Environmental Science & Technology LETTERS

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# Estimating Consumers at Risk from Drinking Elevated Lead Concentrations: An Iowa Case Study

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Cite This: *Environ. Sci. Technol. Lett.* 2020, 7, 948–953 Read Online

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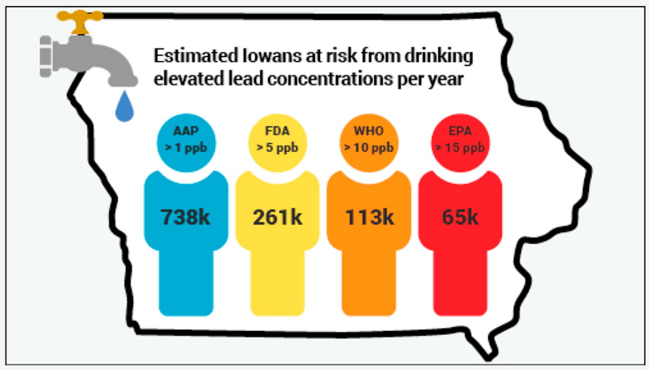
**ABSTRACT:** The Lead and Copper Rule (LCR) addresses lead in drinking water through utility-centric monitoring in high risk homes, corrosion control, and public education. These utility-centric activities, however, do not provide adequate information on lead concentrations in individual homes and leave an *unknown* number of consumers at risk from drinking water lead. To assess the number of consumers at risk from drinking elevated lead concentrations, we mined 166,554 lead samples taken for LCR compliance in Iowa and developed a new approach for estimating the number of consumers at risk. We estimate that 65,000 ± 14,000 people in Iowa are at risk from drinking water lead above the U.S. EPA action level of 15 parts per billion (ppb) each year. We further explored the average household sampling rates of community water systems (CWSs) of different population sizes, where, overall, 8.6% of homes in an Iowa CWS are sampled. Our estimates indicate that, even in the absence of a lead-in-water crisis, a significant number of people are at risk from lead concentrations exceeding available guidelines, raising concerns about the severity of baseline lead concentrations in drinking water nationwide. Our analysis highlights that consumer-centric lead in drinking water policies and avoidance strategies are needed to ensure public protection.




## ■ INTRODUCTION

The United States (U.S.) Centers for Disease Control and Prevention (CDC) states that no level of lead exposure is safe for children.[1] The toxic effects of lead are well known,[2] and elevated blood lead levels (BLLs) are linked to adverse health and developmental effects especially in young children.[3] Although U.S. regulations have dramatically reduced lead exposure in recent decades,[4] substantial evidence supports significant physiological, behavioral, and academic impairments in children with BLLs as low as 2 μg/dL.[5,6] Because there is no way to treat low-level lead toxicity,[7] the American Academy of Pediatrics (AAP) recommends reducing or eliminating all sources of lead before exposure as the most reliable and cost-effective measure to protect the public.[7]

Lead-based paint, dust, and soil have been historically considered the major sources of lead exposure, whereas drinking water was not widely recognized as a significant source.[8] However, since the Washington, DC,[9] and Flint water crises[10] linked lead in drinking water to public health impacts, the U.S. Environmental Protection Agency (EPA) estimates drinking water can contribute about 20% of a person's lead exposure and contribute from 40% to 60% for formula-fed infants.[11] In addition to the EPA's estimate, other sources estimate drinking water can contribute between 7% and 20% of a person's lead exposure.[12−14] Despite this data, some state agencies continue to downplay this source of exposure for children.[15−18]

To address lead in drinking water, the U.S. EPA enacted the Lead and Copper Rule (LCR) in 1991.[19] The LCR requires community water systems (CWSs) to monitor at their consumers' taps.[19,20] A CWS is a public water utility that serves a community of at least 25 residents or 15 homes year round.[19] Lead concentrations cannot exceed an action level (AL) of 15 parts per billion (ppb) in more than 10% of tap water samples (90th percentile approach) collected during any monitoring period [40 C.F.R. §141.80(c)].[19] If CWSs exceed the lead AL, they must optimize corrosion control treatment (CCT) and, if necessary, replace lead service lines (LSLs) in the distribution system.[19,20]

As CWSs comply with the LCR, they carry out utility-centric activities that include the 90th percentile approach, limited

Received: September 17, 2020
Revised: October 15, 2020
Accepted: October 15, 2020
Published: October 20, 2020



sampling requirements, and limited direct mitigation efforts. These activities leave an unknown number of consumers at risk from drinking elevated lead concentrations.[21] Data exist to tie water lead levels to BLLs[22] during the Washington, DC,[9] and Flint water crises,[10,23,24] to lead plumbing systems,[25] and to lead contaminated wells in some developing countries.[26] Studies have also assessed the health risk of lead exposure, such as the chronic daily intake.[27−29] However, there is little data estimating the magnitude of consumers at risk from drinking elevated lead levels in the absence of events or conditions that release high lead concentrations into the water.[21] Estimating populations at risk from water lead is necessary as more communities learn of elevated lead in their homes'[30,31] and schools'[32,33] drinking water, raising questions about the severity of baseline lead concentrations nationwide.[34]

To estimate the severity of baseline lead concentrations statewide, we mined and analyzed lead samples taken for LCR compliance in Iowa. From this data, we calculated the percent of lead samples exceeding concentrations for four widely referenced drinking water guidelines, including EPA's LCR AL of 15 ppb,[19] the World Health Organization's (WHO) drinking water guideline of 10 ppb,[35] the U.S. Food and Drug Administration's (FDA) bottled water regulation[36] of 5 ppb (also the Canadian drinking water guideline),[37] and the recent AAP recommendation for school drinking water fountains of 1 ppb.[7] We further used the LCR samples to estimate the potential magnitude of consumers in Iowa at risk from drinking elevated water lead. In this letter, we define homeowners as "exposed" if they are at risk for having lead levels exceeding a lead guideline in their community tap water.

## MATERIALS AND METHODS

**Iowa LCR Data.** To collect data on lead in drinking water, we created Python scripts to mine 166,554 first draw lead samples taken for EPA LCR compliance over a 29-year period (January 1, 1991, to December 31, 2019) and CWS population counts from the Iowa Drinking Water Watch (DWW) database.[38] DWW is an EPA product associated with the Safe Drinking Water Information System (SDWIS)[39] and is accessible through the Iowa Department of Natural Resources website. We accounted for population and housing changes from 1991 to 2019 using Iowa county population and housing unit counts from the U.S. Census Bureau.[40−42] The Center for Health Effects of Environmental Contamination (CHEEC), which maintains databases related to CWS source water and treatment plant configuration, provided information on 2017 CWS CCT use. Iowa has an estimated 160,000 lead service lines,[43] where CWSs that use CCT primarily use corrosion inhibitors like phosphate. Further details are described in the Supporting Information.

## RESULTS AND DISCUSSION

**Lead Concentrations in Iowa Drinking Water.** To evaluate the distribution of lead concentrations, we plotted the cumulative distribution function of the first draw LCR samples taken in Iowa and grouped them by four lead guidelines (Figure 1). Of the 166,554 lead samples taken, 95,203 (57%) were below 0.1 ppb (and are not shown on Figure 1). About 3% of the samples ($n$ = 5145 samples) exceeded the EPA LCR AL of 15 ppb in the past 29 years. In addition to the EPA LCR, we found that about 5% of the samples exceeded the WHO guideline of 10 ppb ($n$ = 8724),[35] 12% exceeded the U.S. FDA regulation for bottled water at 5 ppb ($n$ = 20,331),[36] and almost one-third of the samples exceeded the AAP recommendation of 1 ppb ($n$ = 53,622).[7] When compared to first draw lead samples taken during crisis events,[9,24] i.e., Flint ($n$ = 268) and Washington, DC ($n$ = 6162), LCR samples taken in Iowa exceed each lead guideline at a lower proportion (Figure S1). For example, in Iowa, 3.1% of the LCR samples exceeded the 15 ppb EPA AL compared to 16% of the samples taken in Flint and 49% in Washington, DC. We find it concerning that even in the absence of a water crisis, 8724 LCR samples exceeded 10 ppb which has been proposed as the "Find and Fix" trigger level in the LCR revisions (LCRR).[44]

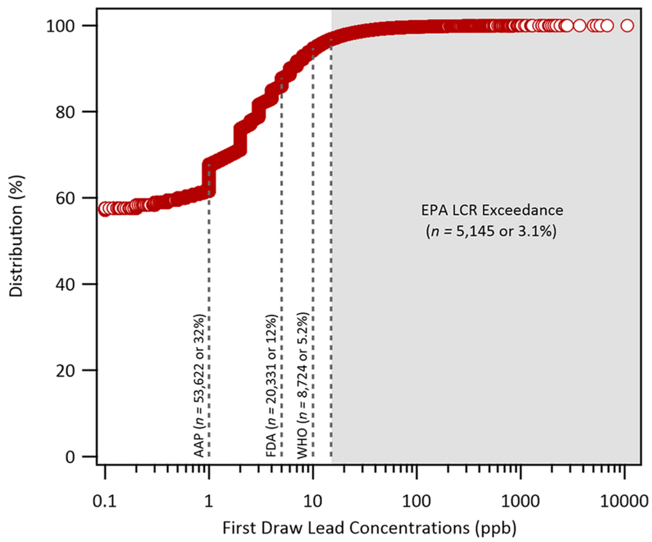



**Figure 1.** Cumulative density function of first draw lead samples taken in community water systems (CWSs) for the U.S. Environmental Protection Agency's Lead and Copper Rule (EPA LCR) compliance in Iowa from 1991 to 2019 ($n$ = 166,554 samples). 95,203 samples were below 0.1 ppb or not given a numerical value. The American Academy of Pediatrics (AAP) recommendation for schools is 1 ppb. The U.S. Food and Drug Administration (FDA) regulation is 5 ppb for bottled water. The World Health Organization (WHO) drinking water guideline is 10 ppb. The EPA LCR regulation is 15 ppb for first draw tap water samples. The number in parentheses is the total number of samples exceeding each lead target. CWSs of every activity status (i.e., active or inactive) are included.

**Iowans Exposed to Elevated Lead Concentrations.** Over the last 29 years, active CWSs (1080 out of 1771 systems) took 156,390 out of the 166,554 (94%) LCR samples in Iowa, annually sampling about 0.5% of 1,150,000 households on Iowa community water ($n$ = 2.84 million Iowans or 89% of the state population). The utility-centric LCR monitoring approach leaves millions of individual homes not sampled annually and an *unknown* number of consumers at risk from drinking lead in water. To estimate the number of consumers in Iowa, we used the LCR samples taken in active CWSs and considered three approaches (Supporting Information). A best-case scenario approach would be to count *only* the homes with samples exceeding a specific lead guideline as exposed. Using this approach, we estimate that 850 ± 90 people annually (0.03% people on CWSs) are exposed to lead levels exceeding 15 ppb in Iowa. At the other extreme, a worst-case scenario approach would assume *every* home in a CWS is exposed to elevated water lead if at least one lead sample is greater than a specified lead guideline. Using this approach, we


https://dx.doi.org/10.1021/acs.estlett.0c00753
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estimate that over one million Iowans are exposed to lead levels exceeding 15 ppb annually (1,030,000 ± 147,000 people or 36%). The large range estimated from the two approaches (850 to 1 million people; 0.03 to 36% of Iowans on CWSs) highlights the challenge of estimating how many people are at risk for having elevated water lead.

To overcome this challenge, we developed a new approach where population was estimated from the proportion of samples exceeding a guideline within each CWS's set of samples. This sample-proportional approach used the LCR samples to determine an exceedance rate for each CWS and used that rate to estimate the homes exposed within in each CWS. Specifically, we calculated the fraction of samples exceeding a lead guideline annually *within each CWS* ($Pb_{samples>15\ ppb}$ / total Pb samples taken). We then multiplied each fraction by the population served by each CWS and summed the number of people exposed in each CWS for each sampling year. The total population for each CWS was divided by the total sampling years. Finally, each CWS average was summed to estimate the average Iowa population exposed to each lead guideline annually (eq 1)

$$\sum_{i=1}^{n=\text{CWSs}} \sum_{j=1}^{n=\text{years}} \left[ \left( \frac{\text{Pb samples}_{>15\ \text{ppb}}}{\text{total Pb samples taken}} \right)_{ij} \times (\text{pop served})_{ij} \times \frac{1}{(\text{year sampled})_i} \right] \quad (1)$$

Using this sample-proportional approach, we estimate 65,000 ± 14,000 people in Iowa are exposed to lead concentrations greater than 15 ppb every year (compared to 850 or 1 million from the only or every home approaches) (Figure 2). This estimate is about 2% of the Iowa population who drink community water. Using the same approach for the other three lead guidelines, we find that about 4% (113,000 ± 18,000 people) are exposed annually to lead concentrations exceeding the WHO guideline and LCRR proposed trigger level of 10 ppb, 9% (261,000 ± 30,000) exceeding the FDA regulation of 5 ppb, and over a quarter (26% or 738,000 ± 62,000) exceeding the AAP recommendation of 1 ppb (Table S2).

Note that our estimates are based on LCR samples taken in CWSs that, if sampled correctly, first target older homes with lead plumbing and LSLs before taking other representative samples [40 C.F.R. § 141.86(a)].[19] The LCR samples should also reflect higher risk homes if the CWS has enough tier 1, 2, and 3 sampling sites [40 C.F.R. §141.86(a)].[19] In addition, CWSs may use the same sampling sites for more than one LCR monitoring period. Since a CWS's LCR sampling rate (e.g., every six months or three years) depends on the lead concentrations found, CWS size, public distribution pipe material, and mitigation efforts, consumers may be at risk from drinking water lead for months or for years. In this letter, we try to normalize this range of uncertain risk to an annual estimate of consumers. Lastly, our estimate includes an unknown number of people who avoid drinking in-home tap water,[45] flush their tap before consumption,[46] or use POU filters.[47,48] Despite these caveats, our estimates indicate that even in the absence of a lead-in-water crisis and in a state with only moderately corrosive community water[49,50] (e.g., pH > 7.0 and alkalinity >50 ppm of $CaCO_3$ or higher) a significant percent of the Iowa population is exposed to lead levels exceeding available guidelines.

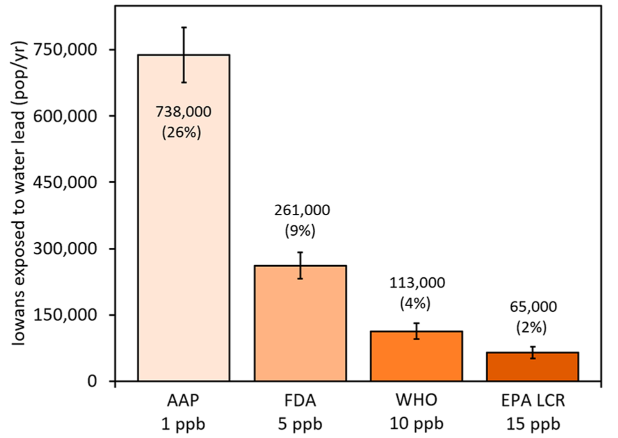


**Figure 2.** Estimated Iowa population exposed to lead levels exceeding different lead in drinking water guidelines or regulations annually (population/year). The estimated average populations exposed are inside or above each bar. Population numbers are rounded off. The number in parentheses is the percent of Iowans exposed on active community water systems (CWSs). Population numbers are estimated by first draw lead samples taken in active CWSs ($n$ = 1080 systems) for EPA Lead and Copper Rule (LCR) compliance from 1991 to 2019 ($n$ = 156,390 lead samples). Population numbers are calculated using the sample-proportional approach (eq 1). The error bars signify the range of uncertainty in each estimated value. Uncertainty calculations are described in the Supporting Information. The American Academy of Pediatrics (AAP) recommendation for schools is 1 part per billion (ppb). The U.S. Food and Drug Administration (FDA) regulation is 5 ppb for bottled water. The World Health Organization (WHO) drinking water guideline is 10 ppb. The EPA LCR regulation is 15 ppb for first draw tap water samples.

We further evaluated whether the Iowa LCR samples revealed any trends based on CWS size and CCT usage. The LCR requires size-based sampling and CCT criteria for CWSs serving populations ranging from very small to very large [40 C.F.R. §141.86(c)].[19] For the last four years of lead sampling, we found no statewide statistical association (odds ratio confidence interval = [0.62, 1.12], $p$-value = 0.22, Table S3) between elevated lead concentrations found in CWSs using or not using CCT (Supporting Information). However, the Iowa data does highlight the large differences in the percent of households sampled as a function of population size and CWS size category. The average household sampling rate decreases sharply as the CWS population served increases (Figure 3). For very small CWSs, the rate is 14% and decreases to 3% for small systems and then to as low as 0.2% for very large systems (Table S4). Overall, the average household sampling rate for a CWS in Iowa is 8.6%. For Iowa, the CWS size-based LCR sampling criteria results in a 100-fold greater chance a consumer is likely to have their home sampled for lead when they live in a very small CWS (~14%) compared to a very large CWS (~0.2%).

We expected to see more sampling in smaller CWSs, however, we also anticipated that the percent of LCR samples with concentrations exceeding a given lead guideline would be greater in smaller CWSs because of less stringent CCT requirements. Interestingly, there is no trend in the average percent of households exceeding a given lead guideline as a function of CWS size (Figure S2). The average percent of


https://dx.doi.org/10.1021/acs.estlett.0c00753
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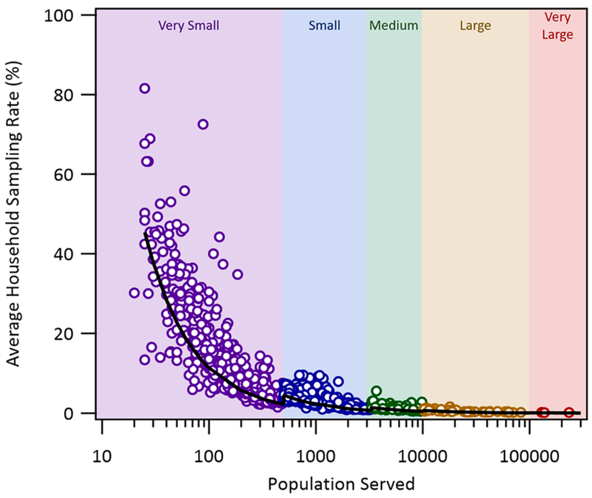


**Figure 3.** Average household sampling rate in community water systems ($n$ = 1073 systems) in Iowa as a function of the population served by each community water system (CWS). The black line signifies the theoretical sampling rate for Lead and Copper Rule (LCR) reduced monitoring requirements [40 C.F.R. §141.86(c)]. The black line was generated by taking the EPA LCR required number of samples for reduced sampling in each population category divided by the calculated number of households (population served/average household size or 2.27 people per household). CWSs are labeled by the five EPA population categories: very small, small, medium, large, and very large. First draw lead samples taken by homeowners in CWSs for LCR compliance from 1991 to 2019 were used to create this figure. The average household sampling rate (%) was estimated by eq S7. This figure does not show 7 out of 1080 active water systems because they did not take any lead samples from 1991 to 2019. Only active CWSs that took lead samples are included.

elevated LCR samples in a CWS only differs by a few percent for each guideline and each CWS size category. For example, the average percent of households in a CWS exceeding 10 ppb ranges from 3.0% to 4.8%, where a CWS in the medium-sized category has the highest percent exceedance, and the very large-sized and very small-sized categories have the lowest percent exceedance. While ideally, there would be a high average household sampling rate (i.e., more coverage) and a low percentage of LCR samples with concentrations exceeding a given lead guideline (i.e., lower exceedance), the relatively stable rates of exceedance across CWS size suggest that the likelihood of having elevated lead levels is somewhat similar, but that the likelihood of not knowing if you have elevated lead levels is higher in larger CWSs. Fortunately, studies have discussed lead mitigation strategies for communities, which vary between sites depending on physical and community considerations.[51−53]

Our estimates of the number of consumers in Iowa at risk for drinking elevated lead concentrations in water raise concerns about the severity of baseline lead concentrations in drinking water nationwide. The LCR's utility-centric approach does not provide adequate information on lead concentrations in individual homes, and the likelihood of not knowing whether individual homes are exposed to elevated lead concentrations increases significantly in larger CWSs typically found in large cities. Our analysis emphasizes the critical need for consumer-centric lead policies and programs for in-home tap sampling and avoidance strategies[52] that provide more direct protection for the consumer. These consumer-centric activities should encourage collaboration with consumers to raise awareness about, test, and mitigate lead in drinking water.[54]

Direct protection to the consumer for most water contaminants is achieved through the U.S. EPA's Safe Drinking Water Act Maximum Contaminant Level (MCL) framework. If the four current lead guidelines (1, 5, 10, and 15 ppb) are used as a surrogate MCL for lead, our estimate of the Iowa population annually exposed to elevated lead ranges from 65,000 people for 15 ppb to 738,000 people for 1 ppb (Figure 2). The greater than 10-fold difference in the estimated population exposed points to the critical need for a health-based guideline, similar to an MCL, for lead in drinking water. While a lead MCL is not considered viable because lead sources can come from within the home and the measured values are semi-random even under relatively controlled first draw protocols,[55,56] our analysis reveals significant exceedance of various water lead thresholds. The ambiguity and lack of consensus on an in-home water lead level needed to trigger health-based action must be addressed so consumers, schools,[54,57] and private well owners[58,59] can have clear guidance on when to implement lead avoidance strategies.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.0c00753.

> Extended explanations on methods and analyses used to collect and prepare data on Iowa lead samples; data-mining program; additional summary statistics and figures on lead in Iowa community water; estimate on Iowa populations at risk and associated uncertainty; odds ratios for corrosion control treatment use in Iowa; and average household sampling rates against percent of samples exceeding different guidelines (PDF)

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https://dx.doi.org/10.1021/acs.estlett.0c00753
Environ. Sci. Technol. Lett. 2020, 7, 948−953

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## Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

This research was supported in part by the National Science Foundation (NSF) Graduate Research Fellowship Program Grant No. 1546595, NSF Division of Graduate Education (DGE) Grant No. 1633098, University of Iowa Center for Health Effects of Environmental Contamination (CHEEC), and U.S. Environmental Protection Agency No. EPA-G2017-ORD-F1.

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