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

Ludovica Gazze, Jennifer Heissel

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Abstract

Concerns about drinking water contamination through lead service lines, which connect street water mains to homes in many cities in the United States, might hinder resource-constrained municipalities from performing important infrastructure upgrades. Construction on water mains might disturb 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 by exploiting unique geocoded data and over 2,200 water main replacements in Chicago, a city with almost 400,000 known lead service lines. By comparing water and blood samples 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.

Keywords— Lead, Children, Health, Infrastructure
JEL CODES: I100, H41, H72.

*Contact: Ludovica Gazze: Ludovica.Gazze@warwick.ac.uk; Jennifer Heissel: jaheisse@nps.edu, Naval Postgraduate School, Department of Manpower Economics, 1 University Circle, Monterey, CA 93943. We thank Monica Deza, Daniel Grossman, Elaine Hill, Casey Wichman, and conference and seminar participants at the Eastern Economics Association Meetings, ASHEcon, and the Harvard School of Public Health. Emily He, Emi Lemberg, and Iris Song provided excellent research assistance. We are indebted to the staff at the Illinois Department of Public Health for sharing the data for this analysis as well as their insights and expertise in interpreting the results. Heissel thanks the the Naval Postgraduate School Research Initiation Program for financial support. The conclusions, opinions, and recommendations in this paper are not necessarily the conclusions, opinions, or recommendations of IDPH or the Department of Defense. The authors have no conflicts of interest related to the subject of the paper. All remaining errors are our own.

1 INTRODUCTION

The provision of safe drinking water is deemed responsible for tremendous improvements in public health in the twentieth century (Alsan & Goldin, 2019). In modern cities, water utilities treat source water at treatment plants and distribute it through water mains that run under streets. Service lines connect each home to these mains. Any pathogens or pollutants that enter the system after the water leaves the treatment plant might constitute a threat to human health.

An estimated 6.5 to 10 millions lead service lines (LSLs) connect street water mains to homes in the United States (Environmental Protection Agency, 2016), and approximately a third of U.S. water systems report at least some LSLs (Cornwell et al., 2016). These lines might expose children to lead in drinking water unless natural sediments or added compounds in the water coat the pipes' interior to prevent lead from leaching (Brown et al., 2011; Environmental Protection Agency, 2006; Triantafyllidou & Edwards, 2012). The deleterious effects of LSLs were highlighted by recent events in Flint, MI, where the switch to a more corrosive water source diminished the protective coating within LSLs, leading to heightened lead exposure (Edwards et al., 2015). Construction for water main upgrades, which requires cutting the service line, might mechanically or hydraulically disturb the mineral coating within LSLs in a manner similar to deprecated partial LSL replacements (Batterman et al., 2019; Del Toral et al., 2013; Quatrevaux, 2017).

Whether LSL disturbances during main construction harm public health matters 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 (ASCE, 2017; CNT, 2016). Thus, U.S. cities face a potential trade-off between upgrading water infrastructure and exacerbating lead exposure. For example, the New Orleans inspector general recommends that the water utility inform residents of LSL disturbance risks and fully replaces LSLs whenever there are disturbances (Quatrevaux, 2017), while Washington, D.C., 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). Concerns about LSL disruption from municipal construction projects prompted a prominent lawsuit against the City of Chicago. The plaintiffs allege that

> drilling, digging, as well as moving or bending of the pipes can all cause the interior

> coating to flake off [...]. When the water is turned back on, the violent rush of water into the pipes disrupts the protective coating, putting residents at further risk of lead exposure. Unsafe lead levels can persist for weeks or months after the disturbance. Also, in reconnecting the residential LSLs to the water mains after replacement or repair, the City performs a partial replacement in which it replaces a portion of the LSL with copper. When sections of a lead pipe are replaced with copper, a galvanic cell (a battery) is created that can cause the release of lead into water as the pipes corrode." ("Berry v. the City of Chicago," 2019)

Lead exposure is associated with reduced IQ (Ferrie et al., 2015), lower educational attainment (Aizer et al., 2018; Grönqvist et al., 2017; Reyes, 2015b), and an increased risk of criminal activity (Aizer & Currie, 2019; Feigenbaum & Muller, 2016; Reyes, 2007, 2015a). The Centers for Disease Control and Prevention estimate that 535,000 children born in the United States in the 2000s had blood lead levels (BLLs) at or above $5\mu g/dl$ (Wheeler & Brown, 2013). A quarter of Chicago zip codes have at least 5% of lead-tested children with BLLs at or above $5\mu g/dL$, and lead exposure correlates with socioeconomic disadvantage (Sampson & Winter, 2016). Historically, the use of lead service lines has been associated with worse health and education outcomes in the presence of corrosive water (Clay et al., 2014; Feigenbaum & Muller, 2016; Ferrie et al., 2015; Troesken & Beeson, 2003). Since the deleading of gasoline, lead paint hazards in homes appear to be the most important source of lead exposure (Zartarian et al., 2017). However, 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 clusters of elevated BLLs in the city. The variation we exploit in this paper allows us to study the effects of water main construction in the presence of LSLs on drinking water quality and children's health, and not the effects of LSLs *per se*.

Use of lead service lines was standard practice in the United States through the 1920s because lead's malleability and flexibility make it easy to work with and resistant to decay and frost (Triantafyllidou & Edwards, 2012). As medical doctors and public health officials begun understanding the health hazards of lead poisoning, lobbying by the lead industry ensured continued use of lead pipes in certain cities (Rabin, 2008). The City of Chicago mandated use of LSLs until the Safe Drinking Water Act amendment of 1986 prohibited lead in service lines or premise plumbing

(Environmental Protection Agency, 2006). Despite this ban, many legacy pipes remain in place across the United States. A recent inventory assessed that 389,893 of the 519,584 retail connections in Chicago are made of lead, 11,232 are lead-free, and the remainder are of unknown materials, possibly including lead.[1]

In response to the Flint scandal, cities are now conducting inventories and planning replacement of LSLs in line with the EPA's recommendations (Environmental Defense Fund, 2018; Neltner, 2018). With estimated costs for LSL replacements ranging from $2500 to over $8,000 per line, the cost of replacing all LSLs nationwide ranges from $16 to $80 billion (Environmental 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. Data from Evanston, Illinois, suggest that costs of water main replacements could increase by 0.8–5.4% if all LSLs connected to a water main had to be replaced during main construction, although actual costs depend on LSL density.[3] Evanston has 79% lead service lines, compared to between 75% and 98% for Chicago.[4]

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 and children's blood levels. Specifically, we spatially link data on over 2,200 main replacements completed across Chicago from 2011 through 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. We compare BLLs of children in the same neighborhood, for example a zip code or block group, who live near water mains slated for replacement and whose BLL tests happen either before or after the construction. Our identification strategy relies on the exogeneity of water sampling and children's BLL test data, where the latter are based on their physician visit,

[1] Source: Illinois Environmental Protection Agency Service Line Material Inventory Reports. Accessed January 28, 2021, at `https://www2.illinois.gov/epa/topics/drinking-water/public-water-users/Pages/lead-service-line-information.aspx`

[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.

[3] Source: Authors' calculation using water main construction costs and LSL location data from Evanston, Illinois. The average main construction project cost $2.64 million and affected 8.5 full and 17.9 partial LSLs. We multiply these numbers by the price range for LSL replacement to obtain the additional costs.

[4] Source: Illinois Environmental Protection Agency Service Line Material Inventory Reports. Accessed January 28, 2021, at `https://www2.illinois.gov/epa/topics/drinking-water/public-water-users/Pages/lead-service-line-information.aspx`

and main replacement in their neighborhood. We find no evidence of changes in testing around main 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 preferred estimates, which control for block group fixed effects, rule out effects of $0.09\mu g/dL$, or 5% over the average BLL in our sample ($1.85\mu g/dL$) and all but one of our 22 robustness checks rule out effects larger than 10%. Moreover, we find no evidence that construction disproportionately affects certain subpopulations particularly burdened by lead exposure. Finally, we find no evidence of heterogeneous effects after the Flint scandal made the issue of lead in drinking water more salient.

A back-of-the-envelope calculation suggests that the costs of requiring LSL replacement during main replacement exceed the potential health benefits in terms of preventing BLLs of $5\mu g/dL$ or above due to LSL disturbances caused by the main replacement. However, we cannot reject that providing faucet filters during construction could be cost-effective. Importantly, while we find no evidence that LSL disturbances during water main construction affect BLLs, we do not speak to whether LSLs in general are associated with lead levels that warrant intervention.

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. Two studies in Chicago examine the effects of physical LSL disturbances on lead in drinking water. First, Batterman et al. (2019) find similar lead levels in tap water samples in 273 voluntarily enrolled homes connected to repaired water mains before and after construction, although the authors identify potential transient peaks in a subset of homes. Our drinking water results confirm these patterns in a larger sample, and our BLL results allow us to investigate heterogeneity and mechanisms in a much larger and less selected sample. Second, Del Toral et al. (2013) find higher water lead levels in 13 homes where LSLs had been physically disturbed in the previous six years, relative to 21 homes without known disturbances.[5] These findings were

[5]They consider meter, including Auto Meter Reader (AMR), installations and replacements, service line leak repair, shut-off valve repair or replacement, and significant street excavation in front of the home. A water meter installation involves a cut to the water main or the service line. Replacing a meter either replaces the existing segment with a disturbance but no new pipe cuts or an additional cut to fit the new meter. AMR installation also requires a physical connection to the water flow.

widely cited in newspaper articles,[6] 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). Our large data set including both drinking water quality and health outcomes allows us to obtain more robust results on the effects of water main construction on lead poisoning than this smaller, cross-sectional study.

Our findings complement the growing literature on the effects of water chemistry changes on health outcomes. In Flint, Hanna-Attisha et al. (2015) estimate that the percent of children with BLLs at $5\mu g/dL$ or above doubled from 2.4% before the switch to 4.9% after the switch. The water crisis was also associated with lower fertility rates and poorer birth outcomes (Danagoulian & Jenkins, 2018; Grossman & Slusky, 2019; Wang et al., 2018), despite evidence of households' avoidance behavior, such as using bottled water (Christensen et al., 2018). Dave and Yang (2020) exploit a switch in water treatment in one of the treatment plants in Newark, New Jersey, to show that exposure to drinking water contaminated by lead in utero is associated with worse birth outcomes. Our findings help us put into perspective these case studies that highlight important breaking points in water system management: our analysis shows that LSL disturbances caused by water main replacements did not pose a health threat in Chicago, Illinois, potentially due to differences in water chemistry and water treatment.

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

[6] See, e.g., M. Hawthorne, "EPA: Pipe Work May Boost Lead in Water," Chicago Tribune, September 25, 2013, https://www.chicagotribune.com/news/ct-lead-pipe-work-20130925-story.html, C. Corley, "Chicago's Upgrades to Aging Water Lines May Disturb Lead Pipes," NPR, April 14, 2016, https://www.npr.org/2016/04/14/474130954/chicagos-upgrades-to-aging-water-lines-may-disturb-lead-pipes, and "Chicago Residents Blame City for Water Contamination in Class Action Lawsuit," Guardian, February 18, 2016, https://www.theguardian.com/us-news/2016/feb/18/chicago-class-action-lawsuit-water-contamination-lead-pipes.

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. Specifically, lead can be found in several pipes and fixtures in homes (Appendix Figure A.2). Depending on water chemistry, sediments in old pipes might 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 (Del Toral et al., 2013; Quatrevaux, 2017; Sandvig et al., 2009). This paper studies exposure through LSL disturbances during water main construction; most water mains themselves do not appear to be made of lead.[7]

Lead exposure through drinking water gained media attention after the city of Flint, Michigan, switched its water source from the Detroit Water and Sewerage Department to the Flint River 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 2015, likely making lead exposure more salient for parents across the United States.

Elevated lead in water is not a new issue, and is not limited to Flint—or even just the home (Edwards et al., 2009; Triantafyllidou & Edwards, 2012; Triantafyllidou et al., 2014). Programs such as changes in water treatment, filter distribution, and avoidance behavior can address lead in water (Edwards, 2014; Grossman & Slusky, 2019; Kennedy, 2016; Ngueta et al., 2014; Triantafyllidou et al., 2014; Zahran, McElmurry, et al., 2017). Therefore, it is crucial to understand what causes lead spikes in water in order to address them in a timely fashion.

[7] Records suggest that most water mains in Chicago are made of cast iron, although some seals might contain lead (Batterman et al., 2019).

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.[8] To deal with leaks, the city approved a 10-year plan to upgrade its water infrastructure in 2011. The "Building a Better Chicago" program includes a large-scale replacement of water mains in the city. Water main replacement typically involves digging up a roadway, laying down new pipe parallel to the old pipe, switching line connections to the structures themselves, removing the old pipe, and then fixing the roadway. Service is generally interrupted only during the service transfer. Any of the digging and general disruption caused by water main construction could shake the LSLs and affect their protective coating, though the most direct disruption of the pipes occur when the service line is transferred from the old to the new water main. This generally occurs towards the end of construction, though larger projects may complete it in sections and construction to cover the holes and fix the streets continues after the transfer.

Chicago completed over 2,200 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 cluster 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 to construction projects. Moreover, Appendix Figure A.4 shows that timing of main replacement is largely uncorrelated with construction duration and age of the water main, suggesting that construction was not prioritized based on main characteristics that could be correlated with severity of LSL disturbances. 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.5. 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 was typically toward the end of the letter.

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

3 DATA

Our analysis exploits several data sets covering the City of Chicago. These data sets include information on potential lead exposure sources (housing age and water main construction), drinking water sample data, and individual-level lead screening data linked to household characteristics.

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.[9] 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.[10] The letter also indicates whether the construction involved a water main or a sewer pipe. Our analysis focuses on water main construction, as we expect the strongest effects from these projects because water mains connect directly to the LSLs bringing water into homes. Our results are robust to including sewer construction that could still disturb the LSLs through drilling and digging the street pavement. 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. When construction end date is missing (55% of cases), we impute it based on average construction duration for projects with similar lengths, although our main specification focuses on construction start to avoid imputation issues.

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, and on homes built prior to 1986, which were mandated to have LSLs. 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.[11]

[9]Accessed December 17, 2018, at `https://www.chicago.gov/city/en/depts/water/supp_info/dwm_constructionprojects.html`.

[10]Occasionally a project was delayed for various reasons, in which case an updated letter with a new timeline would be sent near the new start date. This happened in 7.6% of all letters, and we take the start date of the more recent letter and ignore the original start date.

[11]Accessed August 8, 2017, at `https://data.cityofchicago.org/Buildings/Building-Footprints`

Drinking Water Data. In 2016, the Chicago Department of Water Management (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 and who might be especially aware of the Water Quality Study program and the dangers of lead. According to DWM website, the sampling approach requires collecting four water samples for each test, making the process more likely to detect lead. Our data includes only three water samples and addresses deidentified to the block level for over 4,100 tests performed in 2016–2018.[12] Each set of tests contains a sample taken immediately and samples taken three and five 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.6 shows the spatial distribution of samples.

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. To obtain family characteristics, such as mother's marital status, age, education, and race, 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). 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 all children to be screened with blood lead tests. 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. Screening usually happens during routine pediatric visits. Appendix Figure A.7 shows the proportion of Chicago children who are low-income, Black, Hispanic, or have a single, teenage, or low-education mother by lead screening status. Children of low socioeconomic status are more likely to be screened than average. To the extent that selection into screening is not correlated with proximity to construction projects, our estimates will not suffer from selection bias. Below, we further test for endogeneity in timing of BLL testing and changes in selection into

-current-/hz9b-7nh8.

[12] Accessed August 15, 2018, at http://www.chicagowaterquality.org/Results.pdf. We limit our sample to tests taken in 2016–2017 to overlap with our main replacement sample.

testing around construction projects.

The health test data include address of residence, which IDPH or a delegate local agency uses to contact families of children with high BLLs. Blood lead test records also include test date, BLL, test type, and an identifier for the laboratory that analyzed the blood sample. By geocoding these addresses and exploiting test and construction timing, we link child blood lead history to data on potential sources of lead exposure, including water main construction. Specifically, we link each test to the construction project that would affect it the most in terms of distance and timing. Appendix B details our algorithm to assign geocoded tests to geocoded water main construction projects. First, if a test is within a window of six months prior to 12 months after construction start of two projects both within 150 meters, we assign the test to the nearest water main risk set, with the assumption that the nearest water main affects outcomes the most. Second, if a test is within the same distance and within a window of six months prior to 12 months after construction start of multiple construction projects we assign the earliest. In this case, the later exposure would bias our analysis towards finding persistent effects of main replacements.

Lead screening techniques have improved over time, yet tests are prone to measurement error. For example, laboratories have minimum detection limits (MDL), and those limits vary over time and by lab. In our main 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.[13] We discuss below that our results are robust to using unadjusted test results and a binary indicator for BLLs at or above 5, which is largely unaffected by the correction (Zahran, Iverson, et al., 2017). Because we are interested in the effects of temporary shocks on BLLs, a flow measure of lead poisoning, we cannot further correct for measurement error in single tests by, for example, looking at a child's other tests as do Aizer et al. (2018). This noise in our dependent variable likely increases our standard errors, suggesting that we can reject effect sizes

[13]We determine the MDL for each lab-test type-year cell empirically, where test type is either capillary or venous. We flag a lab as having an MDL 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 lab likely indicates that lab has an MDL. For labs with a thin left tail of test results below the estimated MDL, we reassign those test results to the MDL. Next, we reassign all test results at the MDL to a value equal to the mean of the distribution of tests below that MDL in that year-type cell for labs without MDLs. 43% of lab-year-test type observations have no MDL, that is report tests as low as $1\mu g/dL$, 54% have a 2 or $3\mu g/dL$ MDL, and only 2% and 1% have a 5 or $10\mu g/dL$ MDL, respectively.

smaller than our confidence intervals imply.

We examine two outcomes to study the effects of main construction on children's health. First, we use a continuous measure of BLL (in $\mu g/dL$) because the contribution of lead in water to BLLs is estimated to be relatively low, that is 10 or 20% (Rabin, 2008). Second, because lead poisoning is a tail event we also examine an indicator for BLLs of $5\mu g/dL$ or higher. 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 U.S. children aged $1-5$ years from two consecutive cycles of National Health and Nutrition Examination Survey (NHANES), currently at $5\mu g/dL$.[14] Appendix Figure A.8 maps the distribution of tests below $5\mu g/dL$, $5-9\mu g/dL$, 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. In our main specification we limit the sample to tests in homes within 150 meters of a construction event and within a window of six months prior to 12 months after construction start. We compare tests in homes at different distances from the construction and taken just before construction started to tests likely taken during construction (that is 0–2 months after construction started), as well as to those likely taken after construction ended (that is 3–11 months after construction started). Note that 0-11 months covers the full 12 months (360 days)

[14] Until 2019, the action level for intervention in Illinois was still a BLL of $10\mu g/dL$ or higher.

after construction start, because 0 is included as a post-start month. 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 estimate the following fully parametrized equation.

$$
\begin{aligned}
Y_{itg} = & \sum_d \beta_1^d I_{it}^{\text{W/in dist } d \text{ 0-2 months after start}} + \sum_d \beta_2^d I_{it}^{\text{W/in dist } d \text{ 3-11 months after start}} \\
& + \sum_d \beta_3^d I_{it}^{\text{Ever w/in dist } d} + \gamma_t + \delta_g + X_{it}\theta + \varepsilon_{itg}
\end{aligned} \tag{1}
$$

where Y_{itg} measures outcomes at address i at time t in geography g, that is zip code, tract, Census block group, or water main construction project. Our primary regressors of interest are $I_{it}^{\text{W/in Dist } d \text{ 0-2 months after start}}$. These are indicators for a test taken in the first 90 days (labeled months 0–2) after construction start within distance $d \in \{25m, 50m, 75m, 100m, 150m\}$ from a home. Regressors $I_{it}^{\text{W/in dist } d \text{ 3-11 months after start}}$ measure changes in test levels 3–11 months after construction start, when the construction has ended, on average. The indicators $I_{it}^{\text{Ever w/in dist } d}$ equal one for tests within distance d of a water main replacement in the analysis window of six months prior to 12 months after construction start date. These variables control for time-invariant differences across homes that are at different distances from the water mains with construction. We also account for any constant exposure effects at the neighborhood level by controlling for neighborhood fixed effects δ_g at either the zip, tract, block group, or water main level, depending on the specification. We also include month-year fixed effects γ_t to account for secular trends and seasonal variation in lead exposure, due for example to stagnant water in warmer summer months being associated with higher lead in water and BLL rates (Deshommes et al., 2013; Ngueta et al., 2014). We cluster standard errors at the zip code level to allow for arbitrarily correlated shocks.

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 (that is, half-years). We include lab-by-year fixed effects to account for differences in minimum detectable levels by laboratories over time.

We also report estimates from a more parsimonious specification comparing only tests in homes within 25 meters of a construction project, and therefore likely to be directly connected to the main, to a control group of tests in homes between 100–150 meters of a project. In other words, these regressions omit tests in homes between 25 and 100 meters of a project. Figure 1 illustrates our choice of control distance: in most neighborhoods in Chicago homes 100 meters away from a street will be on the far side of the next street and likely served by the water main under that street. Average lot size in Chicago is 1,369 square meters, which is a square with sides 37 meters long. However, 25 percent of lots in our sample are larger than squares with sides of 47 meters. Because lots in Chicago are often long rectangles, our choice of a 100 meter cutoff for control homes ensures that these homes are served by a different water main. This parsimonious specification is:

$$\begin{aligned} Y_{itg} = & \beta_1 I_{it}^{\text{W/in 25m 0-2 months after start}} + \beta_2 I_{it}^{\text{W/in 25m 3-11 months after start}} \\ & + \beta_3 I_{it}^{\text{100–150m 0-2 months after start}} + \beta_4 I_{it}^{\text{100–150m 3-11 months after start}} \\ & + \beta_5 I_{it}^{\text{Ever exposed w/in 25m}} + \gamma_t + \delta_g + X_{it}\theta + \varepsilon_{itg} \end{aligned} \tag{2}$$

where $I_{it}^{\text{Ever exposed w/in 25m}}$ is an indicator for a test being within 25 meters of a water main in the sample window. This variable identifies homes "treated" by the main construction project, thus partialling out time-invariant differences across homes that are at different distances from the water mains with construction. Thus, the coefficients of interest β_1 and β_2 estimate the effect of ongoing and past construction, respectively, relative to pre-construction outcome levels in "treated" homes. Moreover, β_3 and β_4 tests whether construction increased lead levels in neighboring streets which could indicate spurious results. This is the primary model used in most of the analysis.

Our results will be causal if families do not plan water or blood tests around the start of construction. Construction happened throughout the year, and often started before or very shortly after notification letters were sent. Still, once construction started, families might have been more likely to request a water test or bring their child to the doctor for lead testing. Figure 2 shows no evidence of an uptick in blood lead testing around the start of construction within 25 meters relative to construction 100–150 meters away, assuaging concerns of endogeneity in BLL testing. Moreover, Appendix Table A.3 estimates equation (2) using characteristics of tested children as outcome variables to investigate whether children who are tested for lead poisoning around construction are different than average tested children. We find no evidence of systematic differences in family characteristics on either side of construction start, except for mother's education, which we control for. Section 6.3 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 BLL analysis, but presents a first-stage test. To do so, we estimate Equation 2 without household-level controls. Because we have only 440 observations that contribute to variation, we only present results controlling for month-year of sample and zip code fixed effects.

Table 1 finds limited evidence that main construction might increase lead levels in tap water in Chicago for samples taken without flushing (1 minute) in homes within 25 meters of the construction projects when controlling for zip code fixed effects. The effect appears to vanish 3 and 5 minutes after the start of water flow and three months after construction starts. Appendix Table A.4 conducts the same analysis comparing homes within 100 meters of construction to homes 100–150 meters away and finds similar patterns.

One concern with the water tests sample is that it is quite small, and our estimates are imprecise. 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 BLLs.

6 RESULTS: CHILDREN'S HEALTH

This section presents our findings on the effects of main construction projects on children's BLLs 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 from Equation 2, controlling for different sets of controls and fixed effects in each column. For specifications with neighborhood fixed effects, the table reports the average number of tests per neighborhood.[15] Most specifications estimate a positive, albeit small and statistically insignificant, impact of main construction on BLLs. In our preferred specification, which includes Census block group fixed effects, we can reject an increase in BLLs of $0.09\mu g/dL$, or 5% over the average BLL in our sample ($1.85\mu g/dL$). Our sample includes 35 tests per block group on average. Moreover, Appendix Table A.5 shows no evidence that these small increases in BLLs lead to higher probabilities of BLLs of $5\mu g/dL$ or higher once we control for neighborhood fixed effects. 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 way we bin time relative to constructions start. Figure 3 shows the effects of construction by month relative to construction start for the 0–25 and 100–150m distances. The figure demonstrates that including tests over six months prior and 12 months after construction does not alter our findings for the effect of main replacement on BLLs; instead the effects are consistently null over time.

Figure 4 runs a variety of specification tests. The first model (in red) displays the estimated effect from our preferred specification; here we rule out a 5% effect (indicated by the dotted line). The first set of alternative specifications includes various sample limitations and shows that our findings do not depend on the particular sample we choose. First, our results are robust to limiting the sample to only tests completed by age one or two. These findings assuage concerns that parents might learn about lead hazards when enrolling in schools and preschools and might then seek testing. Furthermore, absence of heterogeneity by age suggests limited scope for different pathways to lead exposure, such as airborne dust from road construction which might affect toddlers more than

[15] We drop singleton cells at the block group level. Because block groups are not necessarily included in a single zip code and water mains can span multiple block groups, regressions with zip code and main fixed effects further drop singleton cells at that level.

infants. Relatedly, Figure 4 finds no evidence that effects of main construction are stronger closer to major roads, where lead residues from leaded gasoline might have accumulated over time, though the standard errors are very large given the small sample size. We also separately estimate effects by summer and non-summer months, in case there is seasonality in lead exposure. We retain our primary analytic sample, but we are encouraged that alternative specifications produce the same conclusion.

There are 81 ZIP codes in our analysis, and we mainly cluster at the ZIP level. The second set of alternative specifications in Figure 4 shows our results are robust to clustering standard errors at the water main construction project level and at the block group levels, which sometimes cross ZIP codes, as well as at the ZIP and yearXlab level to account for the BLL correction.

6.1 Measurement Error

Measurement error might incorrectly lead us to the null results we find here by both increasing our standard errors and biasing our estimates downward. In this section, we discuss four potential areas of measurement error and how we address them.

First, imprecise measurement of the treatment might lead us to understate the true effect of water main construction. Only 75% of pipes in Chicago are known to be made of lead, with 23% of unknown material. If the pipes of unknown origin are largely made of lead, our estimates are approximately close to correct; if they are mainly lead-free we would systematically understate the true effect of main replacement on lead pipes by including some non-lead pipes in our sample. We think of our estimate as an intent to treat effect, where somewhere between 75% and 98% of the pipes are actually treated. At the extreme, if all of the pipes of unknown material are non-lead, we can scale up the estimated effect by the inverse of the probability of a lead pipe (75%) in an approximation of the treatment-on-the-treated effect. Even when we make the unlikely assumption of no lead among the unknown pipes, our preferred specification yields a coefficient of 0.013 μg/dl, which is a 0.7% effect. If we apply the same rescaling to the confidence intervals, we get an upper bound of a 7% effect. This calculation is far from exact, because the uncertainty on which of the pipes have lead might increase the standard error beyond this rescaling factor. Still, these bounds are in line with what we find in all our other robustness checks on measurement error.

An alternative approach to reducing measurement error in our treatment definition is to focus on homes built before 1986. Because the city mandated using LSLs until 1986, these homes should have LSLs unless their owners replaced them. Figure 4 demonstrates that results from the pre-1986 sample almost exactly replicate the primary estimate, with a smaller coefficient, if anything.

We also conducted a supplementary analysis in the City of Evanston, which provided a LSL inventory that allows us to focus on homes with known LSLs. The results of this analysis are in Appendix C. Our estimates on the Evanston sample are very similar to the estimates in the Chicago sample but much noisier given the smaller number of main replacements in Evanston.

A second area of concern is that perhaps some of the homes that are near construction are not actually connected to water main we assign. We test robustness to our assignment choice in several ways. First, we require all homes (from both the treated group 0-25 meters away and the control group 100-150 meters away) to be on the same street. This limits the possibility that construction on some side street is counted as construction for the home. However, this severely restricts the control group, so a second test instead just limits the same-street requirement to the treated homes, but allows the control group to be from a different street. In the former case, the standard errors are quite large, but for both tests the upper bound of the 95% confidence interval still rules out a 10% effect. Results are also null when we limit the sample to pre-1986 houses and, for the treated group, to those on the same street as the construction project. Specifically, this specification can reject effects smaller than 10% of the average BLLs in the population.

We next examine the spatial propagation of the effects of water main construction on BLLs of children living up to 150 meters (about a block away) from construction to assess whether we correctly define which homes are "treated." Figure 5 plots the β_1^d and β_2^d coefficients from Equation 1. By including homes 25–100 meters from construction, this analysis differs from our main estimates, which focus on a parsimonious model comparing 0–25 meters against 100–150 meters from Equation 2. While we do not expect homes 25–100 meters from construction to be treated by the construction, this specification directly tests this hypothesis, with particular interest in the more proximate distances. We interpret the fact that 25–50 and 50–75 meters show no evidence of any effect to suggest that our parsimonious specification does not omit relevant treated households. This finding is in line with lot sizes in Chicago, as discussed above. 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.

As another test of the distance that determines treatment, Appendix Figure A.10 uses different distance cutoffs (e.g., 0–10 meters, 0–20 meters, ..., 0–100 meters) to define treatment in the parsimonious Equation 2. The open red dot shows the point estimate from our preferred specification. The coefficients are larger at very close distances, where we can be more confident that we correctly assign homes to mains, but the standard errors are also larger given that most houses are set back from the street by at least some meters. Again, we take this as evidence that our results are robust across various specification choices, and that we can rule out large effects of water main construction.

A third concern is that we do not know which activities are performed as part of the water main replacement at any given point in time. We examine effects 0–2 months post-construction start because the mean project length is 86 days, we had complete information on projects' start dates, and we think that most replacement activities, including street excavation can shake LSLs causing lead to leach. However, it is possible that the activity that is most likely to cause lead leaching is the cutting of the LSL to connect it to the new main, which happens towards the end of the project. Appendix Figure A.9 displays the month-by-month estimated changes in BLLs relative to construction end, where we impute construction end date when missing based on average construction duration for projects covering similar distances. Here, a coefficient above zero in the months following construction end would indicate a treatment effect at the end of construction. We see no such effect. Relatedly, the third set of alternative specifications in Figure 4 redefines the treatment timing. One alternative definition focuses on 0–2 months following construction end date.[16] Lead in blood has a half-life of 1–2 months, so this time frame still captures exposure by activities up to a month prior to construction end (Centers for Disease Control and Prevention, 2017). Alternatively, we define the treated time frame as the entire construction period, between start and end date. For defining treatment both relative to construction end and during construction, we estimate models where we impute construction end when missing as well as models where we drop water mains with

[16] This model is the same as our Equation 2, except that the time frames (0–2 months and 3–11 months) are relative to construction end. We only display the coefficient for 0–2 months.

missing end date. None of these models find a construction effect. If anything BLLs appear to decrease towards the end of construction. Adding the same-street and pre-1986 restriction to these alternative timing definitions also does not change our conclusions, again rejecting effects smaller than 10% of the average BLLs in the population.

Finally, our results are robust to alternative specifications of our BLL outcome, as shown in the fourth set of alternative specifications in Figure 4. Results do not change when we refrain from adjusting for laboratories' minimum detection limits (MDL). We also show results limited to labs with very sensitive MDL down to 1μg/dl, as well as for venous tests only, which are more accurate. Due to the smaller sample size, results are noisier, but none provide evidence of an effect of water main construction on BLLs.

6.2 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 BLLs on average, holding other factors constant. Moreover, the most common risk factor for lead exposure is the age of housing (Centers for Disease Control and Prevention, 2004). 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). Thus, comparing main replacement effects for children living in older versus newer homes could inform whether lead exposure through drinking water disproportionately affects children at risk of exposure through lead paint.

Table 3 investigates whether children of mothers with low education, Black children, and children residing in low-income neighborhoods or old housing are differentially affected by main construction. To do so, we interact the construction treatment with four separate characteristics by column: an indicator for mother's education below high school, an indicator for Black, an indicator for below-median block group income, and an indicator for homes built prior to 1930. We find no evidence that any of these subpopulations suffer from economically or statistically significant effects from main construction.

Table 3 also provides a useful check on the estimated effect sizes. We know that housing age is strongly related to BLLs, and we would be suspicious if, say, the coefficient on water main construction and the coefficient on housing were of similar magnitude but noisily estimated. Instead, our estimate in the "Trait of interest" row in the last column confirms that children living in pre-1930 housing have BLLs that are 0.27 μg/dl higher than children in post-1930 housing, with small standard errors, holding other factors constant. This estimate is an order of magnitude larger than the estimated impact of water main construction, suggesting that water main construction has a much smaller, if any, effect on lead poisoning than lead paint hazards.

6.3 Avoidance Behavior

Overall, we find no evidence that main construction increases children's BLLs in Chicago. However, parents might 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 notification letters. We noted in Section 2 that recommendations of flushing the water prior to use were included only in the letters starting in 2013, and even then they were not featured prominently.[17] Moreover, we hypothesize that after parents became aware of the water contamination episode in Flint, these construction projects and their potential risk of lead contamination might have become more salient. Thus, Table 4 tests whether construction projects have different effects in different years. We find no evidence that increased avoidance behavior after the modified 2013 letters and after the publicity of the Flint episode in 2015 reduced the effect of exposure to main construction. If anything, effects are smaller in the earlier sample period. Importantly, we cannot rule out systematic avoidance behavior in Chicago pre-dating 2013.

[17] 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.

6.4 Benefits of Lead Mitigation During Water Main Construction

We next calculate whether the implied costs of increased lead exposure from water main replacement means that municipalities should simultaneously replace LSLs or provide water filters to residents when they replace water mains. 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. To be cautious, we err on the side of overestimating the benefit of lead water main replacement. We also acknowledge that low-probability, high-impact events might lead to unexpectedly high costs that cities may want to weigh more heavily than the expected average cost (see, e.g., the discussion of fat tails in Weitzman, 2009).

This exercise does not speak to the general costs of childhood lead exposure from LSLs, and LSL replacement could have benefits in the absence of infrastructure upgrades. The 2021 revision to Lead and Copper Rule will likely increase the rate of LSL replacement in the United States, with the aim of reducing overall lead exposure.[18] Economies of scope imply lower LSL replacement costs when replacements take place concurrently with water main replacement or rehabilitation projects.

For this calculation, we use our estimate of the effect of water main replacement on the probability of having a BLL of $5\mu g/dL$ or above, as the effects of lead poisoning are non-linear in BLLs. In Table A.5 Column 5, we estimate this effect to be -0.5 percentage points, with an upper bound of the 95% confidence interval of 0.4 percentage points. We use $44,803 as a net present value of lost earnings due to IQ losses in children with elevated BLLs.[19] This calculation assumes sustained lead exposure with BLLs elevated for long enough to cause IQ losses. On average, water main construction projects last for less than three months in our sample, so our assumption likely overstates the benefit of the main replacement. Taken together, our results suggest that the expected benefit of preventing lead exposure from main replacement does not exceed $183 per child at the the upper

[18]The 1991 Lead and Copper Rule focused on corrosion control, rather than LSL replacement. However, the 2021 revision to Lead and Copper Rule takes steps to decrease lead exposure by decreasing the threshold at which corrosion control must take place, increasing water testing in schools and daycares, preparing and updating LSL inventories, and minimize loopholes that had allowed municipalities to avoid LSL replacement (Environmental Protection Agency, 2020).

[19]We compute the net present value of lost earnings due to IQ losses in children with BLLs at or above $5\mu g/dL$ using the observed BLLs distribution in our Chicago sample and correlational estimates of the marginal IQ losses due to increased BLLs in Lanphear et al. (2005, 2019) monetized following Schwartz (1994).

bound of the 95% confidence interval.[20]

The cheapest LSL replacement costs \$2,500, and the cheapest water filters cost \$50 for a three-month filter supply. Then, our estimated benefits in terms of preventing a child from having these high BLLs from main construction projects are at most 7% of the costs of LSL replacement but can be as high 367% for water filters.[21] Thus, for cities considering replacing water mains, it might be beneficial to provide water filters, but not necessarily 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. But, our analysis here demonstrates that worries about water main construction alone do not justify the cost.

7 CONCLUSION

We study a large-scale water main replacement program in Chicago, a city with both a high prevalence of LSLs 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 water main maintenance on drinking water quality and children's health. We find no evidence that main maintenance affected lead levels in drinking water or children's BLLs in Chicago. Some of our results imply a possible decrease in BLLs after construction ends. As we do not see a similar change in the water itself, the BLL finding could be due to increased avoidance behavior by parents. We conservatively interpret our findings as main construction having no effect on children's BLLs.

Our findings 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 United States, wasting over two trillion gallons of treated drinking water (ASCE, 2017). Not having to simultaneously incur LSL replacement costs might allow water

[20] Calculated as $0.0041 \times \$44,803$.

[21] As an even more conservative estimate, we could instead use the slightly higher coefficient and standard errors for the estimate of main replacement on BLLs taken at any point during construction in the non-imputed sample (see Table A.6). This is the largest upper bound on the effect on BLLs in Figure 4. We could also assume that every service line of unknown material is not made of lead, and scale up our estimated effect by dividing by 0.75. Then, the upper bound of the benefit is \$1,533 (calculated as $0.0162 \times \$44,803 \div 0.75$.), which is still only 39% of the cost even under these extreme assumptions.

utilities to stretch their budgets further in repairing these mains. This trade-off is especially salient now, as equity considerations are pushing municipalities to fully fund LSL replacements.

Given events in Flint, Michigan, and other cities, in February 2016 the U.S. Environmental Protection Agency put out recommendations on the need to address high lead levels, fully implement and enforce the Lead and Copper Rule, and address aging infrastructure needs at all levels of government (Environmental Protection Agency, 2016). Our results offer a point of comparison with the consequences of the switch in drinking water source in Flint, Michigan. This difference highlights the uniqueness of each water system more generally, and the importance for future research to inform policy decisions around LSL replacement. In a world of limited resources for the mitigation of lead hazards in homes, and toxic hazards more generally, our findings indicate that water main construction might not always require LSL replacement in the presence of robust water management systems.

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 might be larger in the presence of city-wide failure to adopt anti-corrosion treatment, as was the case in Flint.

Our estimates cannot reject that it could be cost-effective to provide affected residents with faucet filters during water main construction, although further research is needed on these programs. Moreover, our findings do not speak to the overall effects of replacing lead service lines which likely include benefits outside water main construction projects.

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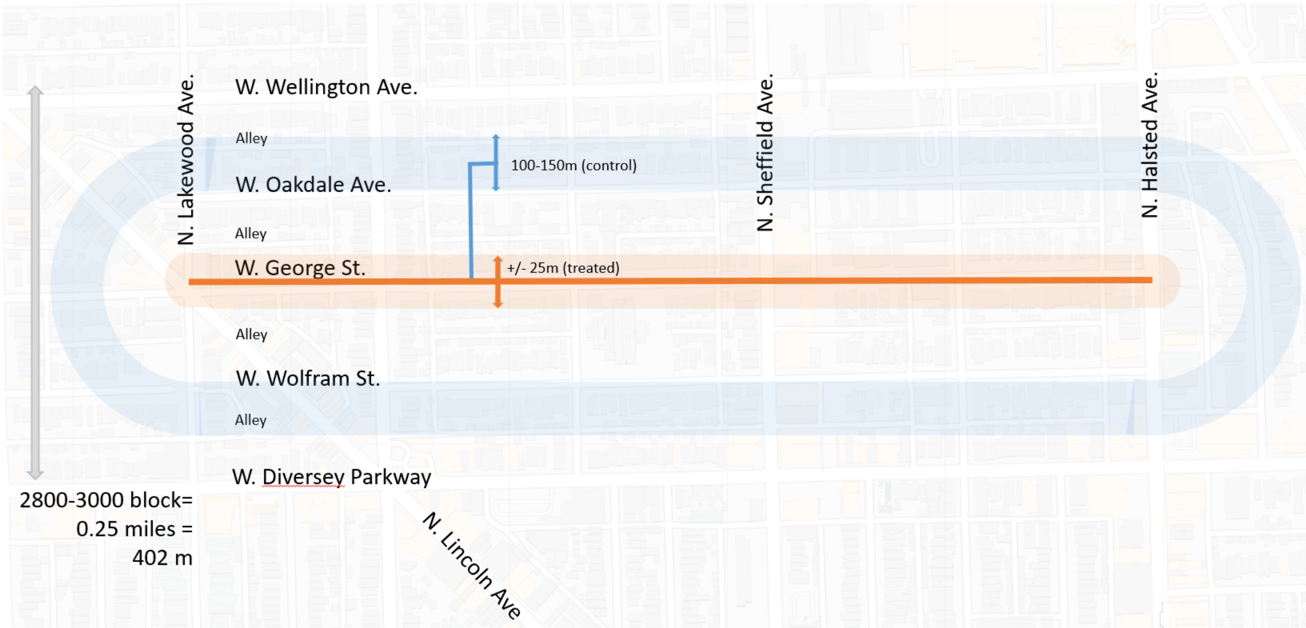
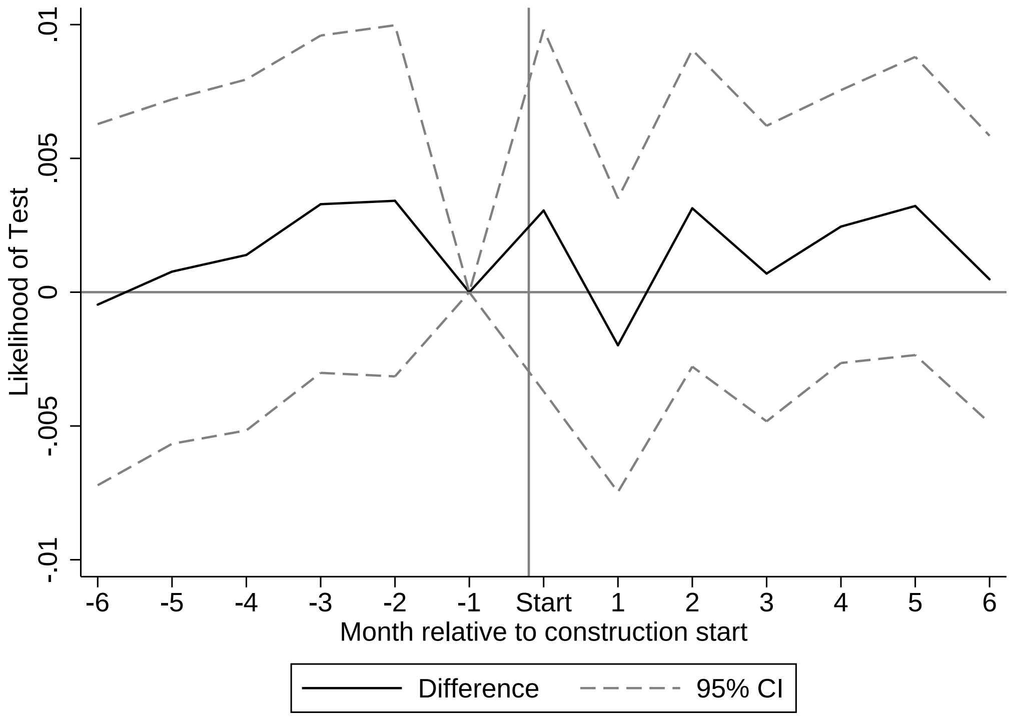
Figure 1: Example Treated and Control Groups



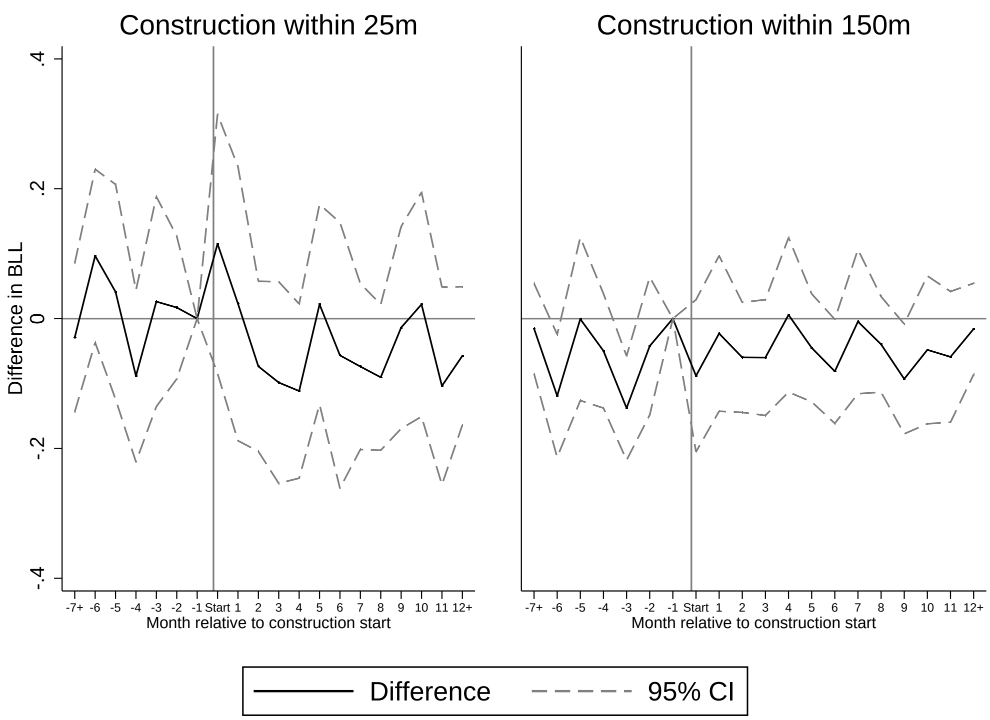
Notes: The figure shows an example water main construction on W. George St. from N. Lakewood Ave. to N. Halsted Ave. Construction began July 3, 2014, and ended September 30, 2014. We define the homes directly on the street (0–25 m from the middle of the street), which are fed by the water main under construction, as "treated." We define the homes on surrounding streets, which are 100–150m away and are served by different mains (e.g., there is a separate water main on W. Wolfram St.), as "controls". *Base map credit: Google Maps.*

Figure 2: Test Timing Relative to Construction



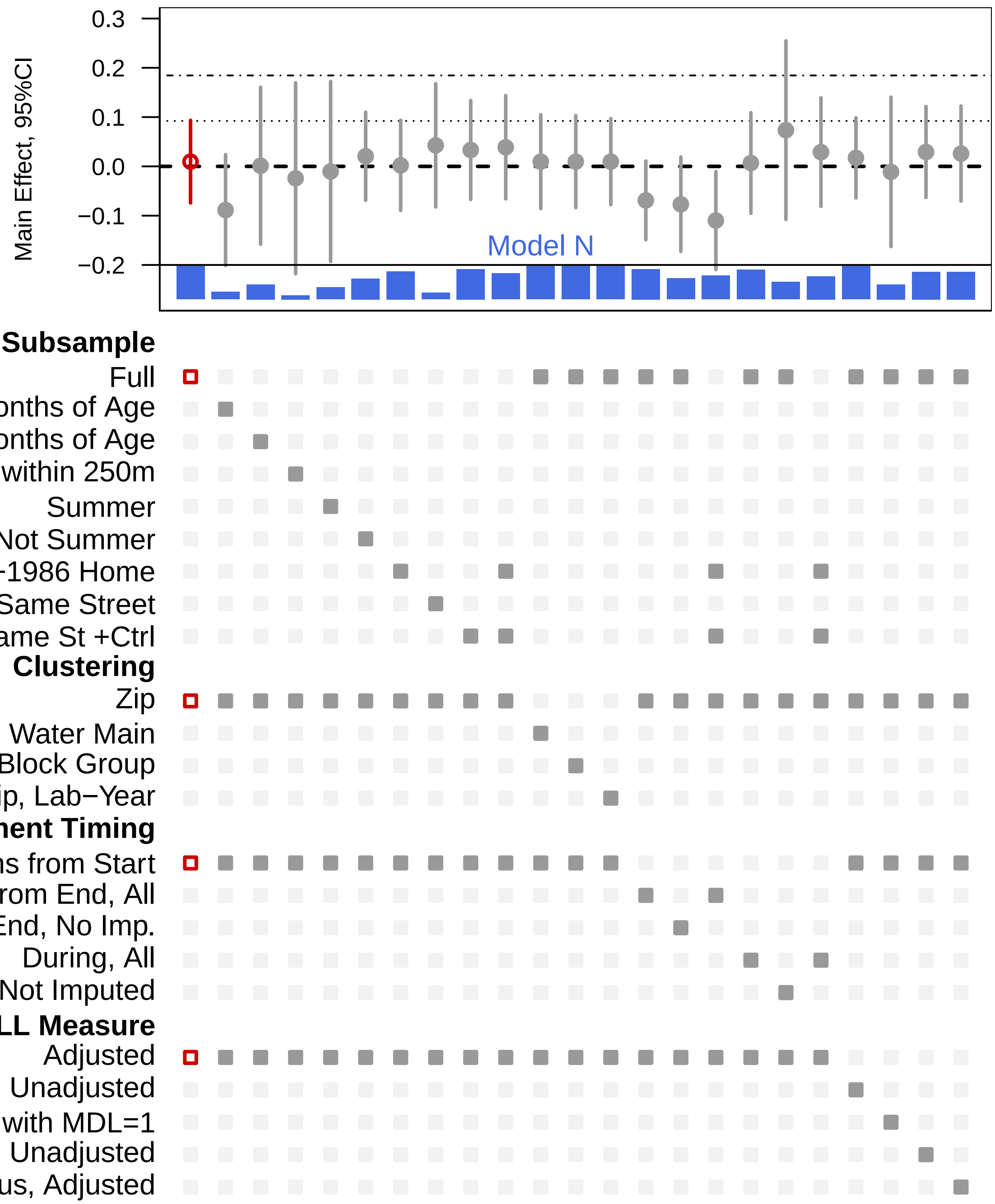
Notes: The figure plots coefficients from a regression of an indicator for a test in our main analysis sample being taken in a given month relative to the start of a construction project within 25 meters, with the month prior to construction start within 25 meters as the reference point and controlling for month relative to construction 100–150 meters. The dashed lines delimit 95% confidence intervals based on standard errors clustered at the zip code level. Additional controls include block group, lab×year, year×month, and semester age FE; indicators for twins, child gender, 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 3: Health Effects of Construction Within 25 and 150 Meters by Test Timing



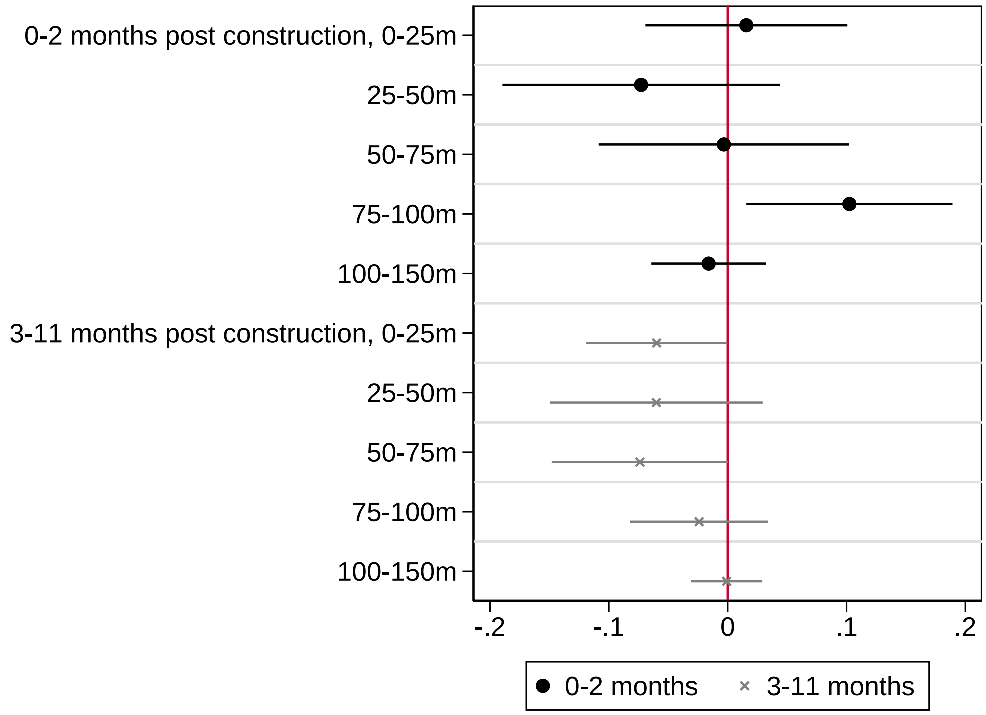
Notes: The figures plot coefficients from a single regression of BLLs on indicators for tests taken in a given month relative to the closest construction project start (within 25 meters or 100–150 meters), with the month prior to construction start as the reference point. The left panel shows effects for tests within 25 meters of a construction project. The right panel shows effects for tests in a 100–150 meter radius from a construction project. The dashed lines delimit 95% confidence intervals based on standard errors clustered at the zip code level. Additional controls include block group, lab×year, year×month, and semester age FE; indicators for twins, child gender, 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 4: Construction Effects on BLLs, Robustness Checks



Notes: Figure plots coefficients from separate estimates of the main effect of service line replacement on BLLs with typical controls (see Figure 5). Horizontal dotted line indicates a 5% effect; dash-dot line indicates a 10% effect. Vertical lines indicate 95% confidence intervals. Blue bars indicate sample size, relative to the preferred model in red. Alternative models limit sample to tests from children <13 or <25 months, tests on streets <250m from major roads, summer/not summer, homes built <1986, tests on same street as main replacement (i.e., not a side street), and treated tests on same street as the main but with the usual control sample. Next set varies clustering. Next set redefines treatment as measured 0-2 months following construction end (with/without imputation if missing end date) and as the entire construction period (with/without imputation). Final set alters BLL measure by not adjusting for minimum detection limits (MDL), limiting to labs with MDL$\geq 1\mu g/dL$, and limiting to venous tests (with/without MDL adjustment).

Figure 5: Health Effects of Construction by Distance



Notes: The figure plots coefficients from a single 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 95% confidence intervals based on standard errors clustered at the zip code level. Controls include block group, lab×year, year×month, and semester age FE, indicators for twins, child gender, mother's marital status/race/ethnicity/education; an indicator for housing built before 1930; and indicators for missing housing age or marital status/race/ethnicity/education.

Table 1: Construction Effects on Lead Levels in Tap Water

Dependent Variable:	Lead at 1 minute (1)	Lead at 1 minute (2)	Lead at 3 minutes (3)	Lead at 5 minutes (4)
0-2 months post construction, 25m	3.9213	4.2304^{+}	1.5361	0.4561
	(2.3944)	(2.4366)	(1.6511)	(0.5972)
3-11 months post construction, 25m	3.5091	2.4079	1.1512	0.6508
	(2.1464)	(2.2104)	(1.1554)	(0.5123)
Ever within 25m	-1.8333	-1.5706	-0.4253	-1.0485
	(2.0693)	(2.2717)	(1.1667)	(0.6520)
0-2 months post construction, 100-150m	-0.0279	1.3341	0.5206	-0.5108
	(1.0944)	(1.4327)	(0.9403)	(0.3804)
3-11 months post construction, 100-150m	5.2747^{+}	5.0316	0.4474	-0.3247
	(2.9074)	(3.8489)	(1.1170)	(0.5612)
Zip Fe		X	X	X
Observations	440	440	440	440
Control mean	6.514	6.514	3.660	2.223
Average cell size		10.476	10.476	10.476

Notes: $+ \, p < 0.10$, $* \, p < 0.05$, $** \, p < 0.01$, $*** \, p < 0.001$. The table shows the effect of tests timing and distance relative to main construction projects on tap water samples. The sample includes tests taken in a window of six months prior to 12 months after construction start within 25 meters and a control group of tests 100–150 meters away from construction in the same time window. The indicator "Ever within 25 meters" controls for differences between homes within 25 and 100–150 meters of construction prior to construction. The omitted category are tests taken up to 6 months prior to construction within 100–150 meters. Additional controls include year×month FE. Standard errors clustered at the zip level are in parentheses.

Table 2: Construction Effects on BLLs

Dependent Variable:	Blood Lead Levels					
Specification:	No FE	Add Controls	Zip FE	Tract FE	Block Group FE	Main FE
	(1)	(2)	(3)	(4)	(5)	(6)
0-2 months post construction, 25m	0.0134	-0.0014	0.0061	0.0039	0.0096	-0.0160
	(0.0525)	(0.0455)	(0.0465)	(0.0445)	(0.0428)	(0.0518)
3-11 months post construction, 25m	-0.0543^{+}	-0.0648*	-0.0645*	-0.0689*	-0.0641*	-0.1015*
	(0.0322)	(0.0287)	(0.0307)	(0.0308)	(0.0301)	(0.0430)
Ever within 25m	0.0603^{+}	0.0552^{+}	0.0685*	0.0689*	0.0601	0.0822*
	(0.0306)	(0.0321)	(0.0338)	(0.0339)	(0.0369)	(0.0363)
0-2 months post construction, 100-150m	0.0047	-0.0148	-0.0141	-0.0173	-0.01911	-0.0217
	(0.0258)	(0.0220)	(0.0214)	(0.0222)	(0.0222)	(0.0258)
3-11 months post construction, 100-150m	0.0130	0.0015	0.0002	-0.0046	-0.0044	-0.0332
	(0.0187)	(0.0146)	(0.0130)	(0.0136)	(0.0146)	(0.0212)
Male		0.0642**	0.0637**	0.0637**	0.0628**	0.0621**
		(0.0191)	(0.0192)	(0.0192)	(0.0195)	(0.0182)
Black		0.2784***	0.1760*	0.1251**	0.1151**	0.1119*
		(0.0497)	(0.0691)	(0.0423)	(0.0408)	(0.0459)
Hispanic		-0.1554***	-0.1669***	-0.1497***	-0.1473***	-0.1324***
		(0.0416)	(0.0408)	(0.0345)	(0.0356)	(0.0338)
Mother has less than high school diploma		0.1347***	0.1298***	0.1214***	0.1140**	0.1079**
		(0.0365)	(0.0357)	(0.0344)	(0.0345)	(0.0356)
Pre-1930 Home		0.3214***	0.3095***	0.2662***	0.2517***	0.2326***
		(0.0291)	(0.0277)	(0.0258)	(0.0256)	(0.0239)
Observations	67,416	67,414	67,416	67,416	67,416	67,236
Control mean	1.845	1.845	1.845	1.845	1.845	1.845
Average cell size			1,142.610	86.100	35.576	29.803

Notes: $+$ $p < 0.10$, $*$ $p < 0.05$, $**$ $p < 0.01$, $***$ $p < 0.001$. The table shows the effect of tests timing and distance relative to main construction projects on BLLs. The sample includes tests in a [-6,+12] months window around construction start within 25 and 100–150 meters. The omitted category are pre-construction tests within 100–150 meters. Columns indicate the fixed effects included in each regression. Controls include lab×year, year×month, semester age FE, indicators for twins and child gender, mother's marital status/race/ethnicity/education, housing built before 1930, and indicators for missing controls. Standard errors clustered at the zip level are in parentheses.

Table 3: Construction Effects on BLLs, Heterogeneity Analysis

Dependent Variable:	Blood Lead Levels			
Trait:	Mother's education (Ref: HS or higher)	Race (Ref: Non-black)	Income (block group) (Ref: Above-median)	Housing vintage (Ref: After 1930)
	(1)	(2)	(3)	(4)
0-2 months post construction, 25m	0.0030	-0.0025	-0.0156	0.0317
	(0.0523)	(0.0361)	(0.0578)	(0.0678)
3-11 months post construction, 25m	-0.0505^{+}	-0.0187	0.0120	-0.0644
	(0.0296)	(0.0379)	(0.0607)	(0.0526)
Ever within 25m	0.0617	0.0498	-0.0209	0.0937
	(0.0370)	(0.0412)	(0.0424)	(0.0607)
Trait of interest	0.1215**	0.1228**	N/A	0.2667***
	(0.0360)	(0.0423)		(0.0299)
Trait X 0-2 months post, 25m	0.0286	0.0305	0.0462	-0.0318
	(0.1037)	(0.0977)	(0.1071)	(0.0756)
Trait X 3-11 months post, 25m	-0.0536	-0.1256^{+}	-0.1397	0.0014
	(0.0565)	(0.0694)	(0.0868)	(0.0776)
Trait X ever within 25m	-0.0064	0.0294	0.1476*	-0.0479
	(0.0602)	(0.0652)	(0.0697)	(0.0819)
0-2 months post construction, 100-150m	-0.0191	-0.0192	-0.0190	-0.0193
	(0.0222)	(0.0222)	(0.0221)	(0.0222)
3-11 months post construction, 100-150m	-0.0044	-0.0044	-0.0047	-0.0045
	(0.0147)	(0.0146)	(0.0146)	(0.0146)
Observations	67,416	67,416	67,416	67,416
Reference mean	1.794	1.715	1.695	1.643
p-value of interaction	0.708	0.767	0.689	0.997

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows heterogeneous effects of tests timing and distance relative to main construction start on BLLs. We include tests in a [-6,+12] months window around construction within 25 ("Ever within 25m") and 100–150 meters. The omitted category are pre-construction tests at 100–150m. Columns interact indicators for tests within 25m and 0–2 or 3+ months of construction with child traits and report the p-value for the test that the effect on children with that trait is 0. We include block group, lab×year, year×month, semester age FE; indicators for twins, child's gender, maternal marital status, race/ethnicity, and education, and indicators for missing controls. Standard errors clustered at the zip level are in parentheses.

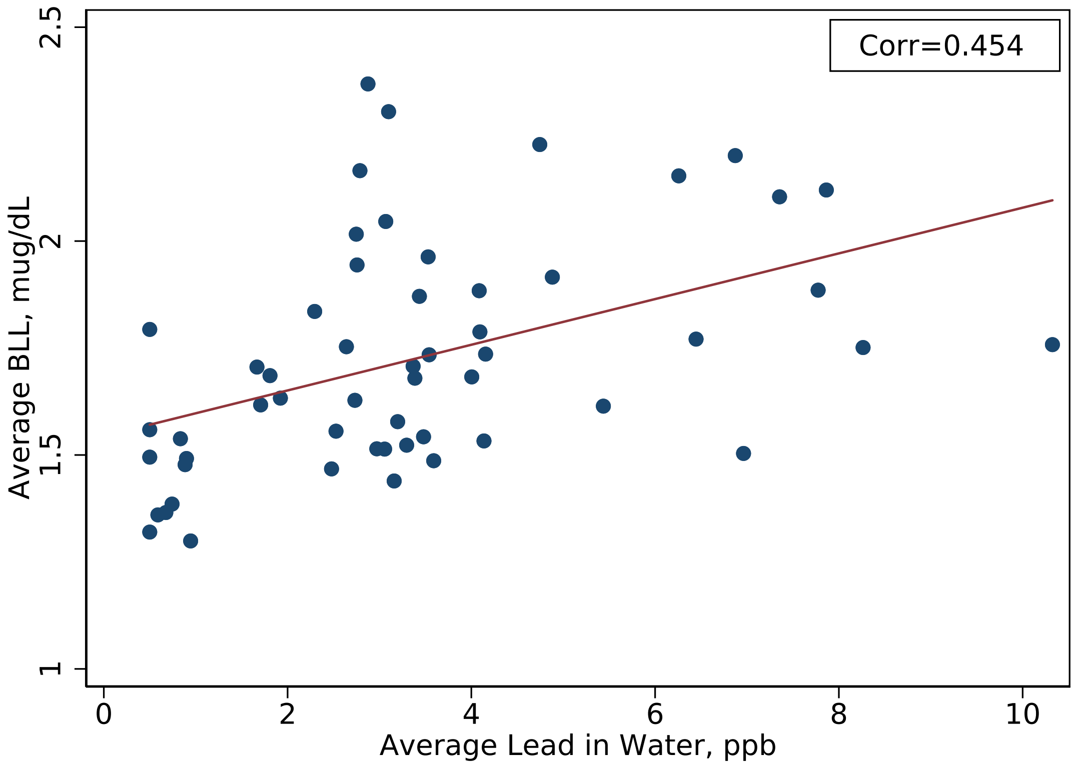
Table 4: Construction Effects on BLLs, By Test Year

Dependent Variable:	Blood Lead Levels		
Sample:	Test in 2011-2012	Test in 2013-2014	Test in 2015-2016
	(1)	(2)	(3)
0-2 months post construction, 25m	-0.1562	0.1030	0.0337
	(0.1062)	(0.0629)	(0.0951)
3-11 months post construction, 25m	-0.0954	-0.1021*	-0.0601
	(0.0929)	(0.0493)	(0.0548)
Ever within 25m	0.1120	0.0544	0.0032
	(0.0692)	(0.0537)	(0.0671)
0-2 months post construction, 100-150m	-0.0057	-0.0619	-0.0365
	(0.0545)	(0.0376)	(0.0476)
3-11 months post construction, 100-150m	-0.0142	-0.0351	-0.0311
	(0.0663)	(0.0300)	(0.0448)
Observations	17,567	28,098	21,222
Control mean	1.938	1.775	1.868

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows heterogeneous effects of tests timing and distance relative to main construction start on BLLs. We include tests in a [-6,+12] months window around construction within 25 ("Ever within 25m") and 100–150 meters. The omitted category are pre-construction tests at 100–150m. Each column is estimated on a different subsample of test years indicated at the top. Controls include block group, lab×year, year×month, semester age FE; indicators for twins, child's gender, mother's marital status, race/ethnicity, education level at birth, housing built before 1930, and indicators for missing controls. Standard errors clustered at the zip level are in parentheses. Observations do not sum to main analytic sample due to singletons in fixed effects in the split samples.

A.1 *Appendix Figures*

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

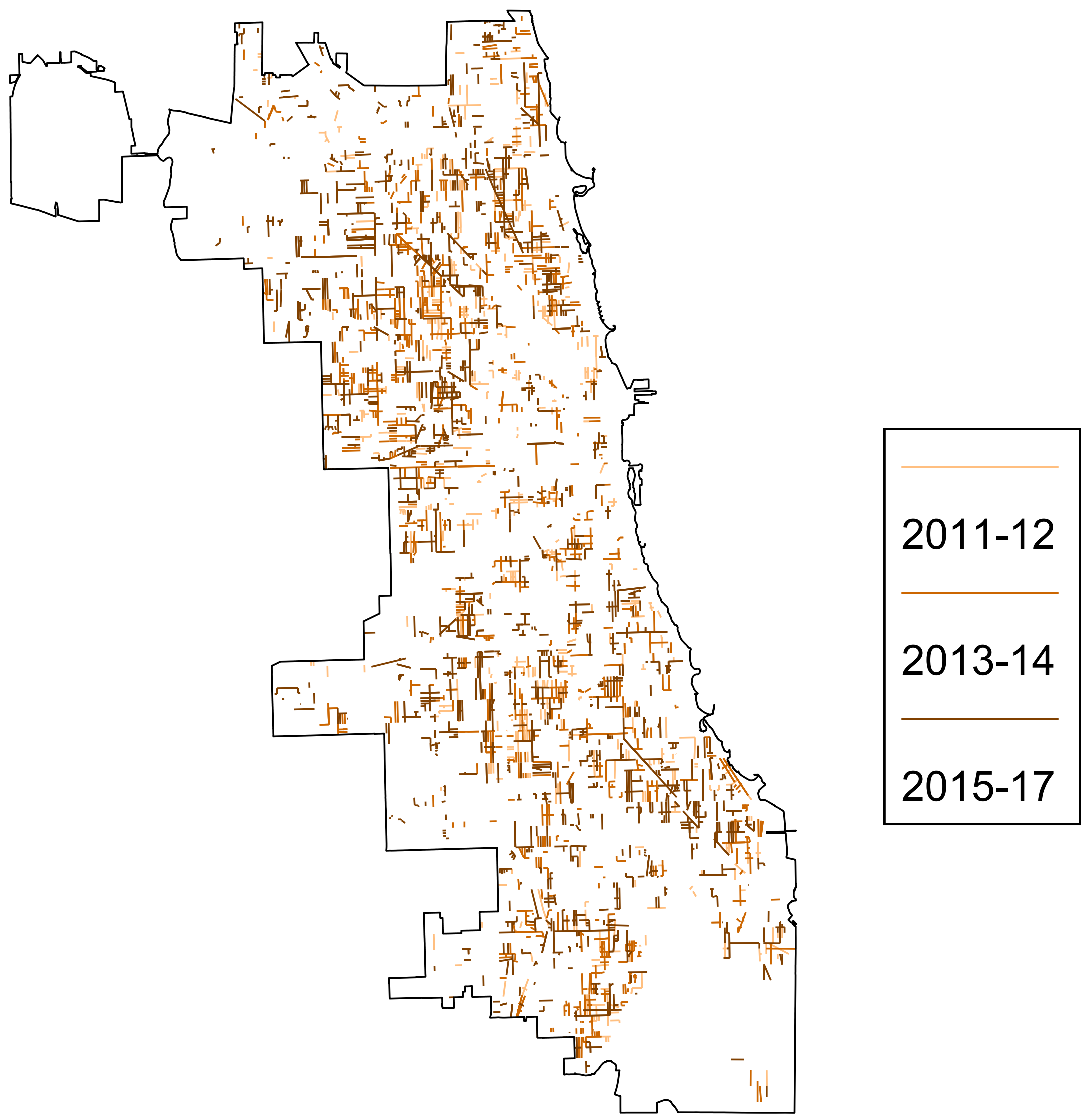


Notes: The figure shows the correlation between average blood lead levels in the 2010–2016 period and average lead in water samples at first draw in the 2016–2018 period in Chicago zip codes.

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's infographic on lead in drinking water, accessed June 15, 2020 at `https://www.epa.gov/sites/production/files/2017-08/documents/epa_lead_in_drinking_water_final_8.21.17.pdf`.

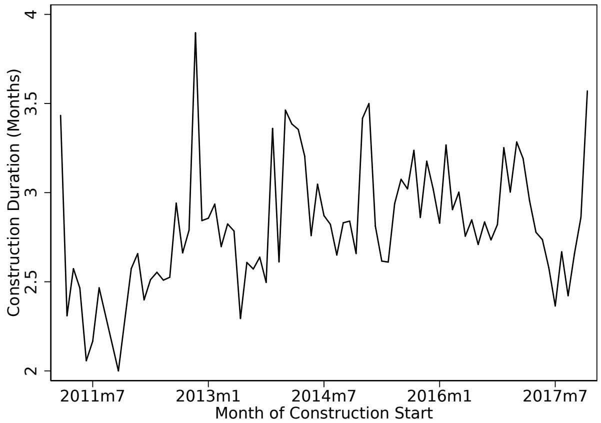
Figure A.3: Water Main Construction Over Time and Space



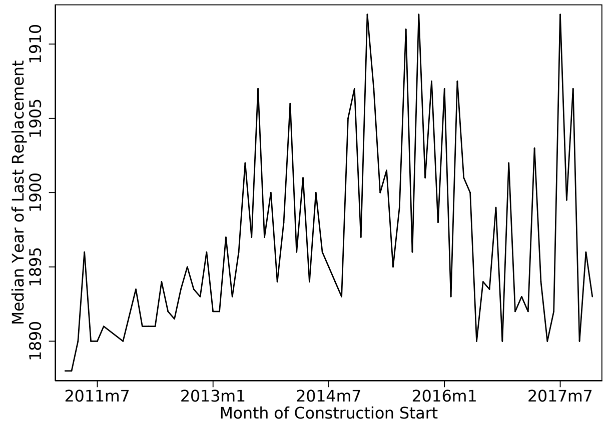
Notes: The figure plots each water main segment affected by a construction project, with different colors indicating different project start years.

Figure A.4: Construction Project Characteristics by Start Month

(a) Construction Duration by Start Month



(b) Average Main Age by Start Month



Notes: The figure displays the average length of main construction projects in months (Panel A) and year of main last replacement (Panel B) by month of construction start for the Chicago main projects.

Figure A.5: 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.

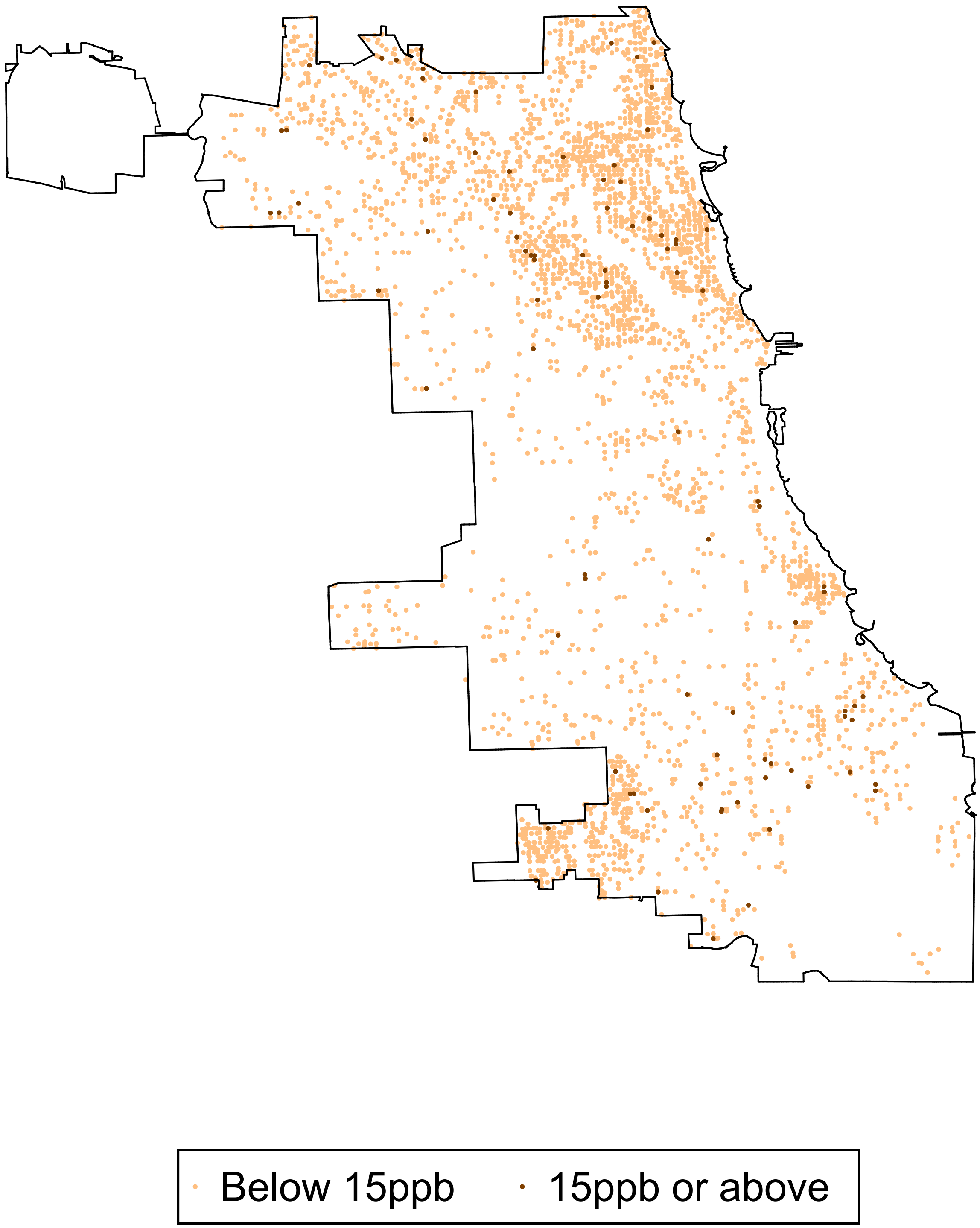
Our crews will soon be installing 1,258 feet of 8-inch water main in W. 68^{th} Street, from S. Morgan Street to S. Halsted Street. The old pipe dates back to 1897, and needs to be replaced.

(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.

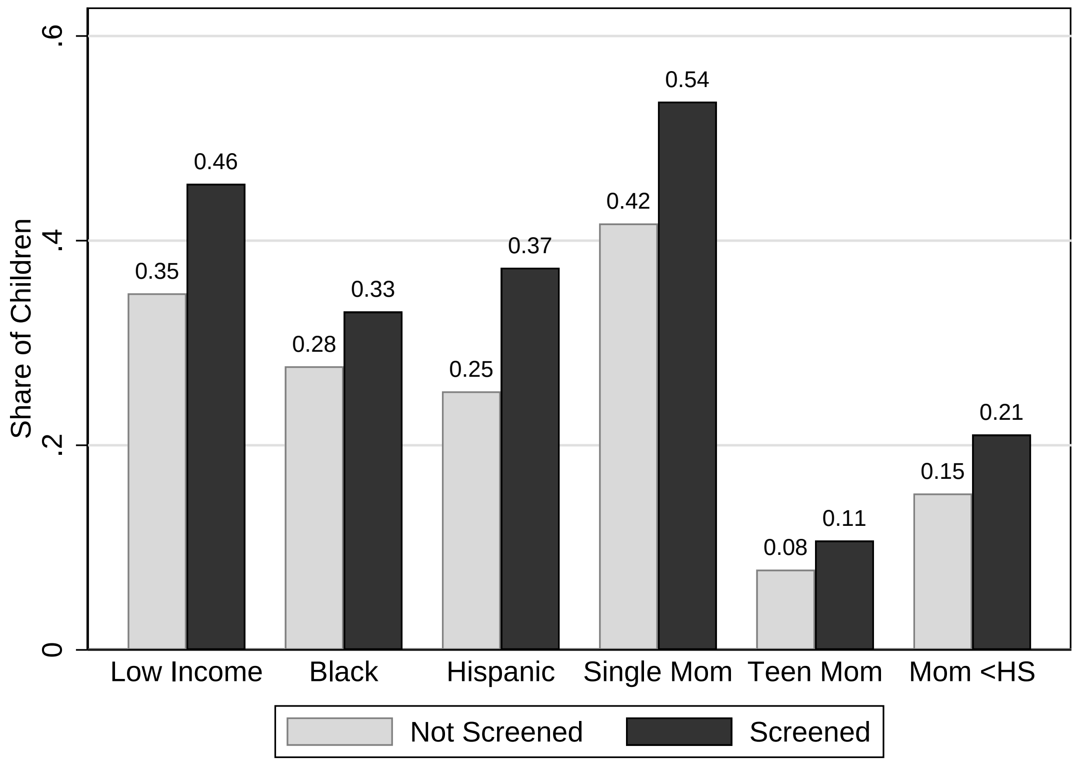
Notes: The figure displays excerpts from a sample letter the City of Chicago sent to announce construction work. The letter was accessed at `https://www.chicago.gov/city/en/depts/water/supp_info/dwm_constructionprojects.html`.

Figure A.6: Water Lead Samples in Chicago



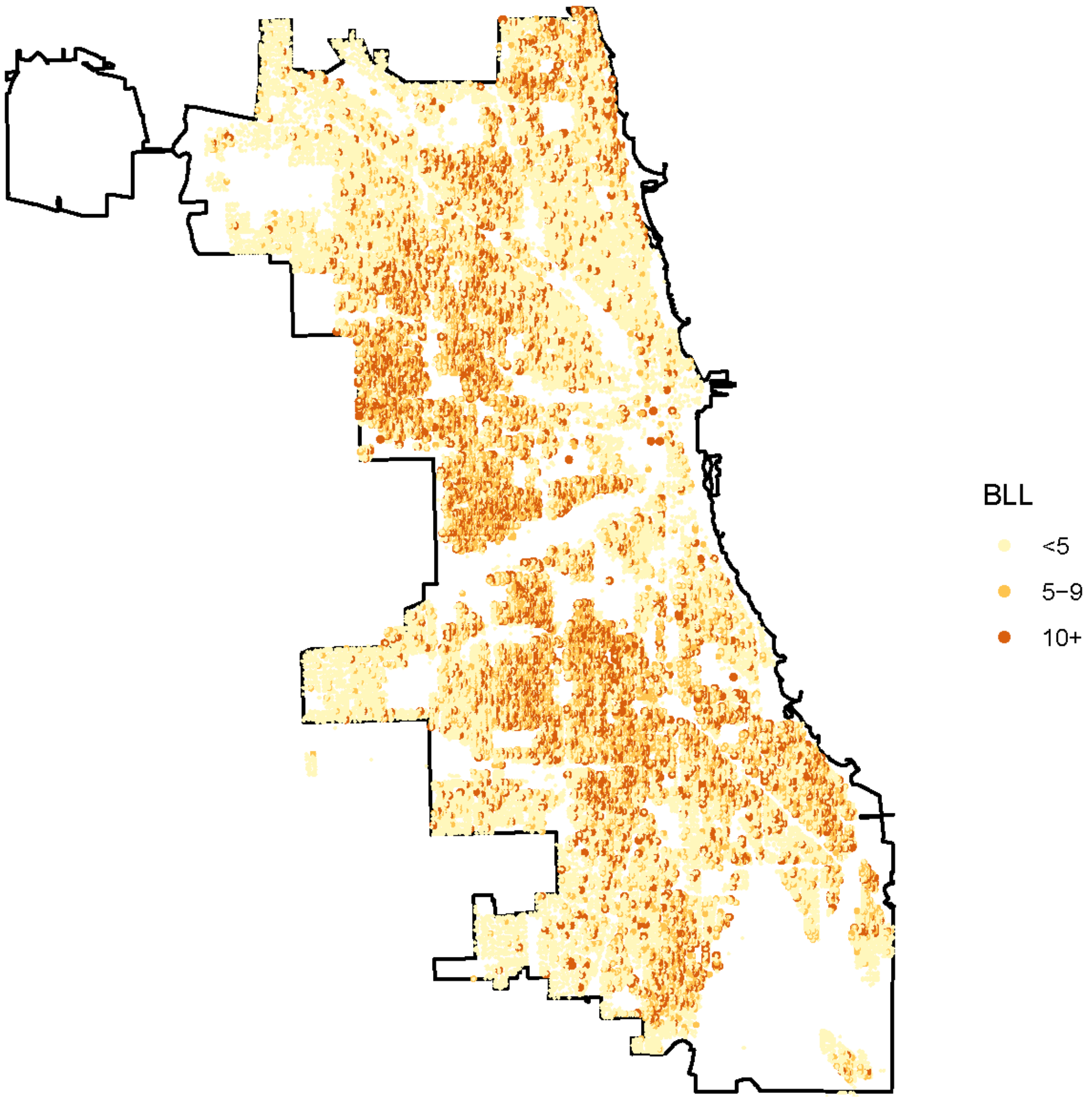
Notes: The figure plots water lead tests in our sample highlighting in darker color blocks with any sample 15ppb or above.

Figure A.7: Children's Demographic Characteristics by Screening Status



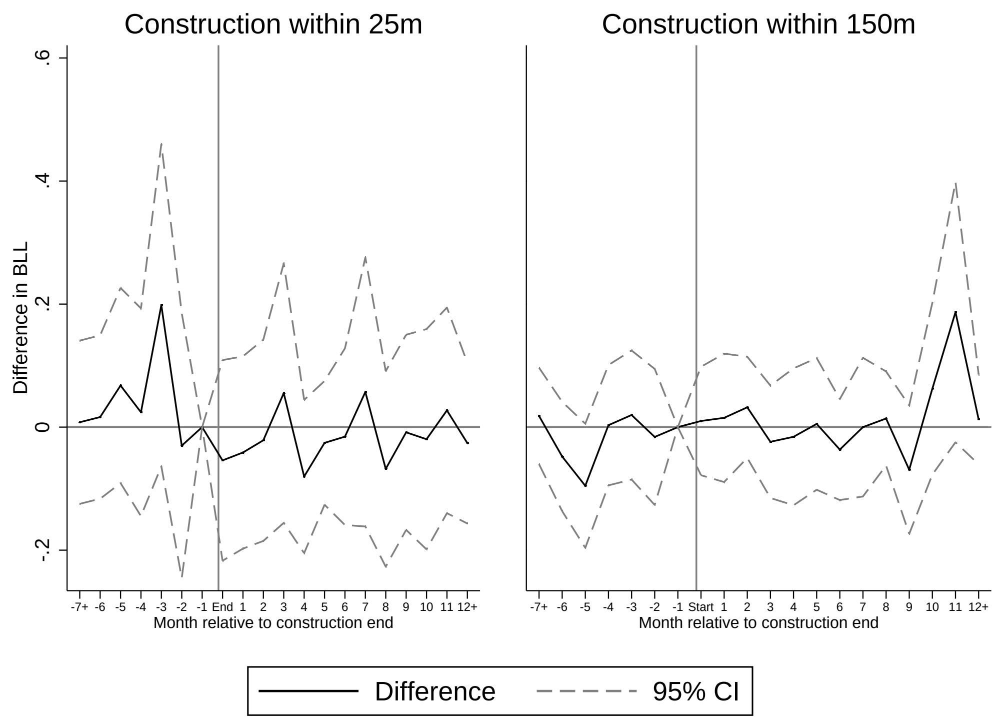
Notes: The figure plots the share of children with each demographic characteristic on the x axis among children born in Chicago between 2009 and 2014 with (black bars) and without (gray bars) a lead test by age 2.

Figure A.8: Blood Lead Levels in Chicago



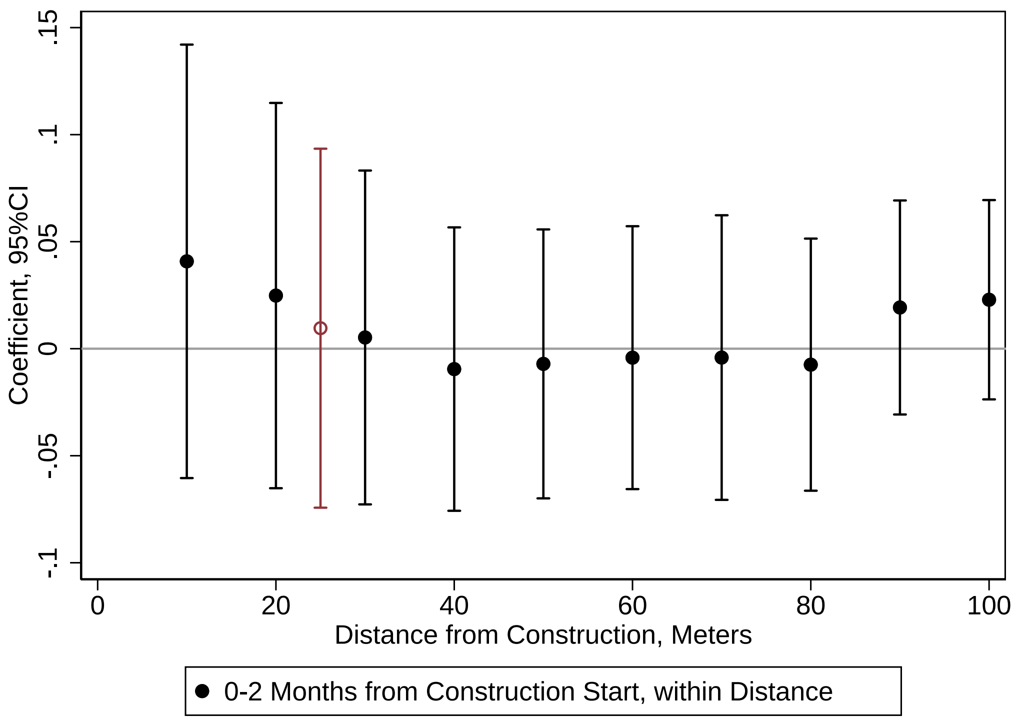
Notes: The figure plots each blood lead test in our sample with different colors indicating different test results.

Figure A.9: Health Effects of Construction Within 25 and 150 Meters by Test Timing Relative to Construction End



Notes: The figures plot coefficients from a single regression of BLLs on indicators for tests taken in a given month relative to the closest construction project end (within 25 meters or 100–150 meters), with the month of construction *end* 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 100–150 meter radius from a construction project. The dashed lines delimit 95% confidence intervals based on standard errors clustered at the zip code level. Additional controls include block group, lab×year, year×month, and semester age FE; indicators for twins, child gender, 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.10: Health Effects of Construction Using Alternative Distance Cutoffs



Notes: The figure plots coefficients from separate regressions of BLLs on indicators for tests taken 0-2 months before construction start of the closest construction project start, using various alternative distances as the cutoff for treatment. The preferred specification (at 25 m) is in red. The lines indicate 95% confidence intervals based on standard errors clustered at the zip code level. Controls include block group, lab×year, year×month, and semester age FE, indicators for twins, child gender, mother's marital status/race/ethnicity/education; an indicator for housing built before 1930; and indicators for missing housing age or marital status/race/ethnicity/education.

A.2 *Appendix Tables*

Table A.1: Summary Statistics: Water Tests

Sample:	Overall (1)	Ever within 25m or 100-150m (2)	Ever within 25m (3)	Pre-construction (0-25 or 100-150m) (4)	Post-construction (0-25 or 100-150m) (5)
Lead at 1 minute	3.81	5.07	3.95	3.47	5.48
	(16.92)	(25.13)	(8.19)	(3.70)	(28.08)
Lead at 3 minutes	3.19	3.39	3.69	3.45	3.37
	(4.56)	(4.59)	(4.65)	(3.96)	(4.73)
Lead at 5 minutes	2.01	2.20	2.27	2.36	2.16
	(2.91)	(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	3,268	968	290	196	786

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, Chicago

Sample:	Overall (1)	Ever within 150m (2)	Ever within 25m (3)	Pre-construction (150m) (4)	Post-construction (150m) (5)
Black	0.33	0.35	0.37	0.34	0.35
	(0.47)	(0.48)	(0.48)	(8.47)	(0.48)
Hispanic	0.43	0.45	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)	37.99	38.20	37.58	38.10	38.38
	(26.85)	(26.83)	(26.30)	(26.92)	(26.66)
BGroup Median Income	43,284	40,891	40,467	41,005	40,665
	(22,783)	(20,986)	(20,460)	(20,291)	(22,296)
Pre1930 Home	0.60	0.68	0.65	0.67	0.71
	(0.49)	(0.47)	(0.48)	(0.47)	(0.45)
Pre1986 Home	0.93	0.95	0.94	0.95	0.94
	(0.25)	(0.23)	(0.23)	(0.22)	(0.24)
Mother has HS Diploma	0.48	0.50	0.51	0.48	0.53
	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)
Mother age at birth	26.81	26.48	26.31	26.35	26.72
	(6.46)	(6.44)	(6.41)	(6.41)	(6.48)
Single mother	0.57	0.60	0.62	0.59	0.61
	(0.50)	(0.49)	(0.49)	(0.49)	(0.49)
BLL	1.84	1.90	1.88	1.91	1.88
	(1.96)	(2.05)	(2.03)	(2.12)	(1.91)
BLL 10+	0.01	0.01	0.01	0.01	0.01
	(0.10)	(0.10)	(0.10)	(0.10)	(0.10)
BLL 5+	0.05	0.06	0.06	0.06	0.05
	(0.22)	(0.23)	(0.23)	(0.23)	(0.22)
Tests per child	2.64	2.68	2.79	2.70	2.64
	(1.56)	(1.56)	(1.58)	(1.57)	(1.54)
Unique children	318,759	157,104	47,641	115,694	63,005

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: Effect of Construction on Selection into Testing

Dependent Variable:	Mother less than HS	Black	Pre1930 Home
	(1)	(2)	(3)
0-2 months post construction, 25m	-0.0175^{+}	0.0050	0.0119
	(0.0096)	(0.0043)	(0.0085)
3-11 months post construction, 25m	-0.0027	-0.0026	0.0088
	(0.0088)	(0.0036)	(0.0079)
Ever within 25m	0.0102	0.0035	-0.0160*
	(0.0088)	(0.0035)	(0.0079)
0-2 months post construction, 100-150m	0.0052	-0.0001	0.0006
	(0.0053)	(0.0025)	(0.0046)
3-11 months post construction, 100-150m	0.0078	-0.0007	0.0052
	(0.0050)	(0.0018)	(0.0053)
Observations	67,420	67,420	67,420
Control mean	0.248	0.349	0.544

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table tests how selection into testing changes with timing and distance relative to main construction start on BLLs by using characteristics of children tested as outcome variables. We include tests in a [-6,+12] months window around construction within 25 ("Ever within 25m") and 100–150 meters. The omitted category are pre-construction tests at 100–150m. Controls include block group, lab×year, year×month, semester age FE, indicators for twins, child's gender, mother's marital status, race/ethnicity, and education level at birth, housing built before 1930 (in columns when these are not the outcome variable), and indicators for missing controls. 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

Dependent Variable:	Lead at 1 minute (1)	Lead at 1 minute (2)	Lead at 3 minutes (3)	Lead at 5 minutes (4)
0-2 months post construction, 25m	5.3547^{+}	6.4240^{+}	0.6263	0.6005
	(3.1552)	(3.3619)	(1.1871)	(0.9133)
3-11 months post construction, 25m	1.0210	1.4300	-0.7559	-0.4004
	(1.2003)	(1.6476)	(0.7378)	(0.4976)
Ever within 25m	-1.1908	-1.2898	0.9657	0.2305
	(1.1431)	(1.4830)	(1.0120)	(0.8022)
0-2 months post construction, 100-150m	-0.0327	1.3742	0.5740	-0.5179
	(0.8375)	(1.1041)	(0.8564)	(0.4343)
3-11 months post construction, 100-150m	5.3525^{+}	5.6468^{+}	0.3501	-0.3396
	(2.8169)	(3.2995)	(1.0468)	(0.5286)
Zip Fe		X	X	X
Observations	756	756	756	756
Control mean	6.473	6.473	3.669	2.212
Average cell size		16.085	16.085	16.085

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows the effect of tests timing and distance relative to main construction projects on tap water samples. The sample includes tests taken in a window of six months prior to 12 months after construction start within 100 meters and a control group of tests 100–150 meters away from construction in the same time window. The indicator "Ever within 100 meters" controls for differences between homes within 100 and 100–150 meters of construction prior to construction. The omitted category are tests taken up to 6 months prior to construction within 100–150 meters. Additional controls include year×month FE. Standard errors clustered at the zip level are in parentheses.

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

Dependent Variable:	Blood Lead Level 5 or higher					
Specification:	No FE	Add Controls	Zip FE	Tract FE	Block Group FE	Main FE
	(1)	(2)	(3)	(4)	(5)	(6)
0-2 months post construction, 25m	-0.0081^{+}	-0.0078^{+}	-0.0073	-0.0063	-0.0047	-0.0082
	(0.0044)	(0.0045)	(0.0045)	(0.0046)	(0.0045)	(0.0054)
3-11 months post construction, 25m	-0.0097**	-0.0108**	-0.0109**	-0.0096*	-0.0078*	-0.0125*
	(0.0036)	(0.0034)	(0.0035)	(0.0036)	(0.0037)	(0.0051)
Ever within 25m	0.0107**	0.0099**	0.0109**	0.0100**	0.0082^{+}	0.0118**
	(0.0034)	(0.0034)	(0.0034)	(0.0036)	(0.0042)	(0.0037)
0-2 months post construction, 100-150m	0.0015	0.0006	0.0007	0.0008	0.0006	0.0003
	(0.0030)	(0.0027)	(0.0026)	(0.0025)	(0.0027)	(0.0027)
3-11 months post construction, 100-150m	0.0029	0.0016	0.0014	0.0015	0.0018	-0.0004
	(0.0026)	(0.0023)	(0.0021)	(0.0022)	(0.0024)	(0.0035)
Male		0.0063**	0.0063**	0.0064**	0.0065**	0.0070**
		(0.0019)	(0.0019)	(0.0020)	(0.0020)	(0.0018)
Black		0.0248***	0.0155*	0.0121*	0.0111*	0.0097^{+}
		(0.0056)	(0.0075)	(0.0052)	(0.0052)	(0.0057)
Hispanic		-0.0153***	-0.0150***	-0.0128***	-0.0120**	-0.0120***
		(0.0037)	(0.0038)	(0.0034)	(0.0036)	(0.0033)
Mother has less than high school diploma		0.0153***	0.0148***	0.0134**	0.0128**	0.0121**
		(0.0042)	(0.0041)	(0.0040)	(0.0039)	(0.0041)
Pre-1930 Home		0.0307***	0.0302***	0.0269***	0.0259***	0.0234***
		(0.0035)	(0.0033)	(0.0030)	(0.0030)	(0.0030)
Observations	67,416	67,416	67,414	67,416	67,416	67,236
Control mean	0.052	0.052	0.052	0.052	0.052	0.052
Average cell size			1,142.610	86.100	35.576	29.803

Notes: $+\ p < 0.10$, $*\ p < 0.05$, $**\ p < 0.01$, $***\ p < 0.001$. The table shows the effect of tests timing and distance relative to main construction projects on the likelihood of BLLs 5+. The sample includes tests in a [-6,+12] months window around construction start within 25 and 100–150 meters. The omitted category are pre-construction tests within 100–150 meters. Columns indicate the fixed effects included in each regression. Controls include lab×year, year×month, semester age FE, indicators for twins and child gender, mother's marital status/race/ethnicity/education, housing built before 1930, and indicators for missing controls. Standard errors clustered at the zip level are in parentheses.

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

Dependent Variable:	Blood Lead Level 5 or higher					
Specification:	No FE	Add Controls	Zip FE	Tract FE	Block Group FE	Main FE
	(1)	(2)	(3)	(4)	(5)	(6)
During construction, 25m	0.0008	0.0045	0.0047	0.0024	0.0031	-0.0019
	(0.0070)	(0.0070)	(0.0071)	(0.0067)	(0.0067)	(0.0077)
After construction, 25m	-0.0081^{+}	-0.0068	-0.0063	-0.0087^{+}	-0.0064	-0.0107^{+}
	(0.0048)	(0.0046)	(0.0045)	(0.0044)	(0.0046)	(0.0054)
Ever within 25m	0.0067	0.0068^{+}	0.0083*	0.0086*	0.0047	0.0111*
	(0.0043)	(0.0040)	(0.0040)	(0.0040)	(0.0042)	(0.0042)
During construction, 100-150m	-0.0071	-0.0052	-0.0050	-0.0067	-0.0066	-0.0064
	(0.0049)	(0.0051)	(0.0051)	(0.0053)	(0.0054)	(0.0054)
After construction, 100-150m	0.0008	0.0005	0.0005	-0.0014	-0.0016	-0.0016
	(0.0028)	(0.0027)	(0.0025)	(0.0028)	(0.0030)	(0.0033)
Male		0.0082**	0.0081**	0.0085**	0.0083**	0.0087**
		(0.0026)	(0.0027)	(0.0027)	(0.0028)	(0.0028)
Black		0.0293***	0.0153*	0.0120*	0.0119*	0.0117*
		(0.0061)	(0.0066)	(0.0053)	(0.0057)	(0.0058)
Hispanic		-0.0098*	-0.0116**	-0.0104**	-0.0092*	-0.0084*
		(0.0045)	(0.0041)	(0.0034)	(0.0037)	(0.0036)
Mother has less than high school diploma		0.0142**	0.0136**	0.0124**	0.0118**	0.0119**
		(0.0044)	(0.0042)	(0.0034)	(0.0037)	(0.0036)
Pre-1930 Home		0.0245***	0.0249***	0.0232***	0.0225***	0.0195***
		(0.0040)	(0.0037)	(0.0041)	(0.0044)	(0.0043)
Observations	35,696	35,696	35,695	35,696	35,696	35,401
Control mean	0.050	0.050	0.050	0.050	0.050	0.050
Average cell size			637.411	47.978	20.753	19.198

Notes: $+ \ p < 0.10$, $* \ p < 0.05$, $** \ p < 0.01$, $*** \ p < 0.001$. The table shows the effect of tests timing and distance relative to main construction projects on the likelihood of BLLs 5+. Indicators for tests taken during and after construction are based on complete start and end dates in the letters. The sample includes tests in a [-6,+12] months window around construction start within 25 and 100–150 meters. Columns indicate the fixed effects included. Controls include lab×year, year×month, semester age FE, indicators for twins and child gender, mother's marital status/race/ethnicity/education, housing built before 1930, and indicators for missing controls. Standard errors clustered at the zip level are in parentheses.

B *Appendix: 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)
   - If a test is within the same distance and within a window of six months prior to 12 months after construction start of multiple construction projects keep the earliest. In this case, the later exposure would bias our analysis towards finding persistent effects of main replacements

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

C *Appendix: Supplementary Evanston Analysis*

Because the City of Chicago could not provide us with an LSL inventory, we collected water main replacement and LSL inventory data from the neighboring City of Evanston, which operates its own water treatment plant. Seventy-nine percent of Evanston service lines are made of lead.[22] Appendix Figure C.1 shows the spatial distribution of water main construction projects, overlaid with the distribution of city-side LSLs in Evanston. Appendix Figure C.2 shows that during the period 2001–2016 the City of Evanston performed 50–100 water main construction projects per year, a much slower pace than in Chicago, limiting the variation we can exploit in our analysis. IDPH provided BLL and vital records data for children born in Evanston.[23]

Figure C.3 reports coefficients from estimating different versions of Equation 2. Because of the limited number of construction projects we have very few children tested while living within 25 meters of construction projects. Therefore we report coefficients for three different regressions for tests within 50, 75 and 100 meters of construction, controlling for block group fixed effects. The Evanston data reports both the city-side service connection (where the water main connects to service line) and the private-side service connection (which the homeowner controls and is closer to the house). We run the model using our typical 0-2 months and 3-11 month indicators, and we interact these with indicators for having a confirmed lead pipe on the city side of the connection (where we know the water main connects to a lead pipe). We report four effect estimates from each of the three distance models. Open circle denote coefficients for any construction within 0-2 months (top panel) or 3-11 months (bottom panel). Closed circle represent the sum of this general effect plus the specific effect on tests at addresses with known LSLs on the city side. If there was an effect of main construction on BLLs through lead pipes leaching, these solid circles should be above zero. Our estimates are instead very close to zero.

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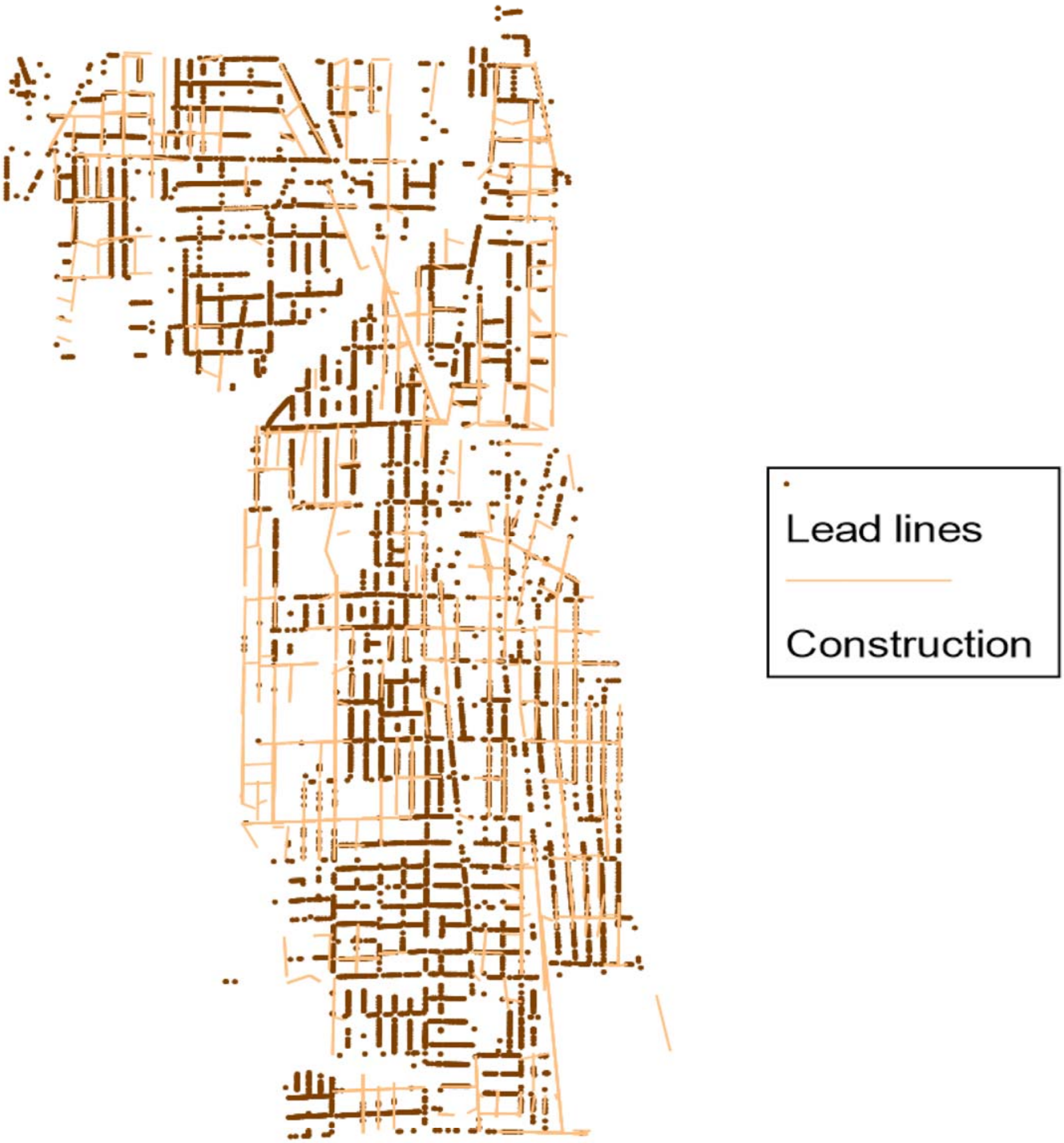
[22]Source: Illinois Environmental Protection Agency Service Line Material Inventory Reports. Accessed January 28, 2021, at `https://www2.illinois.gov/epa/topics/drinking-water/public-water-users/Pages/lead-service-line-information.aspx`

[23]Appendix Table C.1 report summary statistics for this sample.

Our estimates on this Evanston sample are not statistically different from the Chicago sample. However, the Evanston estimates are very noisy relative to Chicago given the much smaller sample size.

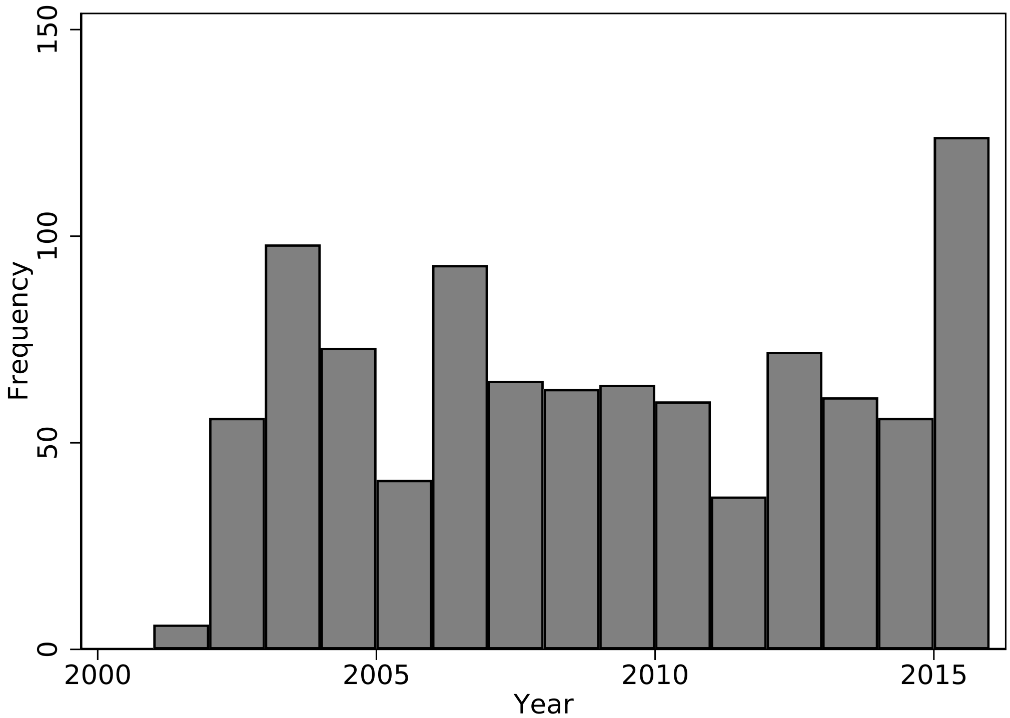
C.1 EVANSTON FIGURES & TABLES

Figure C.1: Water Main Construction and Lead Service Lines over Space, Evanston Sample



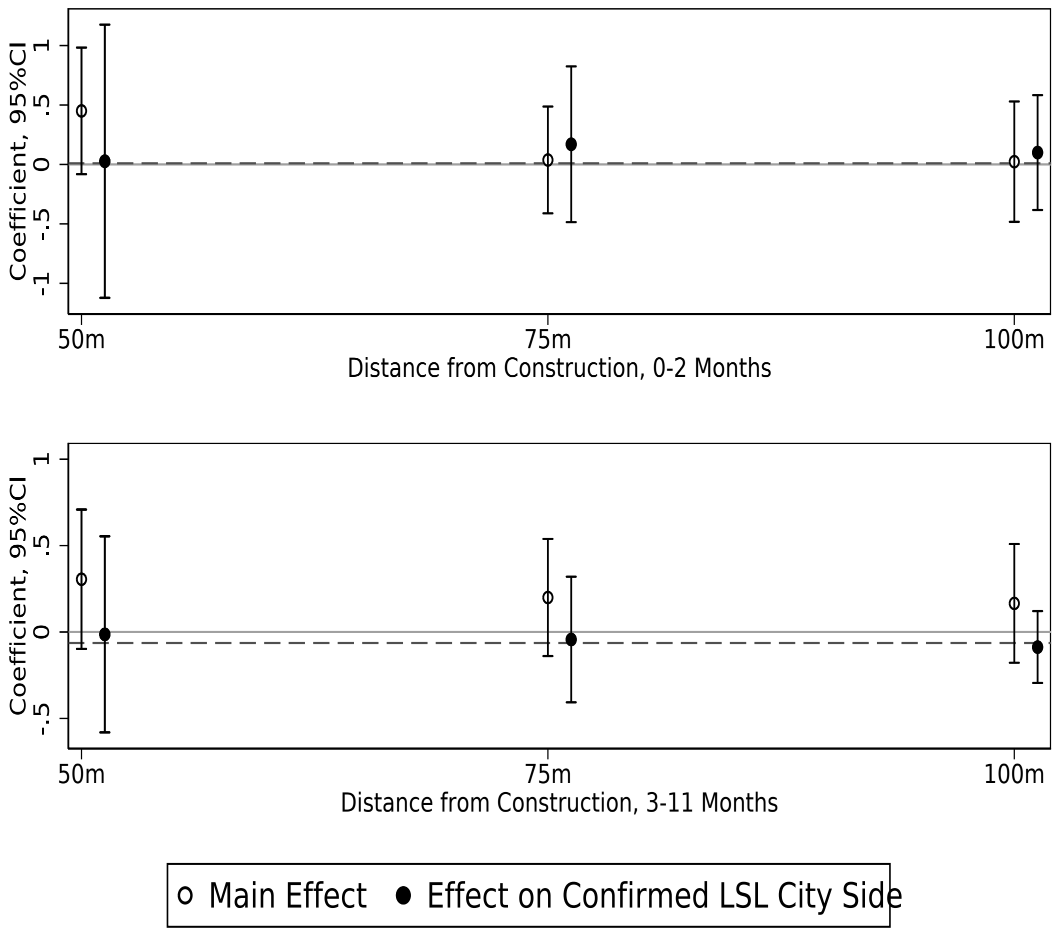
Notes: The figure plots each water main segment affected by a construction project as well as homes with lead service lines

Figure C.2: Water Main Construction over Space Time, Evanston Sample



Notes: The figure plots the number of water main construction projects performed by the City of Evanston each year 2001–2016.

Figure C.3: Health Effects of Construction by Distance and Service Line, Evanston Sample



Notes: The figure plots coefficients from regressions of BLLs on indicators for tests taken within 0–2 (top) and 3–11 (bottom) months from the closest construction project start. Each regression differs for the definition of treated tests: within 50, 75, 100 meters from the construction site. Each regression includes tests taken in a window of six months prior to 12 months after construction start within the given distance and a control group of tests 100–150 meters away. Each regression controls for indicators for tests within the given distance and for tests taken within 0–2 and 3–11 months from construction start 100–150 meters away. Coefficients for a given distance are estimated on a single regression. We plot the effect on all tests and the effect on tests at an address with a LSL on the city side. The vertical lines indicate confidence intervals at the 95% level based on standard errors clustered at the zip code level. Controls include lab×year, year×month, semester age and block group FE, indicators for child gender, twins, mother's marital status/race/ethnicity/education; an indicator for housing built before 1930; and indicators for missing controls. The solid horizontal line marks 0, while the dashed horizontal line is our preferred estimate of the BLL effects in the Chicago sample (Table 2: Column 5).

Table C.1: Summary Statistics: Evanston Sample

Sample:	Overall (1)	Ever within 150m (2)	Ever within 50m (3)	Pre-construction (150m) (4)	Post-construction (150m) (5)
Black	0.23	0.24	0.23	0.28	0.21
	(0.42)	(0.43)	(0.42)	(0.45)	(0.41)
Hispanic	0.15	0.15	0.14	0.16	0.15
	(0.35)	(0.36)	(0.35)	(0.36)	(0.36)
Male	0.52	0.51	0.52	0.51	0.51
	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)
Age at test (months)	31.06	31.12	30.97	30.75	31.39
	(25.08)	(24.86)	(24.42)	(22.97)	(26.15)
Block Group Income	77,028	75,304	76,789	76,342	74,551
	(35,087)	(34,174)	(33,144)	(36,479)	(32,381)
Pre1930 Home	0.44	0.42	0.39	0.44	0.40
	(0.50)	(0.49)	(0.49)	(0.50)	(0.49)
Pre1986 Home	0.94	0.93	0.94	0.95	0.90
	(0.24)	(0.26)	(0.24)	(0.19)	(0.29)
Mother has HS Diploma	0.19	0.19	0.20	0.21	0.18
	(0.39)	(0.40)	(0.40)	(0.41)	(0.38)
Mother age at birth	30.10	29.99	29.71	29.43	30.40
	(6.50)	(6.55)	(6.54)	(6.56)	(6.51)
Single mother	0.26	0.27	0.27	0.29	0.26
	(0.44)	(0.44)	(0.45)	(0.45)	(0.44)
BLL	1.99	2.01	2.03	2.38	1.75
	(2.13)	(2.19)	(2.15)	(2.81)	(1.55)
BLL 10+	0.01	0.01	0.01	0.02	0.01
	(0.11)	(0.11)	(0.12)	(0.13)	(0.09)
BLL 5+	0.06	0.06	0.07	0.09	0.04
	(0.23)	(0.24)	(0.25)	(0.28)	(0.20)
Tests per child	1.81	1.80	1.83	1.78	1.81
	(1.08)	(1.06)	(1.09)	(1.04)	(1.07)
N children	14,177	8,675	2,911	3,894	5,262
N children, any LSL	8,232	4,936	1,582	2,467	2,739
N children, city LSL	6,004	3,430	932	1,745	1,859
N children, both LSL	5,133	2,950	815	1,492	1,602

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