NBER WORKING PAPER SERIES

LEAD IN DRINKING WATER AND BIRTH OUTCOMES: A TALE OF TWO WATER TREATMENT PLANTS

Dhaval M. Dave
Muzhe Yang

Working Paper 27996
http://www.nber.org/papers/w27996

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
October 2020

We thank Shooshan Danagoulian, Shawn McElmurry, Viviane Sanfelice, seminar participants at Wayne State University, and participants at the 2020 Annual Conference of the Eastern Economic Association for their helpful comments and suggestions. All errors are our own. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

Lead in Drinking Water and Birth Outcomes: A Tale of Two Water Treatment Plants
Dhaval M. Dave and Muzhe Yang
NBER Working Paper No. 27996
October 2020
JEL No. H75,I12,I18,Q53,Q58

ABSTRACT

The recent drinking water crisis in Newark, New Jersey's largest city, has renewed concerns about the lead-in-water crisis becoming a persistent and widespread problem owing to the nation's aging infrastructure. We exploit a unique natural experiment in Newark, which exogenously exposed some women in the city to higher levels of lead in tap water but not others, to identify a causal effect of prenatal lead exposure on fetal health. Using birth data that contain information on mothers' exact residential addresses, we find robust and consistent evidence that prenatal exposure to lead significantly raises the probability of low birth weight or preterm births by approximately 1.4 to 1.9 percentage points (14-22 percent), and the adverse effects are largely concentrated among mothers of lower socioeconomic status. Our findings have important policy implications in light of the long-term impact of compromised health at birth and the substantial number of lead water pipes that remain in use as part of our aging infrastructure.

Dhaval M. Dave
Bentley University
Department of Economics
175 Forest Street, AAC 195
Waltham, MA 02452-4705
and IZA
and also NBER
ddave@bentley.edu

Muzhe Yang
621 Taylor Street
Department of Economics
Lehigh University
Bethlehem, PA 18015
muzheyang@lehigh.edu

1 Introduction

The recent crisis of drinking water contamination in Newark, New Jersey's largest city, has renewed concerns regarding elevated lead levels in drinking water becoming a persistent and pervasive problem owing to the nation's aging infrastructure. Corrosion of lead plumbing materials is the most common source of lead in drinking water.[1] Although lead has been banned from use in new plumbing systems in the United States since 1986, much of the country's drinking water infrastructure largely predates this ban (Brown and Margolis, 2012; Centers for Disease Control and Prevention (CDC), 2019). Consequently, drinking water constitutes a significant source of lead exposure for Americans.[2]

Lead is known to have bio-accumulative properties, collecting over time in the human body through repeated exposure and stored in the bones alongside calcium. Of particular concern is in utero exposure, since accumulated lead in a mother's bones is mobilized during pregnancy and released as calcium to aid in the formation of the bones of the fetus (Gulson et al., 1997; Hu and Hernandez-Avila, 2002). Lead in a mother's blood can also easily cross the placenta, directly exposing the fetus to lead poisoning (Al-Saleh et al., 2011). There is no safe threshold of lead exposure that has been identified for children (American Academy of Pediatrics (AAP), 2016; CDC, 2019; EPA, 2020). Lead is a potent neurotoxin, and prenatal lead exposure is associated with impaired neurodevelopment, placing exposed children at higher risks for cognitive impairment, reduced IQ, learning disability, behavioral problems and other functional difficulties (CDC, 2010; WHO, 2011).

Drinking water contamination is becoming an increasingly important and widespread source of prenatal exposure to environmental pollution. Between January 2015 and March

[1] For more details, see https://www.cdc.gov/nceh/lead/prevention/sources/water.htm (accessed on June 22, 2020).

[2] The Environmental Protection Agency (EPA) estimates that drinking water can account for 20 or more percent of total lead exposure for adults and 40 to 60 percent for infants (EPA, 2020). Other modes of exposure occur through other forms of ingestion (e.g., food and chipped lead paint) and inhalation (e.g., tobacco smoking, emissions from leaded gasoline, and industrial pollution). Dermal absorption, mainly through occupational exposure for workers directly handling or working in proximity to lead materials, is also possible.

2018 there were nearly 30 million people in the United States whose drinking water coming from community water systems violated the EPA's Lead and Copper Rule (LCR), which sets maximum actionable levels of these metals in drinking water (Fedinick, 2018). Almost a third of community water systems report that at least some of their public service pipelines contain lead, with the exact number of lead service lines[3] estimated to be between 6.1 and 10.2 million (Cornwell, Brown and Via, 2016; EPA, 2016a).[4] Moreover, these lead service lines contribute as much as 75 percent of the lead that seeps into tap water (Sandvig et al., 2008), and they were responsible for the recent high-profile water crises in Flint of Michigan and Newark of New Jersey.

In this study, we capitalize on a unique natural experiment provided by the 2016 water crisis in Newark, in order to identify a causal effect of prenatal exposure to lead-contaminated drinking water on fetal health. Specifically, we compare two groups of mothers whose homes are served by two water treatment plants, respectively, over the period prior to and subsequent to the first discovery of lead contamination of drinking water in the city. Of the two groups, one was exposed to elevated lead levels in drinking water because of an unintended consequence of one water treatment plant's decision to increase the acidity level of its treated water. The unintended consequence of this increase in the acidity level was reduced effectiveness of the corrosion inhibitor (sodium silicate) used by the plant to control lead release. This caused lead from the pipes and plumbing fixtures to seep into the water, thereby exposing homes serviced by this water treatment plant to significantly elevated levels of lead in their tap water.

Using data on all live births in New Jersey between 2011 and 2018,[5] with information

[3] Service lines are the pipes that connect residences with the water mains (i.e., pipes delivering the water supplied to a city or town).

[4] These estimates are uncertain as approaches used to count lead service lines vary, and there does not exist a complete national inventory of lead service lines to date (Government Accountability Office, 2018). Following the water crisis in Flint, Michigan, the EPA encouraged all states in February 2016 to work with water systems to conduct inventories of lead service lines. Noted challenges include lead service lines on private property, which makes them difficult to locate, as well as a lack of records about the locations of older lead service lines.

[5] At the time of this study, the most recent year of New Jersey birth data released by the New Jersey Department of Health is 2018.

on the mother's exact residential address, we estimate the effects of exposure to higher level of lead contamination in drinking water on birth outcomes. We find robust evidence that this exposure significantly raises the probability of low birth weight (LBW, birth weight < 2,500 grams) or preterm (gestational length < 37 weeks) births by approximately 1.4 to 1.9 percentage points (14–22 percent). There is no indication that these effects are driven by selection into births. We also find some notable dynamics in the response that coincide with how the Newark water crisis unfolded. Moreover, while Newark ranks among the poorest cities in the state and in the nation,[6] we find that the adverse effects of lead exposure within the affected areas are largely concentrated among lower-educated and unmarried mothers. Mothers can also engage in activities to safeguard themselves and their pregnancy from harmful exposures, and we find some evidence of such behavioral responses. Pregnant women in affected areas seek out greater prenatal care in response to the water crisis. The effects on fetal health that we capture are the ones of a shift in water quality, including biological effects and effects of avoidance or compensatory behaviors unmeasured in our data, that is, besides increased use of prenatal care which we control for. These effects, although not disentangled from every possible avoidance or compensatory behavior, are still relevant in informing how lapses in water quality due to a failure in the water system's infrastructure translates into population ill-health in the presence of unmeasured or insufficient avoidance or compensatory behaviors.

Our study makes several contributions to the literature. We provide the first evidence on the impact of the Newark water crisis on birth outcomes. In the process, we add to the very limited evidence base on the adverse effects of water pollution,[7] and specifically on the effects of prenatal exposure to lead in drinking water—a dearth noted by Keiser and Shapiro (2019) and by the CDC in its report on lead exposure among pregnant women (CDC, 2010).[8] Even

[6] Newark has a poverty rate of 28%, compared with the national average of 11.8% (sources: https://www.census.gov/quickfacts/newarkcitynewjersey and https://www.census.gov/quickfacts/fact/table/US/PST045219, accessed on June 22, 2020).

[7] Regarding the literature on the causal effects of early-life exposure to pollution, the majority of that literature has been about air pollution, for which Currie et al. (2014) provide a detailed reviews.

[8] The CDC notes that research on prenatal lead exposure and LBW is inconclusive and "[f]urther research

recent evidence from the Flint water crisis on infant health outcomes has been somewhat mixed (Abouk and Adams, 2018; Grossman and Slusky, 2019; Wang, Chen and Li, 2019). In contrast to these studies of the Flint water crisis, which rely on intra-state comparisons between Flint and other cities in Michigan, the nature of the cause of the water crisis in Newark allows us to exploit plausibly exogenous within-city variation across affected and non-affected households in Newark.

While Newark provides the natural experiment in this study, failure to upgrade the nation's aging water infrastructure has made lead in the water system a national problem, and prompted predictive warnings that Newark's lead-water crisis will not be the nation's last (Khazan, 2019).[9] Our study also broadly contributes to the fetal origins literature, regarding effects of in utero shocks on health (Almond and Currie, 2011; Barker, 1995). With infant health being an important predictor of later-life outcomes, these estimates are critical towards evaluating the cost-benefit calculus of infrastructure investments, including replacing all of the nation's lead service lines, an initiative supported by the EPA as well as many states and communities at a potential cost of between $29 to $47 billion (EPA, 2019).[10]

The rest of the paper proceeds as follows. Section 2 provides the background. Section 3 describes the data, along with our identification strategy and econometric specification. Section 4 discusses the findings, and Section 5 concludes with policy implications.

is needed for a better understanding of several biomedical issues, including pregnancy outcomes and infant development associated with maternal lead exposure during pregnancy" (CDC, 2010, p. iii). While there is a large literature on the health effects of lead exposure (e.g., Bellinger, 2005; CDC, 2010; Gardella, 2001; WHO, 2011), much of this literature is correlational and based on relatively small or selected samples. The better of these studies are longitudinal and prospective (see WHO, 2011). Furthermore, much of the work on children is based on relatively high blood levels of lead (Aizer et al., 2018). Given that lead exposure and blood lead levels among children and mothers (and in the general population) have decreased in the United States (Brown and Margolis, 2012; CDC, 2010) over the past 40 years, it is important to understand how lead contamination affects health in a population that has on average low baseline blood levels of lead that are common today.

[9] Several large cities are served by water systems that have recently exceeded the EPA's action levels for lead, including Baltimore (MD), Green Bay (MI), Jackson (MS), Pittsburgh (PA), Portland (OR), and Providence (RI), among others (Bendix, 2020; Fedinick, 2018).

[10] The EPA (2019) noted 6.1–10 million lead service lines (LSL) nationally, with an average estimated replacement cost of $4,700 per LSL.

2 Background

2.1 Lead and EPA Compliance

Lead was widely used in water pipes and plumbing because of its strength, durability and malleability.[11] When public water systems were designed in the United States, lead became the material of choice, and lead service lines, which are used to connect homes and buildings to the water main, were widespread; virtually all large public water systems in the United States had installed lead service pipes (Rabin, 2008; Troesken, 2008).[12] As public health concern regarding the effects of lead exposure intensified in the 1960s and 1970s, the Safe Drinking Water Act (SDWA) was passed in 1974, giving the EPA authority to set and enforce limits on levels of lead and other contaminants in drinking water (Dignam et al., 2019). Interim standards were set in 1975 for lead concentration in drinking water to be below 50 $\mu g/L$ (i.e., 50 parts per billion or ppb). The 1986 amendment to the SDWA banned the use of lead from all new plumbing materials.[13] In 1991, the EPA's LCR established a lower threshold of 15 ppb for the maximum contaminant level (MCL) for lead in drinking water at customer taps, which is an actionable and enforceable level.[14] As lead contamination of drinking water results from corrosion of plumbing materials, community water systems are required to follow accepted treatment techniques to contain the corrosiveness of the water. Public water systems are generally required to monitor compliance with the EPA's LCR once every three years, by testing first-draw samples at taps in homes and buildings in the service

[11] The symbol for the chemical element, Pb, is derived from the Latin word "plumbum", referencing back to ancient times when the metal was widely used in the construction of water pipes.

[12] See Rabin (2008) for a history of lead water pipes and the influence of the lead industry in the United States.

[13] Lead in residential paint was banned in 1978. A gradual phase-out of lead content in gasoline began in 1973, and lead was virtually eliminated from gasoline by 1988 (Brown and Margolis, 2012).

[14] The EPA's maximum contaminant level goal (MCLG) for lead is zero, consistent with the best available evidence that there is no safe level of exposure to lead; however, this goal is neither actionable nor enforceable as reducing lead levels to zero would be prohibitively costly and may not be possible. MCLs are set as close as possible to MCLG, at levels that are economically and technically feasible. States can set more stringent standards if they choose, but most, including New Jersey, follow the EPA's standards. The maximum allowable lead level for bottled water, set by the Food and Drug Administration, is 5 ppb. For more details, see https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water and https://www.atsdr.cdc.gov/csem/csem.asp?csem=34&po=8, accessed on June 22, 2020).

area, including those deemed to be at high risk of contamination.[15] If the MCLs are not exceeded for three consecutive compliance periods, the public water system can transition to a less frequent cycle of monitoring every nine years. Required actions for non-compliance are triggered when more than 10 percent of the sampled customer taps exceed the 15 ppb MCL for lead. Utilities are required in this case to accelerate their monitoring to consecutive 6-month cycles, undertake further steps to optimize corrosion control until water quality improves, and educate customers about lead in drinking water and actions they can take to reduce their exposure to lead in the meantime. Water systems that continue to exceed the MCL for lead even after installing corrosion control must then start replacing the lead service lines (at a rate of at least 7 percent annually) until compliance is achieved (EPA, 2008).

2.2 Newark Water Crisis

Newark is the most populated city in the state of New Jersey (with a population of approximately 282,000)[16] and home to one of the major international airports in the New York metropolitan area. It is also one of the oldest cities in the nation, with a booming industrial past. The city is divided into five wards (East, West, South, North, and Central), with water supply to residents sourced and serviced through two distribution systems: the Pequannock Water Treatment Plant (WTP) and the Wanaque WTP (see Figure 1 Panel A).

The first indication of elevated lead levels in Newark appeared in March 2016, when 30 Newark public schools recorded lead levels in drinking water above the MCL (15 ppb).[17] Newark public schools receive water from the same sources as the rest of the city. In 2017,

[15] Sampling sites consist of single and/or multiple family structures that are served by a lead service line and/or contain copper pipes with lead solder. For details, see EPA (2008) and https://www.govinfo.gov/app/details/CFR-2011-title40-vol23/CFR-2011-title40-vol23-sec141-86 (accessed on June 22, 2020).

[16] Source: https://www.census.gov/quickfacts/newarkcitynewjersey (accessed on June 22, 2020).

[17] The Newark School District consists of 66 schools (see https://www.nps.k12.nj.us/info/ for details). Almost a quarter of the samples (76 out of 324) tested above the MCL. Follow-up results from additional samples found that 19 percent (735 out of 3,922) tested at elevated lead levels. For summary and timeline of the Newark drinking water crisis, see City of Newark (2018); Corasaniti, Kilgannon and Schwartz (2019); McGeehan (2016); and https://www.nrdc.org/newark-drinking-water-crisis (accessed on June 22, 2020). This section draws information from these sources.

under a mandate from the New Jersey Department of Environmental Protection, Newark switched its monitoring to testing drinking water for contamination twice a year; until then, it was on a triennial monitoring cycle with the previous tests being carried out between 2013 and 2015. The first test results, under the new frequent monitoring cycle and based on tap water samples from residences throughout the city, indicated sharply elevated lead levels for the first half of 2017. At least 22 percent of drinking water samples citywide exceeded the EPA's MCL of 15 ppb. However, most of the lead-contaminated samples were concentrated in the western part of the city that receives water treated by the Pequannock WTP. In this service area, 32 percent of samples contained lead levels exceeding 15 ppb (the EPA standard) and 44 percent exceeded 10 ppb (the European Union and the WHO standards); in contrast, samples from residences in the eastern part of the city where sourced water is treated by the Wanaque WTP continued to show compliance (only 6.5 percent of samples—below the EPA's 10-percent trigger—tested positive for lead levels exceeding 15 ppb or even 10 ppb). As we discuss below, elevated lead levels in drinking water for some residences, but not others, was the result of the two water treatment plants relying on different chemical agents for corrosion control (i.e., corrosion inhibitors). An increase in the acidity level of water treated by the Pequannock WTP reduced the effectiveness of the corrosion inhibitor (sodium silicate) that it was using, exposing homes serviced by this WTP to significantly higher levels of lead in their tap water. This was the conclusion reached in a study conducted by an independent engineering firm, commissioned by the city to investigate the cause of the elevated lead levels in Newark upon receiving notice of non-compliance with the EPA's LCR; the report was released in October 2018 (City of Newark, 2018).[18] By then, Newark had continuously violated the EPA's actionable MCL for lead since the start of the frequent biannual monitoring cycle.

In the city's 2017 annual water quality brochure, mailed to all residents as required by law, Mayor Ras Baraka reassured residents on the first page that "[m]any of you have

[18] Independent testing by the firm (CDM Smith) suggests that some residents may have been exposed to lead levels even higher than those reported in the city's testing samples.

heard or read the outrageously false statements about our water but please know that the quality of our water meets all federal and state standards" (City of Newark, 2017).[19] Under the pressure of litigation from several groups, and with the release of the city-commissioned study results on the extent and cause of the lead contamination, Newark started distributing water filtration devices in October 2018 to residents in the Pequannock service area.[20]

Until this time, the public remained largely unaware of the full extent of the water contamination. As pointed to by trends in Google search queries related to the water crisis in Newark (Figure 2), the first significant spike in interest coincided with reports of elevated lead levels in Newark public schools (around March 2016), which faded within a month or two. The next major spike in interest occurred in October 2018 with the city's plans to distribute water filters to impacted residents.

In March 2019, Newark commenced a program to remove and replace all of the city's lead service lines in the water system at no cost to the homeowner.[21] The Pequannock WTP switched its corrosion inhibitor on May 7, 2019 from sodium silicate, which had become ineffective, to orthophosphate, the same chemical agent used by the Wanaque WTP, which services the eastern part of the city. As it takes at least six months or longer for the orthophosphate to start working, elevated lead levels in water serviced by the Pequannock WTP continued through 2019. Among samples tested from this area in the second half of 2019, 26.9 percent (38.4 percent) contained lead levels in excess of 15 ppb (10 ppb); in

[19] The 2017 Report noted on the first page that the only high lead readings were confined to older homes. Results of the lead testing showing non-compliance with the EPA's MCL for lead were included at the end of the report (p. 5 and p. 7).

[20] Water filters could be picked up at various distribution centers. Community organizations and city employees also canvassed homes in the Pequannock service area and delivered water filters to those with suspected lead service lines. As of August 2019 and by the city's estimate, some 38,000 water filters had been distributed since October 2018. For detail, see https://www.newarknj.gov/news/faqs-regarding-the-city-of-newarks-water-filters-efforts-to-address-lead-in-the-water (accessed on June 22, 2020).

[21] The city's lead service line inventory, undertaken in response to its EPA's LCR violations, shows 18,406 (out of 29,938) of its service pipes were lead (source: https://www.nj.com/essex/2019/08/newarks-handing-out-bottled-water-what-you-need-to-know-about-the-citys-lead-crisis.html, accessed on September 9, 2019). Replacement was originally intended to take place over eight years, with costs shared between the city and the homeowner, but was accelerated in September 2019 to be completed within 24 to 30 months at no cost to the homeowner. By May 2020, the city had replaced about 10,000 of its lead service lines.

contrast, samples from the Wanaque WTP service area maintained compliance.[22] Following tests showing elevated lead levels even among homes using the distributed filters, the EPA warned that the filtration devices might not be adequately eliminating lead, and it instructed the city in August 2019 to provide bottled water to its impacted residents.[23] Figure 2 shows the largest spike in Google search queries related to water contamination in Newark at this time, coinciding with this EPA order and the distribution of bottled water to residents.

2.3 Prior Studies

General Lead Exposure

Lead is a poison, and high levels of lead in blood affect nearly all of the body's organs, with the brain particularly susceptible to its damaging effects. Exposure to lead is associated with adverse neurological, renal, hematological, endocrine, gastrointestinal, cardiovascular, reproductive, and developmental effects (ATSDR, 2007; ATSDR, 2017; WHO 2011). Lead is readily transferred from the mother to the fetus throughout gestation via the placenta. As lead hinders absorption of iron, zinc and calcium, which are essential to proper neurological development, lead exposure in utero (and through breastfeeding) can have lasting adverse health effects, independent of additional exposure at other stages of the life cycle (CDC, 2010).

Most prior epidemiological studies have found measures of blood lead levels to be correlated with health outcomes, cross-sectionally or longitudinally, based on small selected samples. However, those studies are unable to rule out other confounding factors associated with lead exposure (CDC, 2010; Grossman and Slusky, 2019; WHO, 2011). That is, those studies consider the direct association between high blood lead levels and health outcomes,

[22] Source: City of Newark (2018) and New Jersey Drinking Water Watch from the New Jersey Department of Environmental Protection (https://www9.state.nj.us/DEP_WaterWatch_public/index.jsp, accessed in February 2020).

[23] Bottled water was available to residents in the Pequannock service area through distribution centers, with assistance offered to residents unable to pick up in person. A later report by the city in November 2019 confirmed that the distributed filters were often improperly installed or maintained, diminishing their effectiveness in removing the lead.

rather than the effects of exposure to lead, and estimate a "treatment-on-the-treated" effect where variation in the "treatment" is not necessarily exogenous. Although some studies suggest that higher maternal blood lead levels may reduce birth weight, results are mixed and inconclusive (Bellinger, 2005; Gardella, 2001). There is also some evidence that maternal lead exposure may increase the risk of a miscarriage, although the most reliable evidence comes from a population of women with baseline blood lead levels substantially higher than the current mean for the U.S. women.[24] Surveys of the epidemiological literature on lead and pregnant women generally qualify that these studies may not have adequately controlled for confounding factors, and further research is warranted (Bellinger, 2005; CDC, 2010; Gardella, 2001).

More recent work has exploited natural experiments and more plausible exogenous variation in lead exposure to identify its health and developmental effects.[25] Using data linking preschool blood levels and school records in Rhode Island, with a multitude of identification strategies including sibling variation, residential proximity to roads and de-leading of gasoline, and policies requiring landlords to ensure that rental homes are lead-free, Aizer and Currie (2019) and Aizer et al. (2018) find that higher lead exposure results in greater anti-social behaviors, and lower reading and math achievement among children, respectively. Billings and Schnepel (2018) link data on children's blood lead levels with school and arrest records in North Carolina. Comparing children whose blood lead levels are just above and below the cutoff at which children become eligible for lead remediation interventions, the study finds that reducing lead exposure through such early-life interventions improves children's anti-social and educational outcomes and reduces criminal activity. Drawing on variation in airborne lead across counties, driven by the Interstate Highway System and compliance with the 1977 Clean Air Act (CAA) Amendments, Clay, Portnykh and Severnini (2018) find that

[24] See Bellinger (2005), Borja-Aburto et al. (1999), Edwards (2014), and Hertz-Picciotto (2000).

[25] Klemick, Mason and Sullivan (2020) use data on blood test results for children in six states and exploit residential proximity to Superfund cleanup sites to estimate effects of reduced exposure on blood lead levels. They find that Superfund cleanups lowered the risk of elevated blood lead levels by 13–26 percent for children living within 2 km of lead-contaminated sites.

reduced exposure to lead in the air increased completed fertility and improved birth weight.

Exposure to Lead Contamination in Water

As atmospheric lead emissions have declined since the CAA and regulations restricting leaded gasoline, lead exposure through the water system has taken on added relevance. Keiser and Shapiro (2019) provide excellent discussions of the history of regulating water pollution in the United States, notably through the Clean Water Act of 1972 and SDWA of 1974, and the effectiveness of these regulations in decreasing surface water pollution. They also draw attention to the dearth of economic research on water pollution, noting as important challenges the limited availability of data on water quality, hurdles with causal inference, and difficulty in focusing on and disentangling the effects of specific pollutants.

As such, research on the effects of lead exposure through drinking water on fetal health has been very limited. Clay, Troesken and Haines (2014) find higher rates of infant mortality historically, over 1900–1920, in American cities with more lead pipes and more acidic water, which would have resulted in greater corrosion and exposure to lead. Similarly, Troesken (2008) finds higher infant mortality and stillbirth rates in cities in Massachusetts that used lead pipes and had acidic water. Currie et al. (2013) use data on birth records in New Jersey during the period of 1997–2007, matched with water district-level EPA's MCL violations for any chemical and/or bacterial contaminant, to identify the effects of contaminated drinking water on fetal health. Exploiting variation across births for the same mother (i.e., using mother fixed effects), they find that residing in a water district with contaminated water during pregnancy is associated with an increase in LBW (by 14.5 percent) and prematurity (by 10.3 percent) among low-educated mothers. Their study, however, does not specifically identify the effects of lead or any particular contaminant.

Evidence from Recent Drinking Water Crises

More recently, researchers have studied the effects of water contamination crises in Washington, D.C. and Flint, Michigan. Edwards (2014) compares outcomes in Washington, D.C., which experienced high levels of lead in drinking water over 2000–2004, using neighboring Baltimore City as a control, and finds an increase in fetal death rates and a decrease in birth rates during the crisis period.[26]

The Flint water crisis began in 2014, after the city changed its water source to the Flint River and failed to apply corrosion inhibitors to the water. Studies that have assessed the effects of the Flint water crisis on fetal health generally conclude that greater exposure to lead in drinking water adversely impacted birth outcomes, although findings are not uniform. Grossman and Slusky (2019) find a decrease in birth rates, though no significant effects on birth weight or gestation. They interpret the reduction in birth rates as driven by an increase in miscarriages, which would imply that births carried to term may be a selected healthy sample biasing against finding negative effects on birth weight or gestation. It is also possible, however, that the reduction in birth rates could be driven by a reduction in conception due to the adverse reproductive effects of lead exposure for both the mother and the father (ATSDR, 2017; WHO, 2011). In contrast, Abouk and Adams (2018) find a significant reduction in birth weight and a higher incidence of LBW, though only among white mothers. Wang, Chen and Li (2019) also find a significant increase in LBW, though in contrast to Abouk and Adams (2018), they find larger effects among disadvantaged mothers (black or non-college educated), and in contrast to Grossman and Slusky (2019), they find little evidence of an increase in fetal deaths. All three studies use 20 months of post-treatment data, while differing somewhat in the control cities and counties compared against the city of Flint.

[26] Lead was inadvertently released from plumbing materials into drinking water starting in 2000 due to a switch in drinking water disinfectant from chlorine to chloramine.

Contributions

To the best of our knowledge, we provide the first study of how the drinking water crisis in Newark has affected birth outcomes. Our study broadly contributes to the limited literature on the causal effects of water contamination, and specifically to the scarce and mixed evidence base on the effects of prenatal lead exposure on fetal health. The unique cause of the lead crisis in Newark allows us to exploit plausibly exogenous within-city variation, across impacted and non-impacted mothers, to identify causal effects. In contrast, the nature of the Flint water crisis necessitated comparing Flint to control cities and counties, with findings apparently sensitive to the choice of these controls. Since we have data on the mother's exact residential address, unlike the Flint studies, we can control for residential address fixed effects and separate out effects of elevated levels of lead in drinking water (natural experiment) from the effect of having lead pipes at home (past exposure) or from heterogeneities in environmental exposure at the residential address level. The timeline of the Newark crisis, wherein residents remained largely unware of the full scope of the lead contamination for at least the first year post-contamination, allows us to draw out dynamics of the health effects of lead exposure in the presence of stress responses and some, but likely insufficient, avoidance or compensatory behaviors aimed at mitigating the health risk. We also assess the heterogeneity in these effects across relevant at-risk sub-populations. Finally, we note that while Newark provides the natural experiment in this study, the nature of the water contamination (corrosion of lead service lines) is common, with many community water systems in the United States being in violation of the EPA's MCL for lead. The estimates from our study can be used to inform a cost-benefit calculus of public investments in eliminating exposure from lead pipes, an initiative supported by the EPA and many localities.

3 Empirical Framework

3.1 Data

We use the restricted version of the birth certificate data from the New Jersey Department of Health (NJDOH) for this study. The data include all live births that occurred in New Jersey between 2011 and 2018. In addition to the information typically reported in vital statistics data, such as birth outcomes and mothers' demographic characteristics, which are publicly available through, for example, the U.S. National Center for Health Statistics (NCHS), the NJDOH data we obtained contain information on mothers' home addresses, geocoded by latitudes and longitudes.[27] This information allows us to include residential address fixed effects in our estimation, to disentangle the effect of elevated levels of lead in drinking water from the effect of having lead pipes at home, and also identify mothers in the impacted and non-impacted parts of the city. We limit our analysis to singleton births (about 96% of the NJDOH birth data), to avoid confounding factors causing adverse birth outcomes that are specifically related to carrying multiple fetuses in one pregnancy. There are 747,749 singleton live births in New Jersey over our analysis period, with 32,407 singleton live births occurring in Newark.[28]

Appendix Table A1 compares Newark to the U.S., based on 2017–2018 data from the American Community Surveys, on key socio-economic characteristics. Median household income in Newark is $46,400 (36 percent lower than the U.S. average), and the poverty rate in the city (27.2 percent) is roughly double. Newark is predominantly black (49.9 percent) and low-educated (63.2 percent of residents ages 24+ have at most a high school degree). A significantly higher share of residents are uninsured than the U.S. average, partly due to the high share of immigrants, Hispanic, and minorities. The housing stock in the city is

[27] In contrast, the lowest level of geography identified in the vital statistics data available at the U.S. NCHS is the county and city (for cities with at least 100,000 population).

[28] The total number of singleton live births that occurred in Newark used in our study is 30,707. Because this is the total number of observations that contain no missing values for all variables used in our estimation, it is smaller than 32,407.

relatively old, with about two-thirds of homes built prior to 1980 and thus likely to contain lead plumbing fixtures in addition to being serviced by the lead pipelines. Finally, it is notable that the rate of renters in Newark is one of the highest among any major city (72.2 percent). Renters, compared with homeowners, are probably less likely to investigate the presence of lead service lines when making residential decisions or making major investments in their rental dwelling.

3.2 Identification Strategy

We employ a difference-in-differences (DID) research design to identify the causal effect of exposure to lead in drinking water—the "treatment"—on fetal health. We rely on the specific situation in Newark's water treatment and the natural experiment, which resulted in higher levels of lead exposure among some parts of the city but not others, to define the pre- and post-treatment periods as well as the treatment and control groups.

As noted above, water supplied to Newark is treated by two WTPs: the Pequannock WTP and the Wanaque WTP. The unique situation in Newark's water treatment is that the two WTPs rely on different chemical agents for corrosion control: Pequannock uses sodium silicate (City of Newark, 2018), while Wanaque uses orthophosphate (City of Newark, 2019). Both chemicals are approved by the EPA and effective in preventing dissolution of lead into the water by forming a protective layer (i.e., a diffusion barrier) on the interior surface of a lead pipe, although orthophosphate is more commonly used for corrosion control than sodium silicate (EPA, 2016b).

Pequannock's decision to use sodium silicate resulted from a corrosion optimization study conducted by the city of Newark in 1994. In that study both orthophosphate and sodium silicate proved to be effective corrosion inhibitors, but it was found that using orthophosphate could have negative environmental impact because of a specific situation of the water treated by that plant: water treated by Pequannock flows downstream into an uncovered, open-air reservoir, and this open body of water provides a conducive environment for orthophosphate

to trigger algae growth (which is harmful) when that chemical gets into that reservoir (City of Newark, 2018).[29]

Pequannock started using sodium silicate for corrosion control in 1997, and the chemical had been effective since then. In 2016, however, the sodium silicate used by Pequannock was found to have become ineffective: the protective layer of lead service lines formed by the use of that chemical sloughed off. This was due to the pH in the water treated by Pequannock falling out of the range needed for sodium silicate to be an effective corrosion inhibitor (City of Newark, 2018). The lowered pH resulted from a deliberate decision made by Pequannock in 2015, to increase the acidity level (i.e., lowering the pH) of its treated water with the purpose of reducing disinfection byproduct formation (City of Newark, 2018).[30] While previously the pH of water treated by Pequannock was maintained around 8.0, it dropped to approximately 6.9 to 7.3 between 2015 and 2018 (see Figure 3 Panel A),[31] triggering a rapid release of lead from the pipes into the water (City of Newark, 2018).[32]

Our study uses the change in pH in the water treated by Pequannock that resulted from the plant's decision made in 2015 as a natural experiment. We define birth years 2011–2015 as the pre-treatment period and birth years 2016–2018 as the post-treatment period. The risk of prenatal exposure to lead in drinking water significantly increased for babies born post-2016 and born to mothers living in the areas serviced by Pequannock, because of the unintended consequence of the plant's decision that eventually made the corrosion inhibitor (sodium silicate) it had been using ineffective. In contrast, the corrosion inhibitor (orthophosphate) used by Wanaque remained effective between 2016 and 2017 (City of Newark, 2018).

[29] When getting into an open body of water, orthophosphate can cause phosphorus concentrations. With phosphorus being a nutrient for algae, this can cause algal blooms.

[30] This was in response to a 2012 EPA rule that had strengthened monitoring of carcinogenic disinfectant byproducts.

[31] Note that the pH scale uses decimal logarithm, and therefore a decrease in pH by one unit indicates a 10-fold increase in the acidity of the water.

[32] Newark's corrosion control program had been tested in water with a very high pH (8.5 to 9.0), and optimal effectiveness is achieved with a pH of 8 to 9. In fact, the EPA (2016b) generally recommends a target pH of 8.8 to 10. Any anti-corrosion benefits of the silicates are lost when pH is adjusted below 7.5 (Thompson et al., 1997). Using historical data, Clay, Troesken and Haines (2014) show that a pH below 7.3 potentially could trigger a rapid increase in lead leaching into water, based on which they identify a causal effect of lead exposure on infant mortality in American cities during the period of 1900–1920.

In our study the treatment group comprises mothers living in the area serviced by Pequannock, and the control group includes mothers living in the area serviced by Wanaque. These two plants service the entire city separately: Pequannock services the western part of the city, and Wanaque services the eastern part of the city (City of Newark, 2018; City of Newark, 2019). More specifically, among the five wards that constitute the entire city, Pequannock services the west ward, and Wanaque services the east ward, with the other three wards (north, central and south) being serviced by both plants (see Figure 1 Panel A). Service areas of the two plants with the zip code map of the city are shown in Panel B, which is shown in Panel B. The demarcation of the two plants' service areas largely follows the residential zip code boundaries, based on which we define the treatment and control groups.

Figure 3 (Panel B) shows trends in lead contamination in water sampled across the Pequannock (treated) and Wanaque (control) service areas. Prior to 2016, tests from both service areas indicated compliance with the EPA's LCR (i.e., lower than 10 percent of samples testing above 15 ppb).[33] However, after 2016, there is a significant run-up in lead in tap water sampled from residences in the Pequannock service area. Through the end of 2019, tests indicated that this part of Newark had been in consecutive non-compliance since the start of the frequent biannual monitoring cycle. In contrast, trends in lead levels remained flat and in compliance in all periods in the Wanaque service area.

3.3 Econometric Specification

Our regression model uses the following baseline DID specification, which can be interpreted as a reduced-form production function of infant health linking birth outcomes to exposure to

[33] Note that prior to 2016, Newark was on a triennial monitoring cycle; hence, citywide lead tests of drinking water are not available for every year, and were not conducted in 2016. However, as noted earlier, the first indication of lead seeping into drinking water came from tests conducted in Newark public schools, which found 30 (out of 66) schools testing positive for elevated lead levels in 2016. This is consistent with the timing of the reduction in the water pH and ineffectiveness of sodium silicate as a corrosion inhibitor.

lead in drinking water (Corman, Dave and Reichman, 2018; Dave and Yang, forthcoming):

$$y_{i,jkt} = \alpha_0 + \alpha_1 G_k T_t + \mathbf{x}'_{i,jkt}\alpha_2 + \gamma_j + \lambda_t + \epsilon_{i,jkt} \tag{1}$$

In equation (1), $y_{i,jkt}$ denotes a specific birth outcome (e.g., LBW) of an infant born to mother i living at address j in zip code k who gave birth in a year-month indexed by t.[34] The variable G is binary, equal to one for the zip codes of the treatment group, and equal to zero for the zip codes of the control group. Specifically, based on Figure 1, mothers residing in the following zip codes are included in the treatment group: 07103, 07106, 07107, 07108 and 07112; and those residing in the following zip codes are included in the control group: 07102, 07104, 07105 and 07114.[35] The variable T is also binary, equal to one for the post-treatment period, and equal to zero for the pre-treatment period. The key parameter of interest in our study is α_1, an intention-to-treat parameter which captures the effect of in utero exposure to elevated lead levels in drinking water on fetal health, operating through all reinforcing and mitigating mechanisms—that is, through biological, stress-induced, and compensatory self-protective pathways.

We include maternal residential address fixed effects (γ_j), aiming to disentangle the effect of elevated levels of lead in drinking water (from differential exposure post-treatment) from the effect of having lead pipes at home, as well as controlling for any time-invariant unobserved heterogeneities from environmental exposure at the residential address level. Since the residential address fixed effects also accommodate zip code fixed effects, we are controlling for unobserved time-invariant neighborhood factors, such as local infrastructure, built environment, and access to health care. To control for any seasonality effects that exist in pregnancy or birth outcomes, as well as common shocks affecting mothers during

[34] We use a comma between the subscripts i and jkt to emphasize that our data are not longitudinal in i: in the birth data we obtained from the NJDOH there is no unique identifier for each mother, which precludes us from using mother fixed effects.

[35] In an alternative specification we exclude zip codes 07102 and 07104 from the control group, since the demarcation of the two plants' service areas does not follow the zip code boundaries perfectly, especially for zip code 07102 and 07104.

the sample period, we include year-and-month of birth fixed effects (λ_t). Also included in this model is a vector of individual level control variables ($\mathbf{x}$): the sex of the baby; the mother's age, race and ethnicity, educational attainment, marital status, parity, the number of prenatal visits, as well as smoking status;[36] and whether or not the mother has had a previous preterm birth, which we use as a proxy for unobserved maternal health endowment at the time of pregnancy. We estimate all models by ordinary least squares (OLS), with standard errors clustered by year and month of birth.[37]

We extend the baseline specification in several ways to address additional issues. While our preferred specification relies on comparing impacted mothers with non-impacted mothers within Newark, drawing on the Wanaque service area to form the counterfactual, we show that our results are not sensitive to alternate controls that draw on mothers residing in cities and towns neighboring Newark which did not experience elevated lead levels in their drinking water during our sample period. We further assess whether our effects on birth outcomes are driven by compositional shifts in the sample of mothers giving birth across the treated and control areas, or whether driven by changes in fertility or miscarriages.

A critical assumption necessary for the DID research design to credibly identify the causal effect is that, in the absence of the water contamination, trends among mothers residing in the Wanaque service area are a valid counterfactual for trends among mothers living in the Pequannock service area. In order to assess the validity of the counterfactual, we conduct a fully-specified conditional event study based on the following specification and disentangle

[36] In the NJDOH birth data, maternal smoking status is measured by a binary response (yes/no) to the following question: "Did mother smoke cigarettes before or during pregnancy?" As a result, the maternal smoking status measured by this response can capture the status for two different periods—(1) before pregnancy and (2) during pregnancy—not necessarily for the latter exclusively.

[37] We do not cluster standard errors by zip code since there are only nine zip codes in our estimation sample that focuses on the city of Newark. Nevertheless, given that the geographic area of our study is relatively small and we have used residential address fixed effects, clustering standard errors by year and month of birth should be sufficient for capturing any remaining correlation among birth outcomes, which is likely to exist over time, after we control for any common shocks across space by using residential address fixed effects. We show that our inferences are unaffected by implementing a wild-cluster bootstrap at the zip code level, and results are reported in Appendix Table A4 for our main analyses.

the timing of the response:

$$y_{i,jkt} = \beta_0 + \sum_{l=2011,\neq 2015}^{2018} \beta_{1,l} G_k D_l + \mathbf{x}'_{i,jkt}\beta_2 + \gamma_j + \lambda_t + \varepsilon_{i,jkt} \quad (2)$$

In equation (2), D_l is a dummy variable, equal to one if birth year is l (where $l = 2011, \cdots, 2018$ except 2015) and equal to zero otherwise. Here, without loss of generality we use birth year 2015, which directly predated the water contamination, as the reference category.

The event study framework serves two functions. First, it allows us to directly test for differential pre-crisis trends by evaluating the magnitude and statistical significance of the lead coefficient (i.e., $\beta_{1,l}$ where $2011 \leqslant l < 2015$). Second, the event study allows us to decompose the dynamics of the main DID effect from equation (1) across each period over the post-crisis window. This allows us to gauge effect dynamics as the crisis unfolded, from the first post-crisis year when residents remained largely uninformed of the true scope of the lead contamination, to later years when reports became more widespread. As information regarding the water contamination diffused across residents, this would also be expected to elicit self-protective behavioral and/or stress-related responses among pregnant women.

While we are limited in the prenatal behaviors we can observe, we assess whether mothers responded to the crisis by increasing their contact with physicians (prenatal visits) that may have mitigated the effects of lead exposure on their pregnancy outcomes. Finally, we assess the heterogeneity in the fetal health effects across the mother's race and ethnicity, educational attainment, and marital status, to inform if the adverse effects are more pronounced among socioeconomically disadvantaged mothers.

4 Results

4.1 Descriptive Statistics

Table 1 presents the summary statistics for each of the four sub-samples defined jointly by the treatment status and treatment period (columns 1–4), and also for the full sample (column 5). Comparison of the means in Table 1 underscores two points. First, the rates of LBW and preterm births are significantly higher in the treated areas relative to the control areas. This can be driven by the treated areas in Newark being relatively more disadvantaged (greater share of unmarried and black mothers, for instance), although educational attainment appears to be similar across both the treated and control zip codes of the city in the pre-treatment period. The non-treated parts of the city are also home to a larger share of Hispanics and immigrants, and maternal foreign-born and Hispanic status has been found to confer a protective effect against LBW in the United States (Acevedo-Garcia, Soobader and Berkman, 2007). Second, a simple DID calculation (without covariate adjustment) shows an increase in LBW rate by about one percentage point,[38] for the treatment group and in the post-treatment period.

Figure 4 shows LBW rates averaged by the treatment-control status over our sample period (2011–2018). The two panels differ only in the control groups; specifically, Panel B excludes mothers who live in the two zip codes (07102 and 07104), which are serviced by both the Pequannock and Wanaque WTPs and thus are partially treated. The difference in levels in the pre-treatment period is driven by the socio-demographics of the treatment and control areas of the city, as shown in Table 1. In both panels of Figure 4, trends in LBW are largely flat and similar across the treated and control areas until 2015, when Pequannock made the decision of increasing the acidity level of its treated water. The failure of the plant's corrosion inhibitor has been linked to a reduced pH in the treated water. For infants born in 2016 in these areas of the city, there is a sharp and marked increase in LBW

[38] For LBW: (0.103 - 0.086) - (0.062 - 0.055) = 0.01.

with little change among babies born to mothers residing in other parts of the city. This pattern suggests an adverse effect on fetal health due to exposure to lead in water treated by Pequannock. While these are unconditional trends (i.e., without covariate adjustment), they largely prefigure our main analyses which we discuss next.

4.2 Baseline Difference-in-Differences

Our main results from the DID analyses, based on the specification in equation (1), are presented in Table 2 for measures of birth weight and gestation. The odd-numbered models control for area (zip code) fixed effects, and the even-numbered models fully exploit the residential information in the restricted version of the NJDOH birth data and control for residential address fixed effects. Panel A utilizes the broad set of control zip codes of the city, while Panel B excludes the two partially-treated zip codes.

We highlight several key notes of interest from these analyses. First, there is robust and consistent evidence that lead exposure in drinking water is associated with adverse birth outcomes. Specifically, we find an increase of 1.2 (with zip code fixed effects) to 1.9 (with residential address fixed effects) percentage points or 14–22 percent,[39] in the likelihood of LBW among babies born in 2016–2018 and born to mothers living in Pequannock's service area, who were exposed to increased levels of lead in drinking water during pregnancy. That the adverse health effect on continuous birth weight is weaker (at most a 37-gram decrease) indicates that the adverse impact is largely concentrated in the lower tail of the birth weight distribution. Moreover, the higher likelihood of LBW appears to be driven by an increase in preterm births: we find an increase in the probability of a preterm birth of 1.4–1.9 percentage points or 14–19 percent,[40] although we also find a small and marginally significant decrease in fetal growth (measured by the ratio of birth weight over gestation).

[39] Here, $0.012/0.086 \approx 14\%$ and $0.019/0.086 \approx 22\%$, where 0.086 is the average LBW rate for the treatment group in the pre-treatment period (reported in Table 1).

[40] Here, $0.014/0.102 \approx 14\%$ and $0.019/0.102 \approx 19\%$, where 0.102 is the average rate of preterm births for the treatment group in the pre-treatment period (reported in Table 1). In Appendix Table A2 we report the full set of estimates.

Second, while models with and without residential fixed effects show similar patterns, estimated treatment effects are generally larger with their inclusion. This points to a potentially important source of selection bias in the estimation of the fetal health effects of lead exposure, driven by unobserved heterogeneity arising from the residential structure (dwelling-specific exposures that affect fetal health) and associated sorting (unobserved factors driving where people choose to locate and live within the city).[41] The residential address fixed effects allow us to disentangle the impact that was specifically driven by the exogenous variation in lead exposure (e.g., more lead seeping into the tap water) from other longer-term and persistent environmental exposures associated with the dwelling and its neighborhood. Third, it is internally validating that the effect magnitudes increase in Panel B, where we exclude the two partially-treated zip codes (which are serviced by both the Pequannock and the Wanaque water treatment facilities) from the control group.[42]

While our preferred analyses exploit plausibly exogenous within-city variation in the exposure to lead in drinking water, comparing treated and control areas from within Newark only, one concern is that even mothers in the non-treated parts of Newark may be "treated" due to information spillovers and a potential stress response. This may lead our identification strategy to attenuate the estimated adverse health impact of lead exposure in the treated areas. We return to this point later in the paper when we specifically decompose the timing of the effects, which allows us to interpret the dynamics in the context of unfolding of the crisis and the propagation of information.

In Table 3, we show that results are largely robust to utilizing alternative control groups defined by zip codes near Newark, such as the zip codes of Jersey City (Panel A) and the zip codes of cities and towns surrounding Newark (Panel B). For these control groups and during our sample period there were no known reports on lead in drinking water. Our estimates

[41] In our case, excluding residential address fixed effects appears to impart negative selection bias in the estimation of the adverse fetal health impact. This indicates that not accounting for this source of unobserved heterogeneity may risk understating the adverse health impact of lead exposure.

[42] For our main analyses we still include these two zip codes (07102 and 07104) in the control group, to increase sample size and statistical power.

are also robust to controlling for zip code-specific linear time trends (year-month of birth),[43] which parametrically account for unobserved time-varying factors that may differ across parts of the city (results reported in Appendix Table A3). This robustness suggests that omitted variables bias that comes from zip code-level, time-varying unobserved heterogeneities may not be a major concern once we control for residential address fixed effects and year-month of birth fixed effects. This argument in part is also supported by Figure 3, in which we see largely parallel and almost flat trends in LBW between the treatment and control groups during the pre-treatment period. These largely parallel and almost flat trends suggests an absence of zip code specific time trends.

4.3 Selection

One hindrance to our identification of the adverse effects of lead exposure on fetal health is that the estimated effects could be driven by selection into birth. This selection can take three forms. First, the water crisis in affected parts of Newark may have altered (or is confounded with changes in) the composition of women giving birth. If so, then the adverse effects we uncover may conflate a potential shift in the composition of mothers who tend to give birth to less healthy infants even in the absence of exposure to lead. To assess this possibility, we estimate a DID model focusing on the characteristics of the mothers giving birth, and the results are reported in Figure 5.[44] These analyses indicate a higher likelihood of babies born to mothers of higher socioeconomic status (white, college-educated, and having better access to health care indicated by higher number of prenatal visits) in the treatment group and in

[43] Here, each zip code is interacted with a linear time trend of birth year and month.

[44] In this figure point estimates and the associated 95% confidence interval are reported (in the "rope ladder" plots) for Case A—the treatment-control comparison in the pre-treatment period, and also for Case B—the DID estimation based on equation (1), using each demographic characteristic (listed in Figure 5) as the dependent variable. Case A of Figure 5 shows that in the pre-treatment period, consistent with the results reported in Table 1, there is a higher proportion of mothers who are African Americans in the treatment group, while there are higher proportions of mothers who are white or Hispanic in the control group. Given that in our study the treatment group is located in the western part of the city, while the control group is located in the eastern part of the city, results in Case A of Figure 3 indicate a race-induced geographic separation in the city's residential pattern. This race-induced residential sorting can be a confounder in our estimation of the treatment effect, which, if time-invariant, will be controlled for in our DID model (through time-differencing).

the post-treatment period.[45] So, if our treatment effect estimate is biased, the bias will be more likely to result in an underestimate. This is because higher socioeconomic status is usually associated with better health, and an increase in maternal socioeconomic status in the treatment group coinciding with an increase in lead exposure should mitigate an adverse effect on fetal health of lead exposure.[46]

Selection into births may also be driven by delays or failures of conception, or miscarriages. Both of these reflect possible links in the causal chain from maternal lead exposure to effects on birth outcomes. The first could reflect a behavioral pathway, if women are delaying pregnancies in response to the health information shock upon learning about high levels of lead in drinking water, or a biological pathway due to impaired reproductive effects of lead exposure for both males and females (ATSDR, 2017; WHO, 2011). The second reflects a potential biological effect of lead exposure on miscarriages. Note that in the presence of selective attrition or culling, wherein less healthy fetuses are more likely to miscarry resulting in relatively healthier births, any observed adverse effects on birth outcomes from lead exposure would be understated (Grossman and Slusky, 2019). While we do not have information on delayed or failed conception, or miscarriages in the NJDOH birth data, we assess the importance of these selection pathways indirectly, and the findings are reported in Table 4. In column (1) we assess effects of total births at the zip code level, and in column (2) we assess effects on the likelihood of a female birth. The biological fragility of the male fetus to negative health shocks is often used to indirectly test for miscarriages, which would

[45] Another interpretation of increased number of prenatal visits is the behavioral response to the unfolding of the water crisis, which we will discuss later in the paper. Also note that In this figure and among the maternal characteristics controlled for in the regression model (equation 1), the following two variables are not examined: (i) maternal smoking status, and (ii) whether the mother had previous preterm birth. For (i), the variable provided in the New Jersey birth records does not distinguish between maternal smoking during pregnancy and maternal smoking before pregnancy. For (ii), if we use it as a dependent variable, then the estimate in case (b) could represent a treatment effect, as opposed to a change in that maternal health endowment at the time of pregnancy, since a "previous" preterm birth could happen during the post-treatment period for mothers who gave births in 2017 and also 2016 and these mothers in the treatment group were exposed to elevated lead levels in drinking water.

[46] In supplementary analyses (discussed later in the paper) we estimate the treatment effects within socio-demographic groups to assess heterogeneity, and we find compromised fetal health across race and marital status.

result in a greater likelihood of observing a female birth.[47] We do not find any sizable or statistically significant effects of the Newark water crisis on this proxy measure (column 2). And, as shown in column (1), estimated coefficients on the number of births are also statistically insignificant and close to zero in magnitude. We interpret this finding as suggestive evidence that the negative effects of maternal lead exposure on fetal health in Newark are not likely to be driven by pregnancy behaviors or miscarriages.[48] The live births included in the sample used for our estimation seem unlikely to be "survivors of the fittest" who were exposed to lead in utero. One explanation for the lack of culling in utero could be that the exposure to lead did not reach a level high enough to trigger culling.

4.4 Event Study Analyses, Timing and Mechanisms

Our analyses thus far have centered on estimating an average effect of lead exposure over the post-treatment period (2016–2018). Next, we expand the baseline specification into an event study framework (as specified in equation 2), which examines the time-varying treatment effects in event time (as opposed to calendar time). This serves two purposes, allowing us to more formally test for differential pre-treatment trends between the treated and non-treated areas of the city, and also to assess dynamics in the response as the water crisis in Newark unfolded. The estimates are reported in Table 5 and also visually presented in Figure 6.[49] While we lose some statistical power, these results highlight three main points discussed below.

First, consistent with the approximately parallel trends in LBW in the pre-treatment period we observed in Figure 4, results in Table 5 and Figure 6 show that there are no differential trends in LBW between the treatment and control groups in the pre-treatment period, which supports the common-trend assumption needed for our DID-based identifica-

[47] See Eriksson et al. (2010) and Kraemer (2000) for more discussions of the fragile male hypothesis.

[48] In their study of the Flint water crisis, Grossman and Slusky (2019) find a reduction in the birth rate and interpret this decline as driven by a reduction in conception. Wang, Chen and Li (2019) find no significant effect of the Flint water crisis on mortality selection, as proxied by the ratio of male-to-female births.

[49] Appendix Table A5 reports the estimation results of event studies based on the non-Newark control groups, also indicating parallel pre-treatment trends and largely similar results and patterns.

tion strategy. Moreover, results in Table 5 and Figure 6 indicate that differences in LBW observed in the pre-treatment period (reported in Table 1 and shown in Figure 4) are fully explained by the observables included in our regression model.

Second, the marked increase in LBW in the treatment group relative to the control group materializes only after Pequannock's decision to reduce the pH level of its treated water, which led to the corrosion inhibitor in the water to become ineffective. That decision was made in 2015, and the marked increase in LBW corresponds to babies born after 2015.

Third, the treatment effect is positive and remains sustained, although slightly moderated over time. This may reflect the dynamics of the information spread, a potential stress response in the control group, or the population engaging in some avoidance and compensatory behaviors. In fact, during our sample period (2011–2018), 2016 is the first year in which media reported the existence of elevated lead levels (exceeding the EPA's threshold of 15 parts per billion for taking regulatory actions) found in Newark's drinking water.[50] This is consistent with trends in Google search queries shown in Figure 2: there was substantial interest of the public after reports of elevated lead levels found in drinking water in Newark public schools surfaced in early 2016; relative to this initial spike, interest subsided (by about 80%) but continued throughout 2017 and 2018, spiking again towards late 2018 with the publicity surrounding the city's release of its engineering report and the decision to distribute filters to affected residents. It is also notable that there was a slight increase in LBW in 2018 (shown in Figure 4) in the sections of the city that were not exposed to higher levels of lead in drinking water; this may reflect information spillovers and a possible stress response, and the association between maternal stress during pregnancy and adverse birth outcomes has been documented by a large body of medical literature (e.g., studies summarized in Bussières et al., 2015).

To disentangle the biological effects of maternal lead exposure from the stress response

[50] For example, on March 9, 2016 the Associated Press published an article in *The New York Times*, titled "Elevated Lead Levels Found in Newark Schools' Drinking Water" (https://www.nytimes.com/2016/03/10/nyregion/elevated-lead-levels-found-in-newark-schools-drinking-water.html, accessed in December 2019).

and behavioral avoidance pathways, we separately estimate the treatment effect by year of conception, and results are reported in Table 6. As we mentioned earlier, the first signs of the lead crisis in Newark emerged in March 2016 when public schools tested at above the MCL (15 ppb) in drinking water. Hence, mothers who started pregnancies in 2015 and gave births in 2016 were likely to be exposed to higher lead levels but largely remained unaware of the exposure. We find a relatively large, compared with the average over the entire pre-treatment period, treatment effect in this case, which is a 2.2 percentage-point increase in the likelihood of giving birth to a LBW baby. For infants conceived in 2016, interestingly there is no significant effect on LBW, which might reflect heightened awareness and avoidance behaviors on the part of families coinciding with the breaking of the news and spike in the public interest. As the interest subsided (Figure 2 Panel A), for births conceived in 2017, or 2017–2018, we find effect sizes on the order of about a 1.5 percentage-point increase in the probability of LBW—an impact that would include the biological and stress channels along with any avoidance behaviors.[51] Moreover, towards the latter part of the analysis period, the treatment effect may also be attenuated due to information spillovers and a stress response among mothers living in non-impacted parts of the city.

While avoidance behaviors among families can take various forms,[52] many of which are not observed in our data, we examine the presence of such behaviors by assessing whether the drinking water crisis induced greater contact with the medical care community among pregnant women. Table 7 (column 1) presents estimates, from our main DID model (Panel A) and from the event study specification (Panel B), of how prenatal lead exposure impacted reported prenatal care visits. There is some indication that pregnant women in the affected parts of the city increased their prenatal visits in the post-treatment period, relative to the control group, particularly in 2017 and 2018; the effect is small (about 4% relative to

[51] For births conceived and occurring in 2018, the effects are insignificant. But, note that this is a truncated sample with fewer births, since there are births from pregnancies that started in 2018 and ended in 2019. The last year of our NJDOH birth data is 2018, so we do not observe any births that occurred after 2018.

[52] For more information on ways of reducing exposure to lead in drinking water, see the EPA's website https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water#reducehome (accessed in December 2019).

the baseline treatment mean, which is 8.734 reported in Table 1), but it is statistically significant. We interpret this finding as evidence of the presence of behavioral responses aimed at mitigating health risks caused by the drinking water crisis. The literature on the effects of prenatal care on birth outcomes in general has produced mixed and nuanced findings (Corman, Dave and Reichman, 2019). In the context of the water crisis in Newark, however, physicians may provide valuable information to pregnant women on how to avoid ingestion and absorption, for instance by using bottled or filtered water, letting the faucet run prior to drinking to flush out the lead, and increasing intake of calcium, iron and vitamin C, which can inhibit lead absorption and help to get rid of lead from the body.[53]

In column (2) of Table 7, we also consider effects on maternal smoking. One limitation of the smoking measure in the NJDOH data is that it conflates both smoking prior to as well as during pregnancy, and we therefore interpret these results with caution. We find a statistically significant reduction (about one percentage point) in maternal smoking among mothers in affected areas in the post-treatment period.[54] Since most smokers have initiated smoking prior to age 18,[55] a decrease in maternal smoking reflects an increase in cessation, either among women of childbearing age prior to becoming pregnant or among pregnant

[53] In our study, we find that an increase in the number of prenatal visits is associated with a decrease in the likelihood of LBW, suggesting a beneficial effect of prenatal care utilization on fetal health. This result is reported in Appendix Table A2. In that table we also observe a slightly smaller magnitude of the estimated effect of maternal lead exposure on LBW based on the regression model that excludes variables on prenatal care and smoking (columns 3 and 4). This pattern is consistent with the presence of protection behaviors indicated by greater use of prenatal care and less smoking (results reported in Table 7), as well as the negative association between prenatal care and LBW (columns 1 and 2 of Appendix Table A2) and the positive association between maternal smoking and LBW (columns 1 and 2 of Table A2).

[54] Danagoulian and Jenkins (2020), in contrast, find a significant increase in smoking among mothers in Flint (Michigan), after the water contamination there, relative to mothers in other localities in Michigan. The increase in smoking (reduction in cessation rates among pregnant women) is consistent with a stress response induced by the 2014 Flint water crisis. The Newark crisis differed from the Flint crisis, notably in regards to information dissemination and public knowledge. Despite the finding of elevated lead levels in drinking water in Newark public schools in mid-2016, and further violations of the EPA standards in 2017, the 2017 Water Quality Report downplayed the violations. The public was subject to conflicting information, and remained largely unaware of the scope of the water contamination. Public perceptions of the water contamination in Flint were more immediate and pronounced, with Flint switching its water source in April 2014, city residents soon thereafter complaining about the color, taste and smell of their water, the city issuing a boil advisory in August 2014, and General Motors announcing that it is discontinuing the use of Flint tap water due to high levels of chlorine and corrosion.

[55] Data from the 2018 National Survey of Drug Use and Health indicate that over 80% of smokers have initiated smoking by age 18, and over 68% have initiated smoking by age 17.

women. The decline in smoking may be due to greater contact with physicians (increased prenatal care; Wehby, Dave and Kaestner, 2020) or reflect a form of compensatory behavior to counteract the adverse health impact of greater lead exposure.

4.5 Heterogeneous Treatment Effects

Mediated through both biological and behavioral pathways, and potentially moderated by maternal health endowment, the reduced-form impact of prenatal lead exposure on birth outcomes may differ by maternal characteristics. We assess these heterogeneities in Table 8.[56] The analyses underscore the following patterns, although we qualify these interpretations by noting that sample size limitations with the stratified analyses reduce precision. Prenatal lead exposure is associated with a similar increase in LBW for both male and female fetuses, although males are more susceptible to being born preterm. Adverse fetal health effects are generally similar across race and ethnicity subgroups.[57] We also find that the risk of an adverse birth outcome from prenatal lead exposure is greater among unmarried and lower-educated mothers. Women of lower socioeconomic status have been found to have higher rates of calcium deficiency (Wallace, Reider and Fulgoni, 2013), which leads to greater absorption of ingested lead.

5 Conclusion

We provide the first study of the effects of the lead crisis in Newark, informing how prenatal exposure to lead through tap water impacts birth outcomes. Quantifying these effects is important for several reasons. First, a deteriorating water system infrastructure has made lead in the water a national problem, with nearly 30 million people in the nation drinking

[56] Appendix Table A6 reports results based on the alternative non-Newark control group, and the results are similar to those reported in Table 8.

[57] Given the racial makeup of the city, there are too few births to non-Hispanic white mothers across the treated and control groups of our study to reliably identify a separate effect for this group (although we report the estimate in Table 8 for completeness).

water from community water systems that were in violation of the EPA's LCR between January 2015 and March 2018 (Fedinick, 2018). The American Society of Civil Engineers in its 2017 report card rated the nation's drinking water system a D grade, underscoring the aging pipes and emerging problems with contaminants such as lead.[58]

Second, much of our understanding of the health effects of lead comes from potentially endogenous associations between blood lead levels and health outcomes. The water crisis in Newark provides a plausibly exogenous source of variation in lead exposure, allowing us to identify a causal effect of prenatal exposure on fetal health—an effect that is salient because it captures the overall impact in the population, operating through all channels (biological and behavioral, including any avoidance behaviors) when water systems fail. The effect we estimated is also of immediate policy interest since our estimate reflects the presence of behavioral responses that are insufficient for eliminating the health risk due to lead exposure. Moreover, population blood lead levels have declined considerably over the past five decades. Our study therefore captures an increase in exposure relative to a current low baseline.

Third, many public health advocates and experts on water systems have called for full replacement of the nation's estimated 6 to 10 million lead service lines, with some communities already having implemented successful replacement programs and other cities developing plans to do so.[59] A comprehensive evaluation of the cost implications of such public investments requires estimates of the public health impact of lead exposure.

We find robust and consistent evidence that the increased in utero exposure to lead through water contamination in Newark significantly increased the prevalence of infants being born with LBW or preterm. There is little evidence to suggest that these effects are driven by selection into births, and we also find that the added risk is more concentrated among

[58] Source: https://www.infrastructurereportcard.org/cat-item/drinking_water/ (accessed on October 7, 2020).

[59] For instance, Framingham (MA), Lansing (MI), Madison (WI), Medford (OR), Sioux Falls (SD), Springfield (MA), and Spokane (WA) have fully removed lead service lines in their communities. Subsequent to the water crisis, Flint initiated a full replacement program of its lead water service lines in 2016, which is currently underway. Recently, Chicago rolled out a plan for lead service line replacement, fully subsidizing costs for eligible low-income households and waiving permit fees for other homeowner-initiated replacement.

lower-educated and unmarried mothers. Our estimates indicate a 1.4 to 1.9 percentage-point increase in the likelihood of LBW or preterm. These are intention-to-treat effects of residing during pregnancy in areas with increased lead levels in tap water, since not every resident here is being exposed to high levels of lead. As part of the city's lead service line inventory, approximately 61% of the city service lines were constructed of lead.[60] Inflating the treatment effects by this "exposure" probability implies effect sizes between 2.3 and 3.1 percentage points, with respect to higher levels of lead exposure. Our estimates imply an increase of 30 to 40 LBW or preterm births in a given year attributed to the lead-in-water crisis in Newark.[61]

In March 2019, Newark commenced a program to remove and replace all of the city's lead service lines in the water system at no cost to the homeowner, at a projected public cost of $90–$180 million.[62] With the lifetime societal economic burden of a preterm birth estimated to be approximately $66,331 (Institute of Medicine, 2007),[63] the societal cost of the lead crisis in Newark could amount to $1.99–$2.65 million per year, just from an estimated increase of 30 to 40 preterm births linked to the heightened lead exposure each year.[64] Assuming a discount rate for public policy of 2 percent based on the social rate of time preference (Council of Economic Advisers, 2017), societal cost savings from averting this adverse fetal health could be between $100 and $133 million, significantly offsetting cost of public infrastructure investment.[65]

[60] The city's lead service line inventory, undertaken in response to its EPA's LCR violations, shows 18,406 (out of 29,938) of its service pipes were lead (source: https://www.nj.com/essex/2019/08/newarks-handing-out-bottled-water-what-you-need-to-know-about-the-citys-lead-crisis.html, accessed on September 9, 2019).

[61] Here is the calculation, 6,543 (births in the treated zip codes in the post-treatment three-year period, Table 1)×0.014 (or 0.019, Table 2)/3≈30 (or 40) LBW or preterm births.

[62] Source: https://www.newarkleadserviceline.com/replacement (accessed on October 14, 2020).

[63] The Institute of Medicine (2007) estimated the societal burden of a preterm birth to be $51,589 in 2005 dollar. We inflate this estimate to 2018 dollar.

[64] Here is the calculation: 30 (or 40) preterm births×66,331 per preterm births = $1.99 million (or $2.65 million).

[65] There is some debate as to the appropriate discount rate to apply for public policy (see for instance, Council of Economic Advisers,2017; Li and Pizer, 2018) depending on the social rate of time preference or the social opportunity cost of capital, and the length of the time horizon under consideration. The U.S. federal guidance requires agencies to use both a 3% and a 7% real discount rate in regulatory cost-benefit analyses. Under this guidance, the societal cost savings of averting the adverse fetal health would be between

That the public values such investments to improve the water system infrastructure in the nation is apparent from the considerable engagement in avoidance behaviors when contaminant violations in water systems are disclosed to the public (Graff Zivin, Neidell and Schlenker, 2011). According to McCarthy (2017), drinking water pollution worries are also at their highest levels since 2001, with 63% of the public reporting that they are worried a great deal about this issue; concern is even higher among low-income individuals (75%) and non-whites (80%). The cost-saving estimates we previously discussed are likely to be lower-bound estimates given the focus of this study is specifically on adverse fetal health effects; lead exposure among children has also been found to adverse impact their development—increasing anti-social and criminal behaviors and reducing achievement in school.[66]

References

Abouk, R. and S. Adams (2018). "Birth Outcomes in Flint in the Early Stages of the Water Crisis." *Journal of Public Health Policy* 39 (1): 68–85.

Acevedo-Garcia, D., M.-J. Soobader and L. F. Berkman (2007). "Low Birthweight among US Hispanic/Latino Subgroups: The Effect of Maternal Foreign-Born Status and Education." *Social Science & Medicine* 65 (12): 2503–2516.

Aizer, A. and J. Currie (2019). "Lead and Juvenile Delinquency: New Evidence from Linked Birth, School, and Juvenile Detention Records." *The Review of Economics and Statistics* 101 (4): 575–587.

Aizer, A., J. Currie, P. Simon and P. Vivier (2018). "Do Low Levels of Blood Lead Reduce Children's Future Test Scores?" *American Economic Journal: Applied Economics* 10 (1): 307–341.

$66.3 million and $88.3 million (social discount rate of 0.03) and between $28.4 million and $37.9 million (social discount rate of 0.07). Clearly, the cost implications are sensitive to the discount rate employed. With long-term real interest rates decreasing substantially over the past decade, a recent issue brief by the Council of Economic Advisers (2017) recommends lowering the estimate of the social discount rate in applications to public policy cost-benefit calculus.

[66] See, for instance, Aizer and Currie (2019), Aizer et al. (2018), and Billings and Schnepel (2018).

Agency for Toxic Substances and Disease Registry (ATSDR) (2007). Toxicological Profile for Lead (Case No. 7439-92-1). Atlanta, Georgia: ATSDR. Retrieved from http://www.atsdr.cdc.gov/toxprofiles/tp13.pdf on June 22, 2020.

Agency for Toxic Substances and Disease Registry (ATSDR) (2017). Lead Toxicity, Case Studies in Environmental Medicine. Atlanta, Georgia: ATSDR. Retrieved from https://www.atsdr.cdc.gov/csem/lead/docs/CSEM-Lead_toxicity_508.pdf on June 22, 2020.

Al-Saleh, I., N. Shinwari, A. Mashhour, G. E. D. Mohamed and A. Rabah (2011). "Heavy Metals (Lead, Cadmium and Mercury) in Maternal, Cord Blood and Placenta of Healthy Women." *International Journal of Hygiene and Environmental Health* 214 (2): 79–101.

Almond, D. and J. Currie (2011). "Killing Me Softly: The Fetal Origins Hypothesis." *Journal of Economic Perspectives* 25 (3): 153–172.

American Academy of Pediatrics (AAP) (2016). Lead Exposure in Children. Retrieved from https://www.aap.org/en-us/advocacy-and-policy/aap-health-initiatives/lead-exposure/Pages/Lead-Exposure-in-Children.aspx on June 22, 2020.

Barker, D. J. P. (1995). "Fetal Origins of Coronary Heart Disease." *BMJ: British Medical Journal* 311: 171–174.

Bellinger, D. C. (2005). "Teratogen Update: Lead and Pregnancy." *Birth Defects Research Part A: Clinical and Molecular Teratology* 73 (6): 409–420.

Bendix, A (2020). 12 Cities with the Worst Tap Water in the US. Business Insider, March 17, 2020. Retrieved from https://www.businessinsider.com/cities-worst-tap-water-us-2019-3 on June 22, 2020.

Billings, S. B. and K. T. Schnepel (2018). "Life after Lead: Effects of Early Interventions for Children Exposed to Lead." *American Economic Journal: Applied Economics* 10 (3): 315–344.

Borja-Aburto, V. H., I. Hertz-Picciotto, M. Rojas-Lopez, P. Farias, C. Rios and J. Blanco (1999). "Blood Lead Levels Measured Prospectively and Risk of Spontaneous Abortion." *American Journal of Epidemiology* 150 (6): 590–597.

Brown, M. J. and S. Margolis (2012). "Lead in Drinking Water and Human Blood Lead Levels in the United States." *Morbidity and Mortality Weekly Report Supplement* 61 (4): 1–9.

Bussières, E.-L., G. M. Tarabulsy, J. Pearson, R. Tessier, J.-C. Forest and Y. Giguère (2015). "Maternal Prenatal Stress and Infant Birth Weight and Gestational Age: A Meta-Analysis of Prospective Studies." *Developmental Review* 36: 179–199.

Centers for Disease Control and Prevention (CDC) (2010). Guidelines for the Identification and Management of Lead Exposure in Pregnant and Lactating Women. US Department of Health and Human Services, Atlanta, GA. Retrieved from https://www.cdc.gov/nceh/lead/publications/leadandpregnancy2010.pdf on June 22, 2020.

Centers for Disease Control and Prevention (CDC) (2019). Childhood Lead Poisoning Prevention. Last updated on July 30, 2019. Retrieved from https://www.cdc.gov/nceh/lead/prevention/default.htm on June 22, 2020.

City of Newark (2017). 2017 Water Quality Report, City of Newark Department of Water and Sewer Utilities. Newark, NJ. December 2017. Retrieved from https://waterandsewer.newarknj.gov/annual-water-quality-reports on June 22, 2020.

City of Newark (2018). Pequannock WTP Corrosion Control Review and Recommendations—Draft. City of Newark Lead and Copper Rule Compliance Study. City of Newark Department of Water and Sewer Utilities. Newark NJ. October 10, 2018. Retrieved from https://www.politico.com/states/f/?id=00000166-e5f2-dd0d-afe7-eff264510000 and https://www.tapinto.net/towns/newark/articles/study-shows-how-newark-s-lead-problem-got-so-bad on June 22, 2020.

City of Newark (2019). Wanaque Gradient Corrosion Control Review—Initial Draft. City of Newark Lead and Copper Rule Compliance Study Wanaque Gradient. City of Newark Department of Water and Sewer Utilities. Newark NJ. February 1, 2019. Retrieved from https://tapinto-production.s3.amazonaws.com/documents/9396/show_multidocs.pdf and https://www.tapinto.net/towns/newark/articles/draft-study-shows-newark-s-east-ward-unaffected-by-increased-lead-levels on June 22, 2020.

Clay, K., W. Troesken and M. Haines (2014). "Lead and Mortality." *The Review of Economics and Statistics* 96 (3): 458–470.

Clay, K., M. Portnykh and E. Severnini (2018). Toxic Truth: Lead and Fertility. National Bureau of Economic Research Working Paper No. 24607.

Corasaniti, N., C. Kilgannon and J. Schwartz (2019). Tainted Water, Ignored Warnings and a Boss with a Criminal Past: How a Long Line of Questionable Decisions Led to the Crisis over Lead Contamination in Newark. *The New York Times*, August 24, 2019. Retried from https://www.nytimes.com/2019/08/24/nyregion/newark-lead-water-crisis.html on June 22, 2020.

Corman, H., D. M. Dave and N. E. Reichman (2018). "Evolution of the Infant Health Production Function." *Southern Economic Journal* 85 (1): 6–47.

Corman, H., D. M. Dave and N. E. Reichman (2019). "The Effects of Prenatal Care on Birth Outcomes: Reconciling a Messy Literature." In *Oxford Research Encyclopedia of Economics and Finance*, Oxford University Press.

Cornwell, D. A., R. A. Brown and S. H. Via (2016). "National Survey of Lead Service Line Occurrence." *Journal–American Water Works Association* 108 (4): E182–E191.

Council of Economic Advisers (2017). Discounting for Public Policy: Theory and Recent Evidence on the Merits of Updating the Discount Rate. Council of Economic Advisers Issue

Brief, January 2017. Retrieved from https://obamawhitehouse.archives.gov/sites/default/files/page/files/201701_cea_discounting_issue_brief.pdf on October 12, 2020.

Currie, J., J. Graff Zivin, K. Meckel, M. Neidell and W. Schlenker (2013). "Something in the Water: Contaminated Drinking Water and Infant Health." *Canadian Journal of Economics* 46 (3): 791–810.

Currie, J., J. Graff Zivin, J. Mullins and M. Neidell (2014). "What Do We Know About Short- and Long-Term Effects of Early-Life Exposure to Pollution?" *Annual Review of Resource Economics* 6 (1): 217–247.

Danagoulian, S. and D. Jenkins (2020). Rolling Back the Gains: Flint Water Switch Undermines Progress of Maternal Health in Pregnancy (Working Paper).

Dave, D. M. and M. Yang (forthcoming). "Maternal and Fetal Health Effects of Working during Pregnancy." *Review of Economics of the Household*.

Dignam, T., R. B. Kaufmann, L. LeStourgeon and M. J. Brown (2019). "Control of Lead Sources in the United States, 1970-2017: Public Health Progress and Current Challenges to Eliminating Lead Exposure." *Journal of Public Health Management and Practice* 25 (Supplements 1 Lead Poisoning Prevention): S13–S22.

Edwards, M. (2014). "Fetal Death and Reduced Birth Rates Associated with Exposure to Lead-Contaminated Drinking Water." *Environmental Science & Technology* 48 (1): 739–746.

Environmental Protection Agency (EPA) (2008). Lead and Copper Rule: A Quick Reference Guide. June 2008. Retrieved from https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=60001N8P.txt on June 22, 2020.

Environmental Protection Agency (EPA) (2016a). Lead and Copper Rule Revisions White Paper. October 2016. Retrieved from https://www.epa.gov/sites/production/files/2016-10/documents/508_lcr_revisions_white_paper_final_10.26.16.pdf on June 22, 2020.

Environmental Protection Agency (EPA) (2016b). Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems.

Office of Water. EPA 816-B-16-003, March 2016 (Updated). Retrieved from https://www.epa.gov/sites/production/files/2019-07/documents/occtmarch2016updated.pdf on June 22, 2020.

Environmental Protection Agency (EPA) (2019). Strategies to Achieve Full Lead Service Line Replacement. October 2019. Retrieved from https://www.epa.gov/sites/production/files/2019-10/documents/strategies_to_achieve_full_lead_service_line_replacement_10_09_19.pdf on June 22, 2020.

Environmental Protection Agency (EPA) (2020). Basic Information about Lead in Drinking Water. Last updated on August 4, 2020. Retrieved from https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water on September 25, 2020.

Eriksson, J. G., E. Kajantie, C. Osmond, K. Thornburg and D. J. P. Barker (2010). "Boys Live Dangerously in the Womb." *American Journal of Human Biology* 22 (3): 330–335.

Fedinick, K. P. (2018). What's in Your Water? An Updated Analysis. Retrieved from https://www.nrdc.org/experts/kristi-pullen-fedinick/whats-your-water-updated-analysis on September 25, 2020.

Gardella, C. (2001). "Lead Exposure in Pregnancy: A Review of the Literature and Argument for Routine Prenatal Screening." *Obstetric and Gynecologic Survey* 56 (4): 231–238.

Government Accountability Office (2018). Drinking Water: Approaches for Identifying Lead Service Lines Should Be Shared with All States. Report to Congressional Committees GAO-18-620. September 2018. Retrieved from https://www.gao.gov/assets/700/694648.pdf on June 22, 2020.

Graff Zivin, J., M. Neidell and W. Schlenker (2011). "Water Quality Violations and Avoidance Behavior: Evidence from Bottled Water Consumption." *American Economic Review: Papers and Proceedings* 101 (3): 448–453.

Grossman, D. S. and D. J. G. Slusky (2019). "The Impact of the Flint Water Crisis on Fertility." *Demography* 56 (6): 2005–2031.

Gulson, B. L., C. W. Jameson, K. R. Mahaffey, K. J. Mizon, M. J. Korsch and G. Vimpani (1997). "Pregnancy Increases Mobilization of Lead from Maternal Skeleton." *Journal of Laboratory and Clinical Medicine* 130 (1): 51–62.

Hertz-Picciotto, I. (2000). "The Evidence that Lead Increases the Risk for Spontaneous Abortion." *American Journal of Industrial Medicine* 38 (3): 300–309.

Hu, H. and M. Hernandez-Avila (2002). "Invited Commentary: Lead, Bones, Women, and Pregnancy—The Poison Within?" *American Journal of Epidemiology* 156 (12): 1088–1091.

Institute of Medicine (U.S.) Committee on Understanding Premature Birth and Assuring Healthy Outcomes; R. E. Behrman and A. S. Butler, editors (2007). "Preterm Birth: Causes, Consequences, and Prevention." Washington (D.C.): National Academies Press (U.S.); 2007. Retrieved from https://www.ncbi.nlm.nih.gov/books/NBK11362/ on October 12, 2020.

Keiser, D. A. and J. S. Shapiro (2019). "US Water Pollution Regulation over the Past Half Century: Burning Waters to Crystal Springs?" *Journal of Economic Perspectives* 33 (4): 51–75.

Khazan, O. (2019). The Trouble with America's Water: Lead-Tainted Drinking Water Is Not Only a Problem in Flint and Newark. *The Atlantic*, September 11, 2019. Retrieved from https://www.theatlantic.com/health/archive/2019/09/millions-american-homes-have-lead-water/597826/ on June 22, 2020.

Klemick, H., H. Mason and K. Sullivan (2020). "Superfund Cleanups and Children's Lead Exposure." *Journal of Environmental Economics and Management* 100: 102289.

Kraemer, S. (2000). "The Fragile Male." *BMJ: British Medical Journal* 321 (7276): 1609–1612.

Li, Q. and W. A. Pizer (2018). The Discount Rate for Public Policy over the Distant Future. National Bureau of Economic Research Working Paper No. 25413.

McCarthy, J. (2017). In US, Water Pollution Worries Highest Since 2001. Social & Policy Issues, March 31, 2017. Retrieved from https://news.gallup.com/poll/207536/water-pollution-worries-highest-2001.aspx on October 12, 2020.

McGeehan, P. (2016). High Lead Levels Found at More Newark Schools. *The New York Times*, March 31, 2016. Retrieved from https://www.nytimes.com/2016/04/01/nyregion/lead-in-newark-schools-water.html on June 22, 2020.

Rabin, R. (2008). "The Lead Industry and Lead Water Pipes 'A MODEST CAMPAIGN'." *American Journal of Public Health* 98 (9): 1584–1592.

Sandvig, A., P. Kwan, G. Kirmeyer, B. Maynard, D. Mast, R. R. Trussell, S. Trussell, A. Cantor and A. Prescott (2008). Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues. AWWA Research Foundation and the U.S. Environmental Protection Agency. Retrieved from https://archive.epa.gov/region03/dclead/web/pdf/91229.pdf on June 22, 2020.

Thompson, J. L., B. E. Scheetz, M. R. Schock, D. A. Lytle and P. J. Delaney (1997). Sodium Silicate Corrosion Inhibitors: Issues of Effectiveness and Mechanism. In Proceedings of 1997 American Water Works Association (AWWA) Water Quality Technology Conference. Denver, CO.

Troesken, W. (2008). "Lead Water Pipes and Infant Mortality at the Turn of the Twentieth Century." *Journal of Human Resources* 43 (3): 553–575.

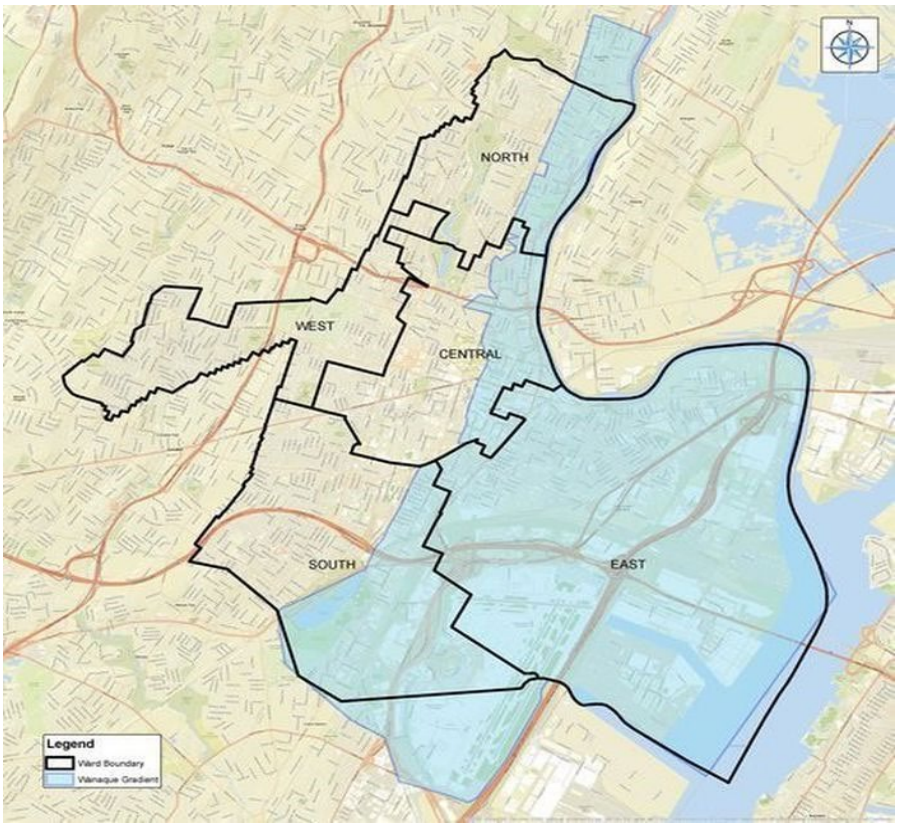
Wallace, T. C., C. Reider and V. L. Fulgoni (2013). "Calcium and Vitamin D Disparities Are Related to Gender, Age, Race, Household Income Level, and Weight Classification but Not Vegetarian Status in the United States: Analysis of the NHANES 2001–2008 Data Set." *Journal of the American College of Nutrition* 32 (5): 321–330.

Wang, R., X. Chen and X. Li (2019). Something in the Pipe: Flint Water Crisis and Health at Birth. IZA Discussion Paper Series No. 12115.

Wehby, G. L., D. M. Dave and R. Kaestner (2020). "Effects of the Minimum Wage on Infant Health." *Journal of Policy Analysis and Management* 39 (2): 411–443.

World Health Organization (WHO) (2011). Lead in Drinking-Water: Background Document for Development of WHO Guidelines for Drinking-Water Quality. Retrieved from https://www.who.int/water_sanitation_health/water-quality/guidelines/chemicals/lead.pdf on June 22, 2020.

Panel A



Panel B

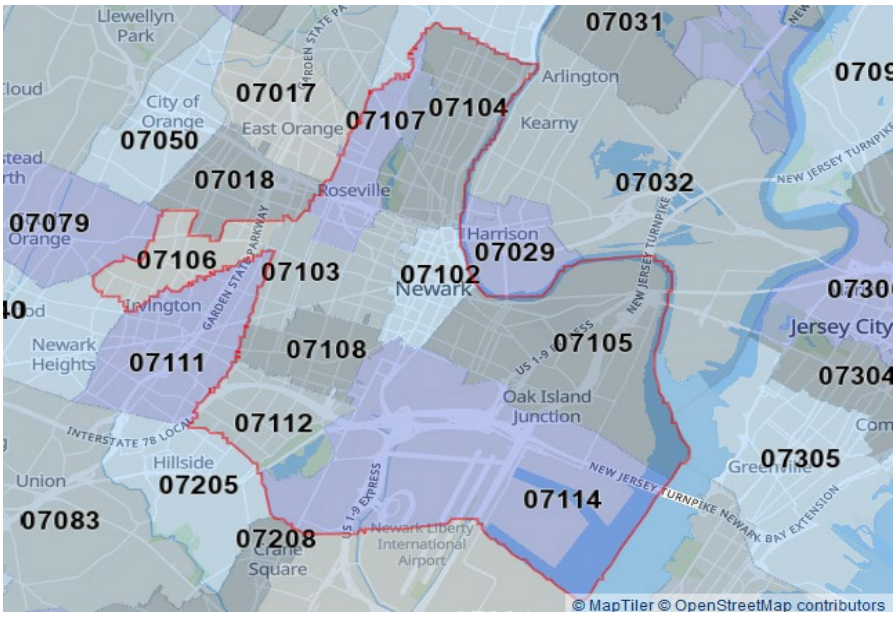
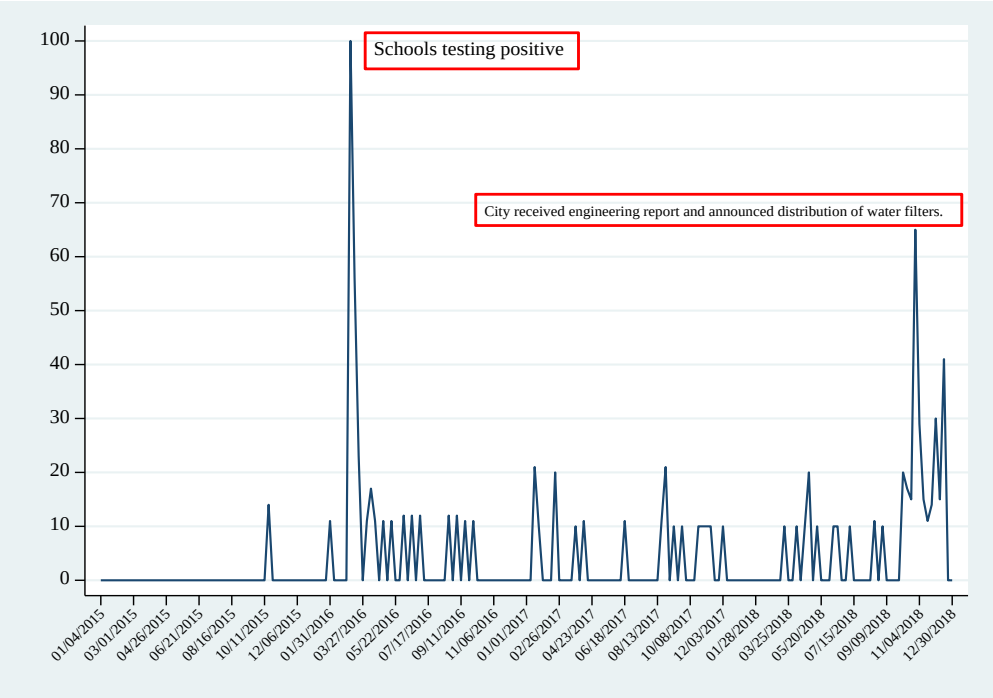


Figure 1: City of Newark and the Areas Served by the Two Water Treatment Plants

Notes: Panel A shows a map of the City of Newark (divided into five wards) and the areas served by the two water treatment plants. The area shaded in blue is served by the Wanaque plant; the rest of the city (i.e., the unshaded area) is served by the Pequannock plant (source: https://www.nj.com/essex/2018/11/newarks_now_under_a_national_spotlight_for_lead_in.html, accessed in November 2019). Panel B shows a map of the city of Newark showing the zip codes within the city's boundary (source: https://www.unitedstateszipcodes.org, accessed in November 2019).

Panel A



Panel B

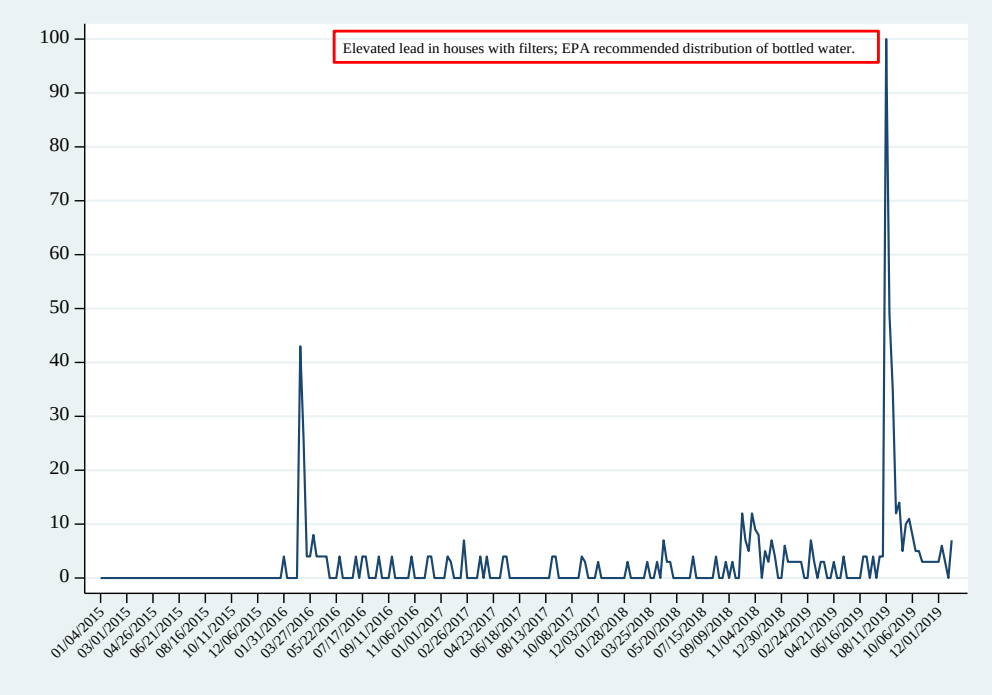
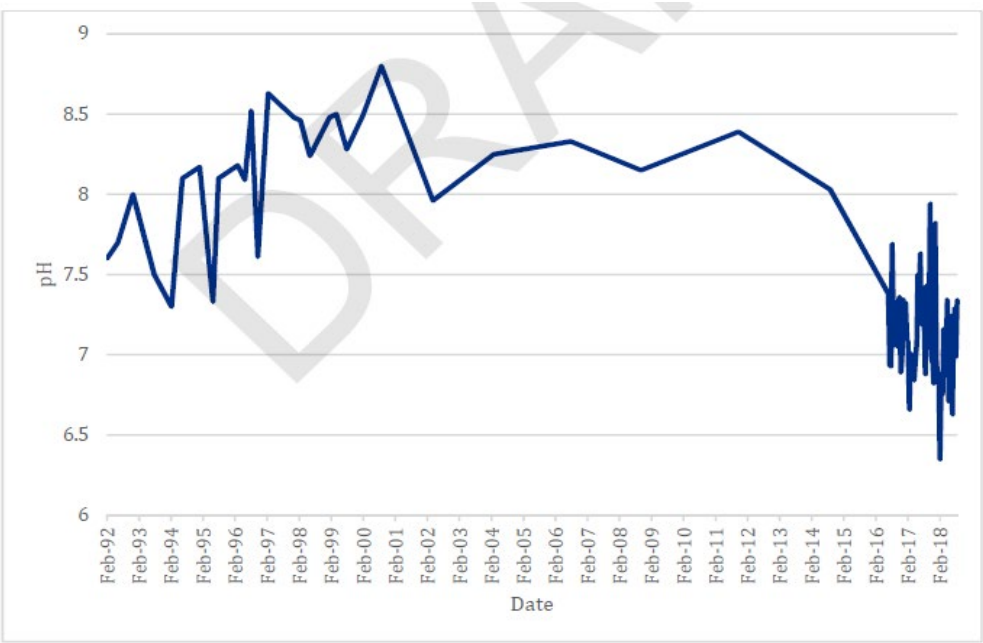


Figure 2: Google Trends Based on Query Terms "Lead + Water + Newark"

Notes: Panels A and B are for 2015–2018 and 2015–2019, respectively. Google trends do not provide the absolute number of queries. In each period (2015–2018 or 2015–2019), the day with the largest number of queries is indexed to be 100 (the maximum), and queries on all other days are measured relative to this maximum.

Panel A



Panel B

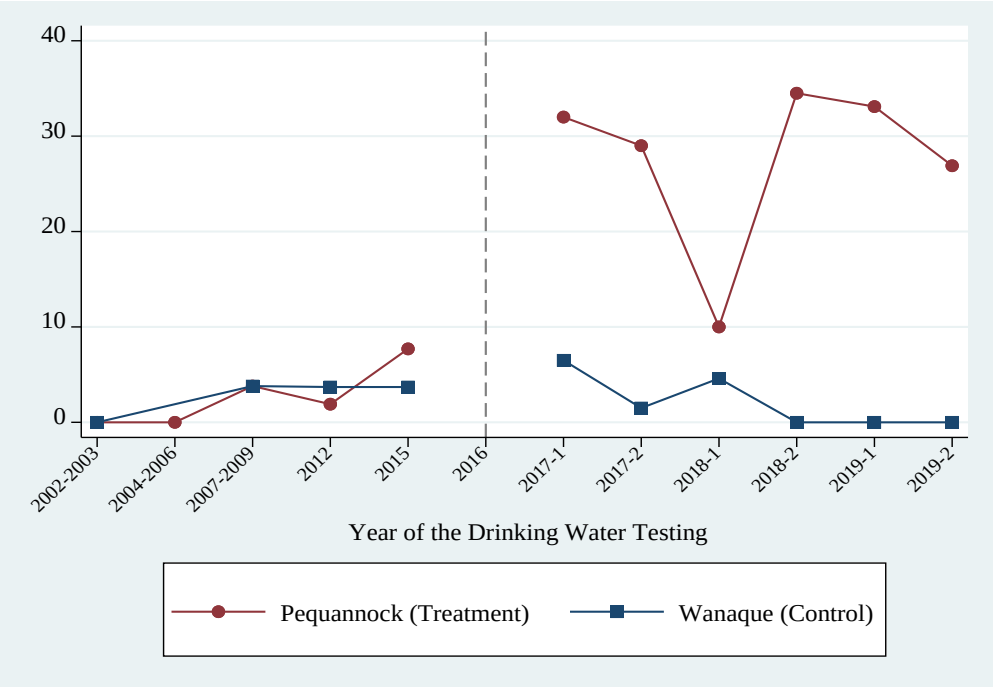
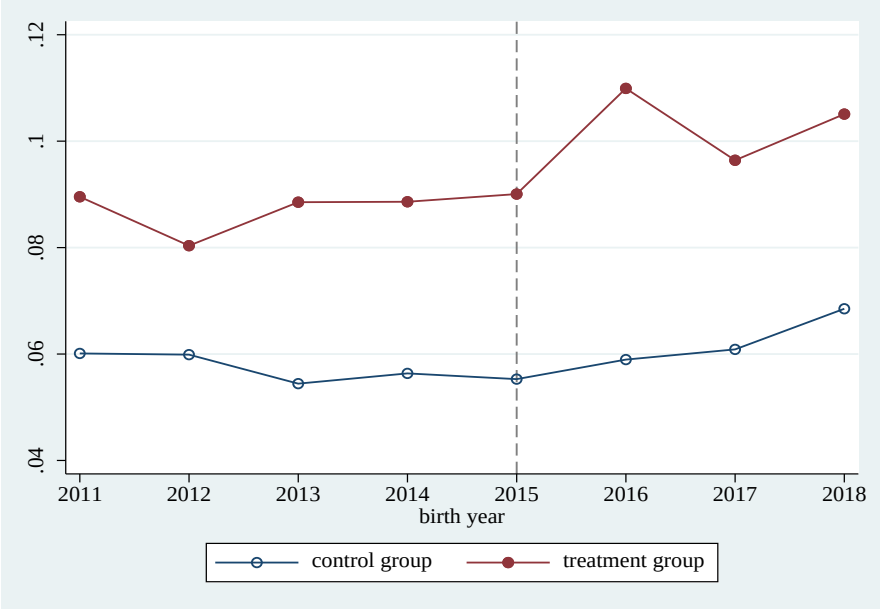


Figure 3: pH Levels of Water Delivered by the Pequannock Plant (Panel A) and Percent of Drinking Water Testing Samples with Results Showing Lead Levels in Drinking Water > 15 ppb (Panel B)

Notes: The figure in Panel A is reproduced from the report by the CDM Smith entitled "Pequannock WTP Corrosion Control Review and Recommendations—Draft. City of Newark Lead and Copper Rule Compliance Study" (City of Newark, 2018). The original figure in the report is denoted "Figure ES-3 – Historic Pequannock WTP Delivered Water pH". The authors have received permission from the CDM Smith to include this figure in this study. In Panel B calculations were based on data from City of Newark (2018) and New Jersey Drinking Water Watch from the New Jersey Department of Environmental Protection (https://www9.state.nj.us/DEP_WaterWatch_public/index.jsp, accessed in February 2020).

Panle A: Main Specification



Panel B: Alternative Specification

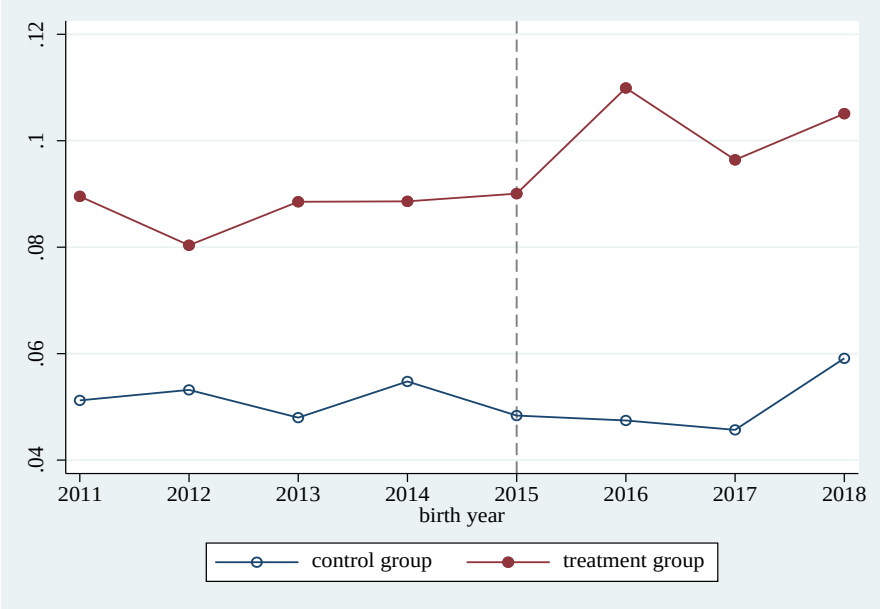


Figure 4: Low Birth Weight Rate Averaged by Treatment/Control Status and Birth Year

Notes: Panels A and B show the low birth weight (LBW, birth weight < 2,500 grams) rate averaged by treatment/control status and birth year. In both panels the treatment group includes the following zip codes (of Newark): 07103, 07106, 07107, 07108 and 07112. In Panel A the control group includes the following zip codes (of Newark): 07102, 07104, 07105 and 07114. In Panel B the control group includes the following zip codes (of Newark): 07105 and 07114.

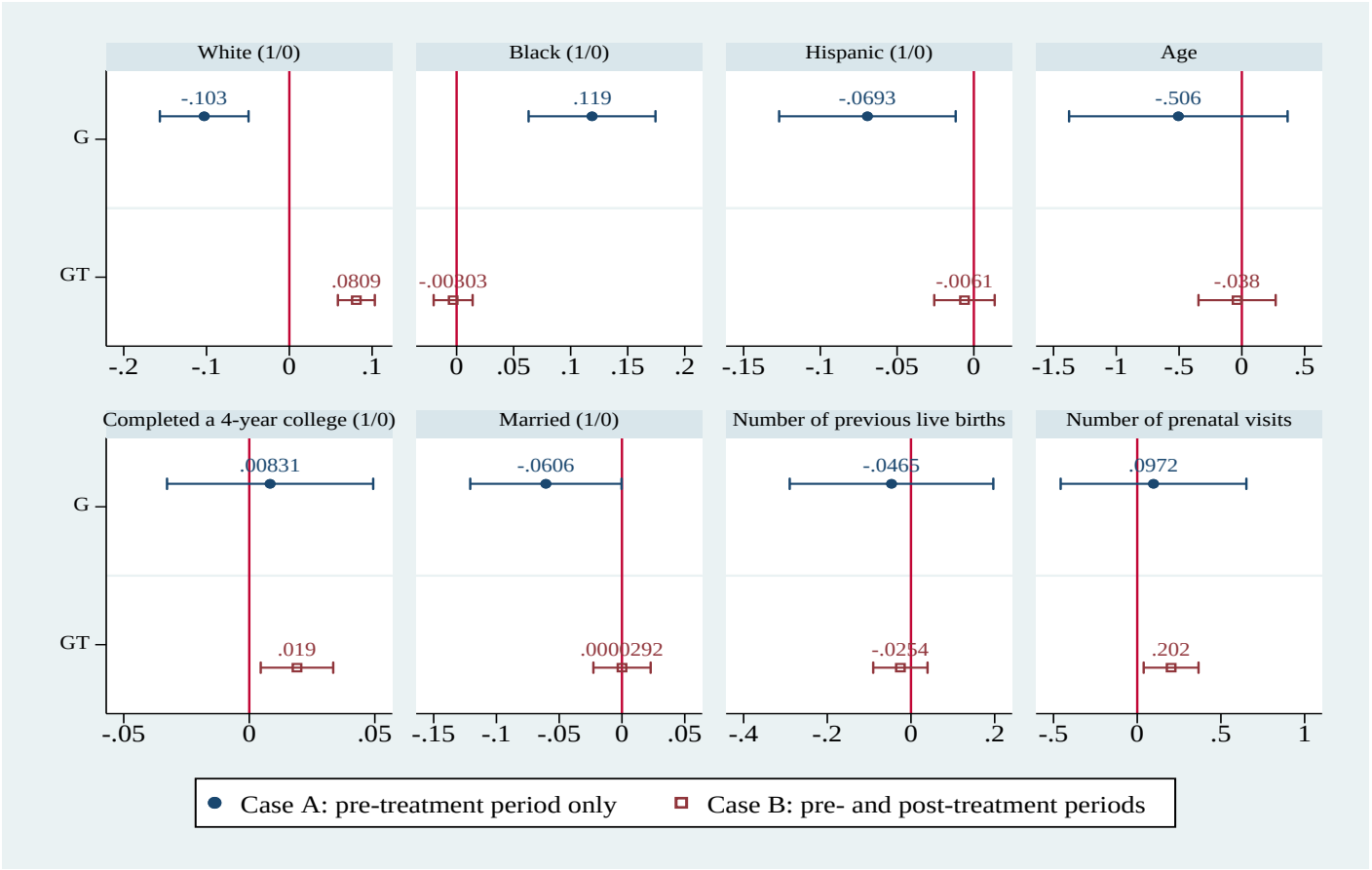
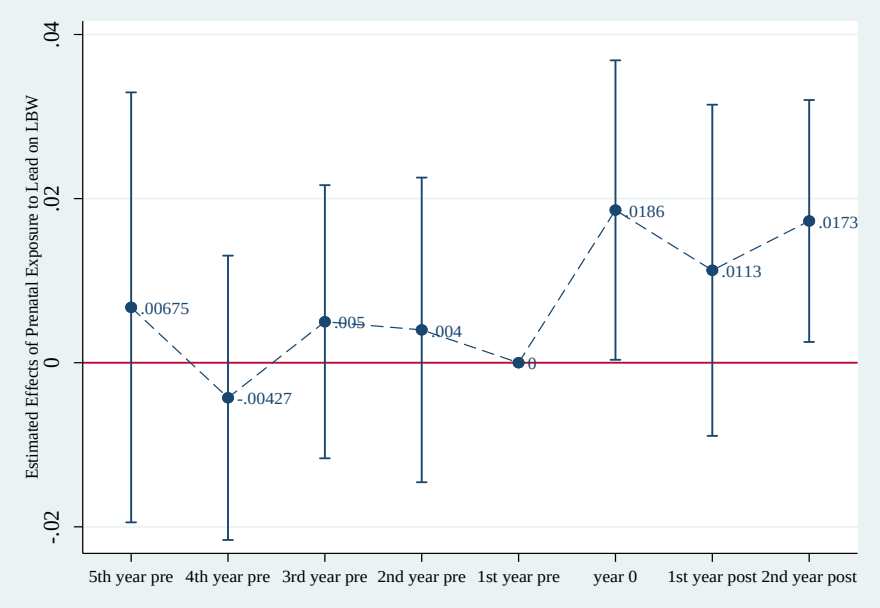


Figure 5: Comparisons of Maternal Demographic Characteristics between the Treatment Group and the Control Group

Notes: The estimation samples include live and singleton births among mothers who live in Newark, New Jersey. The treatment group (G = 1) includes mothers living in the following zip codes (of Newark): 07103, 07106, 07107, 07108 and 07112. The control group (G = 0) includes mothers living the following zip codes (of Newark): 07102, 07104, 07105 and 07114. The pre-treatment period (T = 0) includes births that occurred between 2011 and 2015. The post-treatment period (T = 1) includes births that occurred between 2016 and 2018. Each subgraph contains two "rope ladder" plots, showing the point estimates and the associated 95% confidence intervals of the coefficients "G" and "G×T" of the following two cases, respectively: 1) Case A, where "G" is the coefficient in the ordinary least squares (OLS) regression of a maternal demographic characteristics on an intercept and G, together with year and month of birth fixed effects and residential address fixed effects, only for the pre-treatment period; 2) Case B, where "G×T" is the coefficient in the OLS regression of a maternal demographic characteristics on an intercept, T, and G×T, together with year and month of birth fixed effects and residential address fixed effects, for the entire sample period (i.e., pre- and post-treatment periods). Standard errors in all regressions are clustered by year and month of birth. The numbers of observations in Cases A and B are 19,340 and 30,707, respectively.

Panle A: Main Specification



Panel B: Alternative Specification

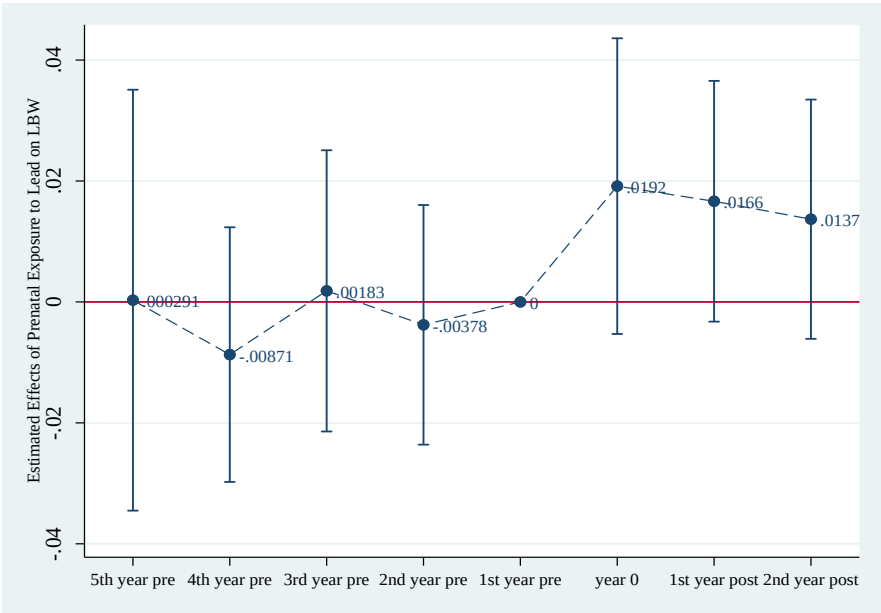


Figure 6: Event Study Analyses, Effects of Prenatal Exposure to Lead on Low Birth Weight

Notes: Panels A and B show the event study of the effects of prenatal exposure to lead on low birth weight (LBW, birth weight < 2,500 grams). The estimation samples include live and singleton births among mothers who live in Newark, New Jersey. The outcome variable is low birth weight (LBW, birth weight < 2,500 grams). The intervals reported (in the "rope ladder" plots) are constructed at the 90% confidence level. Birth years are from 2011 to 2018. Birth year 2016 is defined as year 0, when the treatment was present. The reference category is birth year 2015 (i.e., the year before the treatment was present). In both panels the treatment group includes the following zip codes (of Newark): 07103, 07106, 07107, 07108 and 07112. In Panel A the control group includes the following zip codes (of Newark): 07102, 07104, 07105 and 07114. In Panel B the control group includes the following zip codes (of Newark): 07105 and 07114. Standard errors are clustered by year and month of birth. The number of observations in Panel A is 30,707. The number of observations in Panel B is 23,901.

Table 1: Summary Statistics

Samples:	Control Zip Codes		Treated Zip Codes		Full
	Pre-Lead	Post-Lead	Pre-Lead	Post-Lead	sample
	(1)	(2)	(3)	(4)	(5)
Birth weight (in grams), among singleton births	3300.631	3269.355	3200.420	3166.989	3230.981
	[517.113]	[544.956]	[553.798]	[603.527]	[556.428]
Low birth weight (1/0): birth weight < 2,500 grams, among singleton births	0.055	0.062	0.086	0.103	0.078
	[0.228]	[0.240]	[0.281]	[0.304]	[0.267]
Gestational length (in weeks), among singleton births*	38.667	38.981	38.466	38.729	38.655
	[2.052]	[1.863]	[2.334]	[2.304]	[2.193]
Preterm (1/0): gestational length < 37 weeks, among singleton births*	0.078	0.061	0.102	0.091	0.087
	[0.268]	[0.240]	[0.303]	[0.288]	[0.282]
Female baby (1/0)	0.502	0.500	0.491	0.486	0.494
	[0.500]	[0.500]	[0.500]	[0.500]	[0.500]
Mother's age	28.346	29.332	27.597	28.538	28.271
	[6.043]	[6.136]	[6.222]	[6.118]	[6.168]
Mother being White (1/0)	0.685	0.557	0.222	0.190	0.392
	[0.465]	[0.497]	[0.416]	[0.392]	[0.488]
Mother being Black (1/0)	0.234	0.217	0.730	0.694	0.509
	[0.424]	[0.412]	[0.444]	[0.461]	[0.500]
Mother being Hispanic (1/0)	0.675	0.690	0.273	0.298	0.452
	[0.468]	[0.463]	[0.446]	[0.457]	[0.498]
Mother having completed a four-year college or higher (1/0)	0.141	0.123	0.140	0.134	0.136
	[0.349]	[0.329]	[0.347]	[0.341]	[0.343]
Mother being married (1/0)	0.342	0.384	0.244	0.296	0.304
	[0.475]	[0.486]	[0.430]	[0.456]	[0.460]
Number of previous live births the mother had	1.109	1.158	1.255	1.298	1.210
	[1.230]	[1.227]	[1.390]	[1.413]	[1.331]
Mother having previous preterm birth (1/0)	0.011	0.023	0.013	0.032	0.018
	[0.103]	[0.149]	[0.114]	[0.177]	[0.133]
Number of prenatal visits	9.667	9.712	8.734	8.943	9.182
	[3.564]	[3.886]	[3.831]	[4.070]	[3.848]
Mother having smoked before or during pregnancy (1/0)	0.049	0.049	0.085	0.077	0.068
	[0.215]	[0.216]	[0.278]	[0.266]	[0.251]
Number of observations	8,229	4,824	11,111	6,543	30,707

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The means and standard deviations (in brackets) reported in the table are based on the estimation sample including live and singleton births among mothers who live in Newark, New Jersey. “Post-Lead” means the period including births that occurred in 2016–2018 (i.e., T = 1); “Pre-Lead” means the period including births that occurred 2011–2015 (i.e., T = 0). “Treated Zip Codes” are 07103, 07106, 07107, 07108 and 07112 (i.e., G = 1); “Control Zip Codes” are 07102, 07104, 07105 and 07114 (i.e., G = 0). *: The numbers of observations are 8,088; 4,625; 10,957; 6,261; and 29,931 for columns 1 through 5, respectively.

Table 2: Effects of Prenatal Exposure to Lead on Birth Outcomes

T = 1 if births occurred in 2016–2018 T = 0 if births occurred in 2011–2015 Dependent variable:	Low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)		Preterm (1/0, equal to 1 if gestational length < 37 weeks)		Birth weight (in grams)		Gestational length (in weeks)		Birth weight (in grams) divided by gestational length (in weeks)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: Main specification										
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112										
G = 0 for zip codes 07102, 07104, 07105 and 07114										
G × T	0.0116*	0.0143**	0.0081	0.0142**	-7.9032	-17.4431	-0.0666	-0.1367**	-0.1662	-0.3425
	(0.0060)	(0.0060)	(0.0059)	(0.0063)	(12.9315)	(14.1093)	(0.0486)	(0.0555)	(0.3029)	(0.3349)
Number of observations	30,707	30,707	29,931	29,931	30,707	30,707	29,931	29,931	29,742	29,742
Panel B: Alternative specification										
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112										
G = 0 for zip codes 07105 and 07114										
G × T	0.0190***	0.0188***	0.0163**	0.0192***	-30.1001**	-36.6243**	-0.0985**	-0.1527***	-0.6090*	-0.6679*
	(0.0064)	(0.0069)	(0.0064)	(0.0067)	(13.1704)	(15.5321)	(0.0472)	(0.0561)	(0.3276)	(0.3896)
Number of observations	23,901	23,901	23,316	23,316	23,901	23,901	23,316	23,316	23,167	23,167
Control variables used in Panels A and B										
Individual level demographic variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Zip code fixed effects	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Residential address fixed effects	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in Newark, New Jersey. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits, and mother having smoked before or during pregnancy (1/0). Standard errors (reported in parentheses) are clustered by year and month of birth. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 3: Effects of Prenatal Exposure to Lead on Birth Outcomes, Robustness Checks

T = 1 if births occurred in 2016–2018 T = 0 if births occurred in 2011–2015 Dependent variable:	Low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)		Preterm (1/0, equal to 1 if gestational length < 37 weeks)		Birth weight (in grams)		Gestational length (in weeks)		Birth weight (in grams) divided by gestational length (in weeks)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: Robustness check #1										
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112										
G = 0 for zip codes 07302, 07304, 07305, 07306, 07307, 07310, 07311 (all of Jersey City, NJ)										
G × T	0.0157***	0.0186***	0.0133**	0.0193***	-14.6984	-22.4718**	-0.0272	-0.0824*	-0.3587	-0.5158**
	(0.0053)	(0.0058)	(0.0056)	(0.0063)	(10.0195)	(10.8871)	(0.0401)	(0.0470)	(0.2403)	(0.2547)
Number of observations	44,459	44,459	43,459	43,459	44,459	44,459	43,459	43,459	43,227	43,227
Panel B: Robustness check #2										
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112										
G = 0 for zip codes of New Jersey cities/towns surrounding Newark: Harrison, Kearny, East Orange, Irvington, Hillside, Orange, Belleville, North Arlington, South Orange, Bloomfield, Jersey City, Elizabeth, Union, Bayonne, and West Orange										
G × T	0.0108**	0.0127**	0.0038	0.0066	-14.8925	-19.1745*	-0.0150	-0.0506	-0.3715	-0.4365*
	(0.0047)	(0.0052)	(0.0055)	(0.0062)	(9.4613)	(10.3920)	(0.0375)	(0.0427)	(0.2266)	(0.2445)
Number of observations	101,190	101,190	98,878	98,878	101,190	101,190	98,878	98,878	98,389	98,389
Control variables used in Panels A and B										
Individual level demographic variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Zip code fixed effects	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Residential address fixed effects	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in New Jersey. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits, and mother having smoked before or during pregnancy (1/0). Standard errors (reported in parentheses) are clustered by year and month of birth. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 4: Effects of Prenatal Exposure to Lead on the Number of Births and on Whether the Birth Is Female

T = 1 if births occurred in 2016–2018

T = 0 if births occurred in 2011–2015

Dependent variable:	Number of births for each zip code-year and month of birth pair	Female (1/0): individual-level analysis
	(1)	(2)
Panel A: Main specification		
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112		
G = 0 for zip codes 07102, 07104, 07105 and 07114		
G × T	0.4322	-0.0118
	(0.9983)	(0.0144)
Number of observations	864	30,707
Panel B: Alternative specification		
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112		
G = 0 for zip codes 07105 and 07114		
G × T	0.2803	0.0044
	(1.3366)	(0.0190)
Number of observations	672	23,901
Panel C: Robustness check #1		
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112		
G = 0 for zip codes 07302, 07304, 07305, 07306, 07307, 07310, 07311 (all of Jersey City, NJ)		
G × T	0.2747	0.0009
	(0.9807)	(0.0107)
Number of observations	1,103	44,459
Panel D: Robustness check #2		
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112		
G = 0 for zip codes of New Jersey cities/towns surrounding Newark: Harrison, Kearny, East Orange, Irvington, Hillside, Orange, Belleville, North Arlington, South Orange, Bloomfield, Jersey City, Elizabeth, Union, Bayonne, and West Orange		
G × T	-0.1575	-0.0030
	(0.7527)	(0.0100)
Number of observations	2,735	101,190
Control variables used in Panels A through D		
Individual level demographic variables averaged at the zip code-monthly level	Yes	No
Individual level demographic variables	No	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes
Zip code fixed effects	Yes	No
Residential address fixed effects	No	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in New Jersey.

In column (1), the dependent variable is the total number of births within each cell defined by the mother's residential zip code and her year and month of childbirth. Individual level demographic variables are averaged over each cell defined by the mother's residential zip code and her year and month of childbirth. These individual level demographic variables include infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits, and mother having smoked before or during pregnancy (1/0).

In column (2), estimations use individual level data. The dependent variable is the newborn being female (1/0). Individual level demographic variables controlled for are mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits, and mother having smoked before or during pregnancy (1/0).

In both columns, estimations use standard errors (reported in parentheses) that are clustered by year and month of birth. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 5: Event Study Analysis, Effects of Prenatal Exposure to Lead on Low Birth Weight

Dependent variable is low birth weight (1/0, equal to 1 if birth weight < 2,500 grams).
Birth years are from 2011 to 2018.
Birth year 2016 is defined as year 0, when the treatment was present.
Birth year 2015 is used as the reference category.
Column (1) uses the main specification: G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112; G = 0 for zip codes 07102, 07104, 07105 and 07114
Column (2) uses the alternative specification: G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112; G = 0 for zip codes 07105 and 07114

	(1)	(2)
G × 2nd year post-treatment	0.0173*	0.0137
	(0.0089)	(0.0119)
G × 1st year post-treatment	0.0113	0.0166
	(0.0121)	(0.0120)
G × year 0	0.0186*	0.0192
	(0.0110)	(0.0147)
G × 1st-year pre-treatment	n/a	n/a
G × 2nd-year pre-treatment	0.0040	-0.0038
	(0.0112)	(0.0119)
G × 3rd-year pre-treatment	0.0050	0.0018
	(0.0100)	(0.0140)
G × 4th-year pre-treatment	-0.0043	-0.0087
	(0.0104)	(0.0127)
G × 5th-year pre-treatment	0.0067	0.0003
	(0.0158)	(0.0210)
Number of observations	30,707	23,901
Control variables		
Individual level demographic variables	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes
Residential address fixed effects	Yes	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in Newark, New Jersey. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits, and mother having smoked before or during pregnancy (1/0). Standard errors (reported in parentheses) are clustered by year and month of birth. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 6: Effects of Prenatal Exposure to Lead on Low Birth Weight by Different Years of Conception

Dependent variable is low birth weight (1/0, equal to 1 if birth weight < 2,500 grams).
T = 1 if births occurred in 2016–2018, and the year of conception is X
T = 0 if births occurred 2011–2015
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112
G = 0 for zip codes 07102, 07104, 07105 and 07114

	X = 2015	X = 2016	X = 2017	X = 2018	X = 2017–2018
	(1)	(2)	(3)	(4)	(5)
G × T	0.0220*	0.0037	0.0151*	0.0015	0.0152**
	(0.0129)	(0.0114)	(0.0084)	(0.0115)	(0.0072)
Number of observations	22,019	22,882	23,001	20,291	23,952
Control variables					
Individual level demographic variables	Yes	Yes	Yes	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes	Yes	Yes	Yes
Residential address fixed effects	Yes	Yes	Yes	Yes	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in Newark, New Jersey. Year of conception is defined by the year of the mother's last menstrual period. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits, and mother having smoked before or during pregnancy (1/0). Standard errors (reported in parentheses) are clustered by year and month of birth. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 7: Effects of Prenatal Exposure to Lead on Prenatal Visits and Maternal Smoking

Dependent variable in column (1) is the number of prenatal visits. Dependent variable in column (2) is maternal smoking before or during pregnancy (1/0).	(1)	(2)
Panel A: Main specification		
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112		
G = 0 for zip codes 07102, 07104, 07105 and 07114		
T = 1 if births occurred in 2016–2018		
T = 0 if births occurred in 2011–2015		
G × T	0.1658*	-0.0111*
	(0.0846)	(0.0063)
Number of observations	30,707	30,707
Panel B: Event study		
Birth years are from 2011 to 2018.		
Birth year 2016 is defined as year 0, when the treatment was present.		
Birth year 2015 is used as the reference category.		
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112		
G = 0 for zip codes 07102, 07104, 07105 and 07114		
G × 2nd year post-treatment	0.3596**	-0.0120
	(0.1522)	(0.0109)
G × 1st year post-treatment	0.3320**	0.0004
	(0.1328)	(0.0104)
G × year 0	0.1641	0.0013
	(0.1343)	(0.0114)
G × 1st-year pre-treatment	n/a	n/a
G × 2nd-year pre-treatment	0.0461	0.0076
	(0.1634)	(0.0126)
G × 3rd-year pre-treatment	0.0497	0.0176**
	(0.1291)	(0.0087)
G × 4th-year pre-treatment	0.4377***	0.0052
	(0.1605)	(0.0086)
G × 5th-year pre-treatment	0.1069	0.0196
	(0.3003)	(0.0198)
Number of observations	30,707	30,707
Control variables used in Panels A and B		
Individual level demographic variables	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes
Residential address fixed effects	Yes	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in Newark, New Jersey. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, and mother having previous preterm birth (1/0). Standard errors (reported in parentheses) are clustered by year and month of birth. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Table 8: Heterogeneous Effects of Prenatal Exposure to Lead on Birth Outcomes

G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112; G = 0 for zip codes 07102, 07104, 07105 and 07114
T = 1 if births occurred in 2016–2018; T = 0 if births occurred in 2011–2015

	Infant's sex		Mother's race and ethnicity					Mother having completed a four-year college or higher		Mother's marital status	
Estimation by subsample:	Male	Female	White	White and non-hispanic	White and hispanic	Hispanic	Black	Yes	No	Married	Not married
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Panel A: Low birth weight (1/0, equal to 1 if birth weight < 2,500 grams) as the dependent variable											
G × T	0.0151	0.0150*	0.0139	-0.0355	0.0132	0.0252	0.0156	-0.0041	0.0137**	0.0142	0.0173**
	(0.0097)	(0.0090)	(0.0104)	(0.0745)	(0.0108)	(0.0312)	(0.0149)	(0.0275)	(0.0065)	(0.0116)	(0.0078)
Number of observations	15,536	15,171	12,033	1,728	10,305	13,867	15,633	4,191	26,516	9,321	21,386
Panel B: Birth weight (in grams)											
G × T	-23.3604	-18.0058	-11.6623	-188.3339	3.4321	-14.1941	-14.2604	40.6062	-24.2456*	-30.1622	-26.8781
	(22.5855)	(20.6896)	(23.8350)	(130.9814)	(26.6874)	(22.2643)	(28.7909)	(53.9424)	(14.5554)	(26.9718)	(16.7787)
Number of observations	15,536	15,171	12,033	1,728	10,305	13,867	15,633	4,191	26,516	9,321	21,386
Panel C: Preterm (1/0, equal to 1 if gestational length < 37 weeks)											
G × T	0.0281***	0.0054	0.0149	0.0221	0.0105	0.0131	0.0247	0.0080	0.0143**	0.0241*	0.0141
	(0.0102)	(0.0097)	(0.0140)	(0.0676)	(0.0152)	(0.0124)	(0.0160)	(0.0253)	(0.0071)	(0.0129)	(0.0087)
Number of observations	15,136	14,795	11,720	1,679	10,041	13,500	15,268	4,114	25,817	9,084	20,847
Panel D: Gestational length (in weeks)											
G × T	-0.2361**	-0.0652	-0.1141	-0.4840	-0.0753	-0.1235	-0.2342*	0.0767	-0.1546**	-0.2172**	-0.1287*
	(0.0912)	(0.0790)	(0.0997)	(0.4427)	(0.1070)	(0.0972)	(0.1357)	(0.2044)	(0.0607)	(0.1013)	(0.0687)
Number of observations	15,136	14,795	11,720	1,679	10,041	13,500	15,268	4,114	25,817	9,084	20,847
Control variables used in Panels A through D											
Individual level demographic variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Residential address fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in Newark, New Jersey. Except those used as the conditioning variables shown in columns (1) through (11), individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits, and mother having smoked before or during pregnancy (1/0). Standard errors (reported in parentheses) are clustered by year and month of birth. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Appendix Table A1: Demographics of Newark, NJ

	Newark	U.S.
Median Household Income	46,400	72,500
At or below poverty (%)	27.2	14.0
High school educated or below, Ages 24+ (%)	63.2	44.9
White (%)	26.8	72.2
Black (%)	49.9	12.7
Hispanic (%)	37.6	18.2
Married, Ages 18+ (%)	25.1	38.9
Immigrant (%)	35.0	14.6
No health insurance (%)	16.2	9.1
Residence is rented (%)	72.2	34.0
Homes built ≤ 1979 (%)	66.5	51.9
Population (2018)	282,090	327,200,000

Notes: Unless otherwise noted, statistics are based on the 2017–2018 American Community Surveys.

Appendix Table A2: Effects of Prenatal Exposure to Lead on Low Birth Weight, Full Set of Coefficient Estimates

Dependent variable is low birth weight (1/0, equal to 1 if birth weight < 2,500 grams).
T = 1 if births occurred in 2016–2018
T = 0 if births occurred in 2011–2015

	For Panel A columns (1) and (2) of Table 2		For Panel A columns (1) and (2) of Table 2, without controlling for prenatal visits and smoking	
	(1)	(2)	(3)	(4)
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112				
G = 0 for zip codes 07102, 07104, 07105 and 07114				
G × T	0.0116*	0.0143**	0.0099*	0.0122**
	(0.0060)	(0.0060)	(0.0059)	(0.0060)
Female baby (1/0)	0.0125***	0.0140***	0.0114***	0.0128***
	(0.0031)	(0.0032)	(0.0031)	(0.0032)
Mother's age	0.0026***	0.0027***	0.0016***	0.0019***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Mother being White (1/0)	-0.0054	-0.0053	-0.0082	-0.0080
	(0.0054)	(0.0058)	(0.0053)	(0.0057)
Mother being Black (1/0)	0.0152***	0.0145**	0.0163***	0.0142**
	(0.0056)	(0.0067)	(0.0057)	(0.0068)
Mother being Hispanic (1/0)	-0.0117***	-0.0108**	-0.0192***	-0.0175***
	(0.0044)	(0.0047)	(0.0043)	(0.0047)
Mother having completed a four-year college or higher (1/0)	-0.0094**	-0.0110**	-0.0127***	-0.0139***
	(0.0046)	(0.0050)	(0.0045)	(0.0049)
Mother being married (1/0)	-0.0150***	-0.0132***	-0.0221***	-0.0198***
	(0.0033)	(0.0036)	(0.0034)	(0.0037)
Number of previous live births the mother had	-0.0102***	-0.0105***	-0.0046***	-0.0053***
	(0.0014)	(0.0016)	(0.0014)	(0.0015)
Mother having previous preterm birth (1/0)	0.1702***	0.1717***	0.1694***	0.1696***
	(0.0184)	(0.0190)	(0.0191)	(0.0194)
Number of prenatal visits	-0.0095***	-0.0096***		
	(0.0005)	(0.0005)		
Mother having smoked before or during pregnancy (1/0)	0.0531***	0.0516***		
	(0.0083)	(0.0083)		
Number of observations	30,707	30,707	30,707	30,707
Other control variables				
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes	Yes	Yes
Zip code fixed effects	Yes	No	Yes	No
Residential address fixed effects	No	Yes	No	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in Newark, New Jersey. Standard errors (reported in parentheses) are clustered by year and month of birth. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Appendix Table A3: Effects of Prenatal Exposure to Lead on Birth Outcomes and Maternal Behaviors, Controlling for Zip Code Specific Time Trend

T = 1 if births occurred in 2016–2018 T = 0 if births occurred in 2011–2015 Dependent variable:	Low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)	Preterm (1/0, equal to 1 if gestational length < 37 weeks)	Birth weight (in grams)	Gestational length (in weeks)	Birth weight (in grams) divided by gestational length (in weeks)	Number of prenatal visits	Maternal smoking before or during pregnancy (1/0)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Main specification							
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112							
G = 0 for zip codes 07102, 07104, 07105 and 07114							
G × T	0.0140**	0.0130*	-13.8839	-0.1397**	-0.2103	0.1357	-0.0088
	(0.0066)	(0.0070)	(14.6032)	(0.0586)	(0.3512)	(0.0901)	(0.0066)
Number of observations	30,707	29,931	30,707	29,931	29,742	30,707	30,707
Panel B: Alternative specification							
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112							
G = 0 for zip codes 07105 and 07114							
G × T	0.0191***	0.0202***	-36.7714**	-0.1461**	-0.6713	0.1819	-0.0129
	(0.0072)	(0.0076)	(16.2055)	(0.0619)	(0.4078)	(0.1327)	(0.0078)
Number of observations	23,901	23,316	23,901	23,316	23,167	23,901	23,901
Control variables used in Panels A and B							
Individual level demographic variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Residential address fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Zip code specific linear time trend of year-month of birth	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in Newark, New Jersey. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits except columns (6) and (7), and mother having smoked before or during pregnancy (1/0) except columns (6) and (7). Standard errors (reported in parentheses) are clustered by year and month of birth. * p-value < 0.1; ** p-value < 0.05; *** p-value < 0.01.

Appendix Table A4: Effects of Prenatal Exposure to Lead on Birth Outcomes and Maternal Behaviors, with Wild Cluster Bootstrap

T = 1 if births occurred in 2016–2018 T = 0 if births occurred in 2011–2015 Dependent variable:	Low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)	Preterm (1/0, equal to 1 if gestational length < 37 weeks)	Birth weight (in grams)	Gestational length (in weeks)	Birth weight (in grams) divided by gestational length (in weeks)	Number of prenatal visits	Maternal smoking before or during pregnancy (1/0)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Main specification							
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112							
G = 0 for zip codes 07102, 07104, 07105 and 07114							
G × T	0.0143***	0.0142***	-17.4431	-0.1367**	-0.3425	0.1658*	-0.0111*
	[0.0059]	[0.0098]	[0.1226]	[0.0382]	[0.1229]	[0.0522]	[0.0852]
Number of observations	30,707	29,931	30,707	29,931	29,742	30,707	30,707
Panel B: Alternative specification							
G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112							
G = 0 for zip codes 07105 and 07114							
G × T	0.0188*	0.0192*	-36.6243**	-0.1527	-0.6679**	0.1463	-0.0125*
	[0.0725]	[0.0537]	[0.0452]	[0.1205]	[0.0366]	[0.2365]	[0.0855]
Number of observations	23,901	23,316	23,901	23,316	23,167	23,901	23,901
Control variables used in Panels A and B							
Individual level demographic variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Residential address fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in Newark, New Jersey. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits except columns (6) and (7), and mother having smoked before or during pregnancy (1/0) except columns (6) and (7). Standard errors are clustered by each zip code of the mother's residence. The number of clusters in Panel A is 9, and the number of clusters in Panel B is 7. Reported in brackets are the *p* -values from the wild cluster bootstrap with 10,000 replications. * *p* -value < 0.1; ** *p* -value < 0.05; *** *p* -value < 0.01.

Appendix Table A5: Event Study Analyses, Effects of Prenatal Exposure to Lead on Low Birth Weight (alternative control groups)

Birth years are from 2011 to 2018.

Birth year 2016 is defined as year 0, when the treatment was present.

Birth year 2015 is used as the reference category.

In all columns: G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112.

In column 1 (i.e., alternative control group #1): G = 0 for zip codes 07302, 07304, 07305, 07306, 07307, 07310, 07311 (all of Jersey City, NJ)

In column 2 (i.e., alternative control group #2): G = 0 for zip codes of New Jersey cities/towns surrounding Newark: Harrison, Kearny, East Orange, Irvington, Hillside, Orange, Belleville, North Arlington, South Orange, Bloomfield, Jersey City, Elizabeth, Union, Bayonne, and West Orange

Dependent variable:	Low birth weight (1/0, equal to 1 if birth weight < 2,500 grams)	
	Alternative control group #1	Alternative control group #2
	(1)	(2)
G × 2nd year post-treatment	0.0148	0.0147*
	(0.0096)	(0.0082)
G × 1st year post-treatment	0.0173	0.0116
	(0.0111)	(0.0100)
G × year 0	0.0262***	0.0241***
	(0.0081)	(0.0082)
G × 1st-year pre-treatment	n/a	n/a
G × 2nd-year pre-treatment	0.0135	0.0115
	(0.0088)	(0.0078)
G × 3rd-year pre-treatment	-0.0013	0.0057
	(0.0094)	(0.0071)
G × 4th-year pre-treatment	-0.0101	-0.0008
	(0.0082)	(0.0068)
G × 5th-year pre-treatment	0.0014	0.0060
	(0.0146)	(0.0139)
Number of observations	44,459	101,190
Control variables		
Individual level demographic variables	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes
Residential address fixed effects	Yes	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in New Jersey. Individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits, and mother having smoked before or during pregnancy (1/0). Standard errors (reported in parentheses) are clustered by year and month of birth. * p -value < 0.1; ** p -value < 0.05; *** p -value < 0.01.

Appendix Table A6: Heterogeneous Effects of Prenatal Exposure to Lead on Birth Outcomes Based on Alternative Specification

G = 1 for zip codes 07103, 07106, 07107, 07108 and 07112; G = 0 for zip codes 07105 and 07114
T = 1 if births occurred in 2016–2018; T = 0 if births occurred in 2011–2015

	Infant's sex		Mother's race and ethnicity					Mother having completed a four-year college or higher		Mother's marital status	
Estimation by subsample:	Male	Female	White	White and non-hispanic	White and hispanic	Hispanic	Black	Yes	No	Married	Not married
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Panel A: Low birth weight (1/0, equal to 1 if birth weight < 2,500 grams) as the dependent variable											
G × T	0.0212*	0.0183*	0.0156	-0.0508	0.0134	0.0155	0.0302	0.0134	0.0151*	0.0128	0.0219**
	(0.0110)	(0.0108)	(0.0117)	(0.0728)	(0.0124)	(0.0110)	(0.0263)	(0.0304)	(0.0079)	(0.0127)	(0.0095)
Number of observations	12,105	11,796	8,217	1,422	6,795	9,192	13,582	3,216	20,685	7,172	16,729
Panel B: Birth weight (in grams)											
G × T	-35.0191	-39.7260	-21.5749	-156.4613	2.1943	-26.8834	-19.3887	-11.8588	-35.1516*	-31.8928	-53.0763**
	(26.4556)	(25.0468)	(27.3337)	(130.3681)	(30.7378)	(24.4553)	(46.1736)	(75.3015)	(18.2909)	(30.9498)	(21.0635)
Number of observations	12,105	11,796	8,217	1,422	6,795	9,192	13,582	3,216	20,685	7,172	16,729
Panel C: Preterm (1/0, equal to 1 if gestational length < 37 weeks)											
G × T	0.0259**	0.0137	0.0191	0.0177	0.0127	0.0183	0.0185	0.0154	0.0166**	0.0157	0.0282***
	(0.0113)	(0.0121)	(0.0148)	(0.0678)	(0.0164)	(0.0132)	(0.0233)	(0.0319)	(0.0081)	(0.0130)	(0.0096)
Number of observations	11,805	11,511	8,025	1,386	6,639	8,964	13,262	3,155	20,161	6,998	16,318
Panel D: Gestational length (in weeks)											
G × T	-0.1922*	-0.1312	-0.1347	-0.4456	-0.1018	-0.1669*	-0.2143	0.1476	-0.1651***	-0.1272	-0.2317***
	(0.0969)	(0.0853)	(0.1027)	(0.4388)	(0.1113)	(0.0978)	(0.1908)	(0.2580)	(0.0605)	(0.1074)	(0.0767)
Number of observations	11,805	11,511	8,025	1,386	6,639	8,964	13,262	3,155	20,161	6,998	16,318
Control variables used in Panels A through D											
Individual level demographic variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-month of birth (i.e., monthly) fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Residential address fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Data are from the 2011–2018 New Jersey birth records on all live births collected by the New Jersey Department of Health. The estimation sample includes live and singleton births among mothers who live in Newark, New Jersey. Except those used as the conditioning variables shown in columns (1) through (11), individual level demographic variables controlled for are infant being female (1/0), mother's age, mother's race and ethnicity (1/0 dummy variables for White, Black, and Hispanic), mother having completed a four-year college education or higher (1/0), mother being married (1/0), number of previous live births the mother had, mother having previous preterm birth (1/0), number of prenatal visits, and mother having smoked before or during pregnancy (1/0). Standard errors (reported in parentheses) are clustered by year and month of birth. * p -value < 0.1; ** p -value < 0.05; *** p -value < 0.01.