Infrastructure Upgrades and Lead Exposure: Do Cities Face Trade-Offs When Replacing Water Mains?*

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Abstract

Concerns about drinking water contamination through lead service lines may hinder resource-constrained municipalities from performing important infrastructure upgrades. Construction on water mains may shake the service lines and increase lead levels in drinking water. We estimate the effects of water main maintenance on drinking water and children's blood levels exploiting over 2,500 water main replacements in Chicago, a city with almost 400,000 lead service lines, and unique geocoded data. By comparing tests in homes at different distances from replaced mains before and after replacement, we find no evidence that water main replacement affects water or children's lead levels.

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1 INTRODUCTION

An estimated 6.5 to 10 millions lead service lines (LSLs) connect water mains to homes in the US (Environmental Protection Agency, 2016). These lines may expose children to lead in drinking water unless a protective coating forms within pipes from natural sediments in the water (Brown, Raymond, Homa, Kennedy, & Sinks, 2011; Environmental Protection Agency, 2006; Triantafyllidou & Edwards, 2012). The deleterious effects of LSLs were highlighted by recent events in Flint, MI, where the municipality switched to a more corrosive water source that diminished the protective coating within LSLs, leading to heightened lead exposure (Edwards, Parks, Mantha, & Roy, 2015). Construction for water main upgrades may mechanically or hydraulically disturb the mineral coating within lead pipes, potentially exacerbating lead leaching into drinking water (Del Toral, Porter, & Schock, 2013; Quatrevaux, 2017).

It is important to understand if LSL disturbances during main construction harm public health, because delays or increased costs could hinder infrastructure upgrades. Water utilities in the United States lose 14 to 18% of their treated water due to leaks (CNT, 2016). Municipalities frequently maintain water infrastructure to limit the millions of gallons of water that are lost to leaky pipes every day (ASCE, 2017). Thus, US cities face a potential trade-off between upgrading water infrastructure and exacerbating lead exposure. For example, concerns about LSL disruption from municipal construction projects prompted a prominent lawsuit against the City of Chicago ("Berry v. the City of Chicago," 2019). Similarly, the New Orleans Inspector General issued a report recommending that the water utility informs residents of LSL disturbances risks and proceeds with full replacement whenever there are LSL disturbances (Quatrevaux, 2017). Moreover, Washington, DC, requires the city to pay for LSL replacement whenever the city replaces a water main ("Lead Water Service Line Replacement and Disclosure Amendment Act of 2018," 2018).

Lead exposure has extremely high private and social costs, being associated with reduced IQ (Ferrie, Rolf, & Troesken, 2015), lower educational attainment (Aizer, Currie, Simon, &

Vivier, 2018; Grönqvist, Nilsson, & Robling, 2017; Reyes, 2015b), and an increased risk of criminal activity (Aizer & Currie, forthcoming; Feigenbaum & Muller, 2016; Reyes, 2007, 2015a). The Centers for Disease Control and Prevention estimate that 535,000 children born in the US in the 2000s suffered from lead poisoning, as defined by a blood lead level (BLL) above $4\mu g$ (Wheeler & Brown, 2013). A quarter of Chicago zip codes have at least 5% of lead-tested children with BLLs above $4\mu g/dL$. Since the deleading of gasoline, researchers and policymakers have focused resources on remediating lead paint hazards in homes, considered to be the most important source of lead exposure (Zartarian, Xue, Tornero-Velez, & Brown, 2017). However, drinking water as a potential source of lead exposure has gained the spotlight after the large-scale contamination of drinking water with lead in Flint, Michigan, following the switch in water supply in 2014. Appendix Figure A.1 shows a correlation of 0.45 between blood and water lead levels in Chicago zip codes, suggesting that lead in drinking water could explain some of the remaining clusters of elevated blood lead levels in the city.

Use of lead pipes in service lines was standard practice in the US through the 1950s because lead's malleability and flexibility make it easy to work with and resistant to decay and frost (Triantafyllidou & Edwards, 2012). For these reasons, the City of Chicago mandated use of LSLs until the Safe Drinking Water Act amendment of 1986 prohibited the use of lead in service lines or premise plumbing (Environmental Protection Agency, 2006). Despite this ban, many legacy pipes remain in place in municipalities across the US. A recently completed inventory assesses that 392,614 of the 519,711 retail connections in Chicago are LSLs, while only 3,478 are lead-free, and the remaining 120,760 are of unknown materials.[1]

In response to the Flint scandal, cities are now conducting inventories and planning replacement of LSLs in line with EPA's recommendations (Environmental Defense Fund, 2018; Neltner, 2018). With estimated costs for LSL replacements ranging from $2500 to over $8000 per line, the cost of replacing all LSLs nationwide ranges from $16 to 80 billion (Environ-

[1]Source: Illinois Environmental Protection Agency Service Line Material Inventory Reports. Accessed on 4/22/2019 at `https://www2.illinois.gov/epa/topics/drinking-water/public-water-users/Pages/lead-service-line-information.aspx`

mental Protection Agency, 2016).[2] With competing demands for limiting lead exposure and limiting water loss, it is crucial to understand whether upgrading water mains will exacerbate childhood lead exposure from LSLs.

We exploit a large-scale main replacement program in Chicago and a unique combination of data sources to causally estimate the effects of pipe maintenance on drinking water quality children's blood levels. Specifically, we spatially link data on over 2,200 main and sewer pipe replacements completed across Chicago from 2011 though the end of 2017 to over 4,000 sets of water samples between 2016 and 2017 and over 600,000 blood lead tests performed on over 320,000 children living in Chicago between 2010 and 2016. Our identification strategy relies on the exogeneity of water sampling and children's BLL test data, where the latter are based on their physician's visit, and main replacement in their neighborhood. Specifically, the availability of address information in our BLL data allows us to compare children living in the same geography, for example a zip code or tract, who live near water mains slated for replacement and whose BLL tests happen either before or after the construction.

Our empirical analysis finds no evidence that main construction affects children's health by increasing the lead content of drinking water or BLLs. Our estimates rule out effects of $0.12\mu g/dL$, or 6.3% over the average BLL in our sample ($1.91\mu g/dL$). Moreover, we find no evidence that construction disproportionately affects certain subpopulations particularly burdened by lead exposure. Finally, we find no evidence of mitigated effects or avoidance behavior after the Flint scandal made the issue of lead in drinking water more salient.

A back of the envelope calculation suggests that in the context of main replacement programs, lead service line replacement costs exceed the potential health benefits in terms of preventing BLLs of $5\mu g/dL$ or above due to LSL disturbances during main construction. However, we cannot reject that providing faucet filters for the duration of the construction on the water main could be cost-effective. Importantly, our estimation is specifically about whether LSL disturbances caused by water main construction affect blood lead levels; we do

[2] LSL replacement costs can vary greatly depending on factors including length of the line, accessibility of the line in the home, and whether or not work is already being done on the street.

not speak to whether LSLs in general are associated with greater lead levels on average that would warrant replacements.

To the best of our knowledge, this is the first paper to estimate the causal impact of LSL disturbances from water main construction on drinking water quality and children's health in a large sample. In Chicago, Del Toral et al. (2013) find higher water lead levels in the 13 homes in their sample where LSLs had been physically disturbed in the previous 6 years, relative to the remaining 21 homes without known disturbances. They define a physical LSL disturbance as a meter installation or replacement, Auto Meter Reader (AMR) installation, service line leak repair, external service shut-off valve repair or replacement, or significant street excavation directly in front of the home that could disturb the LSL. In other words, generally these disturbances may happen during infrastructure updates aimed at reducing water losses and water distribution costs, such as the water main replacements we study. These findings were cited in newspaper articles,[3] and they are a major piece of evidence cited by the majority in the appellate court decision to allow a class action lawsuit against the City of Chicago to move forward ("Berry v. the City of Chicago," 2019). The Lead Service Lines Collaborative, an organization dedicated to LSL replacement, also cites Del Toral et al. (2013).[4] However, the study was small-scale and cross-sectional, and may suffer from omitted variables bias.

Our findings complement the growing literature on the effects of the water source switch in Flint on health outcomes. Hanna-Attisha, LaChance, Sadler, and Champney Schnepp (2015) estimate that the percent of children with elevated blood lead levels jumped from 2.4% before the switch to 4.9% once the city switched to the Flint River. The water crisis was also associated with lower fertility rates and poorer birth outcomes in Flint (Danagoulian & Jenkins, 2018; Grossman & Slusky, forthcoming; Wang, Chen, & Li, 2018), despite evidence

[3]See, e.g., https://www.chicagotribune.com/news/ct-lead-pipe-work-20130925-story.html, https://www.npr.org/2016/04/14/474130954/chicagos-upgrades-to-aging-water-lines-may-disturb-lead-pipes, and https://www.theguardian.com/us-news/2016/feb/18/chicago-class-action-lawsuit-water-contamination-lead-pipes, all accessed on 9/9/19.

[4]Accessed on 9/9/19 at https://www.lslr-collaborative.org/research-needs.html.

of households' avoidance behavior, such as using bottled water (Christensen, Keiser, & Lade, 2018). Our findings help us put into perspective the external validity of the Flint case study to learn about the risks of lead exposure through drinking water following routine main replacement programs. While the Flint case highlights important breaking points in water system management, our analysis shows that LSLs disturbances do not necessarily pose a health threat under normal circumstances, at least in Chicago.

2 BACKGROUND

2.1 Lead Exposure through Drinking Water

Children can be exposed to lead through several channels. The most common source of lead exposure is indoor lead dust from deteriorating lead paint used for residential purposes until 1978 (Zartarian et al., 2017). Alternatively, children might inhale lead dust suspended in the air or deposited in the soil. Additional sources of lead emissions include industrial facilities and airports. In the past, leaded gasoline contributed to the accumulation of lead dust in the soil near highways and other major roads. Finally, lead was commonly used in plumbing and solders. Sediments in old pipes usually form a protective coating that prevents lead from leaching; Chicago also actively adds blended phosphate for corrosion control. However, changes in water corrosivity or maintenance activities that shake the pipes might cause the coat to deteriorate and lead to leach (Sandvig et al., 2009; Del Toral et al., 2013; Quatrevaux, 2017). Specifically, lead can be found in several pipes and fixtures in homes (Appendix Figure A.2). This paper studies exposure through lead service lines being disturbed by construction happening on water mains; to the best of our knowledge most mains themselves do not contain lead.

Lead exposure through drinking water gained media attention after the city of Flint, MI, switched its water source from the Detroit Water and Sewerage Department to the Flint River as an interim water source in April 2014 (Kennedy, 2016). The city found elevated lead content in a resident's home in February 2015, almost a year after residents started complaining about the new water that was 70% harder and had a different color and smell than the original water. By September 2015 an independent team from Virginia Tech found "serious" levels of lead in Flint, which the researchers blamed on the city taking no actions to reduce the corrosivity of the Flint River water (Edwards et al., 2015). Media attention on the Flint issue increased throughout the year 2015, making lead exposure more salient for parents across the US.

Elevated lead in water is not a new issue, and is definitely not limited to Flint – or even just the home (Edwards, Triantafyllidou, & Best, 2009; Triantafyllidou & Edwards, 2012; Triantafyllidou, Le, Gallagher, & Edwards, 2014). Programs such as changes in water treatment, filter distribution, and avoidance behavior can address lead in water (Edwards, 2014; Grossman & Slusky, forthcoming; Kennedy, 2016; Ngueta et al., 2014; Triantafyllidou et al., 2014; Zahran, McElmurry, & Sadler, 2017). Therefore, it is crucial to understand what causes lead spikes in water in order to address them in a timely fashion.

2.2 Water Main Replacement in Chicago

In 2016, the City of Chicago reported losing 15% of the water it pumped out of Lake Michigan, or 64 million gallons a day - enough to provide the residential needs of nearly 700,000 people.[5] To deal with these leaks, the city began upgrading its water infrastructure following a ten-year plan approved in 2011. The "Building a Better Chicago" program included a large-scale replacement of water mains in the city. Chicago completed over 2,500 main and sewer pipe replacements across the city by the end of 2017. Appendix Figure A.3 shows both how pervasive the program was and that main replacement projects do not appear to be clustered in any neighborhood at any point in time over the course of our sample period. The fact that construction projects were evenly distributed in time and space throughout our sample validates our identification strategy based on timing and distance of tests relative

[5]Source: Illinois Department of Natural Resources, LMO-2 Form Data, accessed on 04/30/2019 at `https://www.dnr.illinois.gov/WaterResources/Documents/LMO-2_Report_2016.pdf`.

to construction projects. In advance of each replacement, the City alerted residents living on streets affected by construction by sending letters such as the one in Appendix Figure A.4. These letters were typically four to six pages long, and, starting in 2013, included one frequently asked question (FAQ) on potential water quality issues deriving from the main replacement. This FAQ section was typically towards the end of the letter.

3 DATA

The analysis in this paper exploits several data sources covering the City of Chicago. These sources include exposure data such as housing age and water main construction data, drinking water sample data, and individual-level lead screening data linked to household characteristics such as family background.

Exposure to lead hazards. We collected data on all water main replacements conducted through the Building a Better Chicago program between 2011 and 2017 from letters sent to ward residents affected by the construction and published on the program website.[6] We manually entered the information contained in these letters into our database, identifying over 2,200 main construction projects throughout the city. The database includes the start and end location of each street segment that was torn up for replacement, the start and end date of construction, the year that the original pipe was installed, and the size of the new pipe installed. The letter also indicates whether the construction involved a water main or a sewer pipe. In our analysis we focus on water main construction, as we expect the strongest effects from these projects because water mains connect directly to the lead service lines bringing water into homes. Our results are robust to including sewer construction that may have inadvertently disturbed the LSLs. The mean year of construction for the replaced pipes is 1899; 99% of letters cite infrastructure age and 32% cite capacity as a reason for the replacement. The mean project length was 2,567 feet (almost half a mile) and 86 days.

[6] Accessed on 12/17/18 at https://www.chicago.gov/city/en/depts/water/supp_info/dwm_constructionprojects.html.

We exploit housing vintage to separately look at the effect of main replacement on homes built prior to 1930, which have the highest likelihood of lead paint hazards. To do so, we link addresses in our outcome datasets to parcel-level housing data that includes information on construction year and structure type obtained from the city data portal.[7]

Drinking Water Data. In 2016, the Chicago Department of Water Management's (DWM) launched Chicago's Water Quality Study to investigate the possible impact of water main construction and meter installation on residential lead levels. Our sample includes residents who voluntarily sent water samples to DWM; our data may thus measure exposure among residents who are more aware of the Water Quality Study program and the dangers of lead. According to DWM, the sampling approach requires collecting four water samples for each test, making the process more likely to detect lead. In our data, we observe three water samples and addresses deidentified to the block level for over 4,100 tests performed in 2016-2018.[8] Each set of samples contains a water sample taken immediately and samples taken 3 and 5 minutes after the water was turned on in the home, allowing the stagnant water to be flushed. We spatially link these samples to main construction segments if both the start and end point of the sample's street block are within a given distance of the water main segment (e.g., 25 or 150 meters). Appendix Figure A.5 shows the spatial distribution of samples and results.

Blood lead screening and Vital Records. We use data on over 600,000 blood lead tests performed on over 320,000 children born in Illinois and living in Chicago between 2010 and 2016. We match these data to birth certificate data using child name and birth date. Both datasets were provided by the Illinois Department of Public Health (IDPH). Birth records also include family characteristics, such as mother's marital status, age, education, and race. We construct indicators for twins based on mother identifiers and child birth date.

IDPH deems the entire city of Chicago as high risk for lead exposure, meaning it requires

[7]Accessed on 8/8/17 at `https://data.cityofchicago.org/Buildings/Building-Footprints-current-/hz9b-7nh8`.

[8]Accessed on 8/15/18 at `http://www.chicagowaterquality.org/Results.pdf`. We limit our sample to tests taken in 2016-2017.

all children to be screened by taking a blood lead test. Our sample screening rate is 65% by age 2 and 76% by age 6. The Chicago Department of Public Health recommends screening children for lead exposure four to five times before age 4.[9] Screening usually happens in the context of routine pediatric visits. To the extent that selection into screening is not correlated with proximity to construction projects, our estimates will not suffer from selection bias.

The health test data include address of residence, which IDPH or a delegate local agency use to contact families of children with high blood lead levels. By geocoding these addresses, we link child blood lead history to data on potential sources of lead exposure. Blood lead test records also include test date, blood lead level, test type, and an identifier for the laboratory that analyzed the blood sample. Lead screening techniques have improved over time to detect lower lead levels in the blood, yet tests are prone to measurement error. For example, laboratories have minimum detection limits, and those limits vary over time and by lab. In the empirical analysis, we correct for these limits to assign correct population estimates of lead exposure, and we include laboratory-year fixed effects in the regression analysis to control for these corrections.[10]

In our analysis, we examine three outcomes to study the effects of main construction on children's health. First, we use a continuous measure of blood lead level (in $\mu g/dL$). We also use two binary cutoff indicators that indicate high levels of lead. In 1991, the CDC defined BLLs $10\mu g/dL$ or higher as the level of concern for children aged 1–5 years. Since 2012, the term "level of concern" has been replaced with an upper reference interval value defined as the 97.5th percentile of BLLs in US children aged 1–5 years from two consecutive cycles of

[9] See e.g., `https://www.chicago.gov/city/en/depts/cdph/supp_info/healthy-homes/childhood_lead_poisoningpreventionandhealthyhomesprogram1.html` accessed on 3/14/19.

[10] We determine the minimum detection limit cutoff for each laboratory-test type-year cell empirically, where test type is either capillary or venous. We flag a laboratory as having a cutoff if we detect missing or implausibly small probability mass in the BLL results for that cell compared to the state average for the same year-test type. The distribution of BLLs is skewed to the right, therefore an absence of tests below a certain value for a given laboratory likely indicates that laboratory has a minimum detection limit. For laboratories with a thin left tail of test results below the estimated cutoff, we reassign those test results to the cutoff value. Next, we reassign all test results at a cutoff to a value equal to the mean of the distribution of tests below that cutoff in that year-type cell for laboratories without cutoffs. For reference, 43% of lab-year-test type observations have no cutoff of $1\mu g/dL$, 54% have a 2 or $3\mu g/dL$ cutoff, and only 2% and 1% have a 5 or $10\mu g/dL$ cutoff, respectively.

National Health and Nutrition Examination Survey (NHANES), currently at $5\mu g/dL$. Until 2019, the action level for intervention in Illinois was still a BLL of $10\mu g/dL$ or higher. In our analysis we examine the effect of main replacement on both the probability of a BLL of $5\mu g/dL$ or higher and $10\mu g/dL$ or higher. Appendix Figure A.6 maps the distribution of tests $5\mu g/dL$ or below, $5-9\mu g/dL$, and $10\mu g/dL$ or higher. Disadvantaged neighborhoods show a higher concentration of high BLLs.

Appendix Table A.1 presents summary statistics for the water samples. The average first water sample in this dataset has 3.81 parts per billion (ppb) of lead. The EPA sets 15ppb as the intervention level. Lead content falls in subsequent samples at 3 and 5 minutes. Appendix Table A.2 presents summary statistics of the BLL outcomes and child characteristics in our analysis. Our primary analytic sample consists of 377,606 BLL samples from 147,267 individuals.

4 IDENTIFICATION STRATEGY

Chicago replaced thousands of water mains between the years 2011 and 2017, and our analysis rests on the assumption that, for a given home or child, the water main replacement timing is exogenous with respect to when households collected a water sample or went to a physician and received a blood test. We compare tests in homes located around a construction event and taken just before construction started to tests taken in the middle of construction (i.e., up to three months after construction started), as well as to those taken several months after construction. Due to the voluntary nature of the water testing program, we believe that our identification strategy is strongest in the context of blood lead samples, as we compare children who went to the doctor at different times relative to construction. Specifically, we aim to estimate the following fully parametrized equation.

$$Y_{itg} = \sum_d \beta_1^d I_{it}^{\text{W/in Dist d During Const}} + \sum_d \beta_2^d I_{it}^{\text{W/in Dist d After Constr}} + \gamma_t + \delta_g + X_{it}\theta + \varepsilon_{itg} \quad (1)$$

where BLL_{itg} measures outcomes at address i at time t in geography g, that is zip code, tract, or Census block group. Our primary regressors of interest are $I_{it}^{\text{W/in Dist d During Constr}}$. These are indicators for a test taken in the first three months after construction start within distance $d \in \{25m, 50m, 75m, 100m, 150m\}$ from a home. Regressors $I_{it}^{\text{W/in Dist d After Constr}}$ measure changes in test levels in months four to twelve after construction start. The BLL regressions control for a vector of individual-level characteristics X_{it} recorded in the birth certificate and the test data. These include whether the child was a multiple birth; child sex; mother's race, ethnicity, marital status, and education level; indicators for missing birth certificate data; an indicator for living in a house built before 1930; an indicator for missing housing age; and fixed effects for child's age at test in semesters. We include lab-by-year fixed effects to account for differences in minimum detectable levels by laboratories over time. The availability of address information in our BLL data allows us to control for neighborhood fixed effects δ_g at either the zip, tract, or block group, depending on the specification. This specification accounts for any constant exposure effects at the neighborhood level. There may also be seasonality to lead exposure, with stagnant water in warmer summer months particularly associated with higher lead in water and BLL rates (Deshommes, Prévost, Levallois, Lemieux, & Nour, 2013; Ngueta et al., 2014). Thus, we also include month of test fixed effects γ_t. We cluster our standard errors at the zip code level to allow for arbitrarily correlated shocks at the neighborhood level.

In our main analysis we focus on tests in a window six months prior to construction start to twelve months after construction start to further limit concerns that tests and construction projects at the tails of our sample period are not comparable to the rest of the sample. Still, Appendix Figure A.7 shows that including tests over six months prior and twelve months after construction does not alter our findings for the effect of main replacement on BLLs.

Equation 1 does not imply any restriction on the control group. However, we may worry that homes in areas never affected by construction might differ from homes close to construction projects in terms of unobservable characteristics, raising concerns of selection effects. Therefore, in what follows we limit our analysis to comparing (1) homes within 25 meters of a main construction project and tested six months before construction start through 12 months after construction start, to (2) homes within 100 to 150 meters from water main construction in the same timeframe. The 25 meter restriction limits the treated group to only those homes that experienced construction directly on their street; 100 meters is about a block away. The 25 meter group is our treated group; if main construction disturbs lead pipes it should occur most acutely in homes where the LSL is directly attached to the main. Including a control group from 1-2 blocks away helps assuage concerns of selection bias while helping to partial out the impact of our control variables more precisely. We do not directly observe whether a LSL is connected to a given water main, and measurement error could bias our estimates toward zero. Thus, we leave out a section of homes 25 to 100 meters from construction because such homes may or may not have been directly affected by the construction. In other words, the tables in the following sections present estimates from the following regression equation on the sample of tests within 25 meters and between 100 to 150 meters to construction projects in a window of six months prior to construction start to 12 months after construction start:

$$Y_{itg} = \beta_1 I_{it}^{\text{W/in 25m 0-90 days after start}} + \beta_2 I_{it}^{\text{W/in 25m 4-12 months after start}} + \gamma_t + \delta_g + X_{it}\theta + \varepsilon_{itg} \quad (2)$$

Our results will be causal if families do not plan tests around the sporadic start of construction. Construction happened throughout the year, and often started before or very shortly after notification letters were sent. The biggest worry is that, once construction started, families were more likely to request a water test or bring their child to the doctor for lead testing. Appendix Figure A.8 shows no evidence of an uptick in blood lead testing around the start of construction. In fact, Appendix Figure A.9 shows a declining trend in the number of blood lead tests over time, as Chicago lost population. Moreover Appendix Table A.3 shows no evidence of large and systematic differences in family characteristics on either side of construction start, except for mother's education, which we control for. Section 6.2 discusses a second potential concern with our identification strategy, namely avoidance behavior.

5 RESULTS: DRINKING WATER QUALITY

We begin by directly testing whether water main construction projects increase water lead levels. The sample we use here is much smaller than our blood lead level analysis, but presents a first stage test. To do so, we estimate Equation 1 without household-level controls. Moreover, because we only have 1,176 observations that contribute to variation, we do not present results with tract or block group fixed effects. Instead, we control for month of sample, year of sample, and zip code fixed effects. Finally, our results may be attenuated since some service lines put in place before 1986 may have already been replaced.

Table 1 finds no evidence that main construction increases lead levels in tap water in Chicago for samples 1, 3, or 5 minutes after the start of water flow within 25 meters of the construction projects. Appendix Table A.4 conducts the same analysis within 100m and similarly finds no relationship between water main construction and water lead levels, although these effects are estimated somewhat imprecisely.

One concern with the water tests sample is that it is quite small, so the analysis may miss true effects of water main construction on lead levels. Moreover, the city began offering water testing precisely to address concerns of lead in drinking water due to maintenance work, which would violate the assumption that there is no selection in the timing of these tests relative to construction projects. Finally, we are interested in identifying pathways of human exposure to lead. Thus, we next turn to results on children's blood lead levels.

6 RESULTS: CHILDREN'S HEALTH

This section presents our findings on the effects of main construction projects on children's blood lead levels in Chicago. First, our analysis finds no evidence that these construction projects affected children's health by increasing their lead exposure. Second, we investigate potential explanations for this lack of impact. Third, we conduct a back of the envelope calculation to assess whether LSL replacement or tap filter provision during main construction could still be cost-effective given the margin of error in our health impacts estimates.

Table 2 presents our main estimates controlling for more restrictive sets of controls and fixed effects in each additional column. For specifications with neighborhood fixed effects, the table reports the average number of tests per neighborhood.[11] Each specification estimates a positive, albeit small and statistically insignificant, impact of main construction on BLLs. In particular, in our most restrictive specification, which includes Census block group fixed effects, we can reject an increase in BLLs of $0.12\mu g/dL$, or 6.3% over the average BLL in our sample ($1.91\mu g/dL$). Our sample includes 119 tests per block group on average. Moreover, Appendix Tables A.5 and A.6 show no evidence that these small increases in BLLs lead to higher probabilities of BLLs of $10\mu g/dL$ or higher or of $5\mu g/dL$ or higher, respectively. Finally, BLLs appear to slightly decrease, if anything, after construction indicating that any increase in BLLs during construction is temporary. Importantly, our findings do not depend on the particular sample we choose. Appendix Tables A.7 and A.8 show that our estimates are not sensitive to including sewer construction or using all tests within 100 meters of a main construction as treated. The 100 meter sample may add homes that are more offset from the main road but still treated (adding power), but it could also add homes that are actually untreated and on another street (adding measurement error). Appendix Tables A.9 and A.10 demonstrate that our estimates are not sensitive to including only homes built before the 1986 federal ban on LSLs or only tests completed by age 2. The latter is important for

[11] We drop singleton cells at the block level. Because blocks are not necessarily included in a single zip code, regressions with zip code fixed effects further drop singleton cells at that level.

limiting the concern that parents might be told of lead hazards in schools and pre-schools. We retain our primary analytic sample, but we are encouraged that alternative specifications produce the same conclusion.

We next validate our distance restrictions and our decision to use children living 100-150 meters (about a block away) from construction as a control for children living within 25 meters (on the same block) as the construction. Figure 1 plots the β_1^d and β_2^d coefficients from Equation 1. This figure suggests that exposure effects, if present, decay with distance from projects. Children living farther than 100 meters away from construction projects are not likely to suffer from exposure effects, and they thus serve as a useful control group.

6.1 Heterogeneity

Next, we investigate whether our null average effects mask heterogeneous effects, for example by exposure risk through other potential sources of lead exposure. Wheeler and Brown (2013) document that disadvantaged children have higher BLLs in a national sample, and Table 2 shows that children whose mothers have lower levels of education and black children have higher blood lead levels on average, holding other factors constant. Moreover, it is well known that the most common risk factor for lead exposure is the age of housing (Centers for Disease Control and Prevention, 2004). In fact, lead was used as an additive in paint until a federal ban in 1978, although the popularity of lead paint began declining around the 1930s and the concentration of lead in paint started dropping in the 1950s due to a series of voluntary industry standards and local public health campaigns (Reich, 1992). Table 3 confirms that children living in pre-1930 housing have higher BLLs than those living in more recent housing, holding other factors constant.

Table 3 also investigates whether children of mothers with low education, black children, children residing in low-income neighborhoods, and children living in homes built prior to 1930 are differentially affected by main construction. We find no evidence that any of these subpopulations suffer from economically or statistically significant effects from main construction, and if anything construction is associated with lower BLL in the four to twelve months following construction start.

6.2 Mechanisms

Overall, we find no evidence that main construction increases children's BLLs in Chicago. We investigate two potential explanations: quality of water treatment and avoidance behavior. A third potential explanation is attenuation bias due to measurement error in BLLs.

First, perhaps Chicago water is especially noncorrosive and thus main replacement could constitute a danger to human health in other municipalities with less effective water treatment. To investigate this mechanism, we test whether main replacements have differential impacts depending on the water utility's ability to treat water. Precipitation can affect the effectiveness of water treatment in a city. Columns 1-2 of Table 4 tests whether blood tests taken in months with above-median levels of precipitation (2.48 inches) had differential effects from those taken in low-rain months, based on historical rainfall records from each month. We find no evidence that there may be higher effects in the high-rain months. There is also no summer effect (Appendix Table A.11). These results are consistent with effective water treatment mitigating the potential deleterious effects of water main construction both in low- and high-rainfall months.

A second potential explanation for this lack of impact is that parents engage in avoidance behavior upon receiving letters that inform them of the upcoming construction projects. This is especially worrisome for our identification strategy given that households living on a street not affected by construction do not receive warning letters. We noted in Section 2 that recommendations of flushing the water prior to use were only included in the letters starting in 2013, and even then they were not featured prominently.[12] Moreover, we hypothesize that after parents became aware of the water contamination episode in Flint, these construction projects might have become more salient. Thus, Table 4 tests whether construction projects

[12]See https://www.chicagotribune.com/news/ct-lead-pipe-work-20130925-story.html, accessed 9/9/19, for historical confirmation of the change. Letters are also available upon request.

have different effects over time. We find no evidence that increased avoidance behavior after the modified 2013 letters and after the publicity of the Flint episode in 2015 reduces the effect of exposure to main construction. If anything effects are smaller in the earlier sample period.

6.3 Benefits of Lead Mitigation During Water Main Construction

We next calculate the costs of increased lead exposure from construction disturbances implied by our estimates. Importantly, this exercise does not speak to the general costs of childhood lead exposure, from pipes or other sources. Notably, lead remediation in general and LSL replacement in particular likely have benefits also in the absence of infrastructure upgrades. Instead, we specifically speak to whether the costs of water filter provision or LSL replacement outweigh the benefits of limiting increases in lead exposure when conducting water main construction programs.

The upper bound of the 95% confidence interval around our estimated effect of main replacement on the probability of having a BLL of $5\mu g/dL$ or above is 0.86 percentage points. From this, we can compute an upper bound of the benefit of programs aimed at mitigating lead exposure following water main replacement. We compute an upper bound of the net present value of lost earnings due to IQ losses in children with elevated BLLs as being $71,000.[13] Thus, our results suggest that the expected cost increased lead from main replacement per child do not exceed $613 at the the upper bound of the 95% confidence interval. We consider the cheapest lead service line replacement costing $2,500 and the cheapest water filters costing $50 for a three-month filter supply. Then, the benefits in terms of preventing a child from having these high BLLs from main construction projects do not exceed 25% of the costs of LSL replacement but can be as high 1,226% for water filters, with likely benefits that are much smaller. Thus, for cities considering replacing water mains,

[13] We compute the net present value of lost earnings due to IQ losses in children with BLLs above $4\mu g/dL$ using the observed BLLs distribution in Chicago in our sample and correlational estimates of the marginal IQ losses due to increased blood lead levels in Lanphear et al. (2005) which we monetize using estimates in Schwartz (1994).

it may be beneficial to provide water filters, but not necessarily necessary to replace LSLs specifically because of the water main construction. Of course, there are likely benefits of replacing LSLs outside of the additional risk from water main construction.

7 CONCLUSION

We study a large-scale water main replacement program in Chicago, a city with both a high prevalence of lead services lines and old infrastructure in need of upgrading. Our identification strategy exploits differences in the timing of tests and the distance of homes relative to construction projects to estimate the effects of routine pipe maintenance on drinking water quality and children's health. We find no evidence that pipe maintenance affects lead levels in drinking water or children's blood lead levels under routine conditions. Some of our results imply a possible decrease in blood lead levels in the four to twelve months after construction start. As we do not see a similar change in the water itself, the blood lead level finding could be due to increased avoidance behavior by parents. We conservatively interpret our findings as having no effect on blood lead levels in children.

Our results are at odds with the recent analyses of the consequences of the switch in drinking water source in Flint, Michigan. This difference highlights the uniqueness of the Flint case study, and of each water system more generally, and the importance for future research to inform policy decisions around, for example, lead service line replacement. In a world of limited resources for the mitigation of lead hazards in homes, and toxic hazards more generally, our findings indicate that typical water main construction may not always require resources for lead service line replacement.

Specifically, Del Toral et al. (2013) report relatively stable water quality leaving the two water treatment plants in Chicago, likely due to a proprietary blended phosphate used as the primary corrosion control treatment. Water composition also differs across water sources. This points to an important aspect of research on lead pipes: the effects of pipe disturbances depend on a combination of factors, including water composition, municipal treatment strategies, and local infrastructure, that make extrapolation across cities difficult. Effects of LSL disturbance may be larger in the absence of city-wide failure to adopt anti-corrosion treatment, as was the case in Flint.

Our estimates cannot reject that it may be cost-effective to provide affected residents with faucet filters, although further research is needed to precisely estimate the effects of such a program. Our findings also have implications for municipalities needing to upgrade their water infrastructure. In 2017, the American Society of Civil Engineers estimated that there were about 240,000 water main breaks annually in the US, wasting over two trillion gallons of treated drinking water (ASCE, 2017). Not having to simultaneously incur LSL replacement costs might allow water utilities to stretch their budgets further in repairing these mains.

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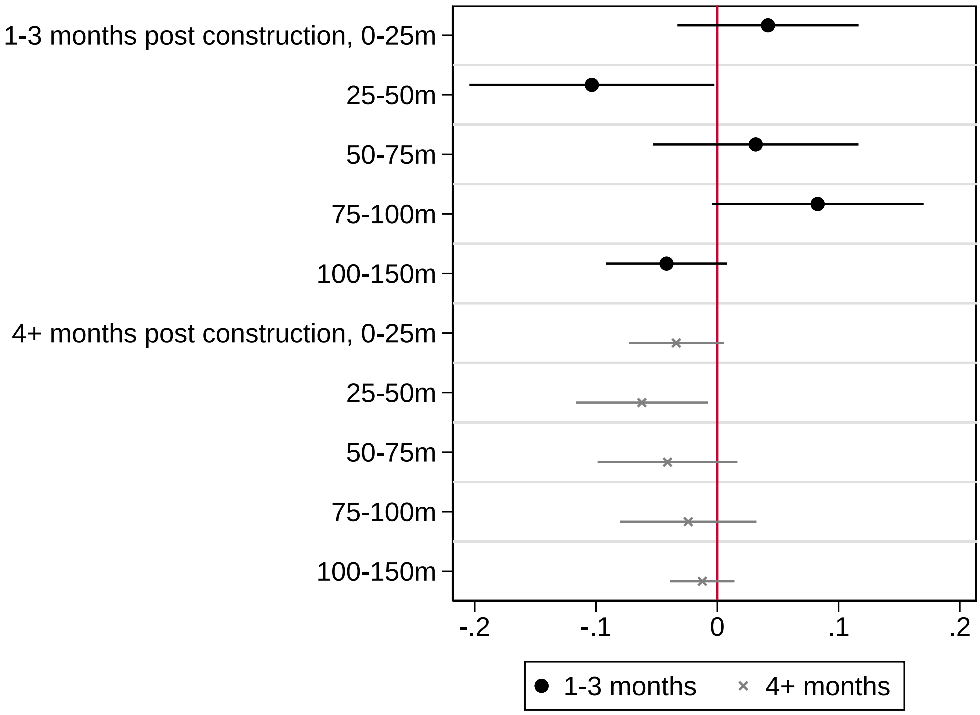
Figure 1: Health Effects of Construction by Distance



Notes: The figure plots coefficients from a regression of BLLs on indicators for tests taken in a given period relative to the closest construction project start, by distance from the construction site. The lines indicate confidence intervals at the 95% level based on standard errors clustered at the zip code level. Controls include Census block group, labXyear, month, and semester age FE plus controls for , child gender, child gender, marriage status, and indicators for mother's marital status/race/ethnicity/education.

Table 1: Construction Effects on Lead Levels in Tap Water

	Lead at 1 minute	Lead at 1 minute	Lead at 1 minute	Lead at 3 minutes	Lead at 5 minutes
1-3 months post construction	2.4291	3.5703	-0.7597	0.5496	-0.3848
	(2.2286)	(2.2207)	(4.4821)	(1.5109)	(0.5588)
4+ months post-construction	0.8660	1.3619	1.9101^{+}	0.5143	0.4939
	(0.6887)	(0.8146)	(1.0336)	(0.6422)	(0.3529)
Ever exposed within 25m	-2.4667^{+}	-3.0642*	-3.6402^{+}	0.1113	-0.2385
	(1.2282)	(1.2936)	(1.8684)	(0.5706)	(0.3029)
Controls		X	X	X	X
Zip FE			X	X	X
Observations	1171	1171	1171	1171	1171
Control Mean	5.612	5.612	5.612	3.247	2.163
Cell Size			23.898	23.898	23.898

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows coefficients from a regression of lead levels in tap water samples on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a residence relative to a control group of residences within a 100-150 meter radius from construction projects. Additional controls include year and month FE. Standard errors clustered at the zip level are in parentheses.

Table 2: Construction Effects on BLLs

	No FE	Add controls	Zip FE	Tract FE	Block Group FE
1-3 months post construction	0.0351	0.0446	0.0492	0.0395	0.0428
	(0.0404)	(0.0418)	(0.0413)	(0.0390)	(0.0387)
4+ months post-construction	-0.0536*	-0.0188	-0.0157	-0.0258	-0.0359+
	(0.0235)	(0.0196)	(0.0192)	(0.0221)	(0.0215)
Ever exposed within 25m	0.0056	-0.0117	-0.0013	-0.0003	0.0043
	(0.0138)	(0.0138)	(0.0141)	(0.0154)	(0.0164)
Male		0.0848***	0.0852***	0.0857***	0.0851***
		(0.0127)	(0.0127)	(0.0128)	(0.0127)
Black		0.2907***	0.1603**	0.0989**	0.0907*
		(0.0392)	(0.0516)	(0.0374)	(0.0356)
Hispanic		-0.1454***	-0.1650***	-0.1456***	-0.1337***
		(0.0368)	(0.0324)	(0.0295)	(0.0282)
Mother has less than HS education		0.1568***	0.1495***	0.1449***	0.1380***
		(0.0239)	(0.0239)	(0.0228)	(0.0224)
Less than 4 yrs of college		-0.1230***	-0.1170***	-0.1129***	-0.1163***
		(0.0193)	(0.0194)	(0.0185)	(0.0192)
Mother has 4 year degree or more		-0.2473***	-0.2135***	-0.2020***	-0.1986***
		(0.0221)	(0.0233)	(0.0230)	(0.0220)
Pre-1930		0.3394***	0.3093***	0.2670***	0.2507***
		(0.0311)	(0.0286)	(0.0246)	(0.0226)
Observations	260224	260224	260209	260224	260224
Control Mean	1.909	1.909	1.909	1.909	1.909
Cell Size			3942.561	293.707	118.878

Notes: $+ \ p < 0.10$, $* \ p < 0.05$, $** \ p < 0.01$, $*** \ p < 0.001$. The table shows coefficients from a regression of BLLs on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Geography fixed effects included in each regression are indicated at the top of each column. Additional controls include labXyear, month, and semester age FE; an indicator for twins; mother's marital status at birth; and indicators for missing housing age or marital status/race/ethnicity/education. Analytic sample constrained to be the sample with variation in the final column for consistency. Standard errors clustered at the zip level are in parentheses.

Table 3: Construction Effects on BLLs, Heterogeneity Analysis

	Lower vs. Higher-education (Reference= HS or higher)	Black vs. non-black (Reference= Non-black)	Below- vs. above-median block group (Reference= above-median)	Built before vs. after 1930 (Reference= after 1930)
1-3 months post construction	0.0519	0.0419	-0.0039	0.0864
	(0.0412)	(0.0502)	(0.0535)	(0.0721)
4+ months post-construction	-0.0108	0.0023	0.0033	-0.0164
	(0.0220)	(0.0255)	(0.0294)	(0.0290)
Ever exposed within 25m	-0.0096	-0.0171	-0.0249	0.0142
	(0.0152)	(0.0212)	(0.0196)	(0.0287)
Trait of interest	0.1311^{***}	0.0840^{*}	N/A	0.2584^{***}
	(0.0249)	(0.0381)		(0.0276)
Trait X 1-3 months post	-0.0422	0.0008	0.0840	-0.0640
	(0.0992)	(0.1066)	(0.0873)	(0.0876)
Trait X 4+ months post	-0.1048^{*}	-0.1036^{*}	-0.0730	-0.0279
	(0.0413)	(0.0453)	(0.0456)	(0.0373)
Trait X ever	0.0638^{*}	0.0597^{+}	0.0556^{+}	-0.0141
	(0.0320)	(0.0319)	(0.0323)	(0.0342)
Observations	260224	260224	260224	260224
Reference Mean	1.865	1.791	1.753	1.696
p-value of interaction	0.916	0.610	0.194	0.640

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows coefficients from a regression of BLLs on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects, as well as interactions of these indicators with indicators of child characteristics described at the top of each column. Additional controls include tract, labXyear, month, and semester age FE; an indicator for twins; mother's marital status, race/ethnicity, and education level at birth; an indicator for housing built before 1930; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses. The p-value for the test of the null hypothesis that the total effect on the sub-population of interest in each column is 0 is reported at the bottom of each column.

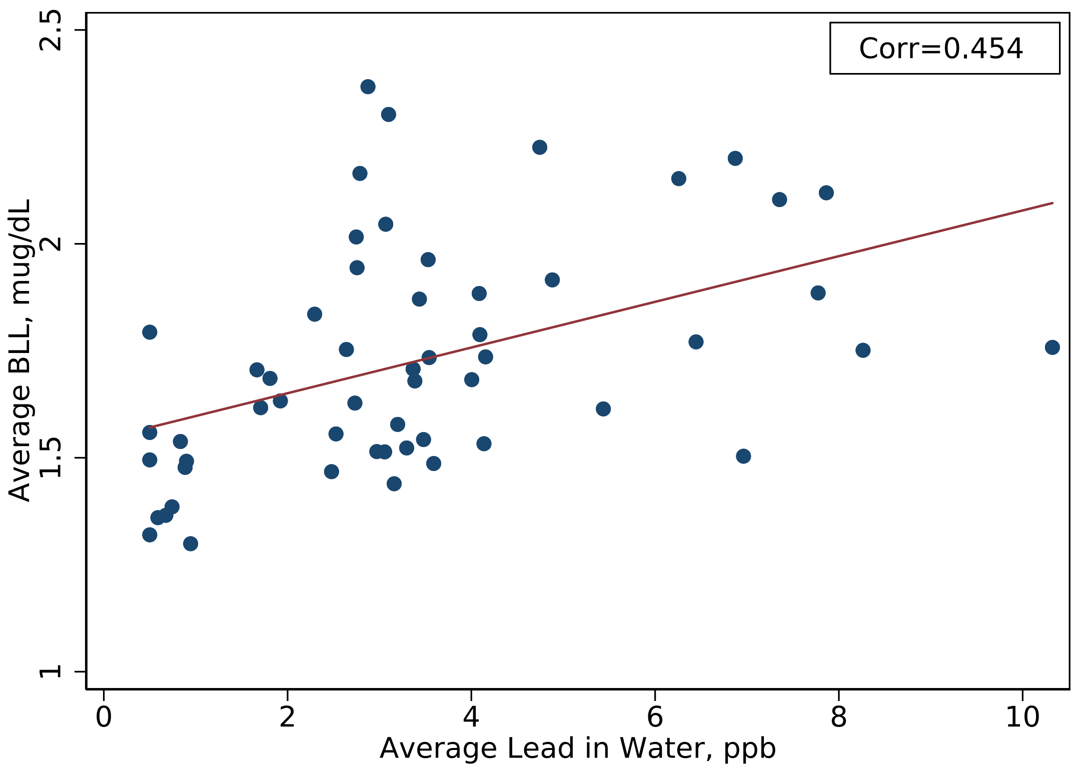
Table 4: Construction Effects on BLLs, By Weather and Test Year

Dependent Variable:	Test in low rainfall months	Test in high rainfall months	Test in 2011-2012	Test in 2013-2014	Test in 2015-2016
1-3 months post construction	0.1094	0.0281	-0.0584	0.1414^{+}	-0.0001
	(0.0901)	(0.0464)	(0.0717)	(0.0776)	(0.0779)
4+ months post-construction	-0.0728^{**}	-0.0014	0.0026	-0.0618^{*}	-0.0728
	(0.0256)	(0.0280)	(0.0635)	(0.0283)	(0.0492)
Ever exposed within 25m	0.0197	-0.0178	-0.0076	0.0291	0.0425
	(0.0220)	(0.0210)	(0.0218)	(0.0272)	(0.0461)
Observations	122713	137293	125909	72650	61341
Control Mean	1.880	1.933	1.986	1.785	1.893

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows coefficients from a regression of BLLs on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Each column is estimated on a subsample of months or years indicated at the top of the column. Additional controls include tract, labXyear, month, and semester age FE; an indicator for twins; mother's marital status, race/ethnicity, and education level at birth; an indicator for housing built before 1930; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses. Sample split by timing. Columns 1-2 split by rainfall in month of the blood test. High rainfall months are those with recorded rainfall about the median (2.48 inches) in observed in that particular month. Columns 3-5 split by year of the blood test. Observations do not sum to main analytic sample due to singletons in fixed effects in the split samples.

Appendix Figures

Figure A.1: Correlation between Blood and Water Lead Levels, Zip Code Averages

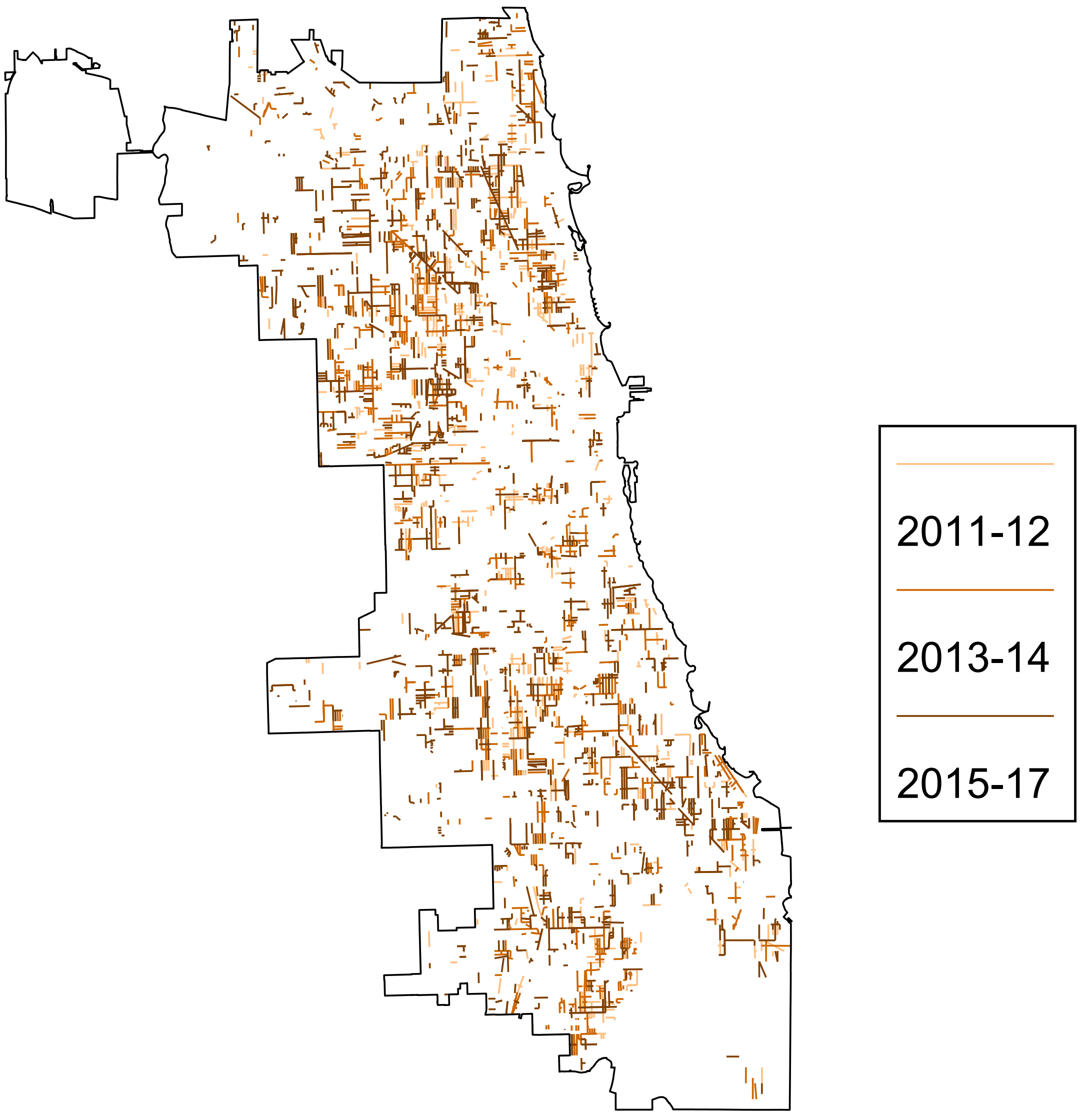


Notes: The figure shows the correlation between average blood lead levels in the 2010-2016 period and average lead in water samples at first draw in the 2016-2018 period in Chicago zip codes.

Figure A.2: Lead Pipes and Fixtures in the Home

Notes: The figure shows different sources of lead exposure through drinking water in homes. Source: EPA.

Figure A.3: Water Main Construction Over Time and Space



Notes: The figure plots each water main segment affected by a construction project, with different colors indicating different project start years.

Figure A.4: Example Letter Announcing Construction

(a) Panel A: Start of First Page

Dear Neighbor,

In coordination with Mayor Rahm Emanuel's, "Building a New Chicago" program and at Alderman Sawyer's (6^{th} Ward) request, I am providing you with information regarding a water construction project in your neighborhood. This is part of our approach to renewing our city's aging infrastructure. I see this as an opportunity to partner with you our customers. As part of this partnership, I want to be certain you are well informed about the project. You should know where to call if you have any questions or concerns.

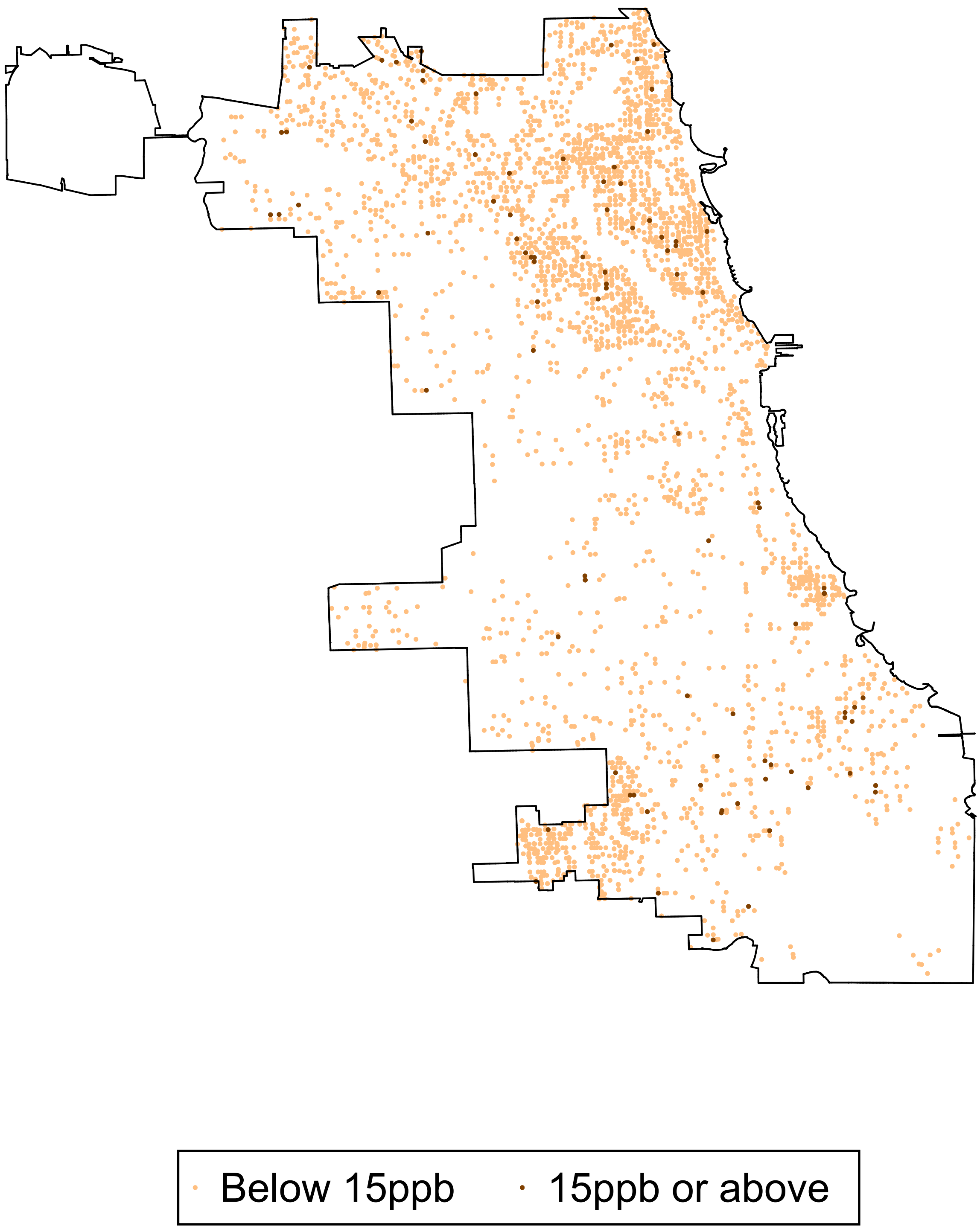
Our crews will soon be installing 1,258 feet of 8-inch water main in W. 68^{th} Street, from S. Morgan Street to S. Halsted Street. The old pipe dates back to 1897, and needs to be replaced.

(b) Panel B: FAQ on Page 4

After your old water main has been replaced and you have been connected to your new water main, please open all your water faucets and hose taps and flush your water for 3 to 5 minutes. Sediment and metals can collect in the aerator screen located at the tip of your faucets. These screens should be removed prior to flushing. This flushing will help maintain optimum water quality by removing sediment, rust, or any lead particulates that may have come loose from your property's water service line as a result of the water main replacement. If you have any questions or concerns about your water quality, please call us at 312-744-8190.

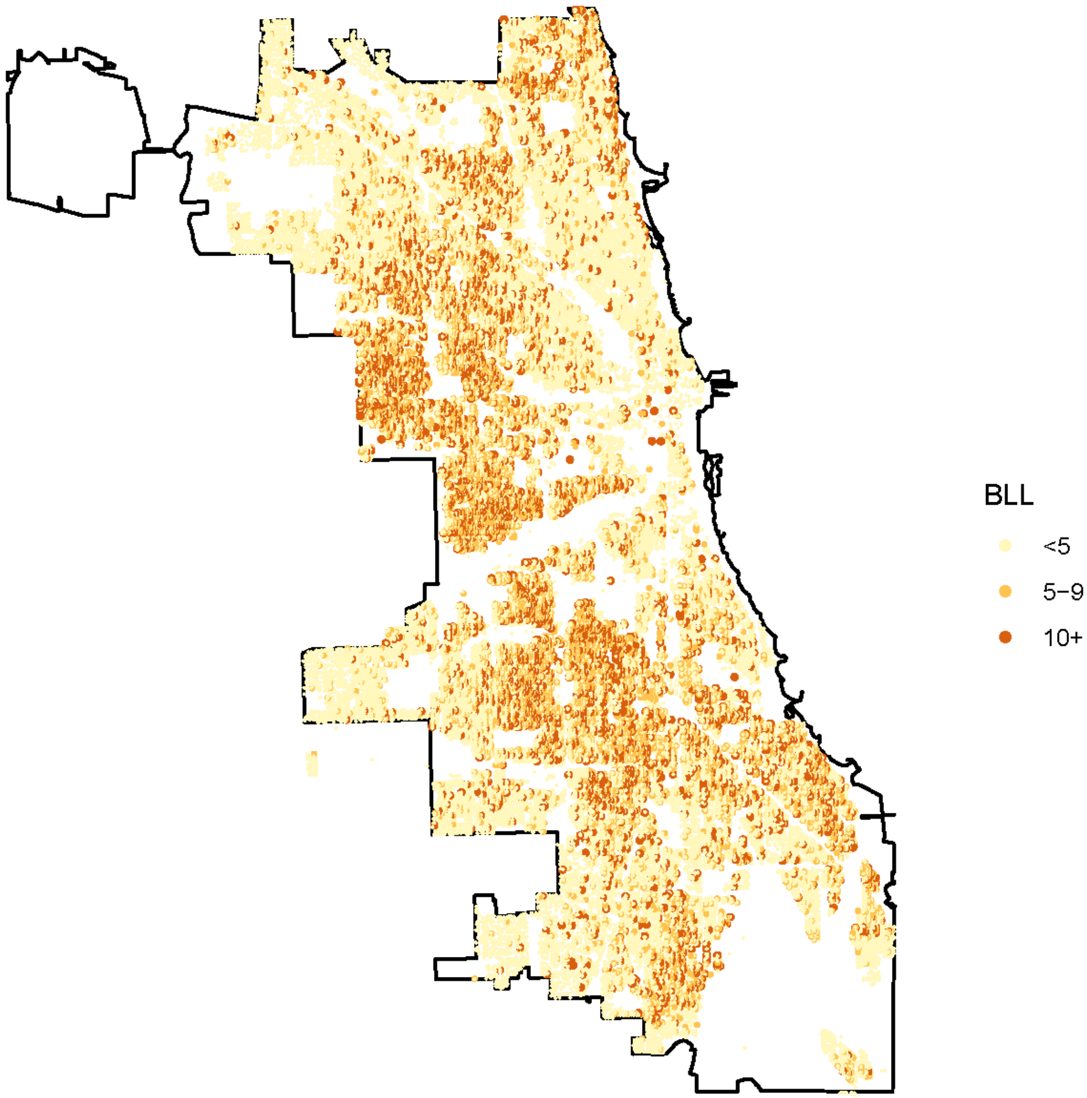
Notes: The figure displays excerpts from a sample letter the City sent to announce construction work. The letter was accessed at `https://www.chicago.gov/city/en/depts/water/supp_info/dwm_constructionprojects.html`.

Figure A.5: Water Lead Samples in Chicago



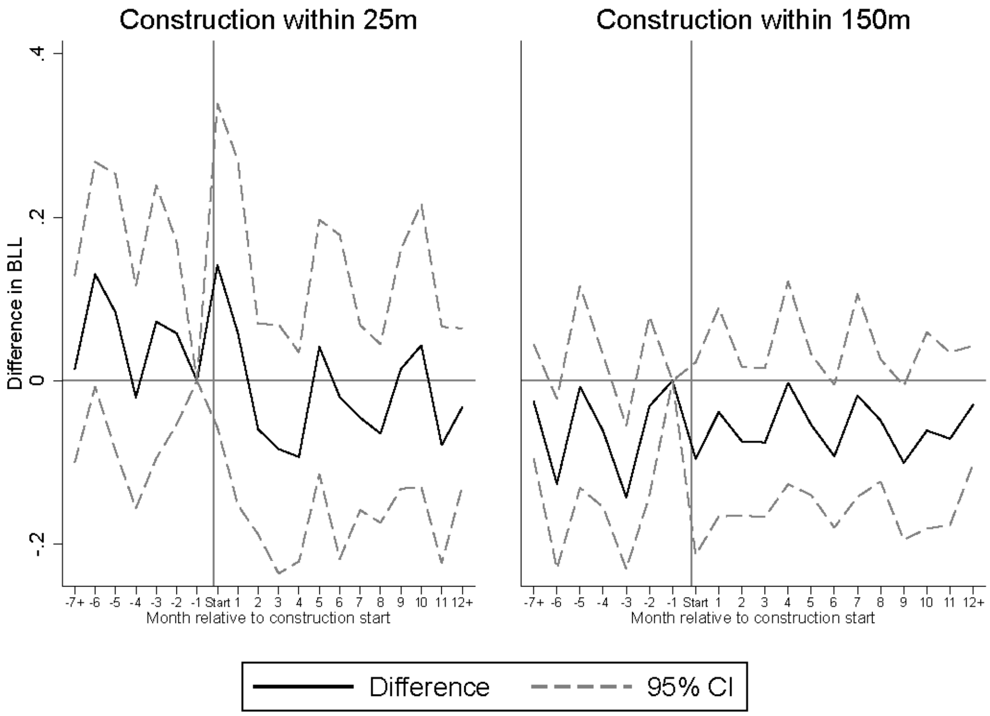
Notes: The figure plots water lead tests in our sample highlighting in darker color blocks with any sample 15ppb or above.

Figure A.6: Blood Lead Levels in Chicago



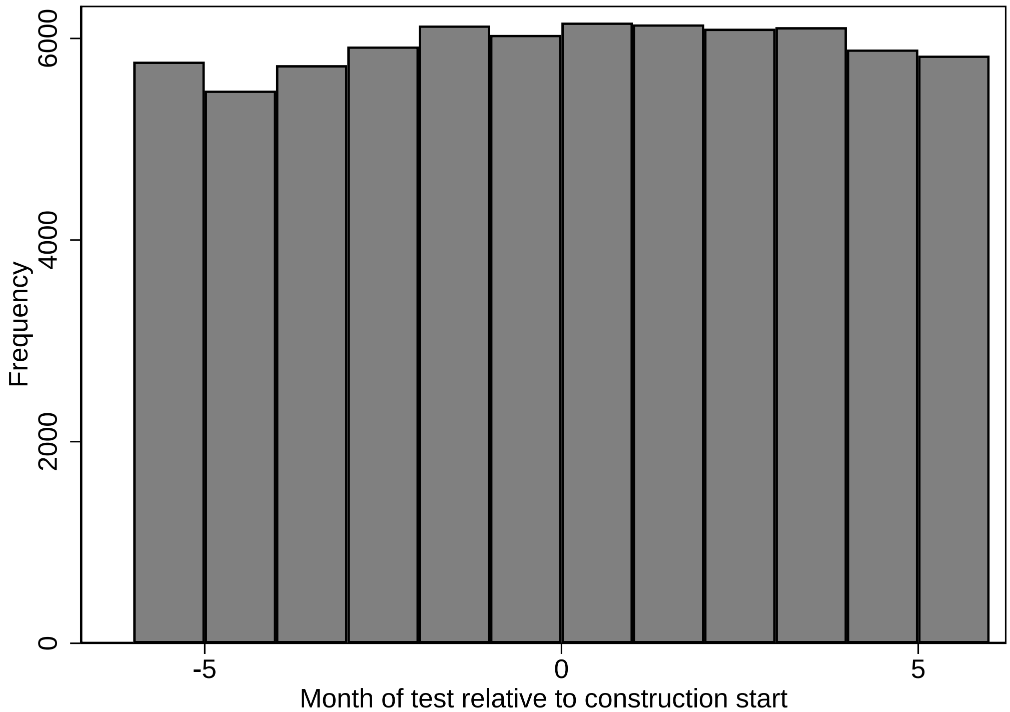
Notes: The figure plots each blood lead test in our sample with different colors indicating different test results.

Figure A.7: Health Effects of Construction Within 25 and 150 Meters by Test Timing



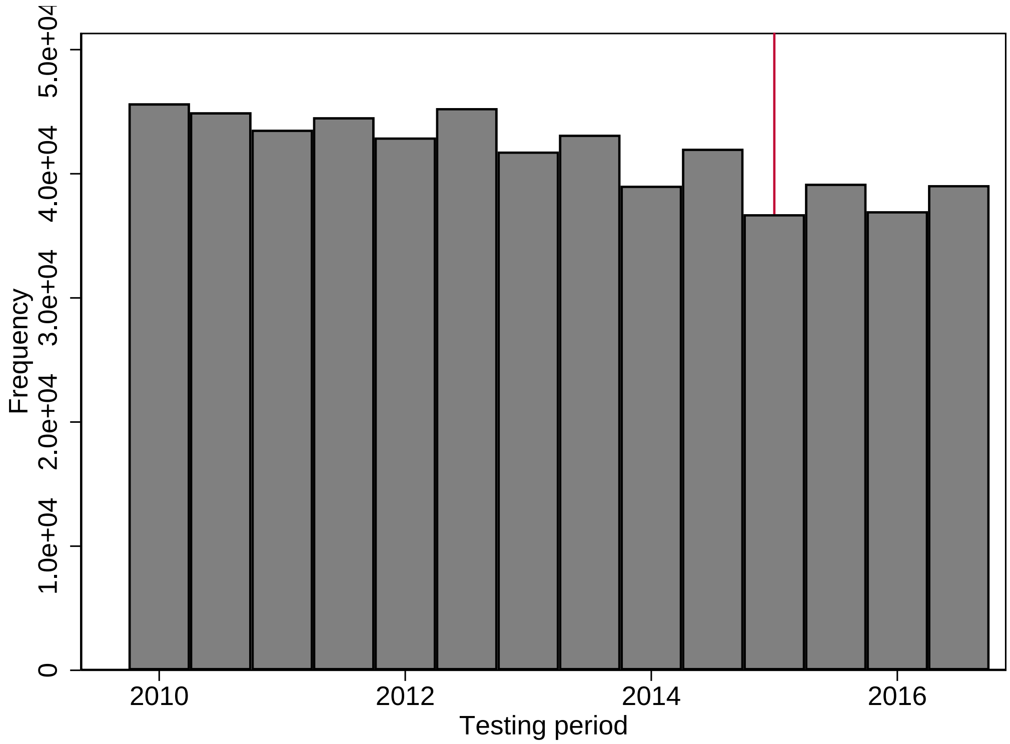
Notes: The figures plot coefficients from a regression of BLLs on indicators for tests taken in a given month relative to the closest construction project start, with the month prior to construction start as the reference point. The left panel shows effects for tests within 25 meters of a construction project. The right panel shows effects for tests in a 100 to 150 meters radius from a construction project. The dashed lines delimit confidence intervals at the 95% level based on standard errors clustered at the zip code level. Additional controls include tract, labXyear, month, and semester age FE; an indicator for twins; mother's marital status, race/ethnicity, and education level at birth; an indicator for housing built before 1930; and indicators for missing housing age or marital status/race/ethnicity/education.

Figure A.8: Test Timing Relative to Construction



Notes: The figure plots the frequency of tests occurring in a six month period around the start of main construction projects in our sample.

Figure A.9: Test Timing over Sample Period



Notes: The figure plots the frequency of tests occurring every semester of our sample. The vertical red line indicates the first semester of 2015, after which the Flint scandal emerges.

Appendix Tables

Table A.1: Summary Statistics: Water Tests

	Overall	Ever within 0-25m or 100-150m	Ever within 25m	Pre-construction (0-25m or 100-150m)	Post-construction (0-25m or 100-150m)
Lead at 1 minute	3.82	5.08	3.95	3.47	5.50
	(16.97)	(25.18)	(8.20)	(3.70)	(28.15)
Lead at 3 minutes	3.20	3.39	3.69	3.45	3.37
	(4.57)	(4.59)	(4.66)	(3.96)	(4.74)
Lead at 5 minutes	2.01	2.19	2.26	2.36	2.15
	(2.92)	(3.14)	(2.96)	(2.94)	(3.19)
Tests per location	1.71	1.53	1.64	1.60	1.51
	(2.34)	(0.77)	(0.70)	(0.76)	(0.78)
Unique locations	3,249	963	289	196	781

Notes: The table shows means and standard deviations (in parentheses) for the water sample data over different analysis samples in each column.

Table A.2: Summary Statistics

	Overall	Ever within 150m	Ever within 25m	Pre-construction (150m)	Post-construction (150m)
Black	0.33	0.35	0.37	0.34	0.35
	(0.47)	(0.48)	(0.48)	(0.47)	(0.48)
Hispanic	0.44	0.46	0.44	0.46	0.44
	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)
Male	0.51	0.51	0.51	0.51	0.51
	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)
Age at Test (months)	37.98	38.17	37.49	38.02	38.42
	(26.82)	(26.79)	(26.18)	(26.86)	(26.65)
Median Income (Block Group)	43285	40800	40293	40904	40615
	(22,775)	(20,922)	(20,262)	(20,153)	(22,213)
Pre1930 Home	0.60	0.69	0.66	0.67	0.71
	(0.49)	(0.46)	(0.48)	(0.47)	(0.46)
Pre1986 Home	0.93	0.95	0.95	0.95	0.94
	(0.25)	(0.23)	(0.23)	(0.22)	(0.24)
Mother Has High School Diploma	0.48	0.50	0.51	0.49	0.53
	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)
Mother Age at Birth	26.80	26.44	26.23	26.29	26.70
	(6.46)	(6.43)	(6.40)	(6.40)	(6.48)
Single Mother	0.57	0.60	0.62	0.60	0.61
	(0.50)	(0.49)	(0.48)	(0.49)	(0.49)
BLL	1.84	1.91	1.90	1.92	1.88
	(1.96)	(2.06)	(2.08)	(2.14)	(1.91)
BLL 10+	0.01	0.01	0.01	0.01	0.01
	(0.10)	(0.10)	(0.10)	(0.11)	(0.10)
BLL 5+	0.05	0.06	0.06	0.06	0.05
	(0.22)	(0.23)	(0.23)	(0.24)	(0.22)
Tests per Child	2.64	2.69	2.83	2.71	2.66
	(1.56)	(1.56)	(1.59)	(1.57)	(1.54)
Unique Children	314634	147267	45721	105444	63621

Notes: The table shows means and standard deviations (in parentheses) for the main variables in our analysis over different analysis samples in each column.

Table A.3: Construction Relationship with Characteristics of Children Tested

	Less than HS	Black	Housing before 1930
1-3 months post construction	-0.0214**	0.0049	0.0032
	(0.0063)	(0.0039)	(0.0079)
4+ months post-construction	-0.0060	0.0012	0.0070
	(0.0043)	(0.0028)	(0.0072)
Ever exposed within 25m	0.0089***	0.0008	-0.0125*
	(0.0025)	(0.0023)	(0.0050)
Observations	260228	260228	260228
Control Mean	0.224	0.335	0.699

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows coefficients from a regression of demographic characteristics of children tested for BLLs on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Additional controls include tract, labXyear, month, and semester age FE; an indicator for twins; mother's marital status, race/ethnicity, and education level at birth; an indicator for housing built before 1930; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses.

Table A.4: Construction Effects on Lead Levels in Tap Water for Construction, within 100 meters

	Lead at 1 minute	Lead at 1 minute	Lead at 1 minute	Lead at 3 minutes	Lead at 5 minutes
1-3 months post construction	4.4666	4.9003	3.7295	0.6372	0.5195
	(3.4392)	(3.4650)	(3.9923)	(1.0997)	(0.8577)
4+ months post-construction	0.2259	0.3820	0.5498	-0.3721	-0.1771
	(0.5235)	(0.7246)	(0.7410)	(0.5303)	(0.3278)
Ever exposed within 25m	-2.2088^{+}	-2.3637^{*}	-2.8744^{+}	0.8762^{+}	0.4333
	(1.1902)	(1.1507)	(1.6016)	(0.5015)	(0.2990)
Controls		X	X	X	X
Zip FE			X	X	X
Observations	1488	1488	1488	1488	1488
Control Mean	5.602	5.602	5.602	3.246	2.160
Cell Size			29.176	29.176	29.176

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows coefficients from a regression of lead levels in tap water samples on indicators for tests taken within three months, and 4-12 months after construction starts within 100 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Additional controls include year and month FE. Standard errors clustered at the zip level are in parentheses.

Table A.5: Construction Effects on Probability of BLLs 10 or higher

	No FE	Add controls	Zip FE	Tract FE	Block Group FE
1-3 months post construction	-0.0009	0.0001	0.0003	0.0000	0.0001
	(0.0017)	(0.0017)	(0.0017)	(0.0017)	(0.0016)
4+ months post-construction	-0.0030**	-0.0010	-0.0009	-0.0011	-0.0014
	(0.0010)	(0.0010)	(0.0010)	(0.0011)	(0.0011)
Ever exposed within 25m	0.0006	-0.0000	0.0001	-0.0000	0.0001
	(0.0007)	(0.0007)	(0.0007)	(0.0008)	(0.0008)
Male		0.0018***	0.0018***	0.0018***	0.0018***
		(0.0005)	(0.0005)	(0.0005)	(0.0005)
Black		0.0036*	0.0007	-0.0004	-0.0008
		(0.0014)	(0.0017)	(0.0017)	(0.0017)
Hispanic		-0.0054***	-0.0057***	-0.0050***	-0.0047***
		(0.0012)	(0.0012)	(0.0013)	(0.0013)
Mother has less than HS education		0.0030**	0.0029**	0.0029**	0.0027*
		(0.0011)	(0.0011)	(0.0011)	(0.0010)
Less than 4 yrs of college		-0.0035***	-0.0034***	-0.0034***	-0.0036***
		(0.0009)	(0.0009)	(0.0009)	(0.0009)
Mother has 4 year degree or more		-0.0062***	-0.0055***	-0.0054***	-0.0054***
		(0.0011)	(0.0011)	(0.0011)	(0.0010)
Pre-1930		0.0072***	0.0067***	0.0061***	0.0055***
		(0.0009)	(0.0009)	(0.0009)	(0.0009)
Observations	260224	260224	260209	260224	260224
Control Mean	0.011	0.011	0.011	0.011	0.011

Notes: $+ p < 0.10$, $* p < 0.05$, $** p < 0.01$, $*** p < 0.001$. The table shows coefficients from a regression of an indicator for BLL 10 or higher on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Geography fixed effects included in each regression are indicated at the top of each column. Additional controls include labXyear, month, and semester age FE; an indicator for twins; mother's marital status at birth; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses.

Table A.6: Construction Effects on Probability of BLLs 5 or higher

	No FE	Add controls	Zip FE	Tract FE	Block Group FE
1-3 months post construction	-0.0070^{+}	0.0004	0.0007	-0.0002	0.0004
	(0.0041)	(0.0042)	(0.0042)	(0.0040)	(0.0040)
4+ months post-construction	-0.0161***	-0.0028	-0.0027	-0.0035	-0.0042^{+}
	(0.0023)	(0.0020)	(0.0018)	(0.0022)	(0.0022)
Ever exposed within 25m	0.0045**	-0.0006	0.0004	0.0004	0.0008
	(0.0015)	(0.0014)	(0.0014)	(0.0014)	(0.0015)
Male		0.0087***	0.0087***	0.0089***	0.0089***
		(0.0011)	(0.0011)	(0.0011)	(0.0011)
Black		0.0272***	0.0157**	0.0097*	0.0087*
		(0.0042)	(0.0051)	(0.0038)	(0.0037)
Hispanic		-0.0153***	-0.0162***	-0.0140***	-0.0130***
		(0.0033)	(0.0031)	(0.0027)	(0.0025)
Mother has less than HS education		0.0156***	0.0148***	0.0142***	0.0135***
		(0.0026)	(0.0026)	(0.0025)	(0.0025)
Less than 4 yrs of college		-0.0139***	-0.0130***	-0.0126***	-0.0129***
		(0.0023)	(0.0023)	(0.0021)	(0.0022)
Mother has 4 year degree or more		-0.0230***	-0.0194***	-0.0188***	-0.0187***
		(0.0024)	(0.0024)	(0.0025)	(0.0024)
Pre-1930		0.0341***	0.0313***	0.0282***	0.0266***
		(0.0036)	(0.0032)	(0.0028)	(0.0026)
Observations	260224	260224	260209	260224	260224
Control Mean	0.059	0.059	0.059	0.059	0.059

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows coefficients from a regression of an indicator for BLL 5 or higher on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Geography fixed effects included in each regression are indicated at the top of each column. Additional controls include labXyear, month, and semester age FE; an indicator for twins; mother's marital status at birth; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses.

Table A.7: Construction Effects on BLLs, Including Sewer Construction

	No FE	Add controls	Zip FE	Tract FE	Block Group FE
1-3 months post construction	0.0221	0.0484	0.0528	0.0451	0.0481
	(0.0388)	(0.0390)	(0.0382)	(0.0362)	(0.0354)
4+ months post-construction	-0.0566*	-0.0125	-0.0092	-0.0186	-0.0287
	(0.0226)	(0.0191)	(0.0190)	(0.0200)	(0.0190)
Ever exposed within 25m	0.0115	-0.0106	0.0000	0.0014	0.0053
	(0.0140)	(0.0142)	(0.0144)	(0.0154)	(0.0162)
Male		0.0790***	0.0795***	0.0796***	0.0789***
		(0.0119)	(0.0120)	(0.0121)	(0.0119)
Black		0.2868***	0.1625**	0.0976**	0.0889**
		(0.0373)	(0.0491)	(0.0354)	(0.0336)
Hispanic		-0.1486***	-0.1677***	-0.1502***	-0.1395***
		(0.0357)	(0.0322)	(0.0288)	(0.0276)
Mother has less than HS education		0.1527***	0.1456***	0.1407***	0.1342***
		(0.0230)	(0.0232)	(0.0219)	(0.0214)
Less than 4 yrs of college		-0.1254***	-0.1192***	-0.1158***	-0.1191***
		(0.0186)	(0.0187)	(0.0181)	(0.0189)
Mother has 4 year degree or more		-0.2489***	-0.2158***	-0.2041***	-0.2017***
		(0.0213)	(0.0222)	(0.0221)	(0.0213)
Pre-1930		0.3335***	0.3037***	0.2598***	0.2447***
		(0.0313)	(0.0288)	(0.0254)	(0.0236)
Observations	275952	275952	275936	275952	275952
Control Mean	1.903	1.903	1.903	1.903	1.903
Cell Size			4118.448	310.407	125.718

Notes: $+ \, p < 0.10$, $* \, p < 0.05$, $** \, p < 0.01$, $*** \, p < 0.001$. The table shows coefficients from a regression of BLLs on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Geography fixed effects included in each regression are indicated at the top of each column. Additional controls include labXyear, month, and semester age FE; an indicator for twins; mother's marital status at birth; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses. The sample includes construction projects on both water mains and sewers.

Table A.8: Construction Effects on BLLs, within 100 meters

	No FE	Add controls	Zip FE	Tract FE	Block Group FE
1-3 months post construction	0.0287	0.0494*	0.0466*	0.0383^{+}	0.0388^{+}
	(0.0248)	(0.0222)	(0.0207)	(0.0198)	(0.0202)
4+ months post-construction	-0.0513*	-0.0071	-0.0127	-0.0249	-0.0258
	(0.0206)	(0.0175)	(0.0139)	(0.0159)	(0.0158)
Ever exposed within 25m	-0.0141	-0.0234*	-0.0114	-0.0050	-0.0017
	(0.0135)	(0.0116)	(0.0099)	(0.0114)	(0.0107)
Male		0.0822***	0.0819***	0.0815***	0.0821***
		(0.0105)	(0.0106)	(0.0107)	(0.0105)
Black		0.2859***	0.1662***	0.0989**	0.0916**
		(0.0340)	(0.0455)	(0.0329)	(0.0297)
Hispanic		-0.1553***	-0.1776***	-0.1642***	-0.1552***
		(0.0322)	(0.0283)	(0.0250)	(0.0231)
Mother has less than HS education		0.1677***	0.1598***	0.1560***	0.1528***
		(0.0214)	(0.0213)	(0.0206)	(0.0203)
Less than 4 yrs of college		-0.1241***	-0.1170***	-0.1131***	-0.1125***
		(0.0164)	(0.0163)	(0.0156)	(0.0157)
Mother has 4 year degree or more		-0.2481***	-0.2133***	-0.2031***	-0.1993***
		(0.0186)	(0.0192)	(0.0195)	(0.0195)
Pre-1930		0.3381***	0.3061***	0.2636***	0.2521***
		(0.0288)	(0.0261)	(0.0237)	(0.0216)
Observations	377,606	377,606	377,606	377,606	377,606
Control Mean	1.911	1.911	1.911	1.911	1.911

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows coefficients from a regression of BLLs on indicators for tests taken within three months, and 4-12 months after construction starts within 100 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Geography fixed effects included in each regression are indicated at the top of each column. Additional controls include labXyear, month, and semester age FE; an indicator for twins; mother's marital status at birth; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses.

Table A.9: Construction Effects on BLLs, Pre-1986 Homes

	No FE	Add controls	Zip FE	Tract FE	Block Group FE
1-3 months post construction	0.0195	0.0435	0.0458	0.0329	0.0379
	(0.0497)	(0.0450)	(0.0444)	(0.0438)	(0.0420)
4+ months post-construction	0.0142	0.0373	0.0400	0.0291	0.0341
	(0.0512)	(0.0461)	(0.0454)	(0.0443)	(0.0425)
Ever exposed within 25m	-0.0448^{+}	-0.0069	-0.0019	-0.0162	-0.0244
	(0.0266)	(0.0255)	(0.0249)	(0.0267)	(0.0253)
Male	-0.0057	-0.0239	-0.0113	-0.0056	-0.0026
	(0.0149)	(0.0156)	(0.0148)	(0.0163)	(0.0170)
Black		0.0877***	0.0883***	0.0892***	0.0876***
		(0.0146)	(0.0147)	(0.0147)	(0.0149)
Hispanic		0.3199***	0.1896**	0.1077*	0.0958*
		(0.0411)	(0.0562)	(0.0426)	(0.0403)
Mother has less than HS education		-0.1497***	-0.1730***	-0.1578***	-0.1455***
		(0.0381)	(0.0332)	(0.0313)	(0.0306)
Less than 4 yrs of college		0.1588***	0.1492***	0.1441***	0.1360***
		(0.0266)	(0.0266)	(0.0252)	(0.0249)
Mother has 4 year degree or more		-0.1256***	-0.1192***	-0.1145***	-0.1188***
		(0.0208)	(0.0213)	(0.0210)	(0.0219)
Pre-1930		-0.2438***	-0.2121***	-0.2008***	-0.1971***
		(0.0245)	(0.0259)	(0.0259)	(0.0248)
Observations	222518	222518	222507	222518	222518
Control Mean	1.939	1.939	1.939	1.939	1.939

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows coefficients from a regression of BLLs on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. The sample is limited to homes built prior to 1986. Geography fixed effects included in each regression are indicated at the top of each column. Additional controls include labXyear, month, and semester age FE; an indicator for twins; mother's marital status at birth; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses.

Table A.10: Construction Effects on BLLs, Including Only Tests by Age 2

	No FE	Add controls	Zip FE	Tract FE	Block Group FE
1-3 months post construction	0.0471	0.0496	0.0482	0.0323	0.0332
	(0.0737)	(0.0681)	(0.0676)	(0.0681)	(0.0686)
4+ months post-construction	-0.0707**	-0.0526*	-0.0555*	-0.0642**	-0.0633*
	(0.0256)	(0.0222)	(0.0214)	(0.0229)	(0.0244)
Ever exposed within 25m	0.0147	0.0016	0.0143	0.0135	0.0198
	(0.0143)	(0.0146)	(0.0152)	(0.0153)	(0.0175)
Male		0.0470***	0.0467***	0.0475***	0.0484***
		(0.0110)	(0.0112)	(0.0114)	(0.0114)
Black		0.2017***	0.0916+	0.0469	0.0368
		(0.0426)	(0.0529)	(0.0429)	(0.0394)
Hispanic		-0.1430***	-0.1699***	-0.1571***	-0.1418***
		(0.0390)	(0.0341)	(0.0289)	(0.0280)
Mother has less than HS education		0.1177***	0.1111***	0.1031***	0.0976***
		(0.0246)	(0.0251)	(0.0249)	(0.0250)
Less than 4 yrs of college		-0.1476***	-0.1409***	-0.1390***	-0.1420***
		(0.0200)	(0.0204)	(0.0205)	(0.0212)
Mother has 4 year degree or more		-0.2081***	-0.1738***	-0.1691***	-0.1664***
		(0.0257)	(0.0254)	(0.0256)	(0.0247)
Pre-1930		0.3266***	0.2871***	0.2470***	0.2291***
		(0.0273)	(0.0236)	(0.0194)	(0.0193)
Observations	107915	107915	107907	107915	107915
Control Mean	1.848	1.848	1.848	1.848	1.848

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows coefficients from a regression of BLLs on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Geography fixed effects included in each regression are indicated at the top of each column. Additional controls include labXyear, month, and semester age FE; an indicator for twins; mother's marital status at birth; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses. The sample includes construction projects on water mains and only tests by age 2.

Table A.11: Construction Effects on BLLs, Summer versus Non-summer months

	Test in non-summer month	Test in summer month
1-3 months post construction	0.0335	0.0712
	(0.0464)	(0.0789)
4+ months post-construction	-0.0350	-0.0419
	(0.0239)	(0.0385)
Ever exposed within 25m	0.0057	0.0018
	(0.0178)	(0.0234)
Constant	1.6588***	1.7428***
	(0.0266)	(0.0482)
Observations	159342	100619
Control Mean	1.843	2.012

Notes: + $p < 0.10$, $*$ $p < 0.05$, $**$ $p < 0.01$, $***$ $p < 0.001$. The table shows coefficients from a regression of BLLs on indicators for tests taken within three months, and 4-12 months after construction starts within 25 meters of a child's residence relative to a control group of children living within a 100-150 meter radius from construction projects. Each column is estimated on a subsample of months or years indicated at the top of the column. Additional controls include tract, labXyear, month, and semester age FE; an indicator for twins; mother's marital status, race/ethnicity, and education level at birth; an indicator for housing built before 1930; and indicators for missing housing age or marital status/race/ethnicity/education. Standard errors clustered at the zip level are in parentheses. Sample split by summer vs. non-summer months. Summer months are those with temperatures above 70 degrees on average per NOAA (June - September). Observations do not sum to main analytic sample due to singletons in fixed effects in the split sample.

Data Linkages

Our algorithm for linking construction projects to BLL and drinking water tests proceeds as follows.

1. We identify addresses that fall within a 25, 50, 75, 100, or 150 meter radius from any construction segment, independent of timing

2. If an address is within 150 meters to multiple construction projects at different times and/or distances, we select linkages as follows:

   - Keep linkages for tests or samples within a $[-6, 12]$ months window around construction start
   - Drop linkages to sewers
   - Keep the closest linkage. In other words, if a test is within a $[-6, 12]$ months window around construction start for project A within 25 meters and project B at 125 meters, this test will only be in the risk set for our "treatment" indicator and not the control (100-150 meters away)

3. For tests linked to multiple mains for which the test do not fall in the $[-6, 12]$ windows, we keep the first construction project observed

4. For children with multiple tests that fall within construction windows, we keep the first test to isolate the effect of initial exposure