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LEAD, MORTALITY, AND PRODUCTIVITY

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ABSTRACT

This paper examines the effect of water-borne lead exposure on infant mortality in American cities over the period 1900-1920. Infants are highly sensitive to lead, and more broadly are a marker for current environmental conditions. The effects of lead on infant mortality are identified by variation across cities in water acidity and the types of service pipes – lead, iron, or concrete – which together determined the extent of lead exposure. Time series estimates and estimates that restrict the sample to cities with lead pipes provide further support for the causal link between water-borne lead and infant mortality. The magnitudes of the effects were large. In 1900, a decline in exposure equivalent to an increase in pH from 6.7 to 7.5 in cities with lead-only pipes would have been associated with a decrease in infant mortality of 12.3 to 14.3 percent or about 22 fewer infant deaths per 1,000 live births. City-level evidence on wages in manufacturing suggests that the adverse health effects of lead may have extended beyond infants.

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1. Introduction

Today lead is a well-known environmental toxin whose adverse effects include infant mortality, morbidity, loss of IQ, and violence. Contemporary analysis has largely focused on lead paint and airborne lead in leaded gasoline and from manufacturing and smelting plants. In the late nineteenth and early twentieth centuries, lead exposure in some locations was far higher than in the second half of the twentieth century, but the delivery mechanism was different. During that period, the dominant source of lead exposure was water. Water acquired lead as it traveled through lead service pipes to homes and businesses. Lead service pipes were widely used. In 1900, 23 percent of the American population lived in cities with some lead service pipes and 11 percent lived in cities with only lead service pipes. The amount of lead leaching depended on the chemical properties of the water passing through the pipes. Doctors and city engineers recognized that lead may have been leaching into the water, but the levels were generally considered safe. Only in the second half of the twentieth century did lead come to be widely recognized as a public health issue.

This paper uses city-level data to examine the effect of water-borne lead exposure on two outcomes, infant mortality and worker productivity in manufacturing, over the period 1900-1920. The focus is on infant mortality, because it is a basic measure of population health and infants are highly sensitive to lead. [1] High levels of lead exposure generally cause morbidity rather than mortality in adults. Common symptoms include fatigue, reduced cognitive functioning and a decrease in gross and fine motor skills. [2] If these symptoms are widespread, they may have effects on outcomes such as worker productivity.

[1] See Needleman and Belinger (1991), National Research Council (1993), and Reyes (2008).
[2] See Bleeker et al. (2007); Dorsey et al. (2006); and Stewart and Schwartz (2007).

Identification of the effect of lead comes from variation in water chemistry across cities with different types of service pipes and from predictions regarding the changing effects of water chemistry and service pipes over time. Water chemistry is exogenously determined by local geology and by whether the water source is above or below ground. The main specification focuses on infant mortality in 1900. A number of strategies are taken to address any residual omitted variable bias. In some specifications, estimation is restricted to cities with lead pipes, so that identification comes solely from exogenous variation in water chemistry. In addition, a rich set of controls are included to control for differences in city size, characteristics, temperature, and water and milk quality. The amount of lead delivered by pipes is in part a function of the age of the pipes. Time series analysis provides further evidence that lead was causing adverse outcomes.

The paper has three main findings. In 1900, a decline in exposure equivalent to an increase in pH from 6.7 (25^{th} percentile) to 7.5 (50^{th} percentile) in cities with lead-only pipes would have been associated with a decrease in infant mortality of 12.3 to 14.3 percent. Given that infant mortality in cities was about 180 per 1000 live births, such a change would lead to about 22 fewer infant deaths per 1,000 live births. Cities could have achieved this by modifying the pH of the water. Even larger gains could be achieved by replacing the lead service pipes with non-lead service pipes. In cities with lead-only service pipes, roughly 25 percent of the decline in infant mortality between 1900 and 1920 appears to have been attributable to decreased lead exposure. In 1899 and over the period 1899-1914, cities with higher infant mortality and cities with lead-only service pipes had lower average wages for manufacturing workers. This suggests that the adverse effects of lead exposure may have extended beyond infant mortality to adult morbidity.

This paper contributes to the literature on the adverse effect of environmental toxins on health. The modern epidemiological literature is large, but the historical literature is very small, despite the high levels of toxins that individuals were exposed to in some historical settings. [3][4][5] The closest paper to this work is Troesken (2008), which examined the effects of lead on infant mortality in Massachusetts in 1900. This paper goes beyond Troesken (2008) in a number of ways. It shows that the adverse health effects of lead were a national and extended over a significant period of time, up to 1920. Further, this paper presents evidence that lead may have been harming worker productivity in manufacturing in these cities.

This paper also contributes to a related literature on the causes of decline in infant mortality. Preston and Haines (1991), in their pioneering book, documented turn of the century infant mortality. Although they discuss possible reasons for the rapid decline in infant mortality over time, including improvements in water and milk quality, the book did not examine the decline directly. Cutler and Miller (2005), using data for 12 large cities for 1900-1936, show the water filtration and chlorination had a large and lasting effect on infant mortality. They attribute 75 percent of the reduction in infant mortality to improvements in water quality. Lee (2007) argues that improvements in milk quality also had a significant effect on infant mortality. In line with the literature, this paper finds that proxies for water and milk quality were strongly related to infant mortality. More importantly, it documents the extent to which declines in the effects of lead over time contributed to declines in infant mortality.

[3] The epidemiological literature is extremely large and cannot be surveyed here. Within the economics literature, Reyes (2008) and Curry and Neidell (2005) examine the effects of toxins on infant mortality.
[4] Interestingly, the literature on the growth of the American economy has had little to say about toxins or health more broadly. See Fogel (1964), Fishlow (1966), Chandler (1977), Rosenberg (1981), Wright (1990), Nelson and Wright (1992), Abramovitz and David (2000), Davis and Gallman (2001), and Kim and Margo (2004). An important exception is Fogel (1994), which emphasizes the role of improved nutrition in the growth of the American economy.
[5] Water-related lead exposure remains a concern, even in well-developed countries. See Hayes and Skubala (2009).

Finally, this paper contributes to the literature on health and worker productivity. Using a variety of econometric approaches, recent studies have shown that healthier workers are more productive.[6] Our findings on health and worker productivity in manufacturing are more tentative, but suggest that lead and high infant mortality more generally did affect wages and value added per worker.

2. Lead Water Pipes

Use and Exposure

Lead service pipes were widely used to connect homes and buildings to street mains. Figure 1 shows the distribution of service pipes for 172 large and medium size cities, which represented 84 percent of the urban population in 1900. The Manual of American Waterworks, 1897 reported data on the types of service pipes – lead. plain iron, galvanized iron, cement-lined iron, or steel – in use by city. In 1897, lead pipes were used exclusively by 42 percent of cities, a mixture of lead and non-lead pipes was used by 25 percent of cities, and non-lead pipes were used by 33 percent of the cities. The sample and cities' choice of service pipes are discussed in detail in section 4.

Evidence suggests that lead dissolved from the interior lining of service pipes was the primary source of lead in drinking water during the late nineteenth and early twentieth century. In its 1900 investigation, the Massachusetts State Board of Health passed water from the same well through iron and lead service lines. Lead levels in water that passed through lead service lines were three times higher than the levels for iron service lines and eight times higher when

[6] Levin (1985), Strauss and Thomas (1998), Shastry (2002) and Miguel and Kremer (2004) examine the effect of worker health on productivity. Bloom, Canning, and Sevilla (2004) and Weil (2007) take a similar approach using macro-level data. Acemoglu and Johnson (2007) and Young (2005) examine the effect of disease on growth.

the water was allowed to stand overnight.[7] An experiment conducted by two New York health officials in the 1930s found similar results.[8]

The amount of lead that water could absorb from service pipes was large. The current EPA limit is 15 parts per billion (ppb), and evidence suggests that most water is well below that limit. The Massachusetts investigation found that in the typical household in the state, the average amount of lead in water after normal use was 315 ppb, and the average amount after standing overnight was 870 ppb. The largest value of a household in any town after ordinary use was 5,000 ppb, and the largest value when left standing overnight was 11,000 ppb. Data for New York City suggest that between 1870 and 1940 lead levels in city water were also very high.[9]

Water was the primary source of lead exposure during the period 1900-1920. The relative importance of air-borne lead today is largely attributable to the dramatic fall in water lead levels over the last century. At 10 parts per billion, which is a little below the current EPA threshold of 15 parts per billion, water would account for 7 percent of adult blood lead and 14 percent of child blood lead. At 350 parts per billion – a level that would have been common a century ago – water-borne lead can account for 90 percent of an adult's blood-lead level.[10]

The Chemistry of Water and Lead

The amount of lead added to drinking water by leaching of lead service lines was affected by the chemistry of the water running through the pipes.[11] Water chemistry depended on a variety of exogenous factors including geology, soil, and whether water was from a surface or underground water source. Acidity and hardness were determined by the types of rock and soil

[7] All reports of the Massachusetts State Board of Health are cited as MSBH. MSBH (1900), pp. 491-97
[8] Quam and Klein (1936).
[9] See Troesken (2006), pp. 6-7.
[10] See Troesken (2006) and the references cited in Chapter 2, footnote 86.
[11] Lead service pipes were 90-100 percent lead. The lead was sometimes mixed with small amounts of copper or antimony.

the water came into contact with as it traveled to the city either on the surface or in an aquifer.[12] As will be discussed further, water chemistry tends to be stable over time.

Figure 2 shows that under laboratory conditions, lead leaching increases nonlinearly at low levels of pH. (Note that low pHs are more acidic and that pH is on a log scale. The 5th percentile of acidity in our sample is 6.4 and the 95th percentile is 8.2, so this is the range of interest.) The historical experience is consistent with the laboratory evidence. Troesken (2006) found similar relationships between water-lead levels and acidity and water-lead levels and hardness using historical data from Massachusetts and Maine.[13]

Figure 2 has three testable implications with respect to infant mortality. [14] First, all else equal, cities without lead pipes should have lower infant mortality than cities with lead pipes. Second, conditional on having lead pipes, cities with low pH should have higher infant mortality than cities with high pH. Third, in cities with lead pipes and pHs below 7.5, cities with lower alkalinity should have higher infant mortality than cities with higher alkalinity. Alkalinity is not reported in the data, but hardness, which is highly positively correlated with alkalinity, is reported. Thus, in cities with lead pipes and pHs below 7.5, cities with lower hardness should have higher infant mortality than cities with higher hardness.

Contemporary Knowledge of Harm

Lead exposure was widely believed to be safe, except at very high levels, into the mid-twentieth century. The delay in understanding the harmfulness of lead in part arose, because lead poisoning was extremely difficult to diagnose. Lead affected multiple body systems, and the symptoms of lead poisoning varied greatly across individuals. For children, diagnosing lead

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[12] For discussions of water chemistry and hydrogeology, see Stumm and Morgan (1996) and Hiscock (2005).

[13] See Troesken (2006), Chapter 6.

[14] The precise relationship between lead and infant mortality will depend on dose-response relationship, but the available evidence suggests that harm was increasing in lead exposure.

poisoning accurately was even more problematic. In a recent social history of lead poisoning in America, Warren (2000) describes cases of childhood lead poisoning during the early twentieth century that were misdiagnosed as feeble-mindedness, summertime colic, appendicitis, polio, convulsions and paralysis of unknown origin.[15]

Other factors beyond the difficulty in diagnosing lead poisoning, including the primitive state of epidemiology and the variation in outcomes associated with lead pipes, also delayed the identification of lead as harmful. Epidemiology required data, but few cities kept systematic data on mortality until the turn of the century. For most cities, it was only with the publication of Mortality Statistics in 1900 that cities could compare their mortality rates to the mortality rates in a wide range of other cities. Even if a city with lead pipes or considering lead pipes had mortality data at hand, inference was complicated by the fact that the negative effects of lead pipes varied with the chemistry of the water supply.

Even as some evidence became available, the consensus remained that lead was only harmful at extremely high levels. With the exception of a few physicians writing in England, medical researchers and governmental authorities argued that lead was a pervasive and unavoidable part of the natural environment and that humans could withstand all but the most extreme levels of exposure.[16] As of 1916, most engineers appear to have believed that concerns about lead service pipes were overblown.[17] In the 1940s, one can find articles in the *Journal of the American Medical Association*, presumably an authoritative medical source, arguing that lead water pipes were generally safe and that consumers had little to worry about.[18]

[15] Warren (2000), pp. 34-35.
[16] See Needleman (1998), (2000), and (2004).
[17] *Engineering News* (hereafter cited as EN), September 28, 1916, p. 595
[18] Troesken (2006), pp. 74, 123-41, 166-68, 186-87.

Indeed, as late as the 1960s, public health officials believed that blood lead levels in children six times the current acceptable level were safe. It was only in the 1970s that lead became a significant public health concern.[19] A national standard for lead in water was first set in 1975. The 1975 standard was 50 ppb. In 1991 it was reduced to 15 ppb.

Given that health was not a major concern, engineers choosing service pipes balanced a variety of other factors including the upfront cost of the pipe, the durability of the pipe, the cost of installation, and political considerations such as whether local manufacturers produced service pipes. Lead service pipes were generally more expensive than other service pipes, but were also more durable. Because of their resistance to corrosion, lead service pipes lasted for thirty-five years. In contrast, plain iron or steel pipe lasted sixteen years; galvanized pipe lasted twenty years; and cement lined pipe lasted twenty-eight years. Lead's malleability made it easier to bend the service main around existing infrastructure and obstructions. As one prominent trade journal wrote: "Lead is in many respects the most satisfactory material to use for service pipes. Its pliability and its comparative freedom from corrosive action make it almost ideal from a mechanical standpoint."[20] Factors such as the types of pipes produced by local firms were likely to have an impact as well, both for costs reasons – pipes were generally expensive to transport – and because local firms were likely to lobby engineers to use their pipes.[21] These issues are examined further in section 4.

3. Ingestion and Health Effects of Lead

[19] See Powell (1997).

[20] Information and quotations in this paragraph come from EN, pp. 594-96 and from the Committee on Service Pipes (1917), p. 328 (hereafter cited as CSP). The editors of the *Engineering News* were not alone in suggesting that lead was the best material for service lines. A survey of the superintendents of forty-one municipal water companies found that about half (20) preferred lead service lines to all other types of lines. This survey was conducted in 1884 by water industry expert from New London, Connecticut. The results were reported in CSP, pp. 346-47.

[21] See Bittlingmayer (1982) for estimates of the costs of transporting cast iron pipes. The costs for other types of pipes were likely to be similar.

In 1900 the vast majority of people living in cities were consuming water that had traveled through service pipes. The most detailed evidence comes from federal censuses of cities in 1890 and 1915. In 1890, almost all large cities had fewer than 20 people per tap.[22] This may sound high, but a tap was a connection to a water main, not a faucet. An apartment building typically only had one or two taps to serve the entire building. By 1915, when more detailed data becomes available, the percentage of the population served was high. The median city had a coverage rate of 95 percent.[23] The worst cities, typically smaller southern cities, had coverage rates of around 70 percent. Alternative water sources were scarce and typically undesirable. Water flowing in creeks, rivers, and ponds was usually highly polluted, as was well water. Bottled water was expensive and of uncertain quality.

Nearly all beverages routinely consumed by adults, including pregnant women, in cities with lead service pipes would have been contaminated by lead. These include water and water-based beverages such as coffee, tea, and beer.[24] The only plausibly uncontaminated beverages would have been fruit juice, wine, and milk, but only if these were produced outside of the city. Running water before using it reduced the leaching of lead, but the resulting levels were still extremely high. For example, in the Massachusetts experiments, running the water reduced the amount of lead in water that traveled through the lead service pipes from 800 ppb to 300 ppb. Modern experience tells a similar story.[25]

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[22] Social Statistics of Cities (1890) Table 29, p. 28. Estimates of per capita consumption in large cities were consistently over 100 gallons per day. Even accounting for industrial use and wastage, most people would have had piped drinking water at home or at work.

[23] Troesken (2004), Table 3.1, p. 39.

[24] Most beer was brewed either at home or at breweries in the city that utilized city water.

[25] See Clement et al (2000).

Fetuses were exposed to lead through their mother's consumption of water, and most milk and water consumed by infants and young children was contaminated. [26] Infants have blood-lead levels that are highly correlated with their mother's blood-lead level, indicating transmission of lead from mother to fetus.[27] Mothers' milk was contaminated. Modern studies show that maternal lead exposure is correlated with lead levels in breast milk.[28] Cows' milk was also contaminated unless the water that the cow drank was coming from a non-lead source. Even if it was coming from a non-lead source, cows' milk was often diluted using water before it was fed to infants.

Modern studies show that lead exposure, even in relatively small amounts, can result in fetal and infant death.[29] Lead can cause mortality through anemia, neurological damage, and kidney failure. Using data on births from 1975-1985, Reyes (2008) showed that the phase-out of leaded gasoline reduced infant mortality rates by 3 to 4 percent.

Lead is associated with adverse health outcomes beyond mortality. The health outcomes are summarized in Table 1 for adults and children by blood-lead levels. At low water-lead levels, blood-lead levels increase rapidly, whereas at high water-lead levels, blood-lead levels increase more slowly.[30] Because adults have a significantly better ability to excrete lead, their blood-lead levels tend to rise more slowly for a comparable level of exposure. A 1993 National Research Council (NRC) report found that even at 10 ug/dL, a low blood-lead level by historical standards, lead impaired nerve conduction and homeostasis in some populations and was associated with high blood pressure in adults. Chronic, long-term lead exposure can impair

[26] For an early study of effects on pregnant women in lead industries, see Department of Labor (1919).
[27] See Goyer (1990).
[28] See Ettinger et al (2004) and Ettinger et al (2006).
[29] See Needleman and Belinger (1991) and National Research Council (1993).
[30] See Troesken (2006), pp. 47-49.

neurological and behavioral functioning among adults. At somewhat higher blood-lead levels, the NRC reported impaired biosynthesis of heme, which is necessary for blood formation. At even higher levels, the available evidence indicates that adults may experience convulsions, mental illness, renal failure, severe anemia, and, in extreme cases, death.

4. Data, Identification, and the Use of Lead Service Pipes

Data

The empirical analysis of lead and infant mortality uses data from four sources: city-level mortality from Mortality Statistics, city-level population and demographic characteristics from the 1900. 1910, and 1920 Censuses of Population, city-level types of service pipes from The Manual of American Waterworks, 1897, and city-level water chemistry from The Water Encyclopedia. Worker productivity data is discussed in section 6.

Data on infant mortality and overall mortality were collected from Mortality Statistics for registration cities every five years from 1900, the year the data series began, to 1920. Registration cities were cities that systematically tracked death rates. All mortality rates are per 100 in population. Infant deaths are more commonly reported relative to live births. For most of the sample period, many cities did not have data on live births. For cities that did have data, the death rate as a percentage of live births and the death rate per 100 in population were highly correlated (0.98).

Almost all large cities and many smaller cities were registration cities. In 1900, there were 330 registration cities. Only seven cities with populations over 40,000 were not registration cities in 1900: Peoria, IL; Fort Wayne, IN; Kansas City, KS; Akron, OH; Wilkes-Barre, PA; Dallas, TX; and Houston, TX. Over time, more cities began systematically collecting death data. By 1920, there were 662 registration cities.

Registration cities were predominantly located in the New England, Mid-Atlantic, and East North Central census regions. This reflects the fact that most cities with sizeable populations were located these regions.

Data from the IPUMs 1900, 1910, and 1920 1-percent samples of the Census of Population are used to control for city characteristics such as city population and shares of the population that were white and foreign-born. 198 cities in 1900 and 263 cities in 1920 had data on both mortality and city characteristics. Matching limits the sample of cities, primarily by eliminating quite small cities.[31]

Information on cities' use of lead pipes in the mid-1890s is from The Manual of American Waterworks, 1897 (Baker 1897).[32] Cities were coded as 1 if they report using iron or other non-lead service pipes, 2 if they report using a mix of lead and non-lead service pipes, and 3 if they report using only lead service pipes. All major cities and most smaller cities in our data sets were listed in the manual. Some cities were listed in the manual, but do not specify the type of service pipe. These cities are not included in the analysis.

Data on cities' water is taken from The Water Encyclopedia (Van Der Leeden 1990). The encyclopedia reports the acidity and hardness of the raw intake water in the 1980s for 166 municipal water systems.[33] For the contemporary characteristics of the raw intake water to be relevant for predicting the extent of lead leaching from service pipes in the early twentieth century, three things need to hold. First, the water source needs not to have changed

[31] In 1900, there were 330 registration cities and 340 cities identified in the IPUMs data. The intersection of the two was 198 cities. The 198 registration cities had an average population of 99,924, whereas the non-registration cities had an average population of 20,506.
[32] There were both earlier and later versions of the manual. The earlier version (1892) was incomplete, and the later version (1915) did not list the type of service pipes.
[33] The encyclopedia does not report acidity and hardness for all cities of interest. Nearest neighbor matching was used to assign acidity and hardness for 7 cities in 1900 with mortality and service pipe data, but not water data. The results are robust to their exclusion.

significantly. Comparison of the water sources listed in the 1897 reference and municipal water systems' information on the internet suggests that the vast majority of cities continued to use the same water sources that they did in 1897.[34] Second, the acidity and hardness for the water source need to be fairly stable over time. Acidity tends to be stable. For example, Davis et al (1994) provides paleolimnological reconstruction of historical pH change in New England lakes as inferred from diatom remains. They find average changes of 0.03 pH units over more than 300 years. [35][36] Hardness is an attribute of the soil and is extremely persistent over time.[37] Third, cities have to not have been treating their water in ways that altered the hardness and acidity of the outgoing water. Today municipalities commonly alter the acidity, and to a lesser degree the hardness, of their water to mitigate corrosion. This practice was uncommon in early twentieth-century America.[38]

The final sample has 172 cities in 1900 and 212 in 1920. In 1900, these cities had a total population of 18,712,950. This represented 62 percent of the urban population, where urban is defined as towns with populations of 2,500 or greater, 84 percent of the cities identified in the

[34] A significant change would be moving from a groundwater source such as a river or lake to an underground source such as an aquifer, since water from these two sources can have different properties. For example, of the thirty largest cities, only four appear to have made changes to their water source. New York added the Delaware River as a source and San Francisco moved from wells to water from the Hetch Hetchy Reservoir. St. Paul, Minnesota shifted from lakes and wells to the Mississippi river, and Toledo shifted from the Maumee River to Lake Erie. Of the four, the one most likely to cause a discrepancy between the current and historical values is San Francisco, because of its shift from an underground source to groundwater from a distant location.

[35] The EPA in its report on The Response of Surface Water Chemistry to the Clear Air Act Amendments of 1990 (2003, p. 5) finds "However, an expectation of large increases in pH is unrealistic based on historical information for sensitive lakes. Today's acidic lakes were marginally acidic in pre-industrial times (typically pH less than 6)." For discussion of the complex relationship between rain acidity and water acidity, see Krug and Frink (1983)

[36] Groundwater acidity could have been affected by industrial air and water pollution. Recall, however, that acidity is a logarithmic sale. So unless industry was dumping highly acidic or highly basic substances into the water on a large scale or very close to the water intake, the effect on the pH of the water is likely to have been fairly small.

[37] According to the United States Geological Survey (2006), "Water hardness is based on major-ion chemistry concentrations. Major-ion chemistry in ground water is relatively stable and generally does not change over time." United States Geological Survey (2006), p. 1.

[38] Troesken (2006), especially pp. 73-75.

IPUMs sample, and 25 percent of the population of the United States in 1900.[39] Figure 3 shows the geographic distribution of the cities in the sample in 1900. In 1920, these cities had a total population of 33,415, 000. This represented 62 percent of the urban population, 88 percent of the population living in cities that were identified in the IPUMs 1920 sample, and 32 percent of the population of the United States in 1920.

Identification

Identification of the effects of lead exploits exogenous variation in the properties of city water. As evidence for the appropriateness of this approach, cities with lead-only pipes were grouped by pH quartiles and average infant death rates were computed. Figure 4 demonstrates that cities with lower pH had consistently higher infant mortality over the period 1900-1920. The small differences between cities with the highest pHs (i.e., the third and fourth lowest pHs) are consistent with the leaching patterns shown in Figure 2.

The following baseline specification is used to identify the effect of lead and pH on infant mortality:

$$mort_i = \alpha_0 + \alpha_1 lead_i + \alpha_2 lead_i \text{ x } ph_i + \alpha_3 ph_i + \beta X_i + \delta S_i + \varepsilon_i \qquad (1)$$

where $mort_i$ is mortality in city i in 1900.[40] Lead is vector of indicator variables indicating whether a city has no-lead pipes, mixed lead and non-lead pipes, or lead-only pipes. The omitted category is no-lead. Because the effects of acidity are expected to differ across cities with no-lead pipes, mixed pipes, and lead pipes, pH is interacted with two lead indicator variables and is

[39] Although IPUMs states that in 1900 "The city of residence is given for households in any city with 25,000+", http://usa.ipums.org/usa-action/variableDescription.do?mnemonic=CITY, the actual data appears to code cities with populations greater than about 2,500. East Cleveland OH is listed as having a population of 2,700. In 1920, cities were only identified if they had populations of 25,000 or more.

[40] Some authors use logged mortality rates, and we considered using them as well. The focus is on (unlogged) rates for two reasons. First, the infant mortality rates in our sample are not very skewed (skewness<=1.1 in all years). More importantly, from a scientific standpoint, it is not obvious that lead should have a proportionate rather than an absolute effect on mortality. The reduction in fit in unreported regressions associated with using logged rates supports the latter interpretation.

included as a control. To address concerns related to selection of cities with lead pipes, an issue which will be discussed further shortly, some specifications will restrict the analysis to cities with lead pipes. All standard errors are robust.

To address concerns about omitted variables, a rich set of controls are included. X_{it} are city characteristics computed from the IPUMs 1900 1-percent sample. These include city population, and the share of the city population that was white, foreign born, and women of child bearing age. Some specifications also include regional fixed effects, to address region-specific differences in mortality rates. S_i is a vector of state climatic characteristics including average temperature and precipitation. These are included because temperature and precipitation are believed to influence mortality, particularly infant mortality.

In some specifications, additional city-level controls are included for water, milk, and women's suffrage. Water purification can influence infant mortality directly and through the health of the mother.[41] Lee (2007) argued that the primary reason why infant mortality in American cities declined in the early twentieth century was improving milk quality. The city death rates from typhoid and non-pulmonary tuberculosis are used as proxies for water and milk quality. Typhoid is a water-borne disease and a fairly sensitive marker of water quality.[42] It is roughly 2 percent of the overall death rate. Non-pulmonary tuberculosis was often the result of contracting bovine, as opposed to human, tuberculosis.[43] The most common way to contract bovine tuberculosis was through contaminated milk. Non-pulmonary tuberculosis was slightly more than 1 percent of the overall death rate. Pasteurization kills bovine tuberculosis, so this is a

[41] See Lee (2007), Ferrie and Troesken (2008), and Condran et al (1984).
[42] Alternatively, one could control for the timing of the adoption of water purification. The primary problem is that water purification tended to be phased in across treatment plants and was not equally effective across cities or over time. Typhoid is a more direct measure of water quality.
[43] See Olmstead and Rhode (2004), Lee (2007), and Meckel (1990).

crude marker for milk quality.[44] Miller (2008) demonstrates that suffrage led to dramatic increases in state and local public health spending. The year that women in the state received the right to vote is controlled for through regional fixed effects.[45] Table 2 presents summary statistics for the dependent and independent variables.

Use of Lead Service Pipes

What determined use of lead pipes? The engineering literature suggests that larger cities would be more likely to use lead pipes, because of their malleability, which allowed installation around existing water, sewer, and gas mains. There may also be geographic variation related to the location of pipe manufacturers. In 1899, the top four states in terms of employment for the production of lead bar, pipe and sheet were Illinois, Pennsylvania, Massachusetts, and New York, and the top two states for wrought iron and steel pipe were Pennsylvania and Ohio.[46] Evidence from the Addyston Pipe case, which involved producers of cast-iron pipe, indicates that there was also a group of manufacturers in Alabama and Kentucky, as well as manufactures in Ohio, New York, New Jersey, Pennsylvania, and Wisconsin.

Cities with lead-only service pipes and cities with lead-only service pipes and low (below median) pH were distributed across census regions. In Figure 5, cities in New England were less likely to use lead pipes than one would expect based on Figure 3. This is reversed when the sample is restricted to cities with lead pipes and low pH. In Figure 6, cities in New England were somewhat more likely to have lead pipes and acidic water and cities in the East North

[44] As with water, milk regulations tended to get phased in over time and their efficacy varied. Cities only began to adopt mandatory pasteurization in the 1910s. Non-pulmonary tuberculosis is likely to be a more direct (although imperfect) measure of milk quality. Other aspects of milk quality are likely to be controlled for by the city size and state temperature data. Bigger cities and cities in warmer places were likely to have lower quality milk, particularly in the summer months, because the milk had to travel substantial distances under warm conditions.

[45] The all cities in the data in the mountain region had suffrage.

[46] 1900 Census of Manufactures, pp. 272, 260.

Central and somewhat less likely to have lead pipes and acidic water. Overall, the geographic distributions of cities in Figures 5 and 6 are not very different than the distribution in Figure 3.

Table 3 explores the determinants of the use of any lead service pipes. The dependent variable in columns 1 and 2 is 0-1, where 1 is whether a city uses any lead pipes (i.e., whether it is mixed lead or lead only). Column 1 confirms that larger cities are more likely to use lead pipes. The main effect is for cities in the top quartile of size, cities above 80,000 in population. It also indicates that there was significant regional variation in the use of lead pipes. In New England, 50 percent of the cities did not use lead pipes, as opposed to about 20 percent in other regions. This may reflect a variety of factors including the proximity to manufacturers, price of various pipes at the time of installation, and regional beliefs about the ideal service pipes.

Column 2 adds a number of control variable including state temperature, state precipitation, the city typhoid rate, and the characteristics of the city water. Temperature and precipitation might influence the choice of pipes if heat, cold, or rain caused them to deteriorate. The city typhoid rate is a measure of water quality and is a check on whether the choice of service pipes was somehow associated with water quality. Only the characteristics of the city water are statistically significant. Cities with harder or lower pH water were more likely to use lead pipes. An increase in hardness of 60, which is roughly the difference between the 25th and 50th percentiles of hardness, increased the probability that a city would choose lead pipes by 4.5 percent. A decrease in pH of 0.8, which is roughly the difference between the 50th and 25th percentiles of pH, increased the probability that a city would choose lead pipes by 14 percent. The engineering literature suggests that the main reason for the latter relationship was corrosion. Acidic water tended to corrode other types of pipes, making lead pipes more attractive.

Columns 3 and 4 use the specifications in columns 1 and 2 to examine the difference between cities with mixed lead and lead only pipes. Again, regions differ in their choice of lead pipes, and top quartile cities in terms of population are more likely to use only lead pipes than cities in the bottom quartile. When additional controls are added, pH and hardness are not statistically significant in predicting whether mixed lead or lead only will be adopted. Typhoid is not statistically significant, suggesting that water quality is not an important determinant. The coefficients on temperature and precipitation are statistically significant, however. Colder states and states with more rainfall were more likely to have lead-only rather than mixed lead service pipes.

Two strategies will be taken to address any possible selection issues arising from the choice of lead pipes. The first is to including a rich set of covariates. The second will be to restrict attention to cities with lead-only service pipes.

5. Lead Service Pipes and Mortality

The Effects of Lead on Infant Mortality

The initial estimation will focus on 1900. 1900 was closest to the year in which service pipes were measured, 1897; cities had little data on infant mortality and the Massachusetts experiments were being conducted, thus cities were almost certainly unaware of adverse health effects of lead; very few cities were filtering and chlorinating their water or pasteurizing their milk, both of which would affect infant mortality; and cities were not yet modifying the acidity and hardness of their water. In later years, these conditions would change, possibly attenuating the relationships between pH and infant mortality.

Table 4 demonstrates lead pipes and low pH were associated with higher city-level infant mortality in 1900. In the baseline regression in column 1, the coefficients on the lead-only indicator variable and on lead-only interacted with pH are statistically significant. Consistent with Figure 2, cities with lead-only pipes had higher infant mortality and the effect was decreasing in pH (increasing in acidity). The coefficients on the mixed lead indicator variable and on mixed lead interacted with pH are not statistically significant, but are of the expected sign.

Columns 2 and 3 indicate that the effects of pH were nonlinear and robust to the addition of a large number of controls. The controls include region fixed effects, city quartile fixed effects, proxies for water and milk quality, demographic characteristics and climate variables. The magnitudes of the coefficients on lead x pH and lead x pH^2 are quite similar in the two columns.

The estimated effects of lead and pH on infant mortality are large. Because of possible selection issues in the choice of lead service pipes, the analysis will focus on the effects of changes in pH for cities with lead-only service pipes. These effects can be thought of in two ways – the effect that a city would receive from directly modifying the pH of the water at the water treatment plant – or a lower bound on the effects of replacing lead service pipes with other non-lead service pipes. The coefficients in column 1 indicate that for a city with lead-only pipes, moving from a pH of 6.7 (25^{th} percentile) to 7.5 (50^{th} percentile) would reduce infant mortality by 12.3 percent. Moving from a pH of 7.5 (50^{th} percentile) to 7.95 (75^{th} percentile) would reduce infant mortality by 6.9 percent. The coefficients in column 3 indicate that for a city with lead-only pipes, moving from a pH of 6.7 (25^{th} percentile) to 7.5 (50^{th} percentile) would reduce infant mortality by 14.3 percent. Moving from a pH of 7.5 (50^{th} percentile) to 7.95 (75^{th} percentile) would reduce infant mortality by a much smaller amount, 1.7 percent.

The coefficients on the disease and demographic control variables are worth noting. The coefficients on typhoid and non-pulmonary tuberculosis are both positive and statistically significant. A one standard deviation increase in typhoid would increase infant mortality by 5 percent and a one standard deviation increase in tuberculosis would increase infant mortality by 4 percent. Cities with more foreign born residents, more non-whites, and larger populations all had statistically significantly higher infant mortality. Mom share is a control for the number of women of child bearing age in city i.[47] It is not statistically significant.

Columns 4 and 5 show that the negative effects of lead on infant mortality are also robust to restricting the sample to cities with some lead pipes and to cities with only lead pipes. In both case, cities with lead-only pipes had higher infant mortality and the effect was decreasing in pH (increasing in acidity). The magnitudes of the effects implied by the coefficients are similar to the effects in column 3.

Table 4 focused exclusively on the effects of pH, yet Figure 2 suggests that hardness, which is highly positively correlated with alkalinity, may affect leaching and thus mortality. One complication is that in Figure 2, increased alkalinity lowered leaching for pH below 7.5 and increased leaching for pH above 7.5. To capture this, a pH-hardness interaction effect was included for pH's below 7.5.[48]

Table 5 provides further evidence on the association among lead pipes, pH, hardness, and infant mortality. In columns 1 and 2 of Table 5, the coefficient on the triple interaction lead-pH-hardness is negative and statistically significant. Conditional on acidity, lower hardness was associated with higher mortality. This is consistent with the patterns in Figure 2, where higher alkalinity/hardness acted to buffer the acidity, reducing leaching. When other covariates are added in column 3, the coefficient on the triple interaction becomes small and statistically

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[47] Women of child bearing ages are defined as married women between the ages of 20 and 40. It was included, because of the possibility that some cities had fewer births and thus fewer infant deaths per 100 population.

[48] In unreported regressions, interaction effects were also included for pH above 7.5. As Figure 2 suggests might be the case, the effects were small and were not statistically significant.

insignificant. The lead-pH interaction effects are statistically significant and of similar size to their values in Table 4.

In sum, Tables 4 and 5 provide evidence that the use of lead service pipes was related to infant mortality in exactly the way that science suggests that it would be. The negative effects of lead on mortality were decreasing in pH (increasing in acidity); the effects were larger at smaller values of pH; and hardness reduced mortality for low values of pH, although it became insignificant when controls were added. The results were robust to inclusion of a rich set of controls and to restricting the sample to cities with any lead pipes and to cities with lead-only pipes.

Although in percentage terms the effect of lead on infant mortality may not seem large, in absolute terms it was enormous. An increase in pH from 6.7 to 7.5 in cities with lead-only pipes was associated with a decrease in infant mortality of 12.3 to 14.3 percent. The overall infant mortality rate per 1,000 live births in 1895 was about 110 for whites and 170 for blacks, and the rate in cities was about 180 in 1900.[49] The estimates suggest that an increase in pH from 6.7 to 7.5 in 1900 would have saved 22 infants per 1,000 live births. Today the infant mortality rate per 1,000 live births is about 7. The share of the population that could have been affected was sizeable. Eleven percent of the United States population in 1900 lived in cities with lead-only service pipes, and 4 percent lived in cities with lead-only service pipes and below median pH. Another 12 percent of the population lived in cities with mixed-lead service pipes, and 6 percent lived in cities with mixed lead service pipes and below median pH.

Further Evidence on Causality

[49] Haines (2008) and Preston and Haines (1991).

This section provides further cross sectional and time series evidence on the relationship between lead, pH, and infant mortality. Thus far, only data for 1900 has been presented. If lead was causing infant mortality, the relationships predicted by Figure 2 should hold in other years.

Lead's effects should also decline over time and be larger for locations with more acidic water. These declines reflect the aging of the stock of lead pipes, the increased tendency of water systems to treat water to reduce acidity, and possible switching of the types of pipes being used away from lead pipes. As lead pipes age, they tend to build up a coating on the inside of the pipes that reduces leaching. Troesken (2006) showed that cities in Massachusetts with higher shares of new lead pipes had higher infant mortality than cities with lower shares of lead pipes and cities with new pipes of other types. Other factors also reduced leaching. After 1905, many cities began to filter their water. Some cities began to treat their water to reduce acidity with the aim of reducing corrosion. One byproduct was reduced leaching. Some cities may have also begun to use non-lead pipes in new housing and to replace broken lead pipes. There is no systematic data on this, but anecdotal reports suggest this was occurring. All of these changes were likely to benefit cities with lead pipes more than cities without lead pipes and cities with lead pipes and low pH more than cities with lead pipes and high pH.

Table 6 shows that the cross-sectional relationships observed in 1900 hold for 1905, 1910, 1915, and 1920. In all of the years, the coefficients on lead-only, lead-only-pH, and lead-only-pH^2 are statistically significant and of the appropriate sign.[50]

The results in Table 6 also suggest that the effects of lead were declining over time. This is consistent with the patterns in Figure 3. The magnitudes of the lead-only effect are declining

[50] The relationships are statistically significant in 1900, 1910, and 1920 with a full set of covariates. They are not in 1905 and 1915, possibly because of the interpolation of the city demographics in those years.

over time. And the magnitudes of the coefficient on lead-only-pH and lead-only-pH^2 are trending towards zero over time.

Table 7 directly tests whether the coefficients were falling over time, by estimating the following specification:[51]

$$mort_{it} = \alpha_0 + \alpha_{1i}\, time \times lead_i + \alpha_{2i}\, time \times region_i + \beta city_i + \varepsilon_{it} \qquad (2)$$

$mort_{it}$ is mortality in city i at time t, time x lead are service pipe-specific time trends (lead-only, mixed lead, no lead), time x region are region-specific time trends, and $city_i$ are city fixed effects.

Column 1 shows that infant mortality was falling over time and that it was falling faster in cities with lead only and mixed lead pipes than in cities with no lead pipes. This is what we would expect, if pipes were ageing, water was being treated to increase the pH, or pipes were being replaced with non-lead pipes.

Column 2 shows that the declines in cities with lead only pipes were not simply being driven by the adoption of water filtration or pasteurization of milk, by changing demographics, or by year to year variation in weather. Declines in the typhoid rate, which were predominantly driven by adoption of and improvements in water filtration, were statistically significantly related to declines in infant mortality. Changes in non-pulmonary tuberculosis, which is a proxy for pasteurization, appear to have been unrelated to changes in infant mortality. Shifts in the share of the population that was white and the number of women of child-bearing age had statistically significant effects on infant mortality of the expected sign. Hotter and drier years had statistically significantly lower infant mortality. The additional of covariates had very little effect on the magnitude and statistical significance of the coefficients on the lead variables.

[51] In unreported specifications, the coefficient on a lead-only-ph^2 term was not statistically significant.

Columns 3 and 4 indicate that the relationship between lead and pH was becoming more positive over time. Cities with lead-only pipes and low pH were experiencing faster declines in infant mortality than cities with lead-only pipes and high pH.

The estimates in Table 7 indicate that the lead may have played a significant role in the decline in infant mortality in cities with lead pipes. Infant mortality declined from 0.396 to 0.223 per 100 between 1900 and 1920. The coefficient on lead-only x time in column 2 suggests that roughly 25 percent of this decline in cities with lead-only pipes may have been as the result of declines in lead exposure.

In sum, the cross sectional results in Table 6 and the time series results in Table 7 provided additional evidence that that relationship between lead service pipes and infant mortality was causal.

6. Lead and Productivity

Mortality and Morbidity

The relationship between lead and mortality is unclear once one moves beyond infant mortality. On average, young children who survive high lead may be more robust than children who faced low or no exposure. Other factors are likely to play roles too, such as (unmeasured) heterogeneity of the health history of non-infants, (unmeasured) heterogeneity in the duration of lead exposure arising from rural to urban migration, and the ability of older children and adults to tolerate relatively high levels of lead exposure.

Table 8 confirms that lead is not strongly related to non-infant mortality.[52] The specifications are similar to those in Table 4. The variable momshare was replaced by controls for the average age of the population, the share of the population under five and the share of the population over

[52] Non-infant mortality is mortality of all individuals over the age of 1.

sixty. The coefficients on the lead variables are small and not statistically significant, as are the implied differences between different pHs for lead-only cities. For example, in column 3 in a lead-only city moving from a pH of 6.7 (25^{th} percentile) to a pH of 7.5 (50^{th} percentile) increases mortality by 0.01, which is less than 1 percent. Further, moving from a pH of 7.5 to a pH of 7.95 in a lead-only city decreases mortality by 0.02, which is less than 2 percent.

Although the link between lead and non-infant mortality is ambiguous, there is considerable evidence that high levels of contemporaneous lead exposure are associated with adult morbidity. Modern evidence comes primarily from industrial studies of workers who have contact with lead through air or skin exposure. These workers exhibit a variety of health problems that might plausibly impact their productivity, including fatigue, anemia, reduced cognitive functioning, and impaired motor skills.[53]

The best historical evidence on water-borne lead exposure comes from an epidemiological study conducted in 1923 by the Massachusetts Board of Health (Wright, Sappington, and Rantoul 1928). The researchers surveyed an approximately random sample of 253 adults from twenty-seven cities with lead pipes in eastern and central Massachusetts. They examined each person, drew blood, gathered data on each person's water supply, measured the length of the lead pipe to their home and surveyed participants about how much they drank and from what sources. It is important to emphasize that none of these people were selected because of their health status or previous experience with lead poisoning. The researchers found 32 percent of the adult males in the sample exhibited two or more symptoms of lead poisoning. Given the conservative nature

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[53] See Stewart and Schwart (2007), Dorsey et al. (2006), and Bleecker et al. (2006). Kosnett et al (2007) review the modern literature on health effects and cognition. See also Shih et al (2007) for a review of the effects on adult cognition.

of the definition and that fact that it relied heavily on evidence of stippling of blood cells, which only occurs in more severe cases, the actual number was probably larger.

The symptoms reported by individuals in the 1923 study and listed in Table 9 could have diminished productivity, but were unlikely to require an adult to miss work. For example, individuals were suffering low hemoglobin, constipation, indigestion, headache, and joint or abdominal pain. It is worth noting that roughly one-quarter of the sample was ingesting fairly low levels of lead (less than 0.1 milligram of lead per day).[54] Slightly less than half of the sample was consuming 0.1-0.5 milligrams of lead per day, and slightly more than one-quarter of the sample was consuming 0.5 milligrams of lead or more.

Thus, cities with high infant mortality due to lead were likely to have higher adult morbidity. One way to (indirectly) examine the effects on adults and the economy more broadly is to look at worker productivity.

Worker Productivity

To examine productivity, data were collected from the 1899, 1904, 1909, and 1914 Censuses of Manufacturing. They include city-level data on the number of workers, wages, the value of capital, and the value of inputs and outputs.[55] These data are quite crude, in the sense that they are city-level and not establishment-level measures. Table 2 contains the summary statistics for 1899.

Table 10 presents evidence that infant mortality and lead were related to wages per worker. Wages may reflect worker health if the average manufacturing worker in a city is less healthy and therefore less productive. The first two columns show that cities with higher infant mortality

[54] Most adults drink at least 1.5 liters of liquid per day, so these individuals would have been drinking water that had less than 100 ppb (= 0.1 mg/L).
[55] We collected data for all of the cities with infant mortality data. For a few cities, manufacturing data were not available.

had lower wages in 1899 and over the period 1899-1914. Cities with one standard deviation higher infant mortality (0.15 in 1899 and 1899-1914) had wages that were 4.0-5.4 percent lower than cities with mean mortality. The next two columns provide evidence that cities with lead pipes had lower wages in 1899 and over the period 1899-1914. Cities with lead pipes had wages that were 5.5-6.4 percent lower than cities without lead pipes. The fifth and sixth columns show that the interaction of lead pipes and pH exhibits the correct relationship in both periods, but is not statistically significant. The final column provides results of a specification where lead and pH are used as instruments for infant mortality. The coefficient on infant mortality is statistically significant, but the instruments are weak (F = 4.7). The estimate implies that cities with one standard deviation higher infant mortality had wages that were 8.7 percent lower than cities with mean mortality.

Table 11 explores the time series effects of infant mortality and lead on wages. The predicted effect of a decline in lead exposure on infant mortality is clear. If lead exposure declines, infant mortality should decline. A decline in lead exposure may not have an immediate effect on worker health, however, because of lead's long term effects on worker health and cognition. Consistent with this, changes within cities in infant mortality had no effect on wages, and the effects of lead appear not to have been changing over time.

Appendix Tables 2-4 investigate the effects of infant mortality and lead on value added per worker, capital per worker, and value added using data for 1899-1914. The most robust relationships are between infant mortality and valued added per worker and between infant mortality and valued added. Cities with high infant mortality had significantly lower value added per worker and value added than cities with low infant mortality. The direct effects of lead tend to be of the expected sign, but are not statistically significant. The IV estimates tend to be negative but statistically insignificant, in part because lead and pH are relatively weak instruments.

Appendix Table 5 examines the time series effects of infant mortality and lead on value added per worker, capital per worker, and value added. In line with Table 11, changes within cities in infant mortality had no effect on outcomes, and the effects of lead appear not to have been changing over time.

In sum, wages and some other measures of productivity in manufacturing were negatively related in cross section to infant mortality and more specifically to lead. Because lead and pH are relatively weak instruments for infant mortality, it is difficult to make strong statements about causality. The results are suggestive, however, and highlight the need for further work on productivity.

7. Conclusion

Using city-level data for 1900-1920, this paper presented evidence that leaching of lead from service pipes into water caused higher infant mortality. The share of the population with exposure to lead was high. Twenty three percent of the U.S. population lived in cities with some lead pipes, and 11 percent lived in cities with lead-only pipes; and roughly half of these cities had relatively acidic water. The effects of lead on infant mortality were substantial. In 1900, an increase in pH from 6.7 (25^{th} percentile) to 7.5 (50^{th} percentile) in cities with lead-only pipes would have been associated with a decrease in infant mortality of 12.3 to 14.3 percent or about 22 fewer infant deaths per 1,000 live births. City officials could have achieved such a change either by modifying the pH of the water or by switching from lead to other types of service pipes. In the latter case, the estimates are lower-bound estimates, since at a pH of 7.5, some lead was still leaching into city water. Time series analysis suggests that roughly 25 percent of the decline in infant mortality in cities with lead-only service pipes from 1900-1920 may have been the result of declines in lead exposure.

Using city-level data for 1899-1914, this paper also investigated the effects of lead and infant mortality on city-level productivity in manufacturing. The evidence on productivity, while not as strong as the evidence on infant mortality, suggests that lead may have been causing morbidity in adults and so adversely affected worker productivity. Average city-level wages in manufacturing were negatively related both to infant mortality and to lead.

The broader significance of these results is twofold. First, they make clear that the impact of environmental pollution can be large and unseen. Few people in 1900 thought lead water pipes were anything more than an arcane engineering decision, without any ramifications on either health or economic activity. Yet, the effects on infant mortality were both large and enduring. Modern studies have documented the relationships between lead exposure and IQ, human capital formation, antisocial behavior, teenage pregnancy rates, and criminal activity.[56] Thus, the adverse effects of lead were likely to have extended beyond infant mortality.

Second, these results suggest environmental pollutants may be related to labor productivity. Improvements in worker health have received almost no attention in discussion of historical productivity. Fogel's 1994 paper was one of the very first to discuss workers, and it emphasized the importance of improvements in nutrition. This paper highlights the need for further work on environmental pollutants and productivity.

[56]It is well-known, for example, that incarcerated populations exhibit higher blood lead levels than does the general population, and these high levels likely preceded life in prison (e.g., Needleman et al. 1996, 2002). There are also studies linking environmental lead levels in specific regions to antisocial behavior and criminal activity, including homicides and violent crime (e.g., Stretesky and Lynch 2001, Nevin 2000, and Reyes 2007).

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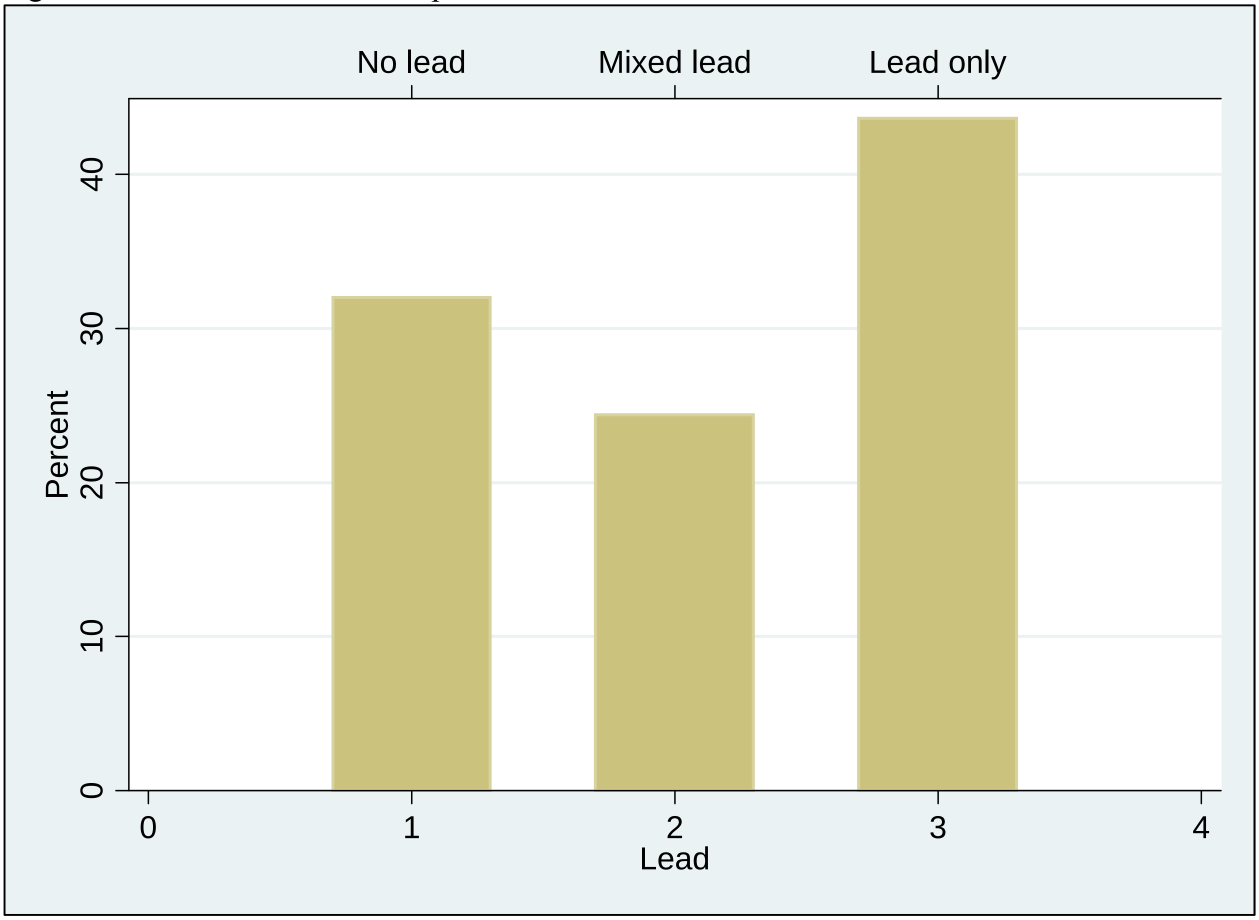
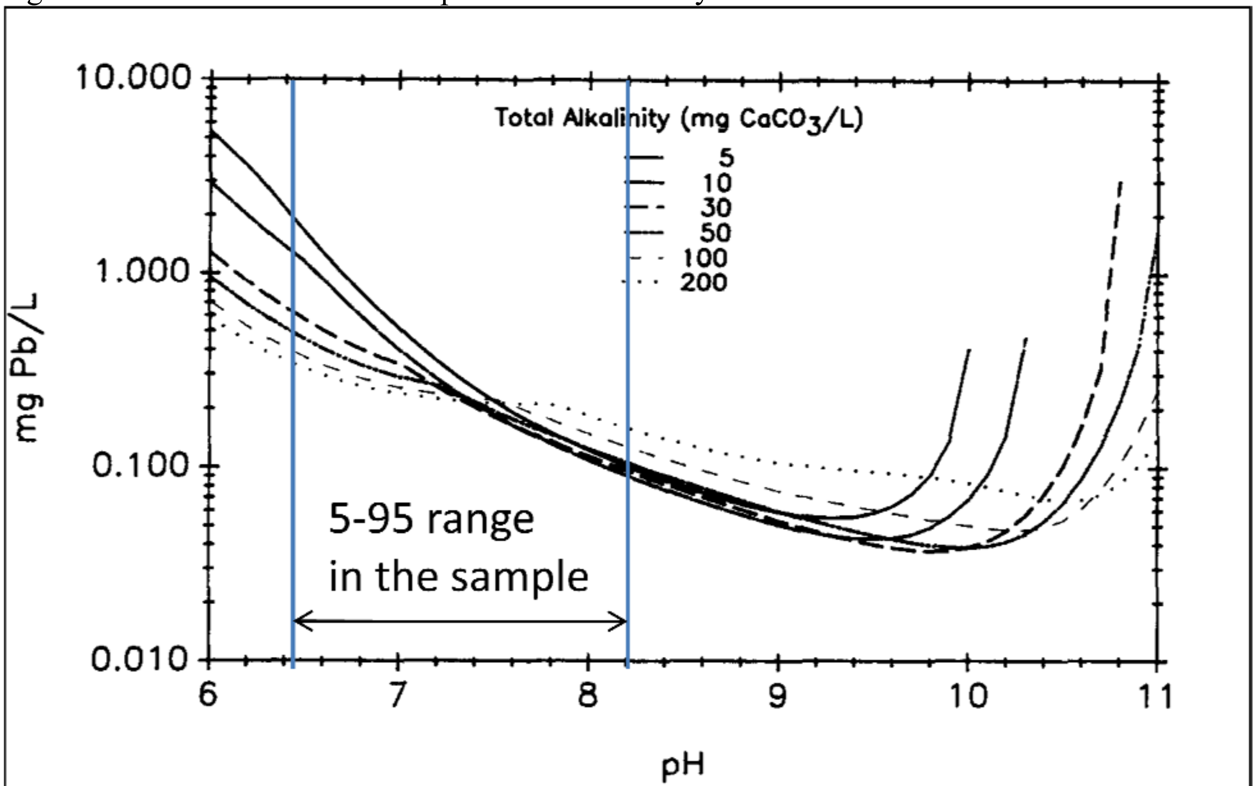
Figure 1: Cities Use of Service Pipes in 1897



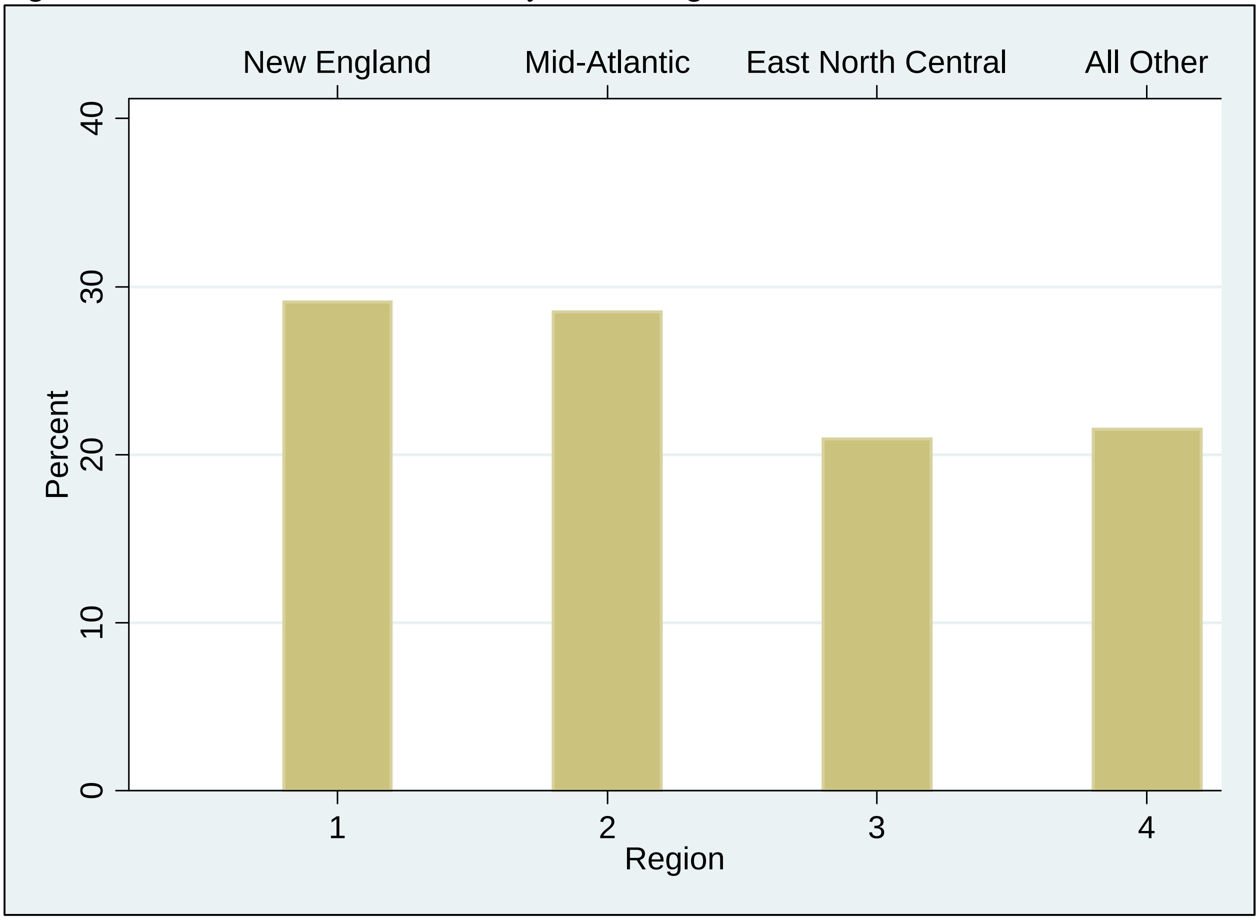
Notes: 1 = No lead, 2 = Mixed lead, 3 = Lead only. The distribution is for the 172 cities in the sample in 1900.

Figure 2: Water-Lead Levels and pH under Laboratory Conditions



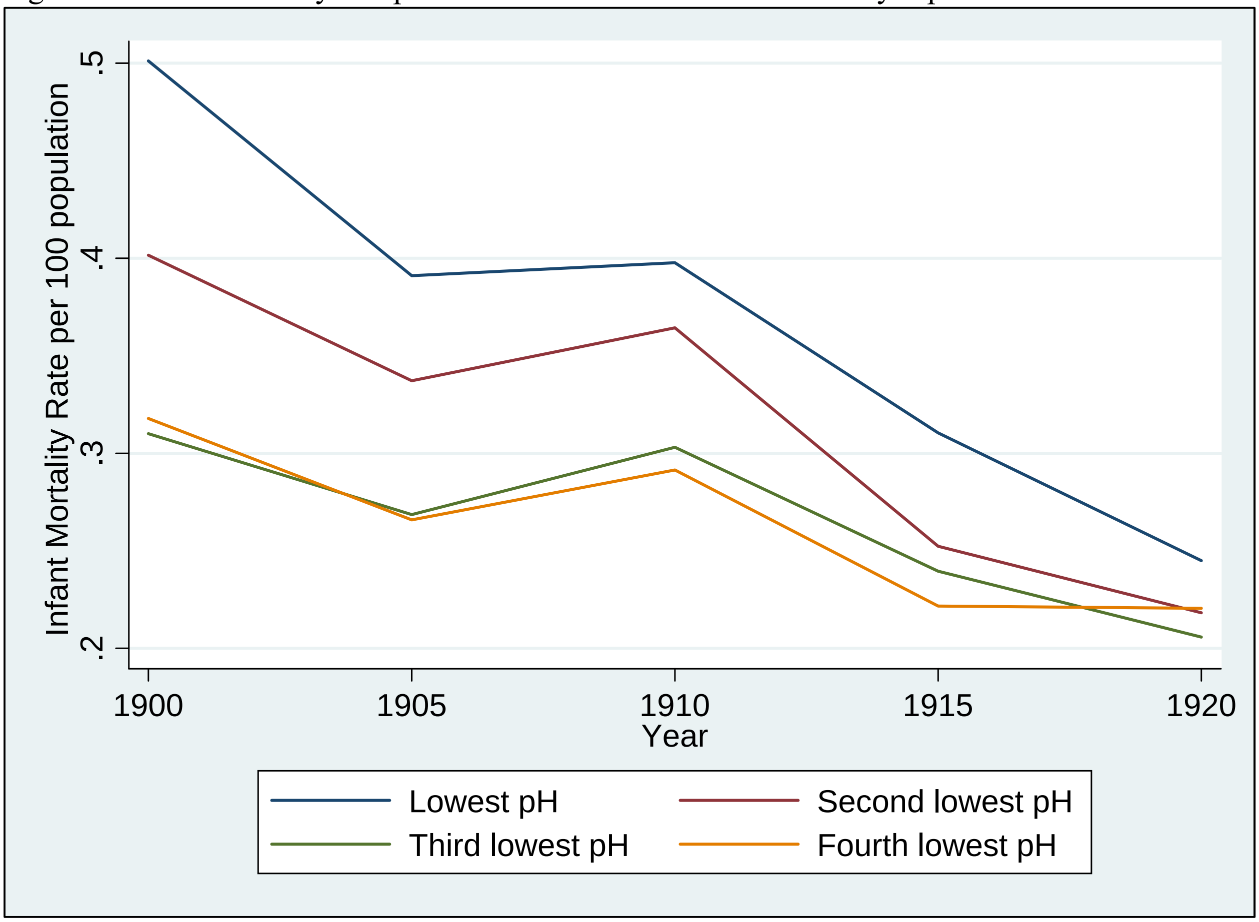
Notes: From Schock (1990). The 5th-95th percentiles of pH in our sample are marked.

Figure 3: Distribution of Cities in 1900 by Census Region



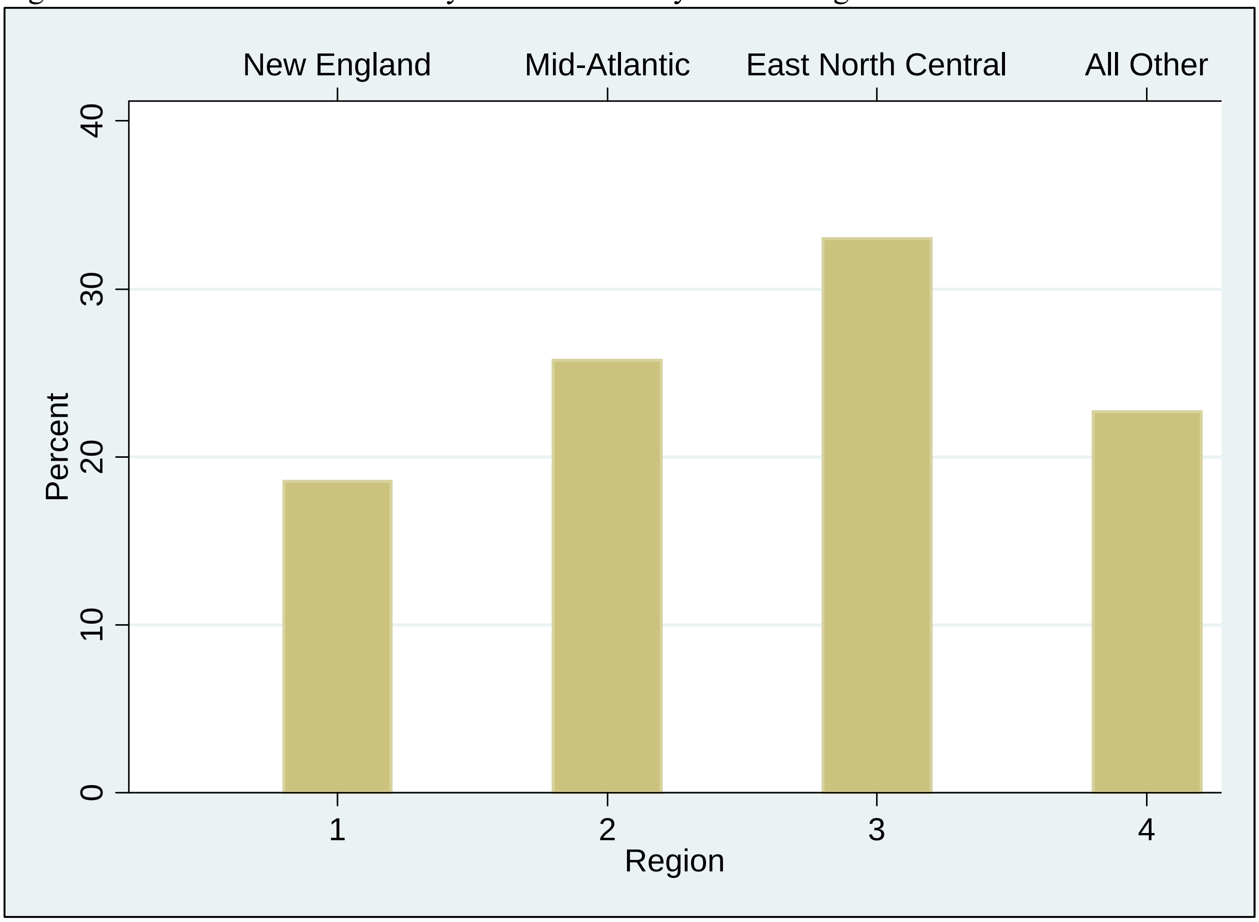
Notes: The distribution is for the 172 cities in the sample in 1900. The "All Other" Census region includes all cities that were located outside of the New England, Mid-Atlantic, and East North Central census regions.

Figure 4: Infant Mortality and pH over Time in Cities with Lead-only Pipes



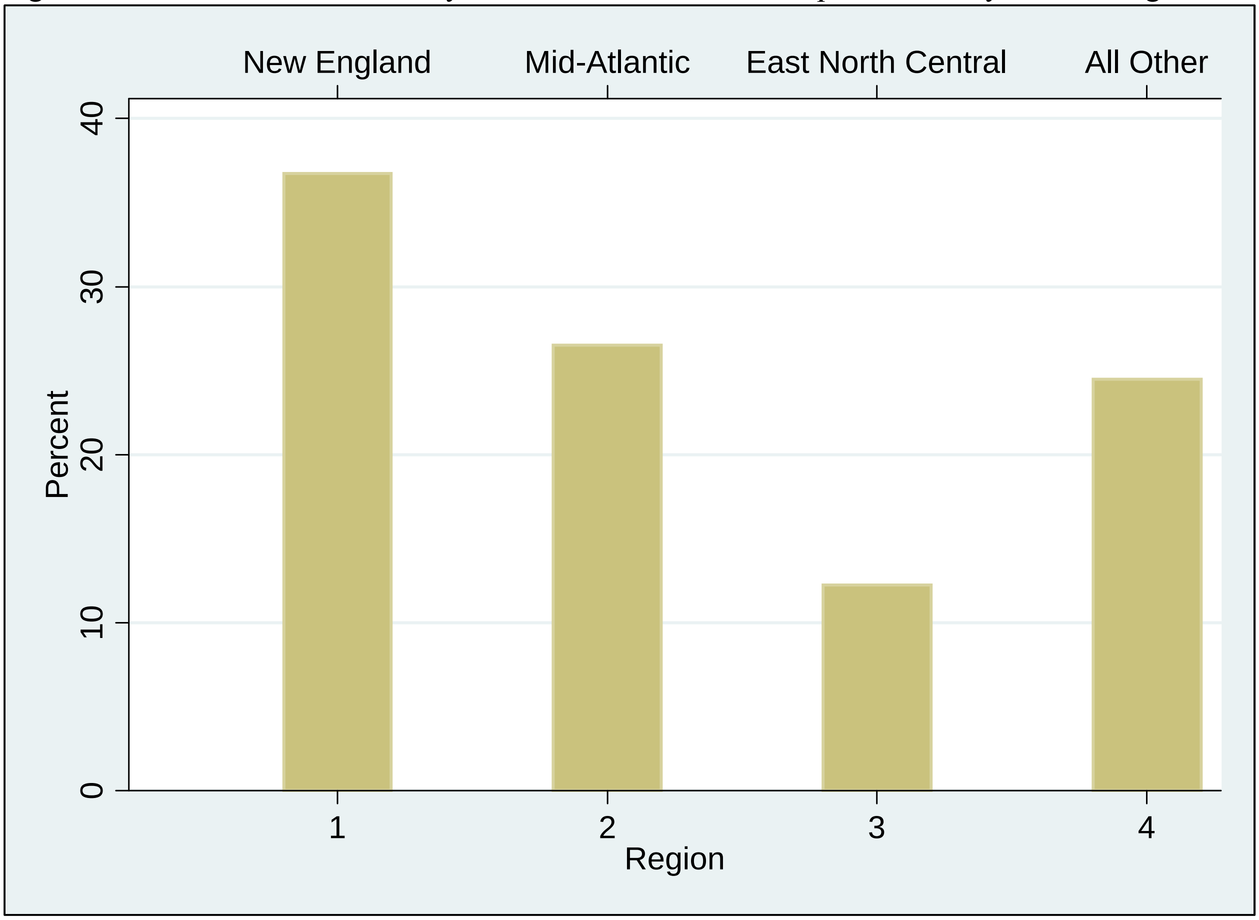
Notes: The distribution is for cities with lead-only service pipes. The number of cities ranged from 75 in 1900 to 92 in 1920. The graph looks very similar if only cities with data in 1900 are included.

Figure 5: Distribution of Lead-Only Cities in 1900 by Census Region



Notes: The distribution is for the 75 lead-only cities in the sample in 1900. The "All Other" Census region includes all cities that were located outside of the New England, Mid-Atlantic, and East North Central census regions.

Figure 6: Distribution of Lead-Only Cities with Below-Median pH in 1900 by Census Region



Notes: The distribution is for the 45 lead-only cities with below-median pH (7.5 or lower) in the sample in 1900. The "All Other" Census region includes all cities that were located outside of the New England, Mid-Atlantic, and East North Central census regions.

Table 1: How Lead Affects Children and Adults

Blood-lead level in µg Pb/dl	Children	Adults
0-9	Uncertain	Uncertain
10-19	Developmental delays, lower Vitamin D metabolism, irregular red blood cells	Hypertension, irregular red blood cells (women)
20-29	Lower nerve conduction velocity	Irregular red blood cells (men)
30-39		Higher systolic blood pressure (men), decreased hearing acuity
40-49	Lower hemoglobin synthesis	Nerve disorders in the extremities, infertility (men); kidney failure
50-100	Colic, frank anemia, kidney failure, brain related disorders	Lower hemoglobin synthesis, lower longevity, frank anemia, brain related disorders
101+	Death	Death

Notes: Based on Troesken (2006), p. 31. The term irregular blood cells refers to erythrocyte protoporphyrin, changes in the size and shape of red blood cells. The term brain related disorders includes mood swings, memory loss, and dementia.

Table 2: Summary Statistics for 1899/1900

Variable	Mean	Std. Dev.	Min	Max
Infant rate	0.396	0.151	0.109	0.844
Non-infant rate	1.438	0.331	0.772	2.702
pH	7.318	0.691	5.7	8.9
Hardness	112.526	98.323	2	445
Typhoid rate	0.041	0.028	0	0.144
NP tub. rate	0.020	0.012	0	0.057
Momshare	0.198	0.032	0.130	0.323
For. born	0.216	0.110	0.000	0.582
White	0.938	0.123	0.324	1.000
City pop in 100s	1087.962	3137.315	85	34355.54
State pcp av	3.328	0.579	0.954	4.754
State temp av	49.324	5.095	40.811	70.622
Avg wages	0.443	0.072	0.285	0.683
Value added /worker	0.851	0.253	0.475	0.285
Capital/worker	1.639	0.785	0.540	7.687

Notes: See Appendix 2 for data sources.

Table 3: Determinants of a City Having Lead Pipes

	(1)	(2)	(3)	(4)
Dep. variable	Any Lead	Any Lead	Lead-only	Lead-only
Sample	Full	Full	Any lead	Any lead
Citypop Q3	0.0761	0.0486	0.241*	0.201
	(0.101)	(0.102)	(0.133)	(0.130)
Citypop Q2	0.0685	0.0573	0.146	0.130
	(0.105)	(0.106)	(0.139)	(0.128)
Citypop Q1	0.280***	0.307***	0.307**	0.311***
	(0.0870)	(0.0886)	(0.121)	(0.116)
Mid-Atlantic	0.323***	0.403***	-0.262**	-0.00399
	(0.0937)	(0.143)	(0.119)	(0.206)
East North	0.320***	0.366**	-0.218*	0.159
Central	(0.0985)	(0.174)	(0.125)	(0.253)
All other	0.270***	0.317*	-0.208	0.368
	(0.103)	(0.171)	(0.127)	(0.276)
pH		-0.176**		-0.160
		(0.0823)		(0.117)
Hardness		0.000742**		0.0000961
		(0.000341)		(0.000489)
Precipitation		-0.0442		0.171*
		(0.0805)		(0.102)
Temperature		-0.00183		-0.0460***
		(0.0100)		(0.0135)
Typhoid		1.467		-1.599
		(1.023)		(1.656)
Constant	0.356***	1.696**	2.639***	5.301***
	(0.0943)	(0.718)	(0.123)	(0.993)
Observations	172	172	117	117
R-squared	0.157	0.196	0.094	0.200

Notes: The dependent variable in columns 1 and 2 equals 1 if a city had any lead service pipes (mixed lead or lead only) and 0 if it had no lead pipes. The dependent variable in columns 3 and 4 equals 1 if a city had lead only service pipes and 0 if it had mixed lead service pipes. Citypop are indicator variables for population quartiles, which run from smallest (Q4) to largest (Q1) Robust standard errors are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Table 4: Effects of Lead and pH on Infant Mortality in 1900

	(1)	(2)	(3)	(4)	(5)
	Inf. Mort	Inf. Mort	Inf. Mort	Inf. Mort	Inf. Mort
Sample	Full	Full	Full	Any Lead	Lead-Only
Lead only	0.486**	5.415**	4.870**	7.332**	
	(0.223)	(2.150)	(2.293)	(2.799)	
Lead only x pH	-0.0611**	-1.441**	-1.323**	-1.990***	-0.597*
	(0.0303)	(0.593)	(0.630)	(0.728)	(0.357)
Lead only x pH^2		0.0956**	0.0899**	0.135***	0.0371
		(0.0406)	(0.0430)	(0.0473)	(0.0239)
Mixed lead	0.455	0.928	-0.641		
	(0.360)	(3.478)	(3.578)		
Mixed lead x pH	-0.0545	-0.210	0.155	1.273*	
	(0.0469)	(0.927)	(0.943)	(0.738)	
Mixed lead x pH^2		0.0121	-0.00905	-0.0880*	
		(0.0615)	(0.0618)	(0.0475)	
pH	-0.0752***	0.800*	0.613		
	(0.0211)	(0.477)	(0.580)		
pH^2		-0.0601*	-0.0449		
		(0.0324)	(0.0391)		
Typhoid			0.882***	0.887***	0.741
			(0.287)	(0.269)	(0.513)
Non-pulm. Tuberc.			1.308*	1.856*	0.675
			(0.693)	(0.999)	(1.861)
Foreign born			0.568***	0.482***	0.705***
			(0.108)	(0.132)	(0.224)
White			-0.651***	-0.642***	-0.802***
			(0.109)	(0.129)	(0.240)
Momshare			-0.354	-0.255	-0.546
			(0.291)	(0.389)	(0.642)
Precip.			0.0252	-0.0295	-0.0334
			(0.0224)	(0.0194)	(0.0201)
Temp.			0.00339	0.0107***	0.0109***
			(0.00277)	(0.00298)	(0.00354)
Region FE	N	N	Y	Y	Y
Citypop quartile FE	N	N	Y	Y	Y
Constant	0.919***	-2.230	-1.412	-4.064	3.065**
	(0.151)	(1.734)	(2.148)	(2.872)	(1.309)
Obs.	172	172	172	117	75
R-squared	0.274	0.298	0.600	0.638	0.660

Notes: Robust standard errors are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Table 5: Effects of Lead, pH, and Hardness on Infant Mortality in 1900

	(1)	(2)	(3)
	Inf. Mort	Inf. Mort	Inf. Mort
Sample	Full	Full	Full
Lead only	0.585***	3.757	4.548*
	(0.224)	(2.395)	(2.585)
Lead only x pH	-0.0685**	-0.961	-1.230*
	(0.0301)	(0.667)	(0.717)
Lead only x pH^2		0.0620	0.0833*
		(0.0459)	(0.0492)
Lead only x pH	-0.000172***	-0.000142***	-0.0000230
x hard if ph≤7.5	(0.0000449)	(0.0000524)	(0.0000572)
Mixed lead	0.578	-1.826	-0.583
	(0.387)	(3.542)	(3.650)
Mixed lead x pH	-0.0660	0.564	0.139
	(0.0498)	(0.949)	(0.964)
Mixed lead x pH^2		-0.0411	-0.00796
		(0.0632)	(0.0634)
Mixed lead only x pH	-0.000163***	-0.000154***	-0.00000559
x hard if ph≤7.5	(0.0000513)	(0.0000569)	(0.0000632)
pH	-0.0540**	0.492	0.546
	(0.0232)	(0.506)	(0.626)
pH^2		-0.0372	-0.0401
		(0.0343)	(0.0422)
pH x hard if ph≤7.5	0.000152***	0.000137***	0.0000214
	(0.0000437)	(0.0000491)	(0.0000534)
Hardness	-0.000192	-0.000274	-0.00000694
	(0.000155)	(0.000169)	(0.000144)
City demog and other controls	N	N	Y
Region FE	N	N	Y
Citypop quartile FE	N	N	Y
Constant	0.753***	-1.219	-1.180
	(0.164)	(1.837)	(2.299)
Observations	172	172	172
R-squared	0.328	0.345	0.602

Notes: The city demographic and other controls are the same controls reported in columns 3-5 of Table 4. Robust standard errors are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Table 6: Effects of Lead and pH on Infant Mortality, 1900-1920

	(1)	(2)	(3)	(4)	(5)
	1900	1905	1910	1915	1920
	Inf. Mort	Inf. Mort	Inf. Mort	Inf. Mort	Inf. Mort
Sample	Full	Full	Full	Full	Full
Lead only	5.968**	4.930**	4.601**	2.741**	3.685***
	(2.390)	(2.285)	(2.086)	(1.251)	(0.897)
Lead only x pH	-1.611**	-1.325**	-1.232**	-0.734**	-1.009***
	(0.661)	(0.626)	(0.566)	(0.341)	(0.246)
Lead only x pH^2	0.108**	0.0889**	0.0826**	0.0495**	0.0685***
	(0.0454)	(0.0426)	(0.0380)	(0.0231)	(0.0168)
Mixed lead	1.926	0.490	0.822	-0.439	1.286
	(3.533)	(2.854)	(2.630)	(1.994)	(1.349)
Mixed lead x pH	-0.506	-0.118	-0.179	0.169	-0.317
	(0.936)	(0.756)	(0.692)	(0.525)	(0.356)
Mixed lead x pH^2	0.0335	0.00778	0.00963	-0.0142	0.0193
	(0.0617)	(0.0498)	(0.0453)	(0.0344)	(0.0234)
pH	0.796	0.625	0.166	0.0108	0.431**
	(0.507)	(0.519)	(0.514)	(0.267)	(0.195)
pH^2	-0.0611*	-0.0461	-0.0151	-0.00348	-0.0310**
	(0.0343)	(0.0345)	(0.0338)	(0.0174)	(0.0129)
Region FE	Y	Y	Y	Y	Y
City quartile FE	Y	Y	Y	Y	Y
Constant	-2.170	-1.813	-0.112	0.334	-1.273*
	(1.853)	(1.919)	(1.927)	(1.011)	(0.729)
Obs.	172	175	214	201	212
R-squared	0.349	0.306	0.234	0.284	0.131

Notes: Robust standard errors are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Table 7: Changes in Lead Effects over Time, 1900-1920

	(1)	(2)	(3)	(3)
	Inf. Mort	Inf. Mort	Inf. Mort	Inf. Mort
Sample	Full	Full	Full	Full
Time	-0.00957***	-0.00844***	-0.00834***	-0.00728***
	(0.00101)	(0.00113)	(0.00106)	(0.00118)
Lead only x time	-0.00213*	-0.00232**	-0.0263***	-0.0254***
	(0.00123)	(0.00118)	(0.00900)	(0.00893)
Mixed lead x time	-0.00233*	-0.00211	-0.0139	-0.0115
	(0.00138)	(0.00136)	(0.0117)	(0.0122)
Lead only x time x pH			0.00335***	0.00321***
			(0.00124)	(0.00123)
Mixed lead x time x pH			0.00164	0.00134
			(0.00155)	(0.00160)
Citypop		-0.00000482**		-0.00000533**
		(0.00000211)		(0.00000217)
Typhoid rate		0.326*		0.334*
		(0.189)		(0.186)
NP tuberc rate		-0.00935		-0.00841
		(0.292)		(0.292)
Foreign born		0.120		0.133
		(0.127)		(0.123)
White		-0.418**		-0.357**
		(0.172)		(0.170)
Momshare		0.371*		0.369*
		(0.220)		(0.220)
State precip		0.0759***		0.0810***
		(0.00578)		(0.00615)
State temp		-0.00673**		-0.00670**
		(0.00269)		(0.00265)
Region x Time	Y	Y	Y	Y
Citypop quart. FE	Y	Y	Y	Y
Constant	0.279***	0.681**	0.302***	0.623**
	(0.0187)	(0.292)	(0.0214)	(0.287)
Observations	974	974	974	974
R-squared	0.817	0.827	0.821	0.831

Notes: Robust standard errors clustered by city are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels. The baeline year is 1900. The panel covers 240 cities that form the unbalanced panel. The number is greater than the largest number of cities in Table 6, because some cities have data for earlier years but not for later years.

Table 8: Effects of Lead and pH on Non-Infant Mortality in 1900

	(1) Non-Inf. Mort.	(2) Non-Inf. Mort.	(3) Non-Inf. Mort.
Lead only	0.646	-5.209	-2.280
	(0.499)	(4.155)	(2.978)
Lead only x pH	-0.0891	1.583	0.660
	(0.0696)	(1.174)	(0.820)
Lead only x pH^2		-0.118	-0.0456
		(0.0819)	(0.0562)
Mixed lead	0.944	9.474	3.320
	(0.964)	(7.190)	(4.665)
Mixed lead x pH	-0.108	-2.418	-0.854
	(0.125)	(1.902)	(1.248)
Mixed lead x pH^2		0.155	0.0557
		(0.125)	(0.0831)
pH	-0.0304	0.497	0.0371
	(0.0483)	(0.918)	(0.740)
pH^2		-0.0363	-0.00158
		(0.0628)	(0.0494)
Typhoid rate			2.761***
			(0.765)
NP tuberc rate			0.756
			(1.519)
Foreign born			-0.114
			(0.273)
White			-1.382***
			(0.231)
Age			0.0352***
			(0.0102)
Sh Pop ≤ 5			-0.000260*
			(0.000154)
Sh Pop ≥ 60			0.000937***
			(0.000349)
State precip			0.0145
			(0.0520)
State temp			0.0187***
			(0.00599)
Year FE	Y	Y	Y
Citypop quart. FE	Y	Y	Y
Constant	1.633***	-0.266	0.640
	(0.337)	(3.314)	(2.882)
Observations	172	172	172
R-squared	0.065	0.098	0.667

Notes: Robust standard errors are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Table 9: Lead Poisoning in Massachusetts, 1923

	Poisoning Cases (n=63)	Non-Poisoning Cases (n=190)
	Percentage of cases in which symptom is observed	
Irregular blood cells	89	10
Headache	52	21
Indigestion	41	26
Low hemoglobin	40	31
Constipation	40	28
Lead line	40	0
Abdominal pain	35	16
Weakness in forearm	22	6
Loss appetite	14	6
Weight loss	13	4

Notes: Authors' calculations based on Wright, Sappington, and Rantoul (1928)

Table 10: Effects of Infant Mortality, Lead, and pH on Wages

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Ln(wages)	Ln(wages)	Ln(wages)	Ln(wages)	Ln(wages)	Ln(wages)	Ln(wages)
Sample	1899	1899-1914	1899	1899-1914	1899	1899-1914	1899-1914
Estimates	OLS	OLS	OLS	OLS	OLS	OLS	IV (F = 4.71)
Inf. Mort	-0.264**	-0.359***					-0.577**
	(0.108)	(0.0861)					(0.279)
Lead only			-0.0553*	-0.0635**	-0.425	-0.328	
			(0.0292)	(0.0247)	(0.268)	(0.246)	
Lead only x pH					0.0501	0.0359	
					(0.0369)	(0.0334)	
Mixed lead			-0.0433	-0.0713**	-0.297	-0.591	
			(0.0365)	(0.0318)	(0.344)	(0.368)	
Mixed lead x pH					0.0348	0.0697	
					(0.0466)	(0.0481)	
pH					-0.0693**	-0.0497	
					(0.0339)	(0.0317)	
Foreign born	0.250	0.397***	0.136	0.261*	0.156	0.280**	0.529***
	(0.173)	(0.132)	(0.178)	(0.134)	(0.178)	(0.129)	(0.199)
White	0.255	0.628***	0.511***	0.849***	0.561***	0.861***	0.509*
	(0.161)	(0.191)	(0.148)	(0.189)	(0.164)	(0.188)	(0.261)
Typhoid rate			0.0648	0.101	-0.00216	0.0794	0.693
			(0.604)	(0.324)	(0.614)	(0.324)	(0.430)
Region FE	Y	Y	Y	Y	Y	Y	Y
Citypop quart FE	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y
Constant	-1.067***	-1.461***	-1.389***	-1.780***	-0.967***	-1.455***	-1.308***
	(0.168)	(0.185)	(0.145)	(0.174)	(0.272)	(0.245)	(0.309)
Observations	165	749	165	749	165	749	749
R-squared	0.207	0.379	0.192	0.365	0.211	0.371	0.373

Notes: Robust standard errors are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels. Pooled samples are clustered by city.

Table 11: Infant Mortality, Lead, and pH on Wages over Time, 1899-1914

	(1) Ln(wages)	(2) Ln(wages)	(3) Ln(wages)
Time	0.0176***	0.0176***	-0.0132
	(0.00156)	(0.00147)	(0.0178)
Inf. Mort Rate	0.0788		
	(0.0973)		
Lead only x time		-0.00117	0.0184
		(0.00163)	(0.0152)
Lead only x time x pH			-0.00260
			(0.00217)
Mixed lead x time		-0.00580	-0.0634
		(0.00470)	(0.0608)
Mixed lead x time x pH			0.00768
			(0.00761)
Time x pH			0.00466*
			(0.00274)
Citypop	0.00000206	0.00000495	0.00000575
	(0.00000538)	(0.00000707)	(0.00000659)
Foreign born	0.179	0.209	0.256*
	(0.176)	(0.160)	(0.152)
White	-0.194	-0.249	-0.141
	(0.471)	(0.497)	(0.421)
Typhoid rate	0.0939	0.0847	0.0377
	(0.262)	(0.247)	(0.238)
City FE	Y	Y	Y
Region x time FE	Y	Y	Y
Year FE	Y	Y	Y
Constant	-0.643	-0.598	-0.692*
	(0.452)	(0.468)	(0.401)
Observations	749	749	749
R-squared	0.793	0.795	0.800

Notes: Robust standard errors clustered by city are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Appendix 1

Table 1A: Cities by Use of Lead Pipes and by Acidity Quantiles for Full Sample

		No-lead (85 cities)		
Akron OH	Canton OH	La Crosse WI	Ogden UT	Waltham MA
Alameda CA	Chester PA	Lewiston ME	Oklahoma City OK	Waterbury CT
Altoona PA	Columbia SC	Lockport NY	Oswego NY	Williamsport PA
Anderson IN	Concord NH	Long Beach CA	Pasadena CA	Wilmington NC
Ann Arbor MI	Durham NC	Lynn MA	Pensacola FL	Worcester MA
Atlantic City NJ	Elizabeth NJ	Mansfield OH	Pittsfield MA	
Auburn NY	Elmira NY	Marion OH	Pomona CA	
Augusta GA	Erie PA	Medford MA	Pontiac MI	
Augusta ME	Evansville IN	Meriden CT	Portland ME	
Baltimore MD	Fitchburgh MA	Mobile AL	Riverside CA	
Bangor ME	Flint MI	Moline IL	Roanoke VA	
Bath ME	Gloucester MA	Mount Vernon NY	Sacramento CA	
Beaumont TX	Green Bay WI	Muskegon MI	Salem MA	
Berkeley CA	Greensboro NC	Nashua NH	San Bernardino CA	
Biddeford ME	Hagerstown MD	New Haven CT	Somerville MA	
Binghampton NY	Hartford CT	Newark OH	Springfield MA	
Brockton MA	Houston TX	Newburyport MA	Springfield MO	
Brookline MA	Jacksonville FL	Newport RI	Tampa FL	
Burlington VT	Kansas City MO	Northhampton MA	Taunton MA	
Cambridge MA	Knoxville TN	Oakland CA	Trenton NJ	
		Lead-Lowest Acidity (43 cities)		
Battle Creek MI	Detroit MI	Lorain OH	Rock Island IL	St. Paul MN
Bay City MI	Fort Wayne IN	Los Angeles CA	Rome NY	Superior WI
Birmingham AL	Grand Rapids MI	Minneapolis MN	Saginaw MI	Syracuse NY
Buffalo NY	Harrisburg PA	New Orleans LA	Sandusky OH	Toledo OH
Burlington IA	Indianapolis IN	Niagara Falls NY	San Francisco CA	Topeka KS
Butte MT	Jackson MI	Omaha NE	Shenandoah PA	Warren OH
Cleveland OH	Kalamazoo MI	Peoria IL	South Bend IN	Washington DC
Columbus OH	Kansas City KS	Port Huron MI	Springfield IL	
Denver CO	Leavenworth KS	Quincy IL	St. Louis MO	
		Lead-Low Acidity (30 cities)		
Allentown PA	Joliet IL	Newark NJ	Rockford IL	
Aurora IL	Kearny NJ	Orange NJ	Scranton PA	
Bethlehem PA	Kenosha WI	Oshkosh WI	York PA	
Chicago IL	Lancaster PA	Plainfield NJ		

East Chicago IN	Lexington KY	Portsmouth OH		
Elgin IL	Lincoln NE	Pottsville PA		
Fond du Lac WI	Madison WI	Racine WI		
Hammond IN	Milwaukee WI	Reading PA		
Irvington NJ	Montclair NJ	Rochester NY		
Lead-High Acidity (42 cities)				
Albany NY	Dayton OH	Lynchburg VA	Norristown PA	Springfield OH
Allegheny PA	Hamilton OH	McKeesport PA	Perth Amboy NJ	Steubenville OH
Amsterdam NY	Hazleton PA	Nashville TN	Philadelphia PA	Troy NY
Bayonne NJ	Hoboken NJ	New Albany IN	Pittsburgh PA	Wheeling WV
Camden NJ	Johnstown PA	New Brunswick NJ	Portsmouth VA	Youngstown OH
Chillicothe OH	Joplin MO	New York NY	Richmond IN	Zanesville OH
Cincinnati OH	Kingston NY	Newcastle PA	Richmond VA	
Colorado Springs CO	Lima OH	Newport KY	Salt Lake City UT	
Covington KY	Louisville KY	Newport News VA	Schenectady NY	
Lead-Highest Acidity (41 cities)				
Atlanta GA	Haverhill MA	New Bedford MA	Poughkeepsie NY	West Hoboken NJ
Boston MA	Holyoke MA	New Britain CT	Providence RI	Wilmington DE
Bridgeport CT	Lansing MI	New London CT	Quincy MA	Winston NC
Charleston SC	Lawrence MA	New Rochelle NY	Raleigh NC	Woonsocket RI
Chelsea MA	Lowell MA	Newburgh NY	Savannah GA	Yonkers NY
Chicopee MA	Malden MA	Newton MA	Seattle WA	
Everett MA	Manchester NH	Norfolk VA	Sioux City IA	
Fall River MA	Memphis TN	Norwich CT	Spokane WA	
Galveston TX	Montgomery AL	Pawtucket RI	Stamford CT	

Notes: Because some cities report the same values for hardness or acidity, not all quartiles have the same numbers of observations.

Table 2A: Effects of Infant Mortality, Lead, and pH on Value Added per Worker, 1899-1914

	(1)	(2)	(3)	(4)
	Ln(vaworker)	Ln(vaworker)	Ln(vaworker)	Ln(vaworker)
Sample	1899-1914	1899-1914	1899-1914	1899-1914
Estimates	OLS	OLS	OLS	IV (F = 4.71)
Inf. Mort	-0.792***			-0.797
	(0.269)			(0.487)
Lead only		-0.0398	-0.277	
		(0.0487)	(0.420)	
Lead only x pH			0.0335	
			(0.0583)	
Mixed lead		0.0199	-0.208	
		(0.0434)	(0.518)	
Mixed lead x pH			0.0312	
			(0.0701)	
pH			0.0158	
			(0.0464)	
Foreign born	0.552	0.155	0.176	0.561
	(0.446)	(0.515)	(0.519)	(0.612)
White	-0.00212	0.530**	0.455*	0.00914
	(0.259)	(0.256)	(0.258)	(0.435)
Typhoid rate		-0.536	-0.556	0.371
		(0.660)	(0.648)	(0.832)
Region FE	Y	Y	Y	Y
City size FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Constant	-0.122	-0.865***	-0.890**	-0.146
	(0.303)	(0.174)	(0.350)	(0.483)
Observations	749	749	749	749
R-squared	0.258	0.222	0.224	0.259

Notes: Robust standard errors clustered by city are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Table 3A: Effects of Infant Mortality, Lead, and pH on Capital per Worker, 1899-1914

	(1)	(2)	(3)	(4)
	Ln(capworker)	Ln(capworker)	Ln(capworker)	Ln(capworker)
Sample	1899-1914	1899-1914	1899-1914	1899-1914
Estimates	OLS	OLS	OLS	IV (F = 4.71)
Inf. Mort	-0.179			-0.480
	(0.157)			(0.645)
Lead only		0.0134	-0.556	
		(0.0552)	(0.543)	
Lead only x pH			0.0790	
			(0.0718)	
Mixed lead		0.0333	-0.222	
		(0.0570)	(0.641)	
Mixed lead x pH			0.0358	
			(0.0844)	
pH			-0.0103	
			(0.0807)	
Foreign born	1.315***	1.199***	1.231***	1.482***
	(0.307)	(0.300)	(0.301)	(0.482)
White	-0.191	-0.0752	-0.135	-0.391
	(0.241)	(0.223)	(0.225)	(0.456)
Typhoid rate		-0.505	-0.530	0.0781
		(0.916)	(0.893)	(1.249)
Region FE	Y	Y	Y	Y
City size FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Constant	0.178	0.0258	0.170	0.461
	(0.251)	(0.218)	(0.590)	(0.587)
Observations	749	749	749	749
R-squared	0.383	0.382	0.386	0.378

Notes: Robust standard errors clustered by city are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Table 4A: Effects of Infant Mortality, Lead, and pH on Value Added, 1899-1914

	(1)	(2)	(3)	(4)
	Ln(valueadded)	Ln(valueadded)	Ln(valueadded)	Ln(valueadded)
Sample	1899-1914	1899-1914	1899-1914	1899-1914
Estimates	OLS	OLS	OLS	IV (F = 4.71)
lnearners	0.449***	0.427***	0.427***	0.442***
	(0.128)	(0.131)	(0.133)	(0.129)
lncap	0.547***	0.547***	0.547***	0.547***
	(0.131)	(0.134)	(0.136)	(0.130)
Inf. Mort	-0.688***			-0.514
	(0.244)			(0.449)
Lead only		-0.0426	0.0412	
		(0.0394)	(0.374)	
Lead only x pH			-0.0111	
			(0.0523)	
Mixed lead		0.00654	-0.0792	
		(0.0291)	(0.346)	
Mixed lead x pH			0.0113	
			(0.0468)	
pH			0.0213	
			(0.0321)	
Foreign born	-0.165	-0.466	-0.462	-0.244
	(0.331)	(0.425)	(0.433)	(0.503)
White	0.106	0.576***	0.535**	0.238
	(0.193)	(0.222)	(0.222)	(0.384)
Typhoid rate		-0.171	-0.177	0.344
		(0.337)	(0.338)	(0.541)
Region FE	Y	Y	Y	Y
City size FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Constant	-0.197	-0.700***	-0.804***	-0.339
	(0.237)	(0.163)	(0.239)	(0.318)
Observations	749	749	749	749
R-squared	0.942	0.939	0.939	0.942

Notes: Robust standard errors clustered by city are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Table 5A: Infant Mortality, Lead, and pH on Outcomes over Time, 1899-1914

	(1) Ln(vaworker)	(2) Ln(capworker)	(3) Ln(valueadded)	(4) Ln(vaworker)	(5) Ln(capworker)	(6) Ln(valueadded)
Time	0.0288***	0.0389***	0.0230***	0.0390*	0.0126	0.0337
	(0.00262)	(0.00342)	(0.00387)	(0.0219)	(0.0421)	(0.0224)
Inf. Mort	0.00530	0.116	-0.00835			
Rate	(0.105)	(0.178)	(0.109)			
Lead only x				-0.0218	0.0464	-0.0242
time				(0.0281)	(0.0397)	(0.0257)
Lead only x				0.00253	-0.00641	0.00287
time x pH				(0.00395)	(0.00522)	(0.00358)
Mixed lead				0.0316	0.00681	0.0425
x time				(0.0421)	(0.0662)	(0.0403)
Mixed lead				-0.00537	-0.000760	-0.00702
x time x pH				(0.00581)	(0.00849)	(0.00564)
Time x pH				-0.00120	0.00351	-0.00124
				(0.00333)	(0.00608)	(0.00337)
Citypop	0.00000118	-0.00000934	0.00000521	0.00000525	-0.0000106	0.0000103*
	(0.00000431)	(0.00000804)	(0.00000516)	(0.00000483)	(0.00000759)	(0.00000582)
Foreign	0.147	-0.225	0.550	0.155	-0.247	0.579
born	(0.321)	(0.800)	(0.504)	(0.313)	(0.814)	(0.485)
White	0.255	-0.343	0.402	0.193	-0.439	0.346
	(0.652)	(0.961)	(0.520)	(0.592)	(0.926)	(0.454)
Typhoid	0.0736	-0.693	0.416	0.0111	-0.624	0.340
rate	(0.327)	(0.490)	(0.366)	(0.310)	(0.469)	(0.338)
lnearners			0.589***			0.577***
			(0.199)			(0.197)
lncap			0.254**			0.257***
			(0.0985)			(0.0957)
City FE	Y	Y	Y	Y	Y	Y
Region x time FE	Y	Y	Y	Y	Y	Y

Year FE	Y	Y	Y	Y	Y	Y
Constant	-0.0486	1.172	1.000	-0.0384	1.294	1.076
	(0.644)	(1.004)	(1.105)	(0.578)	(0.997)	(1.089)
Observations	749	749	749	749	749	749
R-squared	0.926	0.842	0.994	0.928	0.842	0.994

Notes: Robust standard errors clustered by city are in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Appendix 2: Data Sources

City-level mortality data: Mortality Statistics (various years). 1900 data are from the revisions in the 1906 volume. The volumes are available from http://www.cdc.gov/nchs/products/vsus.htm

City-level demographic characteristics: Calculated from IPUMs 1% samples of the Census of Population for 1900, 1910, and 1920. Values are interpolated for 1905 and 1915. The data is available from http://usa.ipums.org/usa/

Lead pipes: The Manual of American Waterworks, 1897

pH and Hardness of the raw intake water: The Water Encyclopedia (1990).

State average annual temperature and average monthly precipitation: Data on mean annual temperature and mean monthly precipitation are from the National Climactic Data Center at the National Oceanic and Atmospheric Administration. The data are available from http://www1.ncdc.noaa.gov/pub/data/cirs/.

They describe the data as follows: "The statewide values are available for the 48 contiguous States and are computed from the divisional values weighted by area. The Monthly averages within a climatic division have been calculated by giving equal weight to stations reporting both temperature and precipitation within a division."[57] The observations were corrected for time of observation bias as described in Karl, et al. (1986). The annual state values for 1895-2000 were averaged to obtain the state average.

City-level manufacturing data: Data are from Table 183, p. 295 in http://www2.census.gov/prod2/decennial/documents/00483993ch06.pdf . Note the reported values often differ from the census numbers for earlier years, because of revisions to exclude manufacturing outside the city limits.

[57] The state data is described in http://www1.ncdc.noaa.gov/pub/data/cirs/state.README