.; Sinks, T. Association between children's blood lead levels, lead service lines, and water disinfection, Washington, DC, 1998-2006. Environ. Res. 2011, 111 (1), 67-74.

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(38) Brown, M. J.; Margolis, S. Lead in drinking water and human blood lead levels in the United States. Morbidity and Mortality Weekly Report 2012, 61 (Suppl;August 10, 2012), 1 - 9.
(39) American Water Works Association. Managing Change and Unintended Consequences: Lead and Copper Rule Corrosion Control Treatment; American Water Works Association: Denver, CO, 2005; p 39.
(40) Renner, R. Plumbing the Depths of D.C.'s Drinking Water Crisis. Environ. Sci. Technol. 2004, 38 (12), 224A - 227A.
(41) Triantafyllidou, S.; Lambrindou, Y.; Edwards, M. Lead (Pb) exposure through drinking water: Lessons to be learned from recent U.S. experience. Global NEST J. 2009, 11 (3), 341 - 348.
(42) Schock, M. R. Understanding corrosion control strategies for lead. J. - Am. Water Works Assoc. 1989, 81 (7), 88 - 100.