Environmental Science & Technology

Profiling Private Water Systems to Identify Patterns of Waterborne Lead Exposure

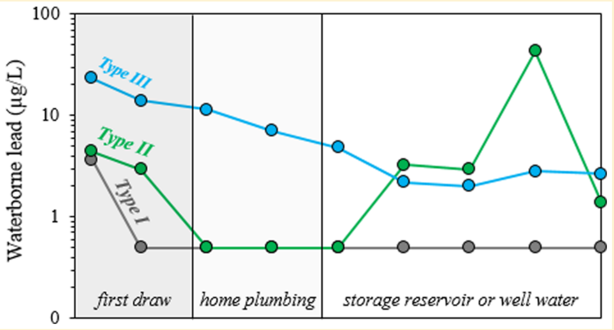
Kelsey J. Pieper,[*,†] Leigh-Anne Krometis,[†] Daniel Gallagher,[‡] Brian Benham,[†] and Marc Edwards[‡]

[†]Biological Systems Engineering, Virginia Tech, 200 Seitz Hall, Blacksburg, Virginia 24061, United States

[‡]Civil and Environmental Engineering, Virginia Tech, 418 Durham Hall, Blacksburg, Virginia 24061, United States

Supporting Information

ABSTRACT: Although extensive literature documents corrosion in municipal water systems, only minimal data is available describing corrosion in private water systems (e.g., wells), which serve as a primary source of drinking water for approximately 47 million Americans. This study developed a profiling technique specifically tailored to evaluate lead release in these systems. When applied in an intensive field study of 15 private systems, three patterns of lead release were documented: no elevated lead or lead elevated in the first draw only (Type I), erratic spikes of particulate lead (Type II), and sustained detectable lead concentrations (Type III). While flushing protocols as short as 15−30 s may be sufficient to reduce lead concentrations below 15 μg/L for Types I and III exposure, flushing may not be an appropriate remediation strategy for Type II exposure. In addition, the sustained detectable lead concentrations observed with Type III exposure likely result from corrosion of components within the well and therefore cannot be reduced with increased flushing. As profiling techniques are labor- and sample-intensive, we discuss recommendations for simpler sampling schemes for initial private system surveys aimed at quantifying lead and protecting public health.



1. INTRODUCTION

Contaminants of human health concern in private water systems (e.g., wells, springs) are increasingly recognized as a source of potential elevated health risk.[1−3] The proportion of waterborne disease outbreaks in private systems since 1971 continues to increase relative to public systems.[2] This is not necessarily surprising as private systems (i.e., systems with <15 service connections and serve <25 individuals for at least 60 days per year) do not fall under the regulatory authority of the U.S. Environmental Protection Agency (USEPA) and are therefore not subject to the protections offered by the Safe Drinking Water Act (SDWA).[4] Approximately 15% of U.S. households, serving more than 47 million residents, are currently reliant on these unregulated private systems.[4]

Preliminary efforts to survey water quality in private systems report that 23−58% of systems exceed at least one SDWA health-based standard.[5−7] However, waterborne metals related to the corrosion of plumbing components are only rarely assessed because there are no regulations, sampling protocols have been designed for public utilities, and the financial burden falls completely on private system homeowners. The limited research available at the state level indicates that 12−19% of private systems sampled exceed the USEPA lead action level of 15 μg/L.[5,6,8] Lead concentrations measured in "first draw" (e.g., sample collected following 6 h of stagnation) have been recorded as high as 2800 μg/L in Pennsylvania and 24 740 μg/L in Virginia. For perspective, a lead concentration of 5000 μg/L or higher qualifies landfill leachate as hazardous waste.[9]

Under the Lead and Copper Rule (LCR), the USEPA monitors and regulates lead concentrations in municipal systems by collecting 1 L first draw samples in consumers' homes.[10] For LCR compliance, no more than 10% of samples may exceed the lead action level of 15 μg/L. In order to reduce lead leaching to water from plumbing, municipalities often implement corrosion control techniques such as addition of corrosion inhibitors and/or adjustments of water quality parameters (e.g., pH, alkalinity). Such corrosion control strategies are not common in private systems, where the decision to install treatment is solely the prerogative of the homeowner. A recent survey of over 2000 private systems in Virginia indicated that only 5% of systems had installed acid neutralizers that adjusted water chemistry to control lead release and 3% had reserve osmosis units that removed lead through filtration,[6] despite the fact that typical source water (e.g., groundwater) can be extremely aggressive toward metals. Previous studies in Virginia, Pennsylvania, and New Jersey report that 18−44% of water samples from private systems are below the USEPA recommended minimum pH of 6.5,[5,6,11]

Received: June 30, 2015
Revised: September 16, 2015
Accepted: October 1, 2015
Published: October 1, 2015

DOI: 10.1021/acs.est.5b03174
Environ. Sci. Technol. 2015, 49, 12697−12704

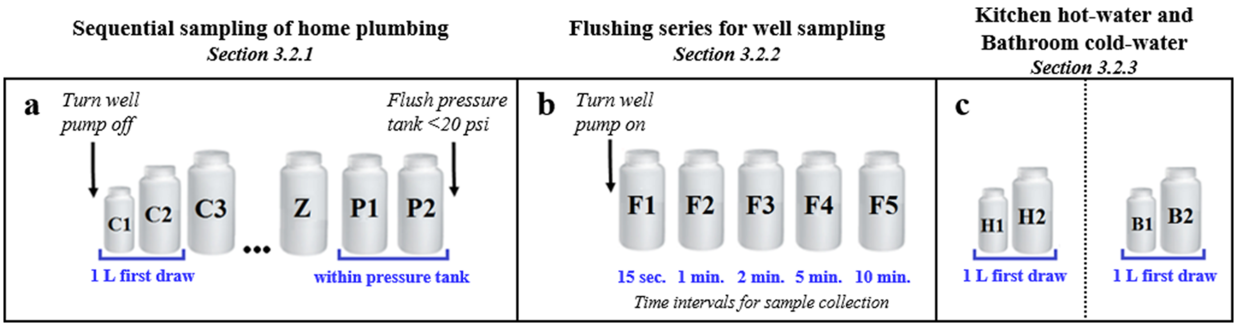


Figure 1. Illustration of the profiling protocol developed for private systems: (a) sequential samples were collected from the kitchen cold-water faucet, and the number of samples was determined from the volume of water within the home plumbing (= *Z* liters); (b) a series of flushed sampled was subsequently collected to quantify lead release from the well, and (c) samples collected from the kitchen hot-water faucet and bathroom cold-water faucet after completion of the kitchen cold-water faucet profile.

which indicates a higher propensity for lead leaching from plumbing.[12,13]

The USEPA encourages homeowners with private wells to run the faucet for a few seconds to as long as 2 min to flush any contaminated stagnant water within the plumbing network to prevent waterborne lead exposure;[14] however, this recommendation is only suggested as necessary for 4 weeks following the installation of a new pump or brass faucet. Although flushing may be a low-cost remediation strategy for many private systems, as elevated lead is often only observed in the first draw,[6] recommended flushing protocols vary greatly with little confirmation of their effectiveness. The CDC recommends a 1−2 min flush, while Virginia Cooperative Extension suggests a minimum of 5 min.[15,16] Recent work targeting municipal systems suggest that effective flushing protocols need to be tailored for specific plumbing configurations and may never be entirely adequate in mitigating health risk if particulate lead is mobilized, which is associated with semirandom concentration spikes.[17−22] Particulate lead has been observed in private systems at levels as high as 99% of the total lead concentration, and, as in municipal systems, its occurrence appears to be sporadic and difficult to predict.[6,8]

Collection of a first draw grab sample only indicates if a given outlet releases an unacceptable lead concentration, and it provides little insight into water conditions in the remainder of the plumbing system.[23] To assess lead concentrations throughout the entire plumbing system, recent municipal studies have developed profiling techniques (i.e., analysis of sequential samples) and identified patterns of lead release with associated public health implications.[17,18,22] This research modifies current profiling techniques to provide an in-depth understanding of the sources of lead release within private systems, which is critical when evaluating the effectiveness of existing remediation strategies to mitigate the risks associated with waterborne lead exposure. By profiling 15 households in Virginia, this research (1) investigates variations in waterborne lead concentrations throughout the entire plumbing network and (2) demonstrates that the lead release patterns known to occur in municipal systems can also occur in private systems.

2. METHODS

2.1. Study Participants. Participants were recruited through the Virginia Household Water Quality Program (www.wellwater.bse.vt.edu), a Virginia Cooperative Extension program that offers water quality testing to private system homeowners in Virginia. During 2012 and 2013, 31% of 250 mL first draw samples submitted from participating households in Albemarle County (37 of 119) contained lead concentrations above the USEPA action level of 15 μg/L. In late 2013 and 2014, these homeowners were asked to participate in a complementary water quality follow-up study to investigate potential sources of waterborne lead. Participation was wholly voluntary, and 15 of the 35 homeowners who were contacted participated. Two of the 37 homeowners had incomplete contact information.

2.2. Profiling Protocol. *2.2.1. Profiling the Home Plumbing System.* Site visits were scheduled in advance to ensure that water remained stagnant for a minimum of 6 h prior to sampling per LCR protocol. At each household, the volume of water between the kitchen faucet and pressure tank was estimated based on inspection of the plumbing and is referred to as volume 'Z' (1 to 3 L). To prevent the well pump from engaging every time a faucet is opened, private systems typically use a pressure tank that maintains water pressure within the home plumbing. While pressure tanks extend the life of well pumps, their presence interrupts profiling techniques, as these tanks store large volumes of water. Therefore, this profiling method controls water flow from the pressure tank to detect lead released from within the home plumbing system (e.g., brass, solder), as well as lead potentially derived from well components (e.g., galvanized iron, brass).

With electricity to the well turned off and flow driven solely by the pressure tank, 250 and 750 mL first draw samples (Figure 1a, C1 and C2) were collected at full flow from the kitchen cold-water faucet to compare first draw results to the previous 2012/2013 extension effort and the LCR. Immediately after, consecutive 1 L samples were collected until *Z* liters were collected. Two additional 1 L samples were then collected to evaluate water quality within the pressure tank and allow for error in volume estimates. These samples (C1−P2) quantified lead release within the home plumbing system. Subsequently, the kitchen cold-water faucet was flushed until the pressure tank read below 20 psi, which is below the common pump cut-in pressure of 30−40 psi.

2.2.2. Flushing Series to Sample Water within the Well. With the electricity restored and the pump turned on, a series of samples was collected to detect lead in water within the well. It was assumed there would be relatively little contamination from the home plumbing as the supply to the house would be primarily fresh source water. Samples were collected after flushing the kitchen faucet for 15 s, 1, 2, 5, and 10 min (Figure 1b, F1−F5). As the average pressure tank fills within minutes, these flushed samples cannot be considered representative of plug flow.

2.2.3. Assessing Influence of Temperature and Sample Location. Immediately after the kitchen cold-water flushed samples were collected (Figure 1b), two first draw samples (250 and 750 mL) were collected from the kitchen hot-water faucet (Figure 1c, H1 and H2) and bathroom cold-water faucet (B1 and B2) at full-flow to assess the influence of temperature and sample location on lead release.

2.2.4. Sampling in Households with Treatment Devices with Storage Reservoirs. The profiling method was modified for households that had a treatment device with a storage reservoir (e.g., acid neutralizer, water softener). Due to the volume of stored water within the treatment unit, sampling water upstream of the pressure tank would not have been possible without extensive flushing. In this study, six households had acid neutralizers and one household had an acid neutralizer and water softener. Therefore, in these households, after the sequential sampling of the home plumbing system, the flushing series began immediately, that is, the pressure tank was not flushed below 20 psi.

2.2.5. Homeowner Interviews and Plumbing Inspections. Each homeowner was briefly interviewed to document behaviors since his/her initial water testing and describe previous participation in the extension effort (e.g., faucet sampled). To document plumbing materials (e.g., copper piping; Supporting Information, Table S1) and plumbing characteristics (e.g., size of pressure tank), the plumbing network was visually inspected at the kitchen and bathroom faucets, pressure tank, and well head.

2.3. General Water Quality Analyses. pH was recorded in the field using a Hanna Instruments HI 98129 probe per method 4500-H^+.[24] Alkalinity was measured within 2 weeks of collection per method 2330 B.[24] To quantify dissolved metals, we pipetted a 10 mL aliquot from each sample and filtered through a 0.45 μm filter on site. For metals analysis, samples (unfiltered and filtered) were acidified with 2% nitric acid and digested for a minimum of 16 h prior to analysis using an ICP-MS per methods 3030 D and 3125 B.[24] Blanks and/or spikes of known concentrations were processed every 10 samples for QA/QC purposes.

2.4. Statistical Analyses. Statistical analyses were conducted in R version 3.0.2[25] assuming an alpha of 0.05 as an indication of significance. Due to the non-normal distribution (Shapiro–Wilk, $p < 0.05$), the Wilcoxon signed-rank test was used for statistical analyses, including an unpaired test of 250 mL first draw lead concentrations (Figure 1a, C1), alkalinity, and pH measurements between households with and without an acid neutralizer installed; a paired test of lead concentrations in the 250 and 750 mL first draw samples (Figure 1a, C1 and C2) based on sampling location and temperature; and a paired test to evaluate differences in lead concentrations in the 250 mL first draw between the extension effort and the follow-up study.

3. RESULTS

3.1. First Draw Lead Concentrations. During the original 2012/2013 extension clinics, 37 homeowners in Albemarle County, VA submitted first draw samples with lead concentrations that exceeded the USEPA action level. Of these, 15 participated in this follow-up study. The mean and median first draw concentrations for samples from these 15 households during the extension effort were 37.5 and 27.6 μg/L, respectively. Despite preselection of households with a history of "high" lead, only two had 250 mL first draw samples that contained lead above 15 μg/L during the follow-up (23.4 and 26.0 μg/L); the mean and median concentrations for all first draw samples were 7.6 and 4.2 μg/L. As a result, the 250 mL first draw samples collected during this follow-up study had significantly lower concentrations compared to the extension effort (Wilcoxon paired test, $p < 0.05$). The median difference in lead concentrations between the two sampling efforts was −22.3 μg/L, which highlights the semirandom nature of lead release and potential benefit of remedial measures implemented since the first sampling.

Only one of the two households with lead concentrations above the action level in the 250 mL first draw was also above the action level in the subsequent 750 mL sample (19.6 μg/L). However, a 750 mL sample from a third household exceeded 15 μg/L, although the initial 250 mL first draw sample did not (3.7 μg/L); the concentration in this sample was 54.9 μg/L, which was 87% particulate lead. Mathematically combining the initial 250 and 750 mL samples for comparison to the LCR's 1 L collection protocol for municipal systems, these three households would not be considered in compliance, as the equivalent 1 L first draw concentrations were 16.3, 21.2, and 42.1 μg/L.

3.2. Reduction in Lead Due to Acid Neutralizers. The lower than expected 250 mL first draw concentrations during this follow-up study could be attributed to the installation or servicing of acid neutralizers during the 1–2 year period between the extension effort and the follow-up study, that is, upon obtaining their original results, homeowners took actions to improve their household water quality (Figure 2). During interviews ($n = 15$), three homeowners indicated that they installed acid neutralizers and four homeowners noted servicing (e.g., changed the resin within) their acid neutralizers based on their 2012/2013 extension water quality results. In addition, three homeowners described replumbing parts of their premise plumbing network, and one of these homeowners also installed an acid neutralizer. No households had a lead filter (e.g., reverse osmosis) installed.

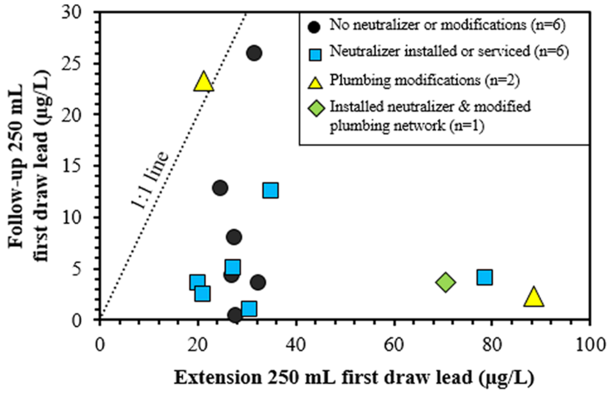


Figure 2. Paired 250 mL lead concentrations collected during the 2012/2013 extension effort and the follow-up study.

While properly maintained acid neutralizers can reduce the corrosivity of water within the premise plumbing, there has been minimal assessment of the installation and servicing of these units in private systems. Although there was no significant difference ($p = 0.35$) in median 250 mL lead concentrations in households with an acid neutralizer ($n = 7$; 3.7 μg/L) versus those without ($n = 8$ 6.2 μg/L), households with an acid

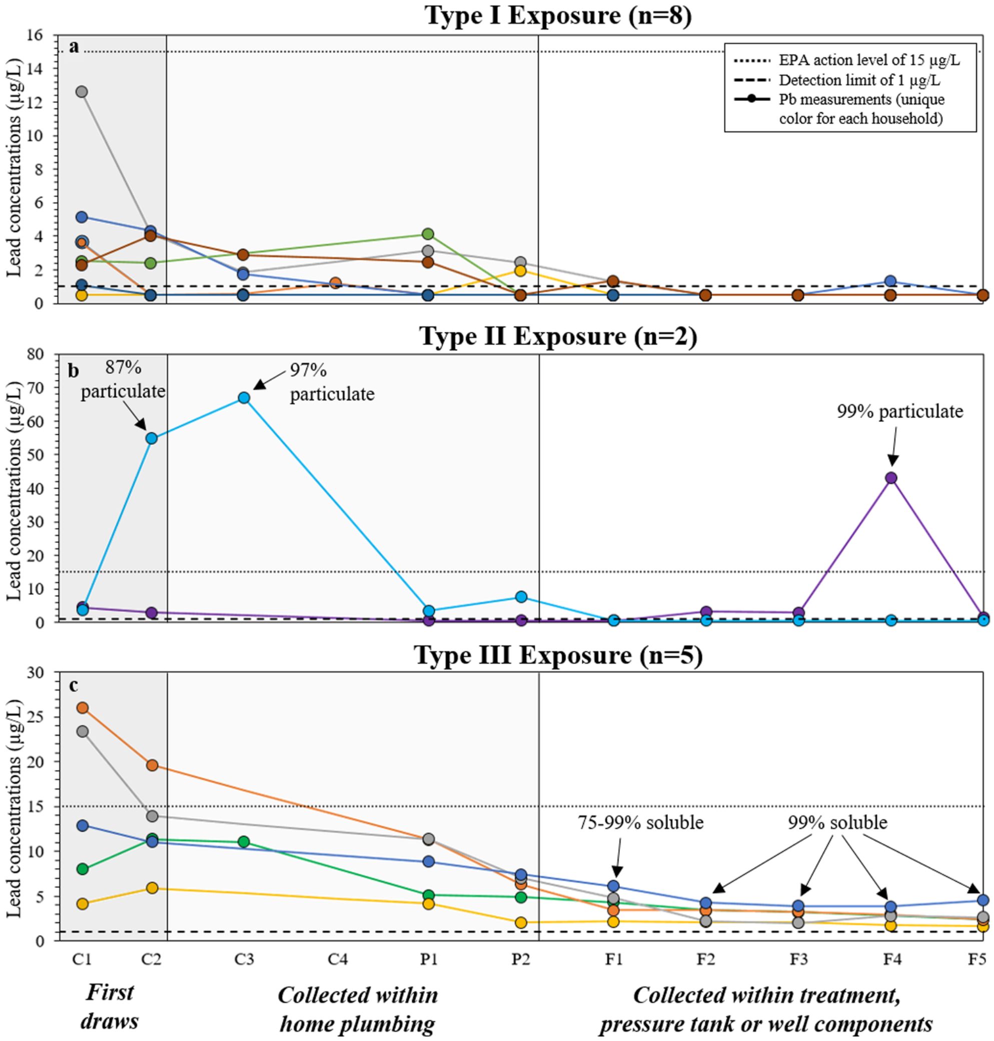


Figure 3. Patterns of waterborne lead release: (a) households with no elevated lead or lead elevated in the first draw only (Type I); (b) erratic spikes of particulate lead mobilized from plumbing during water use (Type II); and (c) sustained detectable lead concentrations (≥ 1 μg/L) even with extensive flushing (Type III). Note: Samples C3 and C4 were not collected in all households due to shorter home plumbing lengths observed.

neutralizer had significantly higher alkalinity (p = 0.02; 96.9 compared to 21.3 mg/L as $CaCO_3$) and pH measurements (p = 0.04; 7.3 compared to 6.3). Langelier Saturation Index (LSI) values are discussed in the Supporting Information (Figure S1). As the relationship between corrosion and aggressive water is well documented,[12,13] the installation or servicing of acid neutralizers may be partly responsible for the lower observed lead concentrations during this effort relative to the 2012/2013 extension effort.

3.3. Reduction in Lead Due to Sampling Location.

When homeowners (n = 15) were asked to identify the faucet used during the 2012/2013 extension clinic, only four homeowners indicated that they collected samples from a kitchen faucet. Eight homeowners could not remember or reported both the bathroom and kitchen faucets, and two homeowners reported collecting from a bathroom. One homeowner collected samples from a laundry sink as this faucet did not have an aerator and did not swivel, per the extension sampling instructions; however, this type of faucet is not approved for dispensing water for human consumption.[26] As faucet fixtures can contribute a large percentage of the total lead in the first draw,[27,28] the influence of the sampling location was further investigated.

3.3.1. Lead Release from Bathroom Faucets. During the follow-up study, two first draw samples (250 and 750 mL; Figure 1c, B1 and B2) were collected from a bathroom faucet after profiling of the kitchen faucet. Seven of the 15 bathroom faucets had 250 mL first draw samples that measured lead above 15 μg/L, with mean and median concentrations for all samples of 19.6 and 13.4 μg/L, respectively. The 250 mL first draws collected from the bathroom faucet had significantly higher lead concentrations than kitchen 250 mL first draws (B1 vs C1; p = 0.03) with a median difference of 2.0 μg/L. As plumbing at the outlet is typically 9.5 mm (3/8 in.) diameter and supply lines are typically 12.7–25.4 mm (1/2–1 in.) diameter, the first 2.4 m (8 ft.) of plumbing would be approximately 250 mL of water. Therefore, a 250 mL first draw is likely primarily representative of lead release at the outlet only.

Concentrations in the subsequent 750 mL samples were generally much lower (median of 2.3 μg/L), with no significant difference in lead concentrations between the 750 mL bathroom and 750 mL kitchen first draw (B2 vs C2; p = 0.62). As the 750 mL sample was composed of water likely within the supply line rather than the faucet, this result is not surprising, though it does further emphasize the importance of sample location. Lead concentrations in the 750 mL first draw from the bathroom faucet were above the action level in two households (17.7 and 132.5 μg/L). In the household with a 750 mL bathroom sample concentration of 132.5 μg/L, 93% of the lead was in the particulate form.

3.3.2. Lead Release from Hot-Water Faucets. During the follow-up study, two first draw samples (250 and 750 mL; Figure 1c, H1 and H2) were collected from the kitchen hot-water faucet to evaluate the effect of temperature. Lead concentrations in the 250 mL first draw were above 15 μg/L in two households, with concentrations of 15.7 and 410.7 μg/L. However, the mean and median concentrations for all 250 mL first draw samples were 34.7 and 2.7 μg/L. The subsequent 750 mL samples were generally much lower (median of 3.6 μg/L), but two 750 mL samples had elevated concentrations (15.9 and 122.6 μg/L). In the household with lead concentrations in the first draws of 410.7 and 122.6 μg/L, 98% of the lead was in the particulate form. High percentages of particulate lead was observed in all first draw samples collected from this household. There was no significant difference between the kitchen hot and cold-water faucets for the 250 mL first draw (H1 vs C1; $p = 0.18$) or the 750 mL first draws (H2 vs C2; $p = 0.89$).

3.4. Profiling. Past surveys of private systems have focused on quantifying lead in first draw samples as lead is primarily derived from the corrosion of plumbing components and rarely found in groundwater.[5,6,8,29] Studies have noted the potential for lead leaching from well components[30] although the USEPA suggests that exposure from well components would be minimized (<5 μg/L) after 4 weeks of use following installation of a well pump.[14] Based on the 15 households profiled, three patterns of waterborne lead release were identified (Figure 3; Supporting Information Table S2): no elevated lead or lead elevated in the first draw only (Type I), erratic spikes of particulate lead mobilized at semirandom times (Type II), and sustained detectable lead concentrations (≥1 μg/L) even with extensive flushing (Type III). Potential sources of lead release were evaluated by assessing the combinations of waterborne metals (e.g., copper, zinc).

3.4.1. Type I—Corrosion of Premise Plumbing Components. Households identified as having Type I exposure ($n = 8$) had nondetectable lead concentrations during the flushing series (<1 μg/L; Figure 3a). Detectable concentrations were observed in the home premise plumbing systems (Figure 1a, C1−P2), with the highest concentrations observed in the first draw samples (C1 and C2) for six households. Brass components at the outlet (e.g., faucets) appeared to be the likely source of lead as water samples often contained elevated levels of copper and zinc (median C1 concentrations of 492 and 1108 μg/L, respectively), which are the three primary metals in brass alloys.[31] This is in keeping with previous investigations of lead exposure indicating that water is typically safe, or hazards are eliminated after a few seconds of flushing at a leaded brass faucet.[6,28]

3.4.2. Type II—Mobilization of Particulate Lead. Samples from two households had lead concentrations above the USEPA action level with the lead primarily in the particulate form (Type II). While lead concentrations in the home plumbing system of one household were low (max of 4.4 μg/L; Figure 1a, C1−P2), there was a lead spike of 43 μg/L (99% particulate) in sample F4 after 6 min of flushing (Figure 3b, purple). This sample also had higher concentrations of particulate copper and zinc (67.5 and 8.2 μg/L), which suggested sloughing of scale from a brass component(s) as a likely source. In the other household, particulate lead (87−97% composition) was mobilized during the profile, but the samples collected during the flushing series (Figure 1b, F1−F5) had nondetectable concentrations (<1 μg/L; Figure 3b, blue). Samples C2 and C3 contained high levels of particulate tin and copper (11−14 and 141−170 μg/L), which indicated that lead was likely released from solder.[32] This pattern of exposure is consistent with studies investigating the occurrence of particulate lead in municipal systems as particulate lead is highly variable and often associated with higher flow rates and hydraulic disturbances.[19,20,33,34]

3.4.3. Type III—Corrosion of Well Components. When components in the well are corroding (Type III), detectable background lead concentrations (≥1 μg/L) are present with continued water use. The 250 mL first draw samples from two households in this category exceeded the USEPA action level; the remaining three households did not with concentrations between 4 and 13 μg/L. In all households, lead levels decreased in subsequent samples, but sustained detectable lead concentrations (2−6 μg/L) were observed throughout the flushing series (Figure 1b, F1−F5; Figure 3c). These background concentrations were composed entirely of dissolved lead, which suggests collection of stagnant well water rather than mobilization of particulate lead. Concentrations of dissolved copper and zinc were elevated in samples with detectable lead concentrations (F1−F5; median concentrations of 125 and 50 μg/L), which suggests leaching of brass components in the well (e.g., pitless adapters, well pump). The corrosion of components in the well is a unique pattern associated with well water as source water from municipal systems typically contains nondetectable lead concentrations.[35] This pattern of exposure is worrisome given it constitutes a chronic avoidable lead burden, which cannot be removed with continued flushing.

4. DISCUSSION AND IMPLICATIONS

4.1. Sampling Protocols in Private Water Systems. Although there is extensive literature evaluating sampling regimes for the detection of lead in water for municipal systems,[20] there are no standardized sampling protocols for private systems. As a result, sampling strategies to evaluate private water quality can vary considerably (e.g., stagnant vs purged sampling, dissolved vs total lead analysis, point-of-use vs point-of-entry).[5,6,8,29] Concurrent evaluation of a suite of parameters during this study provided a basis for recommending a uniform sampling protocol for application in private systems.

To assess waterborne lead in municipal systems, the LCR evaluates 1 L first draw samples using the lead action level of 15 μg/L.[14,36] While sampling is not required for private systems, the USEPA encourages private system homeowners to collect a 250 mL first draw sample and 250 mL flushed sample for comparison to the lead action level.[14] During this study, the median difference in lead concentrations between the 250 mL and calculated 1 L first draw collected from the kitchen cold-water faucet was 0.6 μg/L (C1 vs combination of C1 and C2). Lead concentrations in two 250 mL first draw samples and three 1 L first draw samples exceeded 15 μg/L. First draw samples from bathroom cold-water faucets had a median difference between the 250 mL and calculated 1 L of 2.4 μg/L (B1 vs combination of B1 and B2). While only two households had 1 L first draw samples that exceeded 15 μg/L, lead concentrations in the 250 mL first draw samples were above 15 μg/L in seven households. This research supports the USEPA's recommended first draw analysis of a 250 mL first draw sample for private system surveys. However, in order to accurately characterize waterborne exposure, the protocol should be modified to mimic normal consumption behaviors with first draw and flushed samples collected from a faucet that is used for drinking (e.g., kitchen faucet). In addition, to distinguish Type I versus Type III exposure, the flushed sample should be collected after 1 min of flushing. Based on the 15 households in this study, the average flushing time from the faucet to pressure tank was 16 s. Allowing the tap to run for 1 min would flush all stagnant water in contact with brass components at the outlet and pressure tank.

4.2. Waterborne Lead Exposure Patterns. *4.2.1. Remediation Methods.* Patterns of waterborne lead health risks at individual households were classified within three major categories: no elevated lead or lead elevated in the first draw only (Type I), erratic spikes of particulate lead (Type II), and sustained detectable lead concentrations (Type III). With the random detachment of particulate lead observed in Type II exposure, flushing may be ineffective in protecting health. For cases in which Type I and III lead release is confirmed, flushing protocols as short as 15−30 s are adequate to minimize concentrations below 15 μg/L, as this flushing duration would avoid human exposures to the first draw samples that were typically highest in lead concentration. However, Type III exposures pose a more significant health threat as there is no safe long-term exposure level[37] and sustained chronic low-level lead exposure risks cannot be readily cleared from the line with reasonable flushing times.

Based on the 12 systems in this study where homeowners knew the approximate well depth, the average volume of water stored within the home plumbing system and plumbing connecting to the well pump was 72 L for households without treatment (n = 6) and 100 L for households with treatment (n = 6), which would require a minimum of 15 and 21 min to flush all stagnant water encountering well plumbing (average flow rate of 4.7 L/min). As a result, private systems homeowners would need to flush 2−3 times longer than the recommended flushing protocol for homeowners with a full or partial lead service line. According to the CDC, households connected to a municipal system via a leaded service line should flush a high-volume tap for at least 5 min before flushing the kitchen tap for 1−2 min.[38] As the average person in the U.S. uses approximately 375 L of water per day,[39] flushing a private system to access fresh groundwater would account for 20−25% of a homeowner's total water use for the day and seems impractical. Therefore, installation and maintenance of a certified point-of-use lead filter would protect against chronic low-level lead exposure as flushing is not a practical solution.

Furthermore, acid neutralizers are often recommended as a corrosion control option for private systems; however, these treatment devices only increase pH and alkalinity within the home plumbing system (i.e., do not remove lead). One household in this study installed an acid neutralizer after the 2012/2013 extension effort due to a major pipe failure from corrosive water. Despite having a pH of 7.4 and an alkalinity of 96.9 mg/L as $CaCO_3$ after installation, samples collected during the flushing series (Figure 1b, F1−F5) contained detectable lead (2 μg/L; Figure 3c, orange). This research highlights the importance of characterizing lead release in private systems before selecting and implementing remediation options, as certain strategies may not be effective in reducing exposure.

4.2.2. Associated Health Risks. Assuming 15% of U.S. households rely on private systems and 12−19% of systems had lead concentrations above 15 μg/L during state surveys,[4−6,8] an estimated 5.7−9.1 million private system residents may be at risk of exposure to lead in water above the action level. As the 15 μg/L action level was determined when the CDC blood lead level of concern was 25 μg/dL (micrograms of lead per deciliter of blood), which is 5 times higher than the current threshold of 5 μg/dL,[40,41] achieving the action level itself might not be sufficiently protective. As cases of elevated blood lead levels (EBLLs; $\geq$ 5 μg/dL) in children have been associated with lead contamination from municipal water in the United States, even in cities with modern corrosion control that meet the 15 μg/L action level,[42,43] characterizing waterborne exposure in private systems is imperative to protect the public health.

To date, there has been no investigation of the contribution of lead in water to blood lead levels of children reliant on private systems in the United States. Therefore, to assess the potential health risks associated with private well systems in Albemarle County, VA, observed waterborne lead concentrations were compared to concentrations documented in well systems in a recent study in Tamatave, Madagascar (Figure 4).

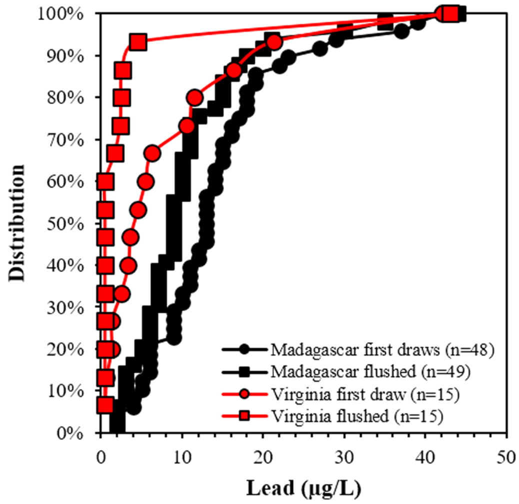


Figure 4. Cumulative distribution of waterborne lead concentrations in first draw and flushed samples collected in Albemarle County, VA, and Tamatave, Madagascar.

This study in Tamatave documented lead release from well components and potential contribution to EBLLs using the USEPA Internal Exposure Uptake Biokinetic Model for Lead in Children (IEUBK model), and used the model default values (i.e., not Madagascar lead exposure values).[44]

Although system construction and demographics are very different between Madagascar and Virginia, the upper 20% of these data sets had similar waterborne lead concentrations in the first draw samples −80th percentiles were 18.0 μg/L in Tamatave and 15.3 μg/L in Albemarle County. Given that the Madagascar study estimated 15−70% of children in Tamatave were at risk of EBLLs due to lead in water concentrations between 4 and 54.5 μg/L, observations of EBLLs in children reliant on water from private systems in the United States with similar lead concentrations would not be unexpected. Further field research is encouraged to directly characterize health risks associated with metals exposure for families dependent on private systems in the United States to determine whether these estimates are reasonable.

It is also important to note that plumbing components in wells are submerged in groundwater, and as a result, the outer surfaces of these components can corrode and release lead. Based on the data and information provided, flushed samples collected in Tamatave appeared to represent stagnant water in contact with the outer surfaces of plumbing components. Despite flushing 2.5 times the volume of water within the plumbing in the well (average volume of 8.8 L using reported diameter of 26 mm), flushed samples still contained high levels of lead. This occurrence illustrates the potential for the outer surfaces of well components to release lead as well as highlighting the large volume of water associated with wells. Therefore, additional emphasis should be given to characterizing the unique flow patterns associated with private systems as this would aid in the development of remediation strategies.

5. LIMITATIONS

Despite multiple emails sent via the Virginia Cooperative Extension over several weeks, only 15 homeowners (43%) chose to participate in this study. These households were selected due to their previously high lead results, though it is important to note that 7 households had installed or serviced acid neutralizers in the interim between the two studies, which was only determined upon the site visit. The presence of acid neutralizers impacts the likelihood of corrosion and likely reduced the overall quantity of waterborne lead observed. However, inclusion of these households highlighted a unique potential concern regarding the effectiveness of acid neutralizers in homes with Type III exposure: one household, despite acid neutralizer installation, still measured background concentrations throughout this effort. This reveals that if the well components are a source of lead (i.e., lead is released upstream of household entry), installation of treatment adjusting water chemistry within the homes, while preventing further release, will not eliminate all exposure. As this was only observed at one site, further sampling is essential to fully understand corrosion in private systems.

Although only 15 homes were studied, this sample size was sufficient to characterize the range of problems occurring in private systems. To illustrate the representativeness of this effort, we evaluated the first draw and 5 min flushed samples collected during the previous 2012/2013 extension effort based on this study's findings.[6] During the extension study, 26% of flushed samples ($n = 552$) had detectable lead concentrations (≥ 1 μg/L), and 4% of samples ($n = 90$) had concentrations greater than 5 μg/L. While most systems appear to have Type I exposure with nondetectable concentrations after 5 min of flushing, the occurrence of detectable lead in flushed samples indicates Type III exposure may be of concern. As for Type II exposure, 75 flushed samples with detectable lead concentrations were analyzed for particulate lead, and 47% ($n = 35$) contained primarily particulate lead (>75% in particulate form).

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b03174.

> Discussion of LSI values, lead measurements collected during the profile, and plumbing characteristics for the 15 households. (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*Tel.: 1-518-928-0177. E-mail: kpieper@vt.edu.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was supported through the Rural Health and Safety Education Competitive Program of the USDA National Institute of Food and Agriculture (#2011-05026) and a student research grant from the Virginia Water Resources Research Center. The authors would like to thank Victoria Nystrom, Sara Gokturk, and Julia Sherry for their assistance with sampling and the homeowners who participated in this study. Lastly, the authors would like thank the ES&T reviewers for their time and feedback, which greatly improved the quality of this manuscript.

■ REFERENCES

(1) Wallender, E. K.; Ailes, E. C.; Yoder, J. S.; Roberts, V. A.; Brunkard, J. M. Contributing factors to disease outbreaks associated with untreated groundwater. *Groundwater* **2014**, *52* (6), 886−897.

(2) Craun, G. F.; Brunkard, J. M.; Yoder, J. S.; Roberts, V. A.; Carpenter, J.; Wade, T.; Calderon, R. L.; Roberts, J. M.; Beach, M. J.; Roy, S. L. Causes of outbreaks associated with drinking water in the United States from 1971 to 2006. *Clin. Microbiol. Rev.* **2010**, *23* (3), 507−528.

(3) Lee, S. H.; Levy, D. A.; Craun, G. F.; Beach, M. J.; Calderon, R. L. Surveillance for waterborne-disease outbreaks—United States, 1999−2000. *MMWR* **2002**, *51* (8), 1−47.

(4) U.S. Environmental Protection Agency Public drinking water systems programs. http://water.epa.gov/infrastructure/drinkingwater/pws/index.cfm (accessed June 29, 2015).

(5) Swistock, B. R.; Clemens, S.; Sharpe, W. E.; Rummel, S. Water quality and management of private drinking water wells in Pennsylvania. *J. Environ. Health* **2013**, *75* (6), 60−66.

(6) Pieper, K.; Krometis, L. H.; Gallagher, D. L.; Benham, B. L.; Edwards, M. Incidence of waterborne lead in private drinking water systems in Virginia. *J. Water Health* **2015**, *13* (3), 897−908.

(7) Knobeloch, L.; Gorski, P.; Christensen, M.; Anderson, H. Private drinking water quality in rural Wisconsin. *J. Environ. Health* **2013**, *75* (7), 16−20.

(8) Swistock, B. R.; Sharpe, W. E.; Robillard, P. D. A survey of lead, nitrate and radon contamination of private individual water systems in Pennsylvania. *J. Environ. Health* **1993**, *55* (5), 6−12.

(9) *Test methods for evaluating solid waste, physical/chemical methods*; SW−846; U.S. Environmental Protection Agency: Alexandria, VA, 2007; http://www.epa.gov/osw/hazard/testmethods/sw846/online/index.htm#table.

(10) *Lead in your drinking water*; EPA 810-F-93-001; U.S. Environmental Protection Agency: Washington, D.C., 1993.

(11) *Private Well Testing Act Program: well test results for September 2002−April 2007*; New Jersey Department of Environmental Protection: Trenton, NJ, 2008; http://www.state.nj.us/dep/pwta/pwta_report_final.pdf.

(12) Dodrill, D. M.; Edwards, M. Corrosion control on the basis of utility experience. *J. Am. Water Works Assoc.* **1995**, *87* (7), 74−85.

(13) Schock, M. R.; Neff, C. H. Trace metal contamination from brass fittings. *J. Am. Water Works Assoc.* **1988**, *80* (11), 47−56.

(14) *Update on lead leaching from submersible well pumps and private drinking water systems*; EPA 812-F-95-002; U.S. Environmental Protection Agency: Washington, D.C., 1995.

(15) Center for Disease Control and Prevention Lead and drinking water from private wells. http://www.cdc.gov/healthywater/drinking/private/wells/disease/lead.html (accessed June 29, 2015).

(16) Ling, E.; Benham, B. L.; Forrester, S. *Virginia Household Water Quality Program: heavy metals in household water*; publication 442-657;

Virginia Cooperative Extension: Blacksburg, VA, 2011; http://www.wellwater.bse.vt.edu/files/HeavyMetals442-657_pdf.PDF.

(17) Clark, B.; Masters, S.; Edwards, M. Profile sampling to characterize particulate lead risks in potable water. *Environ. Sci. Technol.* **2014**, *48* (12), 6836−6843.

(18) Sandvig, A. M.; Kwan, P.; Kirmeyer, G.; Maynard, B.; Mast, D.; Rhodes Trussell, R.; Trussell, S.; Cantor, A.; Prescott, A. *Contribution of service line and plumbing fixtures to lead and copper rule compliance issues*; AwwaRF: Denver, CO, 2008; http://www.nuflowtech.com/Portals/0/pdfs/Service_Line_Lead__Pipes.pdf.

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

(20) Triantafyllidou, S.; Nguyen, C. K.; Zhang, Y.; Edwards, M. Lead (Pb) quantification in potable water samples: implications for regulatory compliance and assessment of human exposure. *Environ. Monit. Assess.* **2013**, *185* (2), 1355−1365.

(21) Deshommes, E.; Tardif, R.; Edwards, M.; Sauvé, S.; Prévost, M. Experimental determination of the oral bioavailability and bioaccessibility of lead particles. *Chem. Cent. J.* **2012**, *6* (1), 138.

(22) 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.

(23) *3Ts for reducing lead in drinking water in schools*; EPA 816-B-05−008; U.S. Environmental Protection Agency: Washington, D.C., 2006; http://www.epa.gov/ogwdw/schools/pdfs/lead/toolkit_leadschools_guide_3ts_leadschools.pdf.

(24) American Public Health Association; American Water Works Association; Water Environment Federation, *Standard methods for examination of water and wastewater*; 20th ed.; American Public Health Association, American Water Works Association, & Water Environment Federation: Washington, D.C., 1998.

(25) *R: A language and environment for statistical computing*; R Development Core Team: Vienna, Austria, 2012.

(26) *International Standard/American National Standard 61: Drinking Water System Components-Health Effects*; NSF International: Ann Arbor, MI, 2013; http://www.nsf.org/newsroom_pdf/NSF_61-13_-_watermarked.pdf.

(27) Gardels, M. C.; Sorg, T. J. A laboratory study of the leaching of lead from water faucets. *J. Am. Water Works Assoc.* **1989**, *81* (7), 101−113.

(28) Patch, S. C.; Maas, R. P.; Pope, J. P. Lead leaching from faucet fixtures under residential conditions. *J. Environ. Health* **1998**, *61* (3), 18−21.

(29) DeSimone, L. A. *Quality of water from domestic wells in principal aquifers of the United States, 1991−2004*; U.S. Geological Survey: Reston, VA, 2009; http://pubs.usgs.gov/sir/2008/5227/.

(30) Maas, R. P.; Patch, S. C.; Pope, J.; Thornton, L. Lead-leaching characteristics of submersible residential water pumps. *J. Environ. Health* **1998**, *60* (6), 8−13.

(31) Lytle, D. A.; Schock, M. R. *Stagnation time, composition, pH and orthophosphate effects on metal leaching from brass*; 600/R-96−103; U.S. Environmental Protection Agency: Washington, D.C., 1996.

(32) *The Lead Ban: preventing the use of lead in public water systems and plumbing used for drinking water*; EPA 570/9−89-BBB; U.S. Environmental Protection Agency: Washington, D.C., 1989.

(33) Schock, M. R. Causes of temporal variability of lead in domestic plumbing systems. *Environ. Monit. Assess.* **1990**, *15* (1), 59−82.

(34) 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.

(35) 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* (13), 1297−1352.

(36) *Lead and copper rule monitoring and reporting guidance for public water systems*; EPA 816-R-10−004; U.S. Environmental Protection Agency: Washington, D.C., 2002.

(37) Center for Disease Control and Prevention Blood Lead Levels in Children Aged 1−5 Years - United States, 1999−2010. *MMWR* **2013**, *62*, (13), 245−248.

(38) Center for Disease Control and Prevention Prevention tips: sources of lead in water. http://www.cdc.gov/nceh/lead/tips/water.htm (accessed June 29, 2015).

(39) U.S. Environmental Protection Agency. Indoor water use in the United States. http://www.epa.gov/WaterSense/pubs/indoor.html (accessed June 29, 2015).

(40) Bellinger, D. C.; Bellinger, A. M. Childhood lead poisoning: the torturous path from science to policy. *J. Clin. Invest.* **2006**, *116* (4), 853−857.

(41) Wheeler, W.; Brown, M. J. Blood Lead Levels in Children Aged 1−5 Years—United States, 1999−2010. *MMWR* **2013**, *62* (13), 245−248.

(42) 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, D.C., 1998−2006. *Environ. Res.* **2011**, *111* (1), 67−74.

(43) Edwards, M.; Triantafyllidou, S.; Best, D. Elevated blood lead levels in young children due to lead-contaminated drinking water: Washington, DC, 2001−2004. *Environ. Sci. Technol.* **2009**, *43* (5), 1618−1623.

(44) Akers, D. B.; MacCarthy, M. F.; Cunningham, J. A.; Annis, J.; Mihelcic, J. R. Lead (Pb) contamination of self-supply groundwater systems in coastal Madagascar and predictions of blood lead levels in exposed children. *Environ. Sci. Technol.* **2015**, *49* (5), 2685−2693.