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Research Article

Effectiveness of Prevailing Flush Guidelines to Prevent Exposure to Lead in Water

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Abstract: Flushing tap water is often promoted as a simple and low cost approach to reducing water lead exposures. This study evaluated lead reduction when prevailing flush guidelines (30 seconds-2 minutes) are implemented in a city compliant with lead-associated water regulations (New Orleans, LA). Water samples (n=1,497) collected from a convenience sample of 376 residential sites (2015-2017) were analyzed for lead in samples collected: at 1) first draw (n=375), and after incremental flushes of 2) 30-45 seconds (n=375), 3) 2.5-3 minutes (n=373), and 4) 5.5-6 minutes (n=218). There was no significant reduction when compared to the first draw lead level, until the 6 minute flush ($p<0.05$); but most sites (52%) still had detectable lead (≥1 ppb) after 6 minutes. Older homes (pre-1950) and low occupancy sites had significantly higher WLLs ($p<0.05$).Each sample type had health-based standard exceedances at over 50% of sites sampled (max: 58 ppb). While flushing is an effective short-term approach to remediate high lead, prevailing flush recommendations are an inconsistently effective exposure prevention measure that can often inadvertently increase exposures. Public health messages should be modified to ensure appropriate application of flushing for specific cities, while acknowledging its short-comings and practical limitations.

Keywords: drinking water; lead; Pb; flush; exposure prevention; intervention; lead service line

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1. Introduction

The knowledge that no safe threshold for childhood lead exposures has been found [1], and increased awareness of lead in drinking water triggered by the events in Flint, Michigan, have contributed to a renewed emphasis on preventing exposure to Pb in drinking water. Waterborne Pb may be a more significant source of total Pb to young children when compared to estimates made three decades ago [2], and can represent the most significant source for formula-fed infants [3]. In 2010, the Unites States (U.S.) Environmental Protection Agency (EPA) acknowledged that significant "exposure to <water> lead may be taking place, even though the action level is not exceeded" [4]. Water lead levels (WLLs) below the drinking water Pb Action Level (AL=15 ppb) are predicted to cause exceedance of the U.S. Centers for Disease Control and Prevention's (CDC) childhood BLL Reference Level [5 micrograms per deciliter (µg/dL)] in 9-25% of exposed children [5,6]. Chronic exposure to water lead levels (WLLs) as low as 1 ppb, which is the detection limit for many laboratories, have been estimated to increase a child's BLL by 35% after 150 days [7]. This information underscores a critical need for vulnerable populations to take proactive precautionary measures to prevent chronic exposures to low-dose waterborne lead.

The EPA's Lead and Copper Rule (LCR) regulates control of Pb in tap water [3]. It mandates that water utilities sample tap water in high-risk homes (i.e., homes with lead service lines (LSLs), and homes with copper pipes with lead solder installed after 1982). The EPA requires that no more than 10% of post-stagnation first draw water samples exceed the Pb AL. In 2015, the National Drinking Water Advisory Council re-emphasized that the LCR was not intended to ensure protection of all individuals from waterborne Pb exposure; rather, it was designed as a regulatory tool to identify system wide problems and broadly reduce lead exposure [8]. Lead from sites built prior to 1986 can be derived from lead service lines (LSL), which are often the greatest contributor to water lead when it is present [9]. Water lead can also come from Pb solder in homes built before 1986, or from galvanized pipes and brass faucet fixtures/fittings through present day construction [10].

Flushing is a widely recommended practice to reduce consumer exposure to Pb. Studies report that repeated periods of extended flushing at high flow rates are an effective remediation strategy when there are high levels of dissolved Pb [11-16]. The Consumer Confidence Report Rule (CCR) (63 FR 44511, §141.154) requires that water utilities promote flushing on all annual reports to consumers, "regardless if a system did or did not detect lead" [17]. This requirement was brought about by EPA's recognition that even in LCR-compliant cities, "there are situations where the most vulnerable populations may be exposed to elevated levels of lead for many months before or without being notified" [17]. The EPA also requires utilities to promote flushing when a utility is not LCR-compliant. The original messaging required by the Public Education provision of the LCR (56 FR 26460 §141.85) was "Run the water for 15-30 seconds [or one minute if the home has a LSL], before drinking water to flush lead from interior plumbing" [3,17].

The Washington D.C. Lead Crisis (2001-2004) first demonstrated that the standard water lead avoidance flushing guidance was inadequate during action level exceedances, and that flushing only 15-30 seconds would directly expose consumers to hazards of water that had been held within the LSLs [3, 15, 18]. A decade of follow up research has since confirmed that flushing protocols which reduce exposure in a given home, are highly dependent on variables that are difficult or impossible to control,

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including, but not limited to: length, configuration, material, condition and disturbance of service lines or plumbing; water use patterns; spatial changes in chemical and microbiological water quality within a given distribution system; and type of Pb released (particulates vs dissolved) [9-11, 14-15, 19-37]. In light of the evidence challenging the efficacy of flushing under different conditions, the EPA identified a need to further evaluate flushing [38], and revised the LCR and CCR to allow utilities to modify the required flush time recommendations if they determine longer flush times are needed [17, 39-40]. The EPA indicated in its updated guidance to utilities that "It is likely that systems with lead service lines will need to collect data to determine the appropriate flushing times" [4].

However, this knowledge has not translated into widespread changes in public health messaging or policies, perhaps because of the dearth of published data on flushing ineffectiveness under select conditions. Despite the new flexibility authorized by the EPA, industry knowledge of the inconsistent effectiveness of flushing, and acknowledgement by government officials about the uncertainty of optimal flush times and frequencies, officials from water utilities [41] and federal agencies [42-44] continued to provide outdated outreach materials with the harmful advice to flush water for 15 - 30 seconds in systems with LSLs. While some utilities and public health officials have resorted to adding a general caveat to their risk reduction messages, that "longer flushing may be required" dependent on site specific site circumstances, that message does nothing to inform consumers when that instruction applies to their situation; and it leaves open what "longer flushing" means.

This study explicitly examines concerns that flushing may not be an effective lead reduction strategy in LCR-compliant cities with LSLs. Prior research on flushing efficacy has typically been conducted in cities with non LCR compliant systems (i.e., high WLLs and LCR exceedances), rather than the lower-to-moderate WLLs that are typically associated with water systems with optimized corrosion control treatment [31]. To address this gap, this study was conducted in New Orleans, Louisiana (NOLA), a city which has consistently met LCR requirements. Best estimates from the mid-1990s suggested that LSLs may comprise 65-80% of the city's service line system [45]. After EPA regulations on flush time recommendations were relaxed, the city's water utility, the Sewerage and Water Board (S&WB), continued to promote the original flush recommendations from 2009 to 2015 [41, 46]. At the commencement of this study, the S&WB encouraged residents to flush their taps "for 30 seconds to 2 minutes before using water for drinking or cooking" daily under normal use conditions [41] (**Figure S1, Supplementary Materials**). New Orleans is also representative of many U.S. cities today, in that it has relatively non-corrosive water, and an aging drinking water infrastructure in need of repair [47]. Hurricane damage to water infrastructure has necessitated a multi-year project to repair and replace corroding water mains, LSLs and other underground utilities throughout the city. While over ten years have passed since Hurricane Katrina, the rebuilding process is ongoing- city and utility officials are also in the process of conducting 16,000 partial lead service lines replacements (PLSLRs) [48].

The primary aim of this study is to evaluate the effectiveness of prevailing flush time recommendations commonly promoted by utilities and public health officials for New Orleans. Specifically, lead levels were measured in cold water post-stagnation samples that were collected at first draw and after various flush times (30 seconds, 2.5-3 minutes and 5.5-6 minutes). A second objective of this study is to identify factors which may be associated with WLLs in an effort to better understand

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conditions which may contribute to high WLLs, and identify sites in potential need of targeted monitoring, outreach, or intervention. Results reveal that low-occupancy and older homes have significantly higher WLLs; and suggest that LSLs may be a main contributor to NOLA WLLs. Flushing according to prevailing guidelines (30 seconds to 2 minutes) does not result in significant or substantial WLL reductions in the city of New Orleans.

2. Materials and Methods

2.1 Site selection and sampling campaign

This study focused recruitment and sampling efforts in NOLA- in particular, on the city's East Bank of the Mississippi River (the city's source water). Specific information about the water treatment plants can be found in the **Supplementary Materials** section. Between February 2015 and November 2016, a convenience sample of 450 NOLA residents were recruited via news media and word of mouth to participate in a free water testing effort. Of the original 450 study participants, 421 returned self-collected water samples (94% return rate), and 381 returned self-administered surveys (85% return rate). A total of 1,497 samples were collected from 375 occupied homes under normal use conditions that met any of the criteria for potential risk, which included: (1) sites with LSLs or galvanized pipes based on S&WB data or self-reports (10%); (2) buildings constructed prior to 1950 based on self-reports an approach used by (59%)[49]; (3) homes of families with lead-poisoned children directed to the study by State's Office of Public Health (8%); and buildings located in high risk neighborhoods, as determined by the S&WB's LCR-compliance data (26%). Participant and household characteristics (and associated mean WLLs) are presented in **Table S2** (**Supplementary Materials**). Some sites met multiple criteria- for example, of the 8% of homes with lead-poisoned children, 76% also lived in pre-1950 homes and one reported having a LSL. Some sites were excluded due to either improper collection of water samples (2 sites) or sampling outside of the water utility's service area (10 sites).

To evaluate WLLs in buildings under atypical conditions, samples were also collected by either the researchers or building owners from 14 sites. These included schools (n=9); and homes with full or partial LSL replacements (n=5). Residents in homes with LSL replacements were encouraged to purchase water filters if continued use of the water for drinking or cooking was expected. All of these sites were analyzed separately from normal use occupied homes.

Participation entailed collecting tap water and completion of a household survey. The study protocols and survey were reviewed and approved by the LSU Health Sciences Institutional Review Board (FWA 00002762) to assure protection of human research subjects (IRB 8870).Participation in the study did not begin until a study consent had been obtained. The lengths of water service lines and premise plumbing pipes were estimated based on resident measurements reported on returned surveys (**Figure S2, Supplementary Materials**). Residents were asked to measure the distance from the middle of the street to the water line as it enters the home (service line length) and the distance from where line enters home to the kitchen tap as measured along wall (premise plumbing). Researchers also derived google map measurements of potential service line lengths for all sites, based on measures taken from

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the center of the street to the front of the home in the satellite view of Google Maps using the distance and area tool.

2.2 Sampling protocol

Residents were provided with a sampling kit that contained: (1) sampling instructions, (2) four 250 mL wide-mouth sampling bottles, (3) pre-paid return postage, and (4) a questionnaire about the household and water use characteristics (see survey in **Supplementary Materials**). To evaluate the effectiveness of flush time recommendations, residents were instructed to collect unfiltered tap water from the kitchen sink, after a 6+ hour stagnation period. Residents were instructed not to clean or take off their aerator prior to the stagnation period or water collection. Residents were instructed to collect water at "normal to high water flow" (estimated flow rate of 3.0 to 8.3 liters/minute [0.8 to 2.2 gallons/minute]) [50]. Specifically, a 250 mL first draw cold-water sample (FD) was collected and the water was shut off. A 250 mL first draw hot sample (FDH) was then collected from the hot water tap and immediately shut off after sample collection (the FDH water sample was not collected after the water temperature increased, rather it was collected at first draw). Two samples were collected after flushing cold water for 30-45 seconds (F30S), and after flushing for an additional 2 minutes (2.5-3 minutes total flushing; F3M). Throughout the entire study, all sites were asked to collect FD, F30S, and F3M samples. Mid-way through the study, it became apparent that flushing did not consistently reduce WLLs. At this point, an extended flush time sample was collected in lieu of the FDH samples. Residents were asked to flush their taps for an additional 3 minutes after collecting the F3M samples. These new samples (F6M) were collected after a 5.5-6 minute total flush time. Samples that were reported by residents to have been collected inappropriately were removed from the analyses. At some sites, multiple sample sets were collected from different water sources throughout the building. For these sites, only results for the tap which had the highest WLLs were retained to represent site conditions.

2.3 Analytical methods

Sampling kits were shipped by residents to Virginia Tech for analysis. Water samples were acidified with nitric acid (2% v/v) and digested for 16+ hours before analysis on a Thermo Electron X-Series Inductively Coupled Plasma – Mass Spectrometry (ICP-MS) per method 3125 B [51]. Blanks and/or spikes of known concentrations were processed every 10 samples for QA/QC purposes, with a reporting limit of 1.0 ppb. Blind negative controls, which consisted of filtered water, were sent to the lab to confirm laboratory reporting (n=9). Other source-specific metals were analyzed to evaluate correlations with WLLs and identify potential Pb sources in NOLA tap water. These included: cadmium, chromium, copper, iron, nickel, tin, and zinc.

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2.4 Statistical analysis

The WLLs for the FD, FDH, F30S, F3M, and F6M samples were summarized using descriptive statistics. Samples with WLLs less than 1 ppb were below our reporting limit (1 ppb) and were considered non-detects (ND). To represent ND numerically, these samples were assigned a value of half the reporting limit (0.5 ppb). The WLL differences between samples collected after various flushing times and the FD sample were tested using the Wilcoxon signed-rank test. Statistical analyses were performed in SAS Version 9.4 (SAS, Cary, NC).The significance level in this study was defined as p-value<0.05, unless otherwise stated.

To identify factors associated with WLLs, mean WLLs and standard deviations for FD samples were calculated by participant and household characteristics. The candidate factors included participant characteristics (income, race and education) and household factors (number of occupants in household, number of children<6 years old, presence or absence of street or sidewalk work within the last 6 months on site block, era of building construction (pre-, and post-1950), home type (single-family, multi-family, apartment complex), home ownership (own or rent), and water usage). Water usage, based on resident reports from last monthly utility bill (monthly total and average daily water usage), had a limited sample size (n=38) so it was not included in modeling. Factors associated with the mean WLL (ppb) and percent of sites with detectable WLL (≥1 ppb) based on all samples types were analyzed using parametric linear mixed models, and mixed-effects logistic models, respectively. Both univariate and multivariable models were conducted to evaluate the relationship between WLLs and participant and household factors. Factors with a p-value<0.2 in the models after adjusting for flush time were candidates for building the multivariable models. The final multivariable models only included predictors with a p-value <0.05.

To evaluate WLLs in relation to health or regulatory criteria for all samples and by sample type, the percent of samples exceeding the following standards, criteria or goals was derived: (1) the American Academy of Pediatrics' (AAP) recommended level for water in schools (AAP RL, >1 ppb) [52]; (2) the U.S. Food and Drug Administration's (FDA) allowable lead level in bottled water (FDA AL, >5 ppb) [53]; (3) the World Health Organization's (WHO) provisional guideline value for Pb in water (WHO GV, >10 ppb) [54], (4) the US EPA's Pb AL (>15 ppb) [3], and (5) the US EPA's Maximum Contaminant Level Goal (MCLG) for Pb, the WLL that EPA considers to be safe, is zero ppb (US EPA 1991 [3].

To determine the most probable location in the water distribution system or premise plumbing that each sample type may have been sitting during the stagnation period, an estimate of the volume of water and flush times required to purge the lines was derived based on estimated flow rates at low flow (3.0 liters per minute) and high flow (8.3 liters per minute); typical premise and service line pipe diameters; and survey respondent measurements of service lines and premise plumbing (**Figure S2, Supplementary Materials**). A 250-mL sample is estimated to represent water in approximately 2.4 meters (or 8 feet) of piping.

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3. Results

3.1 Water lead levels and flushing efficacy for normal use occupied homes

Descriptive summary statistics for WLLs from normal use occupied homes (**Table 1)**, indicate median WLLs for the FD, F30S, F3M and F6M cold water samples of 1.4, 1.7, 1.4 and 1.1 ppb, respectively. Overall NOLA WLLs were typically low relative to the 15 ppb EPA action level, as 88% of all samples from normal-use NOLA sites had WLLs ≤ 5 ppb. However, low-dose waterborne Pb exposures (≥1 ppb) are widespread across the city, as half of all samples from normal use sites (60%) had detectable WLLs of at least 1 ppb or higher (**Table 1**). Median and maximum WLLs were highest for post-stagnation samples collected after the 30 second flush (F30S), and lowest for post-stagnation samples collected after a 6 minute total flush (F6M). There was wide variability in WLLs across the sample pool, with WLLs ranging from non-detect (<1 ppb) in each sample type to a maximum of 58 ppb in F30S samples. The cumulative distributions of total Pb concentrations by water sample type for normal use occupied homes did not change substantially between FD samples and F30S or F3M samples (**Figure 1**). It was not until after 6 minutes of flushing that a decrease in the WLL distribution was observed.

The results of the statistical analyses of changes in WLLs from FD to flushed samples (Wilcoxon signed rank test), and the distributions of changes from FD WLLs to WLLs in flushed and hot water samples (**Table 2, Figure 2**) demonstrate a small but significant increase (0.6 ppb) in median WLLs from FD to F30S sample. No significant change in WLLs was observed from FD to F3M samples. Small (0.2-0.4 ppb) but significant declines in median WLLs was observed in F6M and FDH samples, compared to FD samples **Table 2; Figure 2**). Even after flushing for 5.5 to 6 minutes, over half of F6M samples (52%, n=218) still had detectable Pb (≥1 ppb), while 7% had WLLs > 5 ppb (**Table 1**). Flushing may seems to have induced the mobilization of particulate Pb into water, as evidenced by high "spikes" in some post-flushing samples- WLLs increased by as much as 50 ppb after 30 seconds of flushing (**Table 2**).

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Table 1. Distribution of post-stagnation WLLs (ppb) under normal use conditions (New Orleans, LA, 2015-2017)

Sample Type	N	Median WLL	Mean WLL	SD	25th Percentile WLL[a]	75th Percentile WLL	90th Percentile WLL	Max WLL	% Detectable (≥1 ppb)
FD	375	1.4	2.3	2.5	0.5	2.9	5.3	16.5	65.3
FDH	156	1.3	2.2	2.7	0.5	2.4	4.4	17.8	60.3
F30S	375	1.7	2.9	5.0	0.5	3.2	6.0	58.1	61.3
F3M	373	1.4	2.5	3.0	0.5	3.2	6.1	22.1	58.2
F6M	218	1.1	1.9	2.1	0.5	2.3	4.2	11.9	52.3
All	1497	1.4	2.4	3.4	0.5	2.9	5.6	58.1	60.1

[a]Samples with WLLs below the reporting level were assigned a value of half the reporting limit or 0.5 ppb.
Key: FD: first draw cold sample; F30S: flushing cold water for 30-45 seconds; F3M: flushing cold water for 2.5-3 minutes; F6M: flushing cold water for 5.5-6 minutes; FDH: first draw hot sample; WLL: water lead level; SD: Standard Deviation

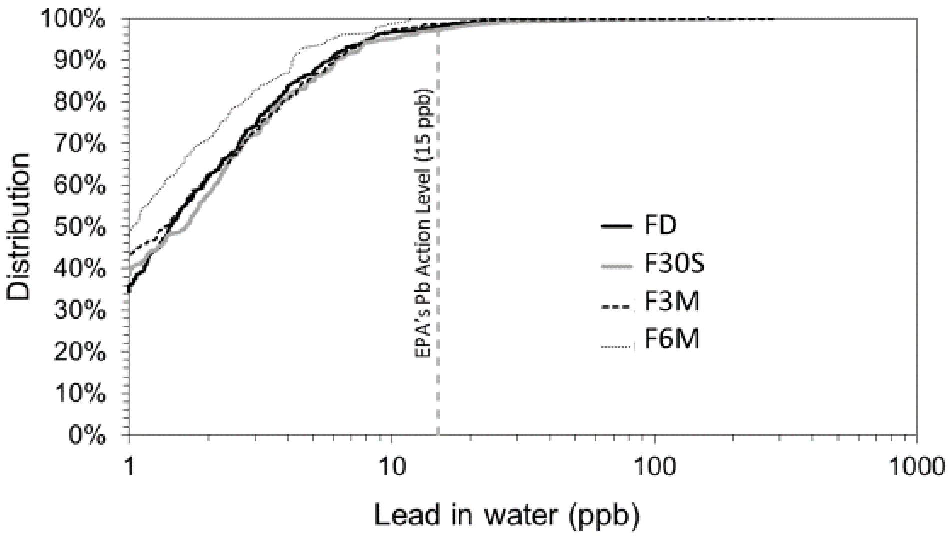

Figure 1. Cumulative distribution of total WLLs in occupied normal-use homes by sample type (n=1497 samples from 375 sites) (FD: first draw; F30S: 30-45 second total flush; F3M: 2.5-3 minute total flush; F6M: 5.5-6 minute total flush)

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Table 2. Change in WLLs after flushing (vs FD WLLs) (ppb)

Samples[a]	N	Median (25%, 75%)	Mean ±SD	Min	Max	90th percentile	p- value[b]
F30S vs. FD	374	0 (-0.4,0.6)	0.6±4.2	-9.4	50.2	1.7	0.040
F3M vs. FD	372	0 (-0.5,0.6)	0.2±2.1	-12.5	15.4	2.1	0.219
F6M vs. FD	218	0 (-0.6,0)	-0.2±1.4	-5.8	7.5	0.7	<0.001
FDH vs. FD	155	-0.1 (-0.9,0)	-0.4±2.4	-12.9	12.1	0.7	<0.001

[a] FD: first draw cold sample; F30S: flushing cold water for 30-45 seconds; F3M: flushing cold water for 2.5-3 minutes; F6M: flushing cold water for 5.5-6 minutes; FDH: first draw hot sample.
[b] Compare with FD based on the Wilcoxon signed-rank test

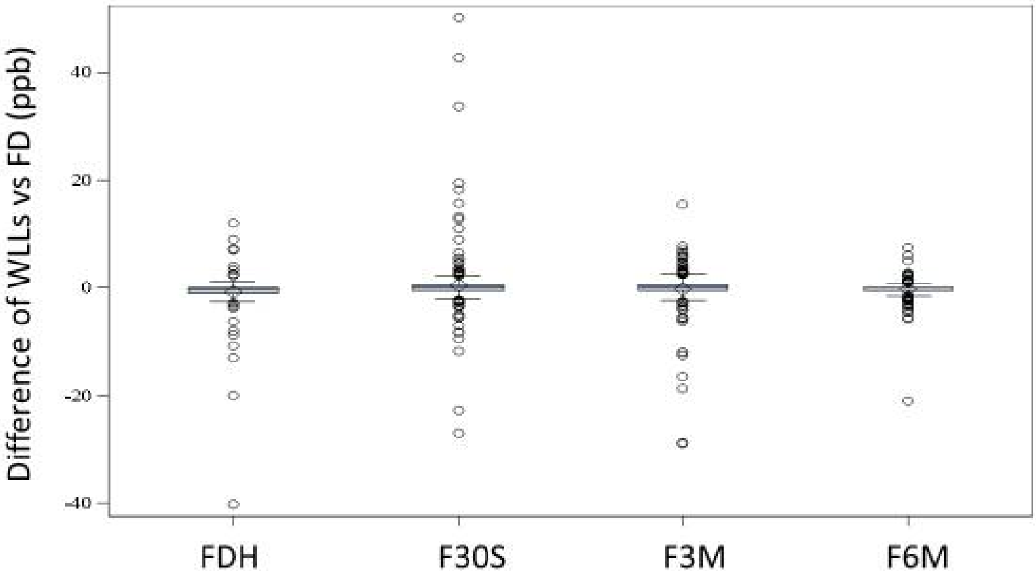

Figure 2. Distributions of the difference in WLLs in cold water samples collected at first draw (FD) compared to WLLs in samples collected after various flush times (F30S: 30 second flush; F3M: 2.5-3 minute flush; F6M: 5.5-6 minute flush) and first draw hot (FDH) samples.

Table 3 presents the number of samples in each WLL category by sample type; and **Table 4** presents the number and percent of samples with a change in WLL detection or with insubstantial WLL changes (< 1 ppb), compared to FD WLLs. The majority of the households (80-81%) had no change in WLL (<1 ppb difference) in flushed samples compared to FD samples (**Table 4**). In general, most NOLA homes with FD WLLs below the reporting limit (<1 ppb) continued to have WLLs <1 ppb in flushed samples. Of sites with FD WLLs <1 ppb, 79%, 83% and 86% also had WLLs <1 ppb in F30S samples (n=136), F3M samples (n=135), and F6M samples (n=86), respectively (**Table 3**). Additionally, most NOLA homes with detectable FD WLLs (≥ 1 ppb) continued to have WLLs ≥ 1 ppb in flushed samples. Of sites with FD

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WLLS ≥1 ppb, 82%, 79% and 75% also had WLLS ≥1 ppb in F30S samples (n=238), F3M samples (n=237), and F6M samples (n=132), respectively. (**Tables 3**).

Table 3. Water lead levels (WLLs) in first draw vs flushed cold samples

FD WLL (ppb)	F30S WLL (ppb) (n)						F3M WLL (ppb) (n)						F6M WLL (ppb) (n)					
	<1	1-4.9	5-9.9	10-14.9	≥15	n	<1	1-4.9	5-9.9	10-14.9	≥15	n	<1	1-4.9	5-9.9	10-14.9	≥15	n
<1	108	27	0	0	1	136	112	22	1	0	0	135	74	12	0	0	0	86
1-4.9	41	134	15	2	4	196	48	127	18	1	1	195	33	75	3	0	0	111
5-9.9	1	6	22	3	3	35	1	10	20	3	1	35	0	8	9	2	0	19
10-14.9	0	2	2	1	0	5	1	1	2	0	1	5	0	0	1	0	0	1
>15	0	0	0	1	1	2	0	0	0	1	1	2	0	0	0	1	0	1
n	150	169	39	7	9	374	162	160	41	5	4	372	107	95	13	3	0	218

Key: FD: first draw cold sample; F30S: flushing cold water for 30-45 seconds; F3M: flushing cold water for 2.5-3 minutes; F6M: flushing cold water for 5.5-6 minutes

Table 4. Flushing effectiveness based on reaching non-detect (ND: <1 ppb)

	F30S (%)	**F3M (%)**	**F6M (%)**
Detect in FD to ND	42 (11%)	50 (13%)	33 (15%)
ND in FD to detect	28 (7%)	23 (6%)	12 (5%)
No change (<1 ppb difference)	304 (81%)	299 (81%)	173 (80%)
Total n of sample type	374	372	218

Key: FD: first draw cold sample; F30S: flushing cold water for 30-45 seconds; F3M: flushing cold water for 2.5-3 minutes; F6M: flushing cold water for 5.5-6 minutes; ND: Non-detect (< 1ppb).

Some sites went from detect in FD samples to non-detect in flushed samples: F30S=11%, F3M=13%, and F6M=15% (**Table 4**). Mean WLLs for samples with detectable lead (≥1 ppb) decreased with increased flushing (F30S: 2.11 ppb, n=224; F3M: 2.04 ppb, n=210; F6M: 2.00 ppb, n=111). This indicates some value in flushing, however, even a six minute flush does not guarantee lower WLLs for all customers- 5% of sites went from non-detect FD WLLs (<1 ppb) to detect (≥1 ppb) after flushing for 6 minutes (n=218) (**Table 4**). Median WLLs for samples with detectable lead (≥1 ppb) remained the same after increased flushing (F30S: 2.00 ppb, n=224; F3M: 2.00 ppb, n=210; F6M: 2.00 ppb, n=111). A small proportion of sites also went from non-detect FD WLLs (<1 ppb) to detect (≥1 ppb) after flushing for 30 seconds (7%, n=374),

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and 3 minutes (6%, n=372) (**Table 4**). For sites which had FD, F30S and F3M samples (n=372), 28% had WLLs that increased by >1 ppb with a 30 second or 3 minute flush.

3.2 Water lead levels and flushing efficacy associated with atypical use conditions

While not a planned part of the study, conditions arose which allowed us to evaluate the impact of a one-time 15-minute utility flush on WLLs after LSL replacements at five residential sites. LSL replacements and construction are known to increase lead in water due to construction disturbances and galvanic corrosion for periods of weeks to years [19, 30, 38]. While over ten years have passed since Hurricane Katrina, the rebuilding process is still ongoing, and the city of New Orleans (NOLA) is still in the process of conducting 16,000 PLSLRs [48]. These conditions were evident during this sampling effort, as 43% of survey respondents reported there was street or side walk work on their block within the last year (n=287). Five of our study participants contacted the S&WB after our testing to request removal of their LSLs. All but one of these residents received a partial LSL replacement (PLSLR) (i.e., only the utility or customer side was replaced); while one had the full LSL replaced (from water main in the street to the home). All of the sites were sampled prior to, and after the LSL replacements and the utility or contractor 15-minute post-replacement flush. Only one of these homes was unoccupied due to ongoing home renovation work. **Table 5** shows sampling procedures and WLL results for each site-unfortunately, collection procedure for the samples varied from home to home. No definitive conclusions can be drawn from the post-LSLR samples due to the small sample size and variance in the sampling procedures. However, the persistent elevation in WLLs (exceeding the EPA AL) can be seen within the week after the line replacement in occupied homes, in both the full LSLR site (6 days later) and PLSLR Sites 3 (1-2 days later). Post-LSL replacement WLLs reached as high as 226 ppb one day after the PLSLR after a post-stagnation 30 second flush. These results suggest that rigorous extended flushing protocols may need to be repeated on a daily basis for an as yet undetermined time period following line replacements.

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Table 5. Water lead levels in pre- and post-LSL replacement samples (n=5)

	WLLs in Post-Line Replacement Samples (ppb)				WLLs in Post-LSL replacement samples (ppb)				
Site	FD	FDH	F30S	F3M	S1	S2	S3	S4	Post-Line Replacement Samples
Full LSLR	6.5	9.1	**49.2**[a]	12.6	**17.8**	3.0	2.8	NS	S1: 6 days after LSLR & 45 sec PS flush S2: 2 weeks after LSLR & 45 sec PS flush; S3: 3 weeks after LSLR & 45 sec PS flush
PLSLR Site 1	5.0	2.6	5.8	9.8	0.5	0.5	0.5	0.5	2 weeks after PLSLR and oversight stagnation: S1: FD; S2: F30S; S3: F3M; S4: F6M
PLSLR Site 2	6.4	5.3	**24.7**	6.8	**16.8**	10.7	5.5	NS	S1: Immediately after PLSLR & 15 min utility flush; S2: 2 days after PLSLR, PS FD; S3: 3 days after PLSLR, PS FD
PLSLR Site 3	**30.0**	**151.9**	7.4	1.3	6.5	**225.8**	**61.8**	NS	S1: Immediately after PLSLR and 15 min utility flush; S2: 1 day after PLSLR, F30S PS flush; S3: 2 days after PLSLR, F30S PS flush
PLSLR Site 4 (uninhabited)	**161.4**	NS	**26.6**	**283.5**	**64.5**	2.5	0.5	0.5	Immediately after PLSLR and 15 min utility flush: S1: FD; S2: F30S; S3: F3M; S4: F6M

[a]Bold WLLs exceeded the EPA AL of 15 ppb. **Key:** LSLR: lead service line replacement; PLSLR: partial lead service line replacement; WLLS: water lead levels; NS: no sample; FD: first draw sample; FDH: first draw hot water sample; F30s: 30 second flush sample; F3M: 3 minute flush sample; PS: Post-stagnation (6+ hour of stagnation prior to water collection); S#: Sample number.

3.3 Identifying predictive factors for WLLs

Select survey variables were evaluated using univariate and multivariate models to identify factors that may be significantly correlated with WLLs. **Table S2** presents factors considered in univariate and multivariate mixed models and associated mean FD WLLs. **Table 6** presents the factors associated with mean WLL (ppb) in all samples after adjusting for flush time; and **Table 7** presents the factors associated with the percent of sites with detectable Pb (≥1 ppb) after adjusting for flush time.

After adjusting for number of occupants and era of home construction, the mean WLL increase for F30S and decrease for F6M samples (compared to FD samples) remained significant [β coefficient=0.68 (p=0.017) and -0.25 (p=0.020), respectively] (**Table 6**). A decreased likelihood of having detectable Pb (≥1ppb) was observed after both the 3- and 6-minute flush time compared to FD samples (OR=0.68 and 0.58 with p<0.001 and <0.001, respectively) (**Table 7**).

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Besides flush time, the number of occupants and age of homes were significantly associated with WLLs (ppb), after adjusting for flush time ($p<0.05$) (**Tables 6-7**). Occupancy was associated with mean WLLs (**Tables 6**), and the percent of sites with detectable WLLs (≥1 ppb) (**Table 7**). The era in which the homes was built was associated with the percent of sites with detectable WLLs (≥1 ppb) (**Table 7**). Lower occupancy homes and older homes (pre-1950) were associated with higher WLLs. Mean WLL in FD samples decreased as occupancy increased: 1 occupant=3.9 ppb; 2-3 occupants=2.4 ppb; and ≥4 occupants = 1.8 ppb (**Table S2**). Likewise, the prevalence of detectable WLLs in FD samples decreased with occupancy: 1 occupant=92%, 2-3 occupants=68% and ≥4 occupants=64%. The latter trend is expected given prior work showing that less water use can increase water lead problems [55-56]. Mean WLLs in FD samples decreased in newer homes: Pre-1950=2.4 ppb; Post-1950=1.9 ppb (**Table S2**); as did the prevalence of detectable WLLs in FD samples: Pre-1950=73.4%; Post-1950=48.5% (n=375), which is expected given increased lead content in plumbing with age. This same trend was observed for prevalence of detectable WLLs in older homes in F30S samples ($p<0.0001$, n=375), and F3M samples ($p=0.010$, n=373), but not for WLLs in F6M samples ($p=0.069$, n=218).

While pre-1950 homes are more likely to have LSLs, the lack of information on LSL presence at all sites limited our ability to evaluate the impact that LSLs may have on WLLs and flushing efficacy. While there was significant difference in mean WLLs by neighborhood and zip code, with higher WLLs in older areas of the city which may have been more likely to have LSLs (Kruskal-Wallis test, $p<0.05$), the lack of random sampling, and the low sample size in many neighborhoods prevents any definitive conclusions about spatial variability in WLLs. While it is suspected that high WLLs associated with low occupancy homes may be due to reduced water usage, and hence greater water stagnation and Pb leaching, it was not possible to evaluate the association between number of occupants and water use due to the low number of sites reporting that data (n=38).

Table 6. Factors associated with mean water lead level in all samples (ppb)[a]

	Univariate model (n=376)		**Multivariable model (n=325)**	
Effect	**Model coefficient (ppb)**	**P-value**	**Model coefficient (ppb)**	**P-value**
Flush time (min)				
0	Reference		Reference	
0.5	**0.57**	**0.019**	**0.68**	**0.017**
3	0.19	0.110	0.19	0.134
6	**-0.28**	**0.001**	**-0.25**	**0.020**
Occupants				
0-1			Reference	
2-3	-	-	**-1.08**	**0.023**
>=4			**-1.67**	**0.0006**
Era build				
Post-1950	-	-	Reference	
Pre-1950			**0.59**	**0.062**
Unknown			**0.98**	**0.041**

[a]Based on the mixed model; bold: $p<0.0$

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Table 7. Factors associated with percent of homes with detectable water lead level (≥1ppb) [a]

	Univariate model (n=376)		Multivariable model (n=325)	
Effect	**OR (95% CI)[b]**	**P-value**	**OR (95% CI)[b]**	**P-value**
Flush time (min)				
0	Reference		Reference	
0.5	0.82 (0.65-1.02)	0.079	0.78 (0.60-1.00)	0.053
3	**0.70 (0.58-0.85)**	**<0.001**	**0.68 (0.54-0.84)**	**<0.001**
6	**0.61 (0.50-0.74)**	**<0.001**	**0.58 (0.47-0.72)**	**<0.001**
Occupants				
0-1	**-**	**-**	Reference	
2-3			**0.26 (0.09-0.74)**	**0.012**
>=4			**0.20 (0.07-0.56)**	**0.003**
Era build	-	-		
Post-1950			Reference	
Pre-1950			**2.95 (1.80, 4.83)**	**<0.001**
Unknown			1.25 (0.60-2.61)	0.545

[a]Based on the mixed model; bold: $p<0.05$; [b]Odds ratio (95% confidence interval)

3.4 Source evaluation

While lack of information on site plumbing materials limited our ability to ascertain the specific source of WLLs in NOLA water system, the observation of peak WLLs in 30-45 second or 2 minute flush samples at 49% of tested sites (n=372), is consistent with the expectation that this flush time is very likely to capture water that was held inside the LSL [3, 11]. An estimate of the volume of water and flush times required to purge LSL of stagnant water was derived based on estimated flow rates, typical pipe diameters, and lengths of service lines and premise plumbing (n=80). **Figure S2** presents the distribution of line lengths (premise + service) reported by survey respondents (n=80). The majority (75%) reported line lengths of 30 meters of less; and one quarter of survey respondents measured premise plumbing plus service line lengths of >30 meters. There were no significant differences in the lengths of service lines for pre- or post-1950 homes (p=0.172). **Figure 3** presents the estimated time to flush by total length of service lines and premise plumbing (¾ or ½ inches in diameter). Based on plumbing line length estimates presented in **Figure 3**, and an estimate that each 250-mL sample represents water in approximately 8 feet of piping; if a home has the average resident-reported premise + service pipe length of 75 feet (23 meters) with a typical pipe diameter of ¾ inches, a flush time of 2.2 minutes would be required to purge any water sitting in the plumbing or service line over night, when water is run at low flow (3.0 liters per minute). Under a different scenario in which residents run their taps at low flow and have an average reported pipe length of 30 m (premise + service line) approximately 3-minutes of flushing might be required. When the water is flushed at high flow (8.3 liters per minute), the same system might be flushed in less than a minute (0.8 minutes). Given that study participants were instructed to collect water at normal to high flows, and the fact that most respondents had plumbing lengths of 30 meters of less, it is likely that WLLs associated with service lines would often reach the tap by 30 seconds. This may explain why a peak WLL as high as 58 ppb was observed for in the F30S sample, which was from a single occupant home. More time is needed to fully flush the system as the length of plumbing increases, as the rate of water flow decreases, and as the diameter of the pipe decreases.

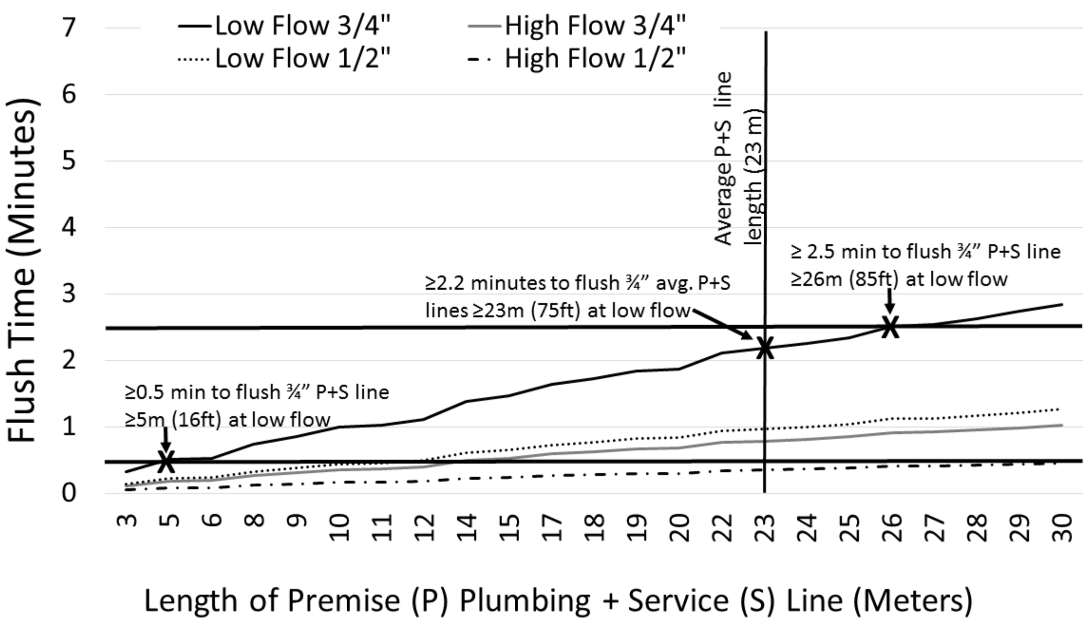

Figure 3. Estimated time to flush premise plumbing (P) and service line (S) (minutes) based on water flow rate (liters per minute), pipe diameter (3/4 or 1/2 inches) and survey-reported P+S length (meters)(n=-80) [Note: Low flow: 3.0 meters per minute; High flow: 8.3 Liters per minute]

To identify the potential source of NOLA's water lead (i.e., type of plumbing), correlations between WLLs and levels of common metals found in other plumbing materials were determined. If specific plumbing materials other than LSLs are associated with high WLLs, one would expect to see positive correlation between WLLs and metals in those alloys. For example, zinc (Zn) may indicate the presence of galvanized water pipes or brass faucet fixtures; nickel (Ni) may indicate the presence of brass faucet fixtures; iron (Fe) may indicate the presence of iron water mains; copper (Cu) may indicate the presence of copper pipe or brass faucet fixtures; tin (Sn) may indicate the presence of leaded solder; chromium may indicate the presence of stainless steel and cadmium (Cd) may indicate the presence of galvanized water pipes. No significant strong correlations were observed between any of the metals and WLLs for any of the flushed samples ($P<0.3$, $p<0.05$), Most samples had no detectable Cd or Sn. These results are consistent with lead from LSLs, which are essentially pure lead, or possibly that many sources are contributing to WLLs in NOLA water.

In Cartier et al. [57], the second consecutive sample was successfully used to confirm the presence of LSLs in 92% of homes for which LSL presence was documented (at water temperatures above 17∘C). In that study, LSL presence was considered confirmed if the second liter sample after a 15-minute stagnation period exceeded 3 ppb. If such an approach were used it is necessary to validate WLL thresholds specific to the system and type of buildings sampled [40]. Given the lack of data to validate LSL presence for NOLA sites, we could not confirm a lead threshold for NOLA that would enable accurate validation of the presence of LSLs. However, we did observe for NOLA homes with validated or reported LSLs (n=38), 37% had WLLs exceeding 3 ppb in FD samples (n=38), as did 37% of F30S samples (n=38), 40% of F3M samples (n=38), and 32% of F6M samples (n=28). In a similar vein, among the set of sites with validated or reported LSLs combined with the set of "pre-1950" homes, which we use as an indicator of potential LSL presence (n=259), 27% of FD samples exceeded 3 ppb (n=259), as did 30% of F30S samples (n=258), 29% of F3M samples (n=257), and 21% of F6M samples (n=143). These data may lend support to the assumption that LSL presence may lead to sustained WLLs.

Further investigations are needed to support the speculation that LSL are a primary risk contributor in NOLA. But together these data suggest that LSLs may be a major contributor to NOLA: 1) the sustained low WLLs throughout the NOLA water systems (i.e., throughout all of the different sample types) (**Figure 1**); 2) the lack of strong significant correlations between WLLs and metals from other plumbing materials, 3) the occurrence of peak WLLs in flushed samples (**Table 1**); and 4) the significantly higher WLLs in homes more likely to have LSLs (pre-1950 homes).

3.5. Comparison to utility compliance sample results and evaluation of sufficiency of FD compliance sampling

Sampling was not conducted as required under the LCR, as samples were not collected exclusively in warm months (June- September), and sampled sites could not be verified as being high-risk (50% of sites with LSLs). Thus WLL results are not be representative of required regulatory compliance samples. In the last utility-reported sampling season, the S&WB's WLL data for post-stagnation first-draw LCR compliance samples had a 90th percentile WLL of 7 ppb- only 1.6% of compliance samples exceeded the 15 ppb Pb AL (n=60, S&WB 2017). Our results for WLLs in FD samples only are consistent with the utility's compliance data, with a 90th percentile of 5.3 ppb- <1% of FD WLLs exceeded 15 ppb (n=375, **Table 1**). A separate analysis was conducted to evaluate WLLs among FD samples, based on sites and samples that may meet LCR sampling requirements (i.e., sites with reported or validated LSLs and pre-1950 homes, and samples collected between June and September). The 90th percentile WLL remained within regulatory limits (5.4 ppb).

There is some debate about how representative LCR's required FD compliance samples are of worst-case scenario exposures (i.e., highest WLLs). First draw samples are also frequently relied upon by many state lead poisoning prevention and school sampling programs to characterize potential risk [58-59]. Each sample type (FD, F30S, F3M and F6M) met LCR AL requirements (90th percentile ≤15 ppb); though there were increases in the percent of sites exceeding the AL from 0.5% in FD samples, to 2.4% in F30S samples (**Table 8**). Even a small increase in the proportion of homes exceeding the AL could have an impact on LCR-compliance in cites that are on the borderline of Pb AL exceedances. While there were increases

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from the 90th percentile FD WLL value (5.4 ppb) after flushing for 30 seconds (6.0 ppb) and 3 minutes total (6.1 ppb) among tested NOLA sites, these increases were minimal (<1 ppb) (**Table 1**) and would not have exceeded the action level trigger, even if worse case flushed samples had been "counted" under the regulation.

3.6 Comparison of WLLs to health guidelines, standards and goals

To evaluate the public health relevance of results, WLLs were evaluated against existing health-based standards, guidelines or goals (**Table 8**). Twelve percent of samples had WLLs which exceeded the Food and Drug Administration's (FDA) Allowable Level (AL) for Pb in bottled water (5 ppb) set in 1994 [53]; while only 2.7% of all samples at normal use occupied homes had WLLs which exceeded the World Health Organization's (WHO) provisional Guidance Value (GV) of 10 ppb set in 2011 [54]. The WHO's provisional GV is not entirely health-based, as other considerations, such as treatment performance and analytical achievability, were considered in GV derivation [54]. WHO maintains that provisional guideline values are set for "contaminants for which calculated health-based values are not practically achievable" [60].

Table 8. Comparison of NOLA WLLs (ppb) in normal use residential sites to standards (2015-2017)

Sample Type	N	% > AAP RL (1 ppb)	% > FDA AL (5 ppb)	% > WHO GV (10 ppb)	%> EPA's AL (15 ppb)
FD	375	65.1	11.7	1.9	0.5
FDH	156	60.3	8.3	3.2	0.6
F30S	375	61.1	14.7	4.3	2.4
F3M	373	58.2	14.2	2.4	1.1
F6M	218	52.3	7.3	1.4	0.0
All	1497	60.0	12.1	2.7	1.1

Key: AAP RL: American Academy of Pediatrics recommended water lead level for schools; FDA AL: United States Food and Drug Administration's Allowable Levels of lead in bottled water; WHO GV: World Health Organization's Guidance Value for lead in water; EPA AL: United States Environmental Protection Agency's Action Level for lead in water; WLLs: Water lead levels; NOLA: New Orleans, LA.

One recommended health-based level that was set more recently is the American Academy of Pediatrics (AAP) recommended WLL limit for schools (RL) of 1 ppb [52]. Overall, 60% of all samples from normal use occupied homes exceeded AAP's recommended Pb level for school water systems (**Table 8**). Excluded from analyses were the WLL results of nine schools. Of the samples collected from the nine schools (n=67), 27% exceeded 1 ppb. The percent of school samples with WLLs exceeding 1 ppb decreased with increased flushing: FD=38%, n=18; F30S=28%, n=18; F3M=17%, n=18; F6M=10%, n=10.

Samples exceeding the AAP recommended level for lead in school water also exceeded the EPA's Maximum Contaminant Level Goal (MCLG) for Pb (0 ppb), the WLL that EPA considers to be safe [3]; and California EPA's Public Health Goal of 0.2 ppb for Pb in water, which was decreased from 2.0 ppb in 2009 based on neuro-developmental effects of Pb for fetuses and children [61]. These results are pertinent, as 33% percent of our sample population reported having children less than six years of age (n=376).

The CDC is considering lowering the childhood blood reference value to 3.5 µg/dL [62]. The US EPA has released tentative results based on the Integrated Exposure Update and Biokinetic model (IEUBK), which estimate that WLLs of 3.8 ppb and 5.9 ppb could result in a 1% increase in the probability of a child (formula-fed infants and children 0-7 years of age, respectively) having a BLL of 3.5 µg/dL for families residing in pre-1950 homes with a high likelihood of having lead-based paint) [63]. Such home conditions are common in NOLA- 79% of this study's respondents resided in pre-1950 homes. The percent of sampled sites with WLLs >3.8 ppb increased from 18% in FD samples, to 20% and 22% in F30S and F3M samples, respectively. This percentage declined to 14% in F6M samples. Similarly, the percent of sampled sites with WLLs >5.9 ppb increased from 8% in FD samples, to 12% and 11% in F30S and F3M samples, respectively. This percentage declined to 6% in F6M samples. Thus, flushing according to prevailing exposure reduction guidelines (3- seconds to 2 minutes) may increase the likelihood of higher WLL exposures, and higher associated BLLs. Those performing longer flushes (F6M) could increase the likelihood of reducing their WLLs exposures and associated BLLs.

3.7 Evaluation of potential exposures to lead in water

Risks do not occur unless both a hazard and an exposure route to that hazard exists. To evaluate potential Pb exposure, survey respondents answered questions about water use habits, flushing practices, use of water treatment or filtration devices (survey in **Supplementary Materials**). Almost all respondents (93%) reported using unfiltered tap water for either cooking or drinking at some point in time (n=277). Only 16% of respondents who reported drinking or cooking with unfiltered tap water, also reported flushing water prior to use (n=267); but of this group, 37% flushed for less than 30 seconds, and only 3 respondents of this group flushed for over two minutes. While there was not widespread application of flushing guidelines among study participants, those who did flush water prior to use, may not be flushing long enough to see significant or substantial WLL decreases (**Tables 6-7**). Despite flushing, 61% of F30S samples, 58% of F3M samples, and 52% of F6M samples continued to exceed 1 ppb (**Table 8**). The greatest risks from exposures to waterborne Pb are expected for infants reliant on formula reconstituted with unfiltered water- 15 respondents reported using unfiltered tap water to reconstitute baby formula (n=129). WLLs for these study participants ranged from <1 to 11 ppb. Based on EPA's preliminary IEUBK model estimates for formula-fed infants, WLLs of 11 ppb could result in elevated BLLs in formula-fed infants (>5 µg/dL) when exposures to other sources like soil Pb or Pb-based paint are taken into consideration [63]. When only water exposures are considered, WLLs of 11 ppb could

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result in formula-fed infant BLLs above the CDC-proposed Pb reference value (>3.5 μg/dL) [62], and/or a 1 μg/dL increase in geometric mean BLLs [63].

4. Discussion

4.1 *Flushing efficacy and practicality*

Our results indicate that flushing taps according to prevailing utility and public health recommendations (i.e., for thirty seconds to two minutes) may not consistently reduce WLLs and associated exposures either significantly or substantially when applied in a city with LSLs and at sites under normal use conditions (occupied residential sites with no prior line disruptions). In some cases, we observed that flushing for such short periods, especially after only 30-45 seconds, actually increased WLLs as predicted when LSLs are present in a city [3, 31, 38]. It is generally agreed that first-draw samples may be more representative of Pb from the faucet and premise plumbing; while water flushed for 30 seconds to 2 minutes may be more representative of Pb in the service lines [64-65]. However, significant, but not always substantial, reductions in WLLs were observed after extended flushing (after 5.5-6 minutes). These samples are most likely representative of water held in the water main, which are generally not expected to contain Pb. When Pb is detected in samples collected after extended flushing, it may suggest the Pb is picked up during flow from premise plumbing or LSLs. This can occur when there is Pb dissolution or particulate detachment from leaded plumbing [11, 15, 64].

In the aftermath of Flint, many school officials have been considering flushing as a routine water Pb exposure prevention measure. While the percent of residential and school samples with WLLs exceeding 1 ppb did decrease after extended flushing for 5.5 to 6 minutes, reductions in WLLs were not always substantial (>1 ppb). If the aim is to prevent childhood Pb exposure altogether, or at least reduce it to the minimal detectable levels (1ppb), as recommended by the AAP, then many NOLA residences (over half in our sample pool), and some schools (1 in 10 samples collected) still had detectable Pb (≥ 1 ppb) after extended flushing for 5.5 to 6 minutes. In cases where extended flushing does reduce Pb to non-detectable levels, the question then becomes how frequently would it be needed (e.g., once a day, after certain time periods of water stagnation, prior to each use, etc). Since sampling was only conducted at one point in time after a 6+ hour post-stagnation event, we could not verify that a one-time flush is sufficient to maintain low WLLs throughout the day. Some studies evaluating flushing at school taps suggest frequent flushes may be needed throughout the day [66-67]. Flushing frequency requirements could also not be ascertained for residential sites.

Prolonged flushing may also not be practical, cost-effective, or sustainable over the long term, especially in cities with declining water resources and/or rising water rates. Like many utilities across the country, NOLA's S&WB approved regular rate hikes in anticipation of water infrastructure repair needs- 10% annually from 2013-2020 [68]. Yet, current water rates are already difficult for some NOLA residents to afford. An estimated 10% of FY 2015 NOLA customers were 30 or more days late in payment; and 19% of customer accounts were shut off for being unable to pay their bills [68]. NOLA's monthly residential water utility rate for FY 2015 was \$0.01 per gallon of water used or \$69.20 per month (assuming an

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average monthly water usage of 9.24 hundred cubic feet or 6,920 gallons)[67]. To put this into context the average FW 2015 water rate for customers of public utilities in the U.S. was $0.005 per gallon or $36.39 for the same monthly water usage [68]. The same rate for Flint, Michigan, which has been touted as one of the highest water rates in the U.S., was $0.0167 per gallon or $115.56 for the same monthly water usage [69].

In the cases where flushing could be effective for remediating high WLLs, such as after PLSLRs, current flush practices (i.e., one-time 15 minute high velocity flush) may not be effective for maintaining low WLLs over a long period of time. Utilities are not always required to promote flushing, such as after PLSLRs in LCR-compliant cities; and flushing messaging is not always consistent. It is widely acknowledged that sites with PLSLRs may have higher WLLs; and may require more rigorous and regular flushing than normal-use residential sites under typical conditions. [38, 70]. As stated previously, NOLA has been undergoing extensive road work, including thousands of PLSLRs [48]. But the LCR only requires education of citizens about the risks of PLSLRs and benefits of flushing to reduce PLSLR-related Pb spikes when the utility exceeds the LCR's AL requirements [3]. When PLSLRs are conducted in LCR-compliant cities, educating consumers about flushing is only required once a year, in the utility's annual CCR. For homes undergoing PLSLRs, NOLA officials recommend on their Roadwork website, that residents "Run cold water at a high flow at all of your faucets for at least 5 minutes each, one at a time, starting with the faucet closest to your water meter"; clean faucets aerators; and continue to flush for at least a month before using the water [71]. At the start of this study, this information was not consistently communicated nor readily available to NOLA residents undergoing roadwork [71]. However, the persistent elevation in WLLs we observed days after the line replacements indicates that care should be taken to flush systems rigorously and regularly after line replacements (**Table 5**). It was only after the preliminary release of our results in 2016 that S&WB revised their risk messaging and increased their flush guidelines to "30 seconds to 5 minutes"; however elsewhere in the same material, the messaging remained "30 seconds to 2 minutes" [73] (**Figure S1, Supplementary Material**). The EPA's Science Advisory Board (SAB) stated that "the lack of mandatory water lead testing and homeowner education associated with voluntarily PLSLR suggests that in practice, voluntary replacement might be associated with greater exposure of the public to lead" [38]. The SAB recommends that utilities test the water and tell consumers to flush the lines "over a period of months" after a PLSLR; but concluded that while "line flushing appears to provide some benefit, the … time to realize the benefit (up to several weeks of flushing in the reviewed studies) likely precludes any practical implementation of this technique" [38]. Despite the general knowledge about the ineffectiveness and potential danger that PLSLRs pose, they are still required by the LCR when certain compliance conditions have not been met [3].

More research is needed to evaluate how frequently flushing would need to be conducted to maintain low WLLs after a PLSLR. One study simulated PLSLRs in NOLA, and observed that intermittent flushing over a two week period was not long enough to stabilize WLLs [19]. In keeping, previous studies suggest several weeks, months, or maybe years may be required to remediate increased WLL exposure after PLSLRs [38, 74]. These facts do not discount the benefits of more rigorous flushing protocols as an effective Pb remediation method for some systems when high WLLs) are present. Improved remediation has been observed with higher velocity flushing (full open tap); continuous

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flushing (as opposed to intermittent flushing); increased flushing frequency and duration; and flushing at multiple taps (9, 11-12, 19, 24].

However, residents should be alerted that when conditions are severe enough to warrant more rigorous flushing protocols, as observed here after PLSLRs, exposures to high WLLs are always a possibility. Flushing can mobilize particulate-bound Pb throughout the plumbing system, which can then serve as a long-term source of acute Pb exposure. Even after flushing water for 10-25 minutes, some Flint homes still had high WLLs [14]- at least one Flint tap still contained WLLs exceeding 15 ppb (217-13,200 ppb) after a 26 minute flush [75]. This was likely due to the presence of highly unstable lead scales and the continuous sloughing of particulate lead during the time in which corrosion control was not used by Flint officials. Factors associated with maintaining low WLLs under such conditions, such as flushing frequency, must be determined on a case by case basis.

4.2 Regulatory implications

Results underscore the importance of critically evaluating existing regulations in terms of their impact on reducing WLLs and Pb exposures. Mounting evidence, and US EPA assertions, also suggest that meeting the LCR does not always guarantee public health protection [4, 10, 39-40]. One critical step in addressing a risk, is to identify the location of the hazard. The EPA recognized a decade ago the need to identify where LSLs were installed, and henceforth required water systems to conduct audits of their service line materials. However, the cost and burden of this endeavor has resulted in a tolerated neglect of this responsibility by regulatory officials. Weaknesses are also evident in LCR compliance sampling requirements. For example, there are no stated requirements to include special-use sites like schools or homes with LSL replacements from LCR compliance sampling, as the intent of the LCR is to evaluate worst-case WLLs under normal residential water use patterns. However, in line with many cities experiencing water infrastructure breakdowns, NOLA has been conducting an unprecedented level of line replacements throughout the city, making these conditions and their associated risks more common. When such replacements were undertaken across the City of Flint, MI, all residents were notified of the risks and were provided free filters to remove lead for at least 6 months after replacements occurred [76]. Similar education and preventative measures are not required in LCR-compliant cities. But even when cities meet LCR AL requirements, other weaknesses inherent in the regulation, that is the requirements to collect only first draw samples, could impact LCR compliance status, as the highest WLLs in NOLA water did not appear until after a 30-second or 2-minute flush at most sites. While this change in sampling protocol would not have affected NOLA's LCR compliance status, the difference we observed between FD and F30S samples in terms of the percent of samples exceeding the Pb AL (~2%) may be enough to impact compliance status for borderline systems with LSLs. Whether cities are compliant or not, there is always a risk of Pb exposure, especially in cities with LSLs, thus LCR communication requirements should be revised to require regular consumer education on more evidence-based technologies for reducing exposures. Finally, over the years, health-based standards for Pb in blood have declined, but the Pb AL for drinking water has never received a similarly critical re-evaluation. As over one quarter of all samples

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collected from the nine NOLA schools tested (n=67) exceeded AAP's recommended WLL for schools (1 ppb)(**Table 8**), reconsideration of the Pb AL in consideration of vulnerable populations, and perhaps also inclusion of school water systems in LCR compliance sampling protocols may be prudent.

4.3 *Public health and risk communication implications*

Infants, children and pregnant and lactating women are the most vulnerable populations- for these populations, the U.S. CDC [78] and National Toxicology Program (NTP) [1] have asserted that there is no safe level of Pb exposure. Yet, despite weaknesses in the LCR [77], the CDC still recommends no water testing is needed in the homes of a lead-poisoned child if other sources of high Pb were found in the home, if residents are not on private well water, and if the city's water meets LCR AL requirements [78]. As such, public health officials may not have not been monitoring WLLs in the homes of lead-poisoned children, or educating impacted families about lead in water issues. This can be a cause for concern, as in the case of LCR-compliant NOLA, residential WLLs as high as 58 ppb were measured. Model estimates (IEUBK) suggest that WLLs this high, if sustained, could result in a 5% increase in the probability of a child having an elevated BLL above the CDC's current reference value (5 μg/dL), just by water exposure alone [63]. When other sources are considered, WLLs exceeding just 3.8 ppb, a level the EPA estimates could raise a formula-fed infants chances of having a BLL exceeding 3.5 μg/dL, ranged from 18% in FD samples, to 22% in F30S samples. While the cumulative impact of low-dose chronic waterborne Pb exposure on fetuses, infants, children and pregnant women is uncertain, one study found that for every 1 μg/L increase in WLLs, childhood BLLS may increase by 35% after 150 days of exposure [7]. Given the fact that these low dose levels of Pb are widespread in NOLA water, a large proportion of the city's population of pregnant women and children may be at potential risk if they drink or cook with unfiltered tap water on a regular basis. Survey responses indicate that consumption of unfiltered tap water either through drinking or cooking is not uncommon.

Changes in public health policies could be made to address ensure that CDC goals for preventing childhood Pb exposures are met. One critical change would be to encourage WLL testing in the homes of lead-poisoned children. Environmental monitoring of WLLs for the purpose of exposure assessment could also be targeted to homes in cities with LSLs- especially older or low-occupancy homes, risk factors which have been identified in this and prior studies [55-56]. Older homes are commonly identified as most likely to have LSLs based on nationwide utility information [68]; and homes with low occupancy are hypothesized to have lower water use rates, more water stagnation, less buildup of corrosion control scale, less flushing out of particulates, and higher WLLs (55-56). And until better site-specific evidence-based flush recommendations can be developed, public health officials, educators, water engineers and utility operators should work together to design communication strategies and consistent risk reduction messaging that promote evidence-based solutions; are transparent about uncertainties; and translate current science about low dose Pb impacts on child and reproductive health to motivate proactive health-protective behaviors. Homogenized remediation guidelines are always susceptible to error, given the wide variability that can exist between buildings, e.g., in pipe age, lengths, materials, and diameters; scale

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buildup; and home occupancy and water use. Promotion of these practices need to be reconsidered as other more effective, evidence-based, low-cost technologies, such as NSF-certified faucet mount filtration devices, are now widely [80]. In acknowledgement of this issue, the US EPA's LCR Working Group recommended to US EPA officials in 2015, that the CCR be revised to exclude the currently required messaging: "When your water has been sitting for several hours, you can minimize the potential for lead exposure by flushing your tap for 30 seconds to 2 minutes before using water for drinking or cooking" [81]. Rather than promoting one-size-fits-all flush guidelines, greater effort should be expended on motivating and enabling proactive evidence-based solutions. Officials should explain health risks related to low dose Pb exposures to child-bearing women and health care providers to motivate proactive behaviors; and instruct residents in the correct selection, implementation and maintenance of NSF-certified filters. More research is needed to field test cost-effective household water filtration systems; evaluate these interventions' likelihood for reducing chronic exposures to low dose waterborne Pb and associated BLLs; and measure the short- and long-term health impacts of chronic cumulative exposure to low dose waterborne Pb. If the intention is to prevent lead exposure, empowering individuals with the knowledge needed to motivate and support implementation of evidence-based household water treatment technologies should be paramount.

4.4 Study Limitations

This study could not answer the questions of what factors are critical to the efficacy of flushing (i.e., what impacts do water quality conditions or plumbing components have on flushing efficacy); and what are optimal flush conditions (flush time and frequency) under different water quality and plumbing scenarios. Specific conditions that could increase the risk of random Pb spikes (e.g., presence of LSLs) could not be evaluated given the lack of resident knowledge and utility information. This information gap also prevented us from targeting the highest risk homes as required under the LCR (sites with LSLs, or copper with Pb solder); which in turn prevented us from evaluating LCR-compliance. However, this study does highlight the fact that flushing can be an inconsistently effective lead exposure prevention measure even in LCR-compliant cities, if the purpose of the flushing is not to remediate high WLLs, but rather to prevent chronic low-dose lead exposure in vulnerable populations.

Some weaknesses in the study design which could limit the generalizability of results. Sampling was conducted in only one city, yet each community water system has a unique set of water quality parameters which may have led to different conclusions. Sampling was also conducted on a small subset of NOLA homes, and as demonstrated here, there can be significant variability in WLLs between sites within the same city. However, this fact also supports the conclusion of this study, which is that in the absence of information on determining factors, a one-size-fits-all optimal flush time for sites within a city may be an unreliable exposure prevention measure.

Convenience sampling may have introduced bias into both the WLL and survey results. NOLA is comprised of a large proportion of minorities (59% African-Americans); and residents with low household incomes (38% make < $25,000) [82]. However, study participants were primarily Caucasian (75%), with incomes ≥$75,000 (53%), and with college or graduate level educations (90%) (**Table S2,**

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Supplementary Materials). Samples were also collected by study participants, with no way to verify that samples were collected properly. Given the logistical difficulty in collecting post-stagnation water samples, utility compliance samples are also collected by residents. This may have resulted in some misclassification, but it also provided the advantage of generating samples from a large number of sites. Finally, this study presents environmental monitoring data for waterborne lead levels that were collected from each site at only one point in time. A prospective study engaged in the ongoing collection of biological data, as well as collection of data on other environmental lead hazards (e.g., soil, dust, paint, food, etc.) is essential to characterize true exposures and associated adverse health outcomes.

1. Conclusions

- Overall NOLA WLLs were typically low (≤ 5 ppb); however, low-dose waterborne Pb is widespread across the city (60% of samples had WLLs ≥1 ppb). The sustained low WLLs throughout the NOLA water systems, the lack of strong correlations between WLLs and other metals, and the occurrence of peak WLLs in flushed samples, may indicate that LSLs may be a major contributor to NOLA WLLs. Older homes (pre-1950), which are more likely to have LSLs, had significantly higher WLLs ($p<0.05$).
- Prevailing flush guidelines that are promoted by water utilities and public health officials (flushing taps for 30 seconds to 2 minutes) do not consistently decrease waterborne Pb when used for the express purpose of exposure prevention. In fact, significant increases in median WLLS were observed in samples collected after a 30 flush, where maximum WLLs reached up to 58 ppb. Significant declines in WLLs were only seen after extended flushing (6 minutes), but these changes were not substantial (< 1ppb). Over half of these extended flush samples (52%) still had detectable lead (≥1 ppb). Variability in WLLs and the randomness of WLL release should serve as a warning to public health officials, that the promotion of short-period flushing (30 seconds to 2 minutes) should not be employed for the purpose of Pb exposure prevention to protect vulnerable populations in cities with LSLs.
- Both first draw and flushed samples from the majority of residential sites (>50%) exceeded health-based standards for children, including the American Academy of Pediatrics' 2016 recommended level for Pb in school water systems (>1 ppb); and the California EPA's 2009 Public Health Goal for fetal and child exposures to water Pb (0.2 ppb). This a concern as the majority of survey respondents reported either drinking or cooking with unfiltered tap water at some point in time (93%, n=277). Of those consuming unfiltered water, only 16% reported flushing prior to use. While there was not widespread application of flushing guidelines among study participants, those who did flush water prior to use, may not be flushing long enough to see significant or substantial WLL decreases- only three respondents using unfiltered tap water flushed for over two minutes (7%, n=267).

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Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Information on S&WB's water treatment system, Figure S1: "Tips for reducing lead exposure from drinking water" (Source: NOLA S&WB's 2016 Consumer Confidence Report), Figure S2: Percent of survey respondents by reported length of premise plumbing + service line measurements (meters)(n=80), Table S1: New Orleans 2015 water quality data for finished water (after purification), Table S2: Participant and household characteristics of respondents, Survey for homes: Lead exposure assessment for drinking water study.

Author Contributions: Conceptualization, Adrienne Katner and Marc Edwards; Methodology, Marc Edwards and Adrienne Katner; Software, Komal Brown, Kelsey Pieper, Hui-Yi Lin and Xinnan Wang; Validation, Jeffrey Parks, Kelsey Pieper, Komal Brown and Hui-Yi Lin.; Formal Analysis, Hui-Yi Lin, Komal Brown, Xinnan Wang, Kelsey Pieper; Investigation, Komal Brown, Jeffrey Parks, Adrienne Katner, Chih-yang Hu; Resources, Adrienne Katner, Marc Edwards, Jeffrey Parks, Hui-Yi Lin; Data Curation, Komal Brown, Xinnan Wang, Hui-Yi Lin, Komal Brown, Adrienne Katner; Writing-Original Draft Preparation, Adrienne Katner, Kelsey Pieper and Komal Brown; Writing-Review & Editing, Adrienne Katner, Kelsey Pieper, Komal Brown, Hui-Yi Lin, Marc Edwards, Sheldon Masters, Jeffrey Parks, Chih-yang Hu and Howard Mielke; Visualization, Adrienne Katner, Komal Brown, Kelsey Pieper, Hui-Yi Lin and Xinnan Wang; Supervision, Adrienne Katner; Project Administration, Adrienne Katner; Funding Acquisition, Adrienne Katner.

Funding: This research was supported in part through the Louisiana Board of Regents (LBOR) Pilot Funding for New Research Pilot Funding Program (PFund)(LEQSF-EPS(2015)-PFUND-406), and the Experimental Program to Stimulate Competitive Research (EPSCoR), which is funded by the National Science Foundation (NSF)(Contract # LEQSF(2015-18)-RD-A-13); the Louisiana State University Health Sciences Center (LSUHSC), School of Public Health Pilot Grant Award Program; and the National Institute of General Medical Sciences of the National Institutes of Health (NIH), which funds the Louisiana Clinical and Translational Science Center (LACATS)(1 U54 GM104940). The content is solely the responsibility of the authors and does not necessarily represent the official views of LBOR, NSF, LSUHSC, or NIH.

Acknowledgements: Marie Hurt of A Community Voice and Beth Butler of Southern United Neighborhoods provided substantial support in community outreach, study recruitment, water sample collection, study and outreach material design, and communication of study results. Marc Edwards of Virginia tech provided considerable technical support and reduced price services for laboratory analyses. Gail Fendley of Lead Safe Louisiana and Joseph Clavijo of Episcopal Diocese of Louisiana supported efforts to recruit study participants and communicate study results. John Ludlam, Pavolo Iosipiv, and Emilie Taylor in the Tulane School of Architecture's The Albert and Tina Small Center for Collaborative Design provided support in the design of study and outreach materials, study recruitment and communication of study results. Anne Johnson Bludsaw of the Louisiana Department of Health Healthy Homes and Lead Poisoning Prevention Program provided support in study recruitment. Miguel del Toral of the US EPA provided advice on the LCR and waterborne lead on an as-needed basis. Joye Pate, Lizzie Huval, Joseph Quintana, Corey Cole, and Jack and Caroline Galliano in the Louisiana State University Health Science Center Summer Research Internship Program for support in biokinetic modeling, water quality data mining, historical document reviews and general study support.

Conflicts of Interest: The authors declare they have no actual or potential competing financial interests. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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