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LEAD AND MORTALITY

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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 that the water ran through – lead, iron, or concrete – which together determined the extent of lead exposure. Estimates that restrict the sample to cities with lead pipes and panel estimates 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 6.675 (25th percentile) to 7.3 (50th percentile) in cities with lead-only pipes would have been associated with a decrease in infant mortality of 7 to 33 percent or at least 12 fewer infant deaths per 1,000 live births. 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 that the water ran through – lead, iron, or concrete – which together determined the extent of lead exposure. Estimates that restrict the sample to cities with lead pipes and panel estimates 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 6.675 (25th percentile) to 7.3 (50th percentile) in cities with lead-only pipes would have been associated with a decrease in infant mortality of 7 to 33 percent or at least 12 fewer infant deaths per 1,000 live births.

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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 from city water mains through lead service pipes to homes and businesses.[1] Lead service pipes were widely used. In 1900, 11 percent of the American population lived in cities with lead service pipes and 23 percent lived in cities where some service pipes were lead. The amount of lead in drinking water depended on the chemical properties of the water passing through the pipes. More acidic water leached lead faster. Doctors and city engineers recognized that lead was leaching into drinking water, but water lead levels were 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 infant mortality 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.[2] High levels of lead exposure generally cause morbidity rather than mortality in adults.[3]

Identification of the effect of lead comes from variation in water chemistry across cities with different types of service pipes. Water chemistry is exogenously determined by local geology

[1] Service pipes are the pipes that connect the water main, which usually runs under a street, with a building. Most residential service pipes were between 0.5 and 2 inches in diameter.
[2] See Needleman and Belinger (1991), National Research Council (1993), and Reyes (2008).
[3] Common symptoms include fatigue, reduced cognitive functioning and a decrease in gross and fine motor skills. See Bleecker et al. (2007); Dorsey et al. (2006); and Stewart and Schwartz (2007).

and by whether the water source is above or below ground. The main specification focuses on infant mortality in 1900. A number of approaches are taken to address any residual omitted variable bias. A rich set of controls are included to address differences in city size, characteristics, temperature, and water and milk quality. In some specifications, estimation is restricted to cities with lead pipes, so that identification comes solely from exogenous variation in water chemistry. The amount of lead delivered by pipes is in part a function of the age of the pipes. Analysis using repeated cross sections and panel data provides further evidence that lead was causing adverse outcomes.

The paper finds that in 1900, a decline in exposure equivalent to an increase in pH from 6.675 (25th percentile) to 7.3 (50th percentile) in cities with lead-only pipes would have been associated with a decrease in infant mortality of 7 to 33 percent. Given that infant mortality in cities was about 180 per 1000 live births, such a change would lead to at least 12 fewer infant deaths per 1,000 live births. Cities could have achieved this by modifying the pH of the water or by replacing the lead service pipes with non-lead service pipes.

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.[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 two important ways. First, it shows that the adverse health effects of lead were national. Second, it documents that the adverse effects extended over a significant period of time.

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[4] 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.
[5] Water-related lead exposure remains a concern, even in well-developed countries. See Hayes and Skubala (2009).

This paper also contributes to a related literature on the causes of decline in infant mortality. In their pioneering book, Preston and Haines (1991) documented high infant mortality at the turn of the twentieth century. 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. This paper finds that proxies for water quality were strongly related to infant mortality. Further, it documents the extent to which declines in the effects of lead over time contributed to declines in infant mortality.

2. Lead Water Pipes

Use and Exposure

Lead service pipes were widely used to connect homes and buildings to street mains. In 1900, our sample includes 172 large and medium size cities. They represented 84 percent of the urban population. 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 the water was allowed to stand overnight.[6] An experiment conducted by two New York health officials in the 1930s found similar results.[7]

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.[8]

Water was the primary source of lead exposure during the period 1900-1920. 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 would account for 90 percent of an adult's blood-lead level.[9] The relative importance of air-borne lead today is largely attributable to the dramatic fall in water lead levels over the last century.

The Chemistry of Water and Lead

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[6] All reports of the Massachusetts State Board of Health are cited as MSBH. MSBH (1900), pp. 491-97

[7] Quam and Klein (1936).

[8] See Troesken (2006), pp. 6-7.

[9] See Troesken (2006) and the references cited in Chapter 2, footnote 86.

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.[10] Water acidity and hardness were determined by the types of rock and soil the water came into contact with as it traveled to the city either on the surface or in an aquifer.[11] As will be discussed further, water chemistry tends to be stable over time.

Figure 1 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 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.[12]

Figure 1 has three testable implications with respect to infant mortality. [13] 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 7.3, 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 7.3, cities with lower hardness should have higher infant mortality than cities with higher hardness.

Contemporary Knowledge of Harm

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[10] Lead service pipes were 90-100 percent lead. The lead was sometimes mixed with small amounts of copper or antimony.
[11] For discussions of water chemistry and hydrogeology, see Stumm and Morgan (1996) and Hiscock (2005).
[12] See Troesken (2006), Chapter 6.
[13] 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.

Into the mid-twentieth century, lead in drinking water was widely believed to be harmless. 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 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.[14]

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.[15] As of 1916, most engineers appear to have believed that concerns about lead service

[14] Warren (2000), pp. 34-35.
[15] See Needleman (1998), (2000), and (2004).

pipes were overblown.[16] 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.[17]

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.[18] 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."[19] 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 –

[16] *Engineering News* (hereafter cited as EN), September 28, 1916, p. 595
[17] Troesken (2006), pp. 74, 123-41, 166-68, 186-87.
[18] See Powell (1997).
[19] 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.

and because local firms were likely to lobby engineers to use their pipes.[20] These issues are examined further in section 4.

3. Ingestion and Health Effects of Lead

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.[21] 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.[22] 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. 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.[23] 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

[20] 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.
[21] 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.
[22] Troesken (2004), Table 3.1, p. 39.
[23] Most beer was brewed either at home or at breweries in the city that utilized city water.

amount of lead in water that traveled through the lead service pipes from 800 ppb to 300 ppb. Modern experience tells a similar story.[24]

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.[25] Infants have blood-lead levels that are highly correlated with their mother's blood-lead level, indicating transmission of lead from mother to fetus.[26] Mothers' milk was contaminated. Modern studies show that maternal lead exposure is correlated with lead levels in breast milk.[27] 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.[28] 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.[29] 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. Chronic, long-term lead

[24] See Clement et al (2000).
[25] For an early study of effects on pregnant women in lead industries, see Department of Labor (1919).
[26] See Goyer (1990).
[27] See Ettinger et al (2004) and Ettinger et al (2006).
[28] See Needleman and Belinger (1991) and National Research Council (1993).
[29] See Troesken (2006), pp. 47-49.

exposure can, however, impair neurological and behavioral functioning among adults. At higher levels of exposure, 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 city-level data on mortality, population and demographic characteristics, the types of service pipes in use and water chemistry. 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.[30]

Information on cities' use of lead pipes in the mid-1890s is from The Manual of American Waterworks, 1897 (Baker 1897).[31] 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 did not specify the type of service pipe. These cities were not included in the analysis.

Data on cities' water characteristics are from multiple sources. Historical water sources were identified using Baker (1897) The Manual of American Water Works; United States Geological Survey (1934) The Industrial Utility of Public Water Supplies in the United States, 1932; city websites, which sometimes have histories of the water utility; and other sources. pH and hardness of the historical water sources are primarily taken from United States Geological Survey (1954) The Industrial Utility of Public Water Supplies in the United States, 1952 or from The Water Encyclopedia (Van Der Leeden 1990), which report the acidity and hardness of the raw intake water for many water systems in the early 1950s and 1980s. Supplemental information was drawn from USGS reports.

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[30] 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.

[31] 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.

For water characteristics from the early 1950s to be relevant for predicting the extent of lead leaching from service pipes in the early twentieth century, two things need to hold. First, 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. [3233] Hardness is an attribute of the soil and is extremely persistent over time.[34] Second, 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 before the mid-twentieth-century in America.[35]

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 IPUMs sample, and 25 percent of the population of the United States in 1900.[36] These cities were predominantly in the New England (29 percent), Mid-Atlantic (28 percent), and East North

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[32] The EPA in its report on <u>The Response of Surface Water Chemistry to the Clear Air Act Amendments of 1990</u> (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)

[33] 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.

[34] 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.

[35] Troesken (2006), especially pp. 73-75. Only 14 percent of the 172 cities in the 1900 sample report using lime to control the pH of the water in 1932.

[36] 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.

Central (21 percent) census regions, with the remaining cities (22 percent) being located in other census regions. 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 2 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 1.

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

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

where $mort_i$ is mortality in city i in 1900.[37] 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, ln(pH) is interacted with two lead indicator variables and is included as a control.[38] To ensure the main effects are evaluated within the range of the sample

[37] 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.

[38] In unreported regressions, a variety of functional forms were explored. ln(pH) provided a good fit and so did the (less parametric) linear specification that allowed different slopes above and below pHs of 7.3.

pH, ln(pH) = ln(pH-5.675) so that it equals 0 at a pH of 6.675, which is the 25th percentile of pH. Most specifications will use ln(pH-5.675), but some will use a less-parametric specification. 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.

To address concerns about omitted variables, a rich set of controls are included. X_i are city characteristics computed from the IPUMs 1900 1-percent sample. These include city population quartiles, the share of the city population that was white, foreign born, and women ages 20-40, and regional fixed effects. 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.

Some specifications include city-level controls for water quality, milk quality, and women's suffrage. Water purification can influence infant mortality directly and through the health of the mother.[39] 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.[40] It is roughly 4 percent of the overall death rate. Non-pulmonary tuberculosis was often the result of contracting bovine, as opposed to human, tuberculosis.[41] The most common way to contract bovine tuberculosis was through contaminated milk. Non-pulmonary tuberculosis was 2 percent of the overall death

[39] See Lee (2007), Ferrie and Troesken (2008), and Condran et al (1984).
[40] 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.
[41] See Olmstead and Rhode (2004), Lee (2007), and Meckel (1990).

rate. Pasteurization kills bovine tuberculosis, so this is a crude marker for milk quality.[42] 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.[43] 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. Interestingly, because the cities in our sample are all fairly large, the correlation between city population and the use of any lead pipe is 0.13 and the correlation with use of lead only is -0.02. To explore this further, cities were divided into quartiles by size. In the lowest quartile, cities under 21,500, 26 percent of cities used only lead pipes and 58 percent used some lead pipes. In contrast, in the highest quartile, cities over 804,000, 66 percent used only lead pipes and 89 percent used some lead pipes. The intermediate quartiles fall between the top and bottom quartile in terms of their use of only lead pipes and some lead pipes.

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

[42] 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.

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

iron and steel pipe were Pennsylvania and Ohio.[44] 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.

Table 3 explores the determinants of a city's use of lead-only pipes. In column 1, the coefficients on ln(pH-5.675) and ln(hardness) are not statistically significant. As expected, larger cities are more likely to use only lead pipes. The main effect is for cities in the top quartile of size, cities above 804,000 in population. [45] It also indicates that there was significant regional variation in the use of lead pipes. (The omitted region is New England.) Temperature and precipitation might influence the choice of pipes if heat, cold, or rain caused them to deteriorate. Cities in states with higher average temperatures were statistically significantly less likely to use lead pipes. 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. The coefficient on typhoid is not statistically significant.

Column 2 examines the determinants of cities using lead-only pipes and having water with pH $\leq$ 7.3. The results look very similar to the results in column 1. The coefficient on typhoid remains insignificant. Column 3 presents the results of an ordered logit on lead. The coefficients on ln(pH-5.675) and ln(hardness) are not statistically significant. The coefficient on typhoid remains insignificant. In sum, conditional on city size, region, and temperature, neither pH nor

[44] 1900 Census of Manufactures, pp. 272, 260.
[45] In unreported regression, the fit was poorer when quadratics of city population or the log of city population were used instead of quartile indicator variables. This is not surprising, given that quartile indicator variables impose fewer restrictions on the functional form.

water quality, as measured by the typhoid death rate, appear to be influencing the use of lead 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 lead-only and lead-only x ln(pH-5.675) are statistically significant and of the expected sign. Cities with lead-only pipes had higher baseline mortalities than cities without lead pipes. At a pH of 6.675 (the 25th percentile of the acidity distribution), the main effect is 0.074. Thus, a city with lead pipes and a pH of 6.675 had infant mortality that was 19 percent higher than an equivalent city without lead pipes.[46] Further, the relationship between ln(pH-5.675) and mortality was significantly more negative for cities with lead-only pipes than for cities without lead pipes. It was -0.049 for cities without lead pipes and -0.124 (=-0.049-0.075) for cities with lead pipes. Adding control variables in columns 2 and 3 improves the fit of the regressions, but does not change the main findings.

[46] 0.19 = (0.074/0.396)

Column 4 presents a more flexible functional form, which allows the effects of pH to be linear but to differ depending on whether the pH is below or above 7.3. There are a full set of interaction effects, and the number of observations in each cell ranges from 20 to 44. At a pH of 6.675, the main effect is 0.063. Thus, a city with lead pipes and a pH of 6.675 had infant mortality that was 16 percent higher than an equivalent city without lead pipes.[47]

The coefficient on pH-6.675 for cities with lead-only pipes is negative, statistically significant and large when pH $\leq$ 7.3. Above a pH of 7.3, the coefficient on pH for cities with lead-only pipes in column 4 is small and not statistically significantly different than the effect for cities with no lead pipes and pH $\leq$ 7.3. This is consistent with Figure 1, which suggested that leaching increased rapidly for pH values below 7.3.

It is worth discussing the coefficients for mixed lead. One challenge is not knowing what the mix is. It could be 90 percent lead or 10 percent lead. If mixed lead were equal to 0.5, then one would expect that the slope of the interaction term would be half that of the lead one. If all of the old pipes were lead and all of the new pipes were not lead, this would shift the average lead exposure downward. In Table 4, column 4, the pH-6.675 interaction coefficients are -0.267 (lead) and -0.073 (mixed), which suggests that exposure for mixed lead is about 30 percent. The main effects (0.063 for lead and 0.0194 for mixed) are of the same order of magnitude.

The coefficients on the disease control variables are also worth noting. The coefficients on typhoid and non-pulmonary tuberculosis are both positive and the coefficient on typhoid is statistically significant. A one standard deviation increase in typhoid would increase infant

[47] 0.16 = (0.063/0.396)

mortality by 7.1-7.7 percent.[48] This is consistent with Cutler and Miller's (2005) finding that water quality is an important determinant of infant mortality.

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. For example the coefficients in columns 3 indicate that for a city with lead-only pipes, moving from a pH of 6.675 (25^{th} percentile) to 7.3 (50^{th} percentile), a change in natural logs of nearly 0.5, would be associated with a 0.038 (=(0.062 + 0.013)*0.5) decline in infant mortality. The mean infant mortality in cities with lead pipes is 0.409, so this represents a decline of 9 percent. Column 4 suggests that a similar change in pH would be associated with a decline of 0.13 (= (0.27-0.06)*0.625). This is a decline of 32 percent.

Table 4 focused exclusively on the effects of pH, yet Figure 1 suggests that hardness, which is highly positively correlated with alkalinity, may affect leaching and thus mortality. One complication is that in Figure 1, increased alkalinity lowered leaching for pH below the mid-7 range and increased leaching for pH above this range. To capture this, the effects of hardness were allowed to differ depending on whether the pH is below or above 7.3 (the median in the sample).

Table 5 provides further evidence on the association among lead pipes, pH, hardness, and infant mortality. For ease of presentation, given the large number of interaction terms, the results

[48] 0.071 = (0.028/0.396) and 0.077 = (0.0303/0.396)

are presented for cities with lead-only pipes.[49] Column 1 shows the effects of ln(pH-5.675). As in Table 4, the coefficient on ln(pH-5.675) is negative and statistically significant. Column 2 adds ln(hardness) to the specification in column 1. The coefficient on ln(pH-5.675) remains negative and statistically significant, but the magnitude has fallen by about 25 percent. Moving from a pH of 6.675 (25th percentile) to 7.3 (50th percentile), would be associated with a 0.027 (=(0.053)*0.5) decline in infant mortality. This is a decline of 7 percent.

Drawing on Figure 1, column 3 uses a linear specification and a full set of controls for water chemistry, which are allowed to differ depending on whether pH is above or below 7.3, the sample median. The coefficients on pH-6.675, hardness, and hardness x (pH-6.675) are statistically significant and of the expected sign. The marginal effect of an increase pH is -0.271 + 0.0018*hardness. The effect is negative but is smaller at higher levels of hardness.[50] At a hardness of 30, which is close to the median for this (sub)sample, an increase in pH from 6.675 to 7.3 would decrease infant mortality by 0.625*(0.22) = 0.14. This is a decline of 33 percent.[51] The marginal effect of an increase in hardness is -0.0010 + 0.0018*(pH – 6.675).

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. Cities with lead pipes had higher infant mortality than cities without lead pipes. Conditional on having lead pipes, cities with low pH had higher mortality than cities with high pH. And in cities with lead pipes and pHs below 7.3, cities with lower hardness had higher infant mortality than cities with higher hardness.

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[49] The results are similar for the full sample.
[50] The 5-95 range for hardness for this subsample is 8-153. So for all but a few observations, the marginal effect is negative.
[51] 0.33 = 0.14/0.409. (0.049 is the mortality for infants in lead only cities.)

The effect of lead on infant mortality in absolute terms was large. In Table 5 an increase in pH from 6.675 to 7.3 in cities with lead-only pipes was associated with a decrease in infant mortality of 7 to 33 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.[52] The estimates suggest that an increase in pH from 6.675 to 7.3 in 1900 would have saved at least 12 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.

Further Evidence on Causality

This section provides further 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 1 should hold in other years.

The effects of lead 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

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

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 except 1920, mortality was statistically significantly higher in a city with lead pipes than in a comparable city without lead pipes. Moreover, in all of the years, the coefficients on lead-only x ln(pH-5.675) are negative and statistically significantly different than the coefficient on no-lead x ln(pH-5.675). Consistent with the patterns in Figure 2, the magnitudes of the coefficients on lead-only x ln(pH-5.675) were declining over time, particularly after 1905.

Appendix Table 1A directly tests whether the coefficients were falling over time, by estimating the following specification:

$$mort_{it} = \alpha_0 + \alpha_{1i} \text{ time x lead}_i + \alpha_{2i} \text{ time x region}_i + \beta city_i + \varepsilon_{it} \qquad (2)$$

$mort_{it}$ 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. The additional of covariates in column 2 has very little effect on the magnitude and statistical significance of the coefficients on the lead variables.

Columns 3 and 4 allow the trends to differ among the three types of pipes and for each type of pipe for pHs above and below 7.3. Cities with lead-only pipes and pH≤7.3 were experiencing faster declines in infant mortality than cities with lead-only pipes and pH>7.3 and, more generally, than cities of all types with pH>7.3.

In sum, the cross-sectional results in Table 6 and the panel data results in Table 1A provide additional evidence that that relationship between lead service pipes and infant mortality was causal.

Non-Infant 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 7 confirms that lead is not strongly related to non-infant mortality.[53] The specifications are similar to those in Table 4. The variable women ages 20-40 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 sixty. The coefficients on the lead variables are not statistically significant, with the exception of lead only variable in column 2, as are the implied differences between different pHs for lead-only cities.

6. Conclusion

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

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 6.675 (25^{th} percentile) to 7.3 (50^{th} percentile) in cities with lead-only pipes would have been associated with a decrease in infant mortality of 7 to 33 percent, which translates into 12 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 7.3, some lead was still leaching into city water.

These results 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.[54] Thus, the adverse effects of lead were likely to have extended beyond infant mortality.

[54]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).

7. References

Baker, Moses N. 1897. *The Manual of American Water-Works*. New York: The Engineering News Publishing Company.

Bittlingmayer, George. 1982. "Decreasing Average Cost and Competition: A New Look at the Addyston Pipe Case." *Journal of Law and Economics*, 25: 201-229.

Bleecker, M.L., and D.P. Ford, C.G. Vaughan, K.S. Walsh, K.N. Lindgren. 2007. "The Association of Lead Exposure and Motor Performance Mediated by Cerebral White Matter Change," *Neurotoxicology*, 28:318-23.

Census of Manufactures. Various Years.

Clement, M., R. Seux, and S. Rabarot. 2000. "A Practical Model For Estimating Total Lead Intake From Drinking Water." *Water Research*, 34: 1533-1542.

Condran, G. A., H. Williams, and R. Cheney. 1984. "The Decline in Mortality in Philadelphia from 1870 to 1930: The Role of Municipal Services." *Pennsylvania Magazine of History and Biography* 108: 153-177.

Committee on Service Pipes. New England Water Works Association. Report of Committee on Service Pipes. Presented to the Association on March 14, 1917. Reprinted in the *Journal of New England Water Works Association*. Volume 31. No. 3. September 1917, pp. 323-389. Cited in text as CSP.

Currie, Janet and Matthew Neidell. 2005. "Air Pollution and Infant Health: What Can We Learn From California's Recent Experience?" *Quarterly Journal of Economics* 120: 1003-1030.

Cutler, David and Grant Miller. 2005. "The Role of Public Health Improvements in Health Advances: The Twentieth-Century United States." *Demography* 42:1-22.

Davis, R.B., D. S. Anderson, S. A. Norton, J. Ford, P. R. Sweets, J. S. Kahl. 1994. "Sedimented diatoms in northern New England lakes and their use as pH and alkalinity indicators." *Canadian Journal of Fisheries and Aquatic Sciences*. 51:1855-1876.

Dorsey, C.D., B.K. Lee, K.I. Bolla, V.W. Weaver, S.S. Lee, G.S. Lee, A.C. Todd, W. Shi, and B.S. Schwartz. 2006. "Comparison of Patella Lead With Blood Lead and Tibia Lead and Their Associations with Neurobehavioral Test Scores," *Journal of Occupational and Environmental Medicine,* 48:489-96.

Engineering News. Various issues. Cited in text as EN.

Environmental Protection Agency. 2003 *Response of Surface Water Chemistry to the Clean Air Act Amendments of 1990, Executive Summary*. http://www.epa.gov/ord/htm/CAAA-ExecutiveSummary-1-29-03.pdf

Ettinger Adrienne, Martha María Téllez-Rojo,Chitra Amarasiriwardena, David Bellinger, Karen Peterson, Joel Schwartz, Howard Hu, and Mauricio Hernández-Avila. 2004. "Effect of Breast Milk Lead on Infant Blood Lead Levels at 1 Month of Age." *Environmental Health Perspectives* 112: 1381–1385.

Ettinger, Adrienne, Martha María Téllez-Rojo, Chitra Amarasiriwardena, Karen E. Peterson, Joel Schwartz, Antonio Aro, Howard Hu, and Mauricio Hernández-Avila. 2006. "Influence of Maternal Bone Lead Burden and Calcium Intake on Levels of Lead in Breast Milk over the Course of Lactation." *American Journal of Epidemiology* 163:48-56.

Ferrie, Joseph and Werner Troesken. 2008. "Water and Chicago's Mortality Transition, 1850-1925." *Explorations in Economic History*, 45: 1-16.

Goyer, R. A. 1990. "Transplacental Transport of Lead." *Environmental Health Perspectives*, 89:101-105.

Haines, Michael R. 2008. "Fertility and Mortality in the United States". EH.Net Encyclopedia, edited by Robert Whaples. January 22, 2008. URL http://eh.net/encyclopedia/article/haines.demography

Hayes, C.R. and N.D. Skubala. 2009. "Is There Still a Problem with Lead in Drinking Water in the European Union," *Journal of Water and Health*, 7:569-80.

Hiscock, Kevin. 2005. *Hydrogeology: Principles and Practice*. Wiley-Blackwell.

Krug, Edward and Charles Frink. 1983. "Acid Rain on Acid Soil: A New Perspective." *Science*. 221: 520-525.

Lee, Kwang Sun. 2007. "Infant Mortality Decline in the Late 19th and Early 20th Centuries." *Perspectives in Biology and Medicine*. 50:585-602.

Massachusetts. State Board of Health. *Annual Reports*. Various years, 1890-1900. Cited in text as MSBH

Meckel, R. A. 1990. "Pure milk for babies: Improving the urban milk supply." In *Save the babies: American public health reform and the prevention of infant mortality, 1850–1929*, 62–91. Baltimore: Johns Hopkins Univ. Press.

Miller, Grant. 2008. "Women's Suffrage, Political Responsiveness, and Child Survival in American History." *Quarterly Journal of Economics*, 123: 1287-1327.

Mortality Statistics. Various years. Department of Commerce, Bureau of the Census. Washington, D.C.: Government Printing Office.

National Research Council 1993. *Measuring Lead Exposure in Infants, Children and Other Sensitive Populations*. Washington, DC: National Academy Press.

Needleman, H.L. 1998. "Clair Patterson and Robert Kehoe: Two Views on Lead Toxicity," *Environmental Research*, 74:95-103.

Needleman, H.L. 2000. "The Removal of Lead from Gasoline: Historical and Personal Reflections," *Environmental Research*, 84:20-25.

Needleman, H. 2004. "Lead Poisoning." *Annual Review of Medicine*, 55: 209-222

Needleman, H. L. and D. Belinger 1991. "The Health Effects of Low Level Exposure to Lead." *Annual Review of Public Health*, 40: 111-140.

Needleman, H.L., J.A. Reiss, M.J. Tobin, et al. 1996. "Bone Lead Levels and Delinquent Behavior," *Journal of the American Medical Association*, 24:711-17.

Needleman, H.L., C.E. McFarland, R. Ness, et al. 2002. "Bone Lead Levels in Adjudicated Delinquency: A Case-Control Study," *Neurotoxicology and Teratology*, 24:711-17.

Nevin, R. 2000. "How Lead Exposure Relates to Temporal Changes in IQ, Violent Crime, and Unwed Pregnancy," *Environmental Research*, 83:1-22.

Olmstead, Alan and Paul Rhode. "An Impossible Undertaking: The Eradication of Bovine Tuberculosis in the United States." *Journal of Economic History*, 64: 734-772.

Powell, Mark. 1997. "The 1991 Lead/Copper Drinking Water Rule & the 1995 Decision Not to Revise the Arsenic Drinking Water Rule: Two Case Studies in EPA's Use of Science." Working Paper, Resources for the Future.

Preston, Samuel H. and Michael R. Haines. 1991. *Fatal Years: Child Mortality in Late-Nineteenth Century America*. Princeton: Princeton University Press.

Quam, G.N., and Arthur Klein. 1936. "Lead Pipes as a Source of Lead in Drinking Water." *American Journal of Public Health*, 26:778-80.

Reyes, Jessica W. 2007. "Environmental Policy as Social Policy? The Impact of Childhood Lead Exposure on Crime." The B.E. Journal of Economic Analysis & Policy, 7: Article 51.

Reyes, Jessica W. 2008 “The Impact of Prenatal Lead Exposure on Infant Health” Working Paper.

Schock, Michael. 1990. “Causes of Temporal Variability of Lead in Domestic Plumbing Systems.” *Environmental Monitoring and Assessment*, 15: 59-82.

Stewart, W.F., and B.S. Schwartz. 2007. “Effects of Lead on the Adult Brain: A 15-Year Exploration,” *American Journal of Industrial Medicine*, 50:729-39.

Stretesky, P.B., and M.J. Lynch. 2001. “The Relationship Between Lead Exposure and Homicide,” *Pediatric and Adolescent Medicine*, 155:579-82.

Troesken, Werner. 2004. *Water, Race, and Disease*. Cambridge: MIT Press.

Troesken, Werner. 2006. *The Great Lead Water Pipe Disaster*. Cambridge: MIT Press.

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

Stumm, Werner and James Morgan. 1996. *Aquatic Chemistry*, 3rd Edition. Wiley-Interscience.

United States. Department of Labor. Bureau of Labor Statistics. 1919. *Women in the Lead Industries*. By Alice Hamilton. Bulletin No. 253. Washington, DC: Government Printing Office.

United States. Geological Survey. 1934. Industrial Utility of Public Water Supplies in the United States, 1932. Geological Survey Water-Supply Paper 658.

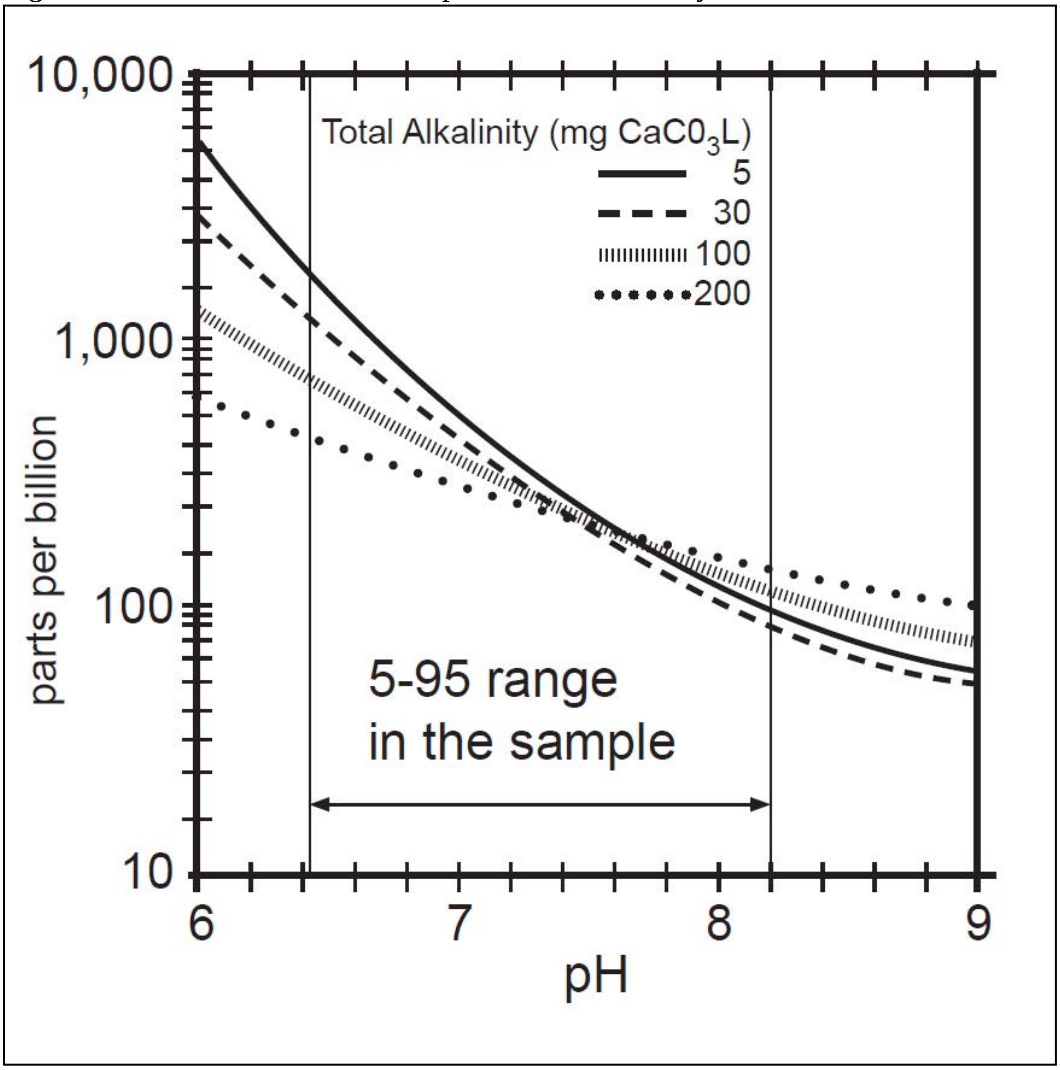
United States. Geological Survey. 1954. Industrial Utility of Public Water Supplies in the United States, 1952. Geological Survey Water-Supply Paper 1299.

United States. Geological Survey. 2006. Explanation of Hardness. http://water.usgs.gov/owq/Explanation.html

Van Der Leeden, Frits. 1990.*The Water Encyclopedia*, Second Edition. by, CRC.

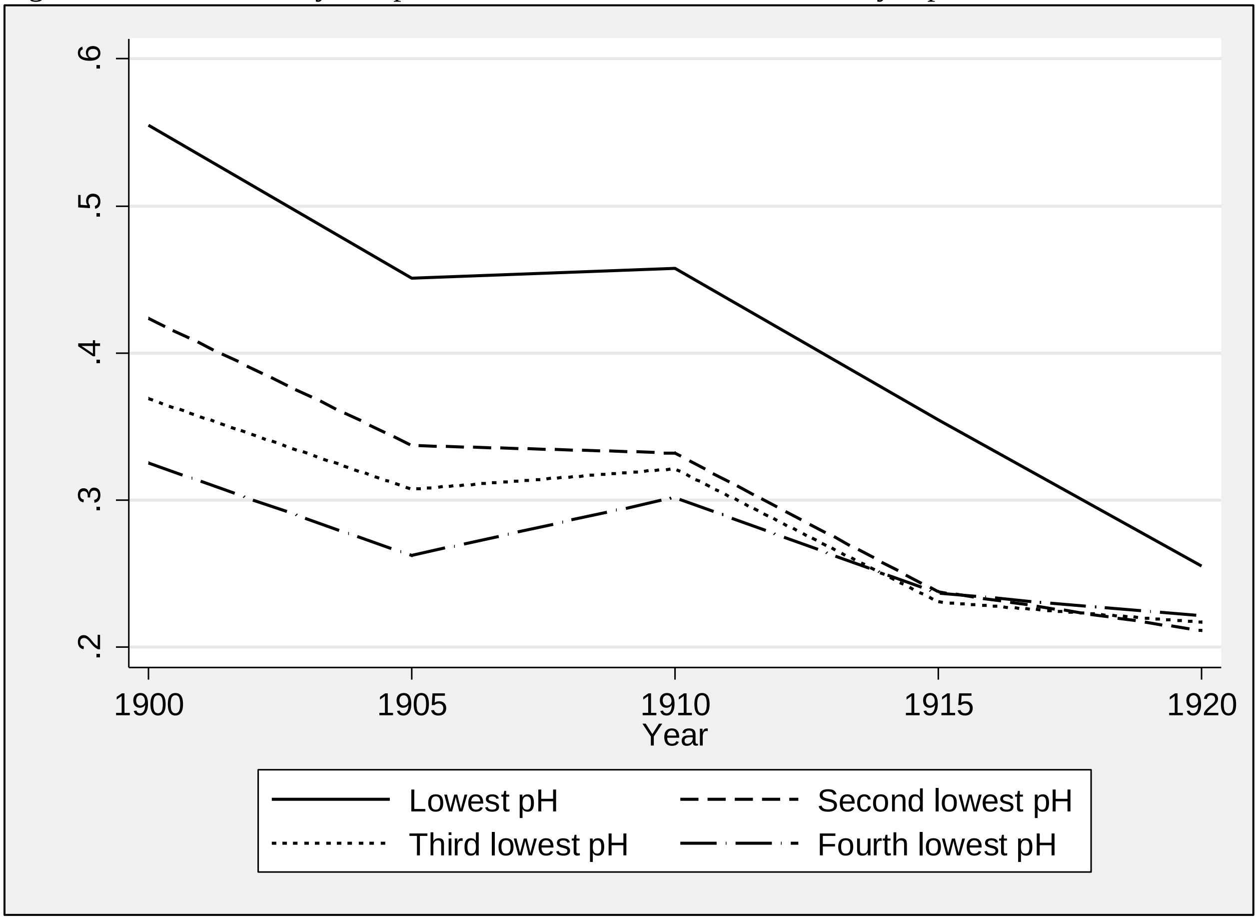
Warren, Christian. 2000. *Brush with Death: A Social History of Lead Poisoning*. Baltimore: Johns Hopkins University Press.

Figure 1: Water-Lead Levels and pH under Laboratory Conditions



Notes: Based on Schock (1990), Figure 4. This is a solubility diagram for lead at 25 degrees Celsius, assuming the formation of both $PbCO_3(s)$ and $PB_3(CO_3)_2(OH)_2(s)$. The 5th-95th percentiles of pH in our sample are marked.

Figure 2: 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.

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 mortality rate	0.396	0.151	0.109	0.844
Non-infant rate	1.438	0.331	0.772	2.702
pH	7.22	0.62	5.7	8.3
Hardness in ppm	109.26	105.47	2	453
Percent Lead only	0.44			
Percent Mixed lead	0.24			
Percent No lead	0.32			
Typhoid mortality rate	0.041	0.028	0	0.144
Non-pulmonary tuberculosis mort. rate	0.020	0.012	0	0.057
Percent women ages 20-40	0.198	0.032	0.130	0.323
Percent foreign born	0.216	0.110	0.000	0.582
Percent white	0.938	0.123	0.324	1.000
City pop in 100s	1087.96	3137.31	85	34355.54
State precipitation in inches	3.32	0.57	0.95	4.75
State temperature in Farenheit	49.32	5.09	40.81	70.62

Notes: The unit of analysis is a (unweighted) city. There are 172 cities in the 1899/1900 sample. Mortality rates are all per 100 in population. Hardness is measured in parts per million (ppm). State precipitation is the average monthly precipitation. State temperature is the average annual temperature. See Appendix 2 for data sources.

Table 3: Determinants of a City Having Lead Pipes in 1900

	(1)	(2)	(3)
Dep. variable	Lead-only	Lead-only & pH ≤ 7.3	Ordered logit
Sample	Full	Full	Full
ln(pH-5.675)	-0.058		-0.361
	(0.072)		(0.244)
ln(hardness)	0.035	0.019	0.165
	(0.053)	(0.049)	(0.206)
Citypop Q2	0.221**	0.218**	0.722*
	(0.108)	(0.106)	(0.436)
Citypop Q3	0.191*	0.179*	0.685
	(0.110)	(0.106)	(0.446)
Citypop Q4	0.410***	0.402***	1.706***
	(0.104)	(0.102)	(0.426)
Mid-Atlantic	0.126	0.111	1.152**
	(0.122)	(0.121)	(0.543)
East North	0.215	0.198	1.394**
Central	(0.164)	(0.162)	(0.707)
All other	0.403**	0.378*	1.883**
	(0.196)	(0.195)	(0.845)
Precipitation	0.082	0.083	0.249
	(0.051)	(0.051)	(0.212)
Temperature	-0.179***	-0.173***	-0.558**
	(0.056)	(0.056)	(0.248)
Typhoid	-0.011	-0.015	0.057
	(0.038)	(0.038)	(0.121)
Observations	172	172	172
R-squared	0.135	0.132	0.080

Notes: ln(pH -5.675) has a value of 0 at a pH of 6.675, which is the 25th percentile of the acidity distribution. Citypop are indicator variables for population quartiles, which run from largest (Q4) to smallest (Q1). The omitted citypop quartile is Q1. The omitted region is New England. Precipitation, temperature, and typhoid have been standardized to have means of zero and standard deviations of 1. For the ordered logit, 1 = no lead, 2 = mixed lead, 3 = lead only. A constant was estimated but not reported. Heteroskedastic robust standard errors are shown 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)
Dep. Var	Inf. Mort	Inf. Mort	Inf. Mort	Inf. Mort
Sample	Full	Full	Full	Full
ln(pH – 5.675)	-0.049	-0.015	-0.013	
	(0.033)	(0.026)	(0.027)	
Mixed lead	-0.029	0.002	-0.005	
x ln(pH– 5.675)	(0.039)	(0.033)	(0.033)	
Lead only x	-0.075**	-0.060**	-0.062**	
ln(pH– 5.675)	(0.037)	(0.027)	(0.028)	
pH-6.675				0.058
				(0.070)
Mixed lead x				-0.073
(pH-6.675)				(0.104)
Lead only x				-0.270***
(pH-6.675)				(0.094)
No lead x				-0.105
(pH-6.675) x 1(pH> 7.3)				(0.096)
Mixed lead x				-0.026
(pH-6.675) x 1(pH> 7.3)				(0.103)
Lead only x				-0.029
(pH-6.675) x 1(pH> 7.3)				(0.080)
Mixed lead	0.043	0.022	0.018	0.019
	(0.035)	(0.031)	(0.031)	(0.046)
Lead only	0.074***	0.068***	0.070***	0.063*
	(0.028)	(0.025)	(0.026)	(0.034)
No lead x				0.009
1(pH> 7.3)				(0.079)
Mixed lead x				-0.078
1(pH> 7.3)				(0.090)
Lead only x				-0.031
1(pH> 7.3)				(0.054)
Typhoid			0.028***	0.030***
			(0.008)	(0.008)
Non-pulm.			0.015	0.012
Tuberc.			(0.010)	(0.009)
Demog & Other Controls	N	Y	Y	Y
Obs.	172	172	172	172
R-squared	0.304	0.552	0.584	0.602

Notes: ln(pH -5.675) has a value of 0 at a pH of 6.675, which is the 25th percentile of the acidity distribution. For ease of interpretation in column 4, pH = original pH – 6.675. (The two lead variables are both equal to zero at 6.675.) 1(pH> 7.3) is an indicator variable that is 1 if pH is greater than 7.3 and 0 otherwise. In columns 1-3, there are 3 indicator variables for pipes (no lead, mixed, lead only). The omitted category is no lead. In column 4, there are 6 indicators variables (no lead w/pH≤7.3, mixed w/pH≤7.3, lead only w/pH≤7.3, no lead w/pH>7.3, mixed w/pH>7.3, lead only w/pH>7.3). The omitted category is no lead w/pH≤7.3. All specifications include regional fixed effects, and city population quartile fixed effects. Demographic and other controls are fraction foreign born, fraction white, fraction women of ages 20-40, state temperature and state precipitation. A constant was estimated but not reported. Heteroskedastic robust standard errors are shown 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	Lead-only	Lead-only	Lead-only
Ln(pH-5.675)	-0.070***	-0.053***	
	(0.018)	(0.020)	
Ln(hardness)		-0.024	
		(0.020)	
pH-6.675			-0.2706***
			(0.077)
hardness			-0.0010*
			(0.000)
hardness x			0.0018*
(pH-6.675)			(0.001)
pH-6.675			0.2562**
x 1(pH> 7.3)			(0.117)
hardness			0.0007
x 1(pH> 7.3)			(0.001)
hardness x			-0.0018
(pH-6.675) x 1(pH>7.3)			(0.001)
Lead			-0.0564
x 1(pH> 7.3)			(0.1011)
Obs.	75	75	75
R-squared	0.665	0.673	0.697

Notes: ln(pH -5.675) has a value of 0 at a pH of 6.675, which is the 25th percentile of the acidity distribution. For ease of interpretation in column 4, pH = original pH – 6.675. (The two lead variables are both equal to zero at 6.675.) 1(pH> 7.3) is an indicator variable that is 1 if pH is greater than 7.3 and 0 otherwise. The omitted category is lead w/pH≤7.3. All specifications include regional fixed effects, and city population quartile fixed effects. Demographic and other controls are fraction foreign born, fraction white, fraction women of ages 20-40, state temperature and state precipitation. A constant was estimated but not reported. Heteroskedastic robust standard errors are shown 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
ln(pH-5.675)	-0.013	0.013	-0.008	0.021	0.034*
	(0.027)	(0.032)	(0.032)	(0.025)	(0.017)
Mixed lead x	-0.005	-0.010	-0.046	-0.048	-0.063***
ln(pH-5.675)	(0.033)	(0.036)	(0.040)	(0.030)	(0.020)
Lead-only x	-0.062**	-0.081***	-0.064*	-0.050*	-0.050**
ln(pH-5.675)	(0.028)	(0.030)	(0.034)	(0.029)	(0.021)
Mixed lead	0.018	0.040	0.028	0.041**	0.026*
	(0.031)	(0.025)	(0.027)	(0.020)	(0.015)
Lead-only	0.070***	0.067***	0.047**	0.047**	0.017
	(0.026)	(0.020)	(0.023)	(0.018)	(0.013)
Typhoid	0.028***	0.013***	0.036***	0.073***	0.080***
	(0.008)	(0.004)	(0.010)	(0.012)	(0.022)
Non-pulm.	0.015	-0.007	0.018**	0.011	0.016
Tuberc.	(0.010)	(0.005)	(0.009)	(0.012)	(0.012)
Obs.	172	175	214	200	211
R-squared	0.584	0.528	0.468	0.518	0.367

Notes: ln(pH -5.675) has a value of 0 at a pH of 6.675, which is the 25th percentile of the acidity distribution. The omitted category is no lead. All specifications include regional fixed effects, and city population quartile fixed effects. Demographic and other controls are fraction foreign born, fraction white, fraction women of ages 20-40, state temperature and state precipitation. A constant was estimated but not reported. Heteroskedastic robust standard errors are shown in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Table 7: Effects of Lead and pH on Non-Infant Mortality in 1900

	(1)	(2)	(3)
Dep. Var	Non-Inf. Mort	Non-Inf. Mort	Non-Inf. Mort
Sample	Full	Full	Full
ln(pH – 5.675)	-0.050	0.047	
	(0.070)	(0.055)	
Mixed lead	0.102	-0.021	
x ln(pH– 5.675)	(0.093)	(0.072)	
Lead only x	-0.022	-0.027	
ln(pH– 5.675)	(0.085)	(0.059)	
pH-6.675			0.101
			(0.108)
Mixed lead x			-0.001
(pH-6.675)			(0.203)
Lead only x			-0.027
(pH-6.675)			(0.147)
No lead x			-0.048
(pH-6.675) x 1(pH> 7.3)			(0.164)
Mixed lead x			-0.323
(pH-6.675) x 1(pH> 7.3)			(0.212)
Lead only x			-0.109
(pH-6.675) x 1(pH> 7.3)			(0.136)
Mixed lead	0.079	0.076	0.084
	(0.074)	(0.056)	(0.074)
Lead only	0.006	0.089*	0.075
	(0.059)	(0.048)	(0.060)
No lead x			-0.031
1(pH> 7.3)			(0.145)
Mixed lead x			0.319
1(pH> 7.3)			(0.219)
Lead only x			0.121
1(pH> 7.3)			(0.103)
Typhoid		0.076***	0.074***
		(0.021)	(0.020)
Non-pulm.		0.012	0.011
Tuberc.		(0.020)	(0.020)
Demog & Other Cont.	N	Y	Y
Obs.	172	172	172
R-squared	0.221	0.665	0.671

Notes: Notes: ln(pH -5.675) has a value of 0 at a pH of 6.675, which is the 25th percentile of the acidity distribution. For ease of interpretation in column 3, pH = original pH – 6.675. (The two lead variables are both equal to zero at 6.675.) 1(pH> 7.3) is an indicator variable that is 1 if pH is greater than 7.3 and 0 otherwise. In columns 1-2, there are 3 indicator variables for pipes (no lead, mixed, lead only). The omitted category is no lead. In column 3, there are 6 indicators variables (no lead w/pH≤7.3, mixed w/pH≤7.3, lead only w/pH≤7.3, no lead w/pH>7.3, mixed w/pH>7.3, lead only w/pH>7.3). The omitted category is no lead w/pH≤7.3. All specifications include regional fixed effects, and city population quartile fixed effects. Demographic and other controls are fraction foreign born, fraction white, over 60 and under 5, average age, state temperature and state precipitation. A constant was estimated but not reported. Heteroskedastic robust standard errors are shown in parentheses. ***, **, and * denote statistical significance at the 1, 5, and 10 percent levels.

Appendix 1

Table 1A: 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	-0.0117***	-0.0105***	-0.0122***	-0.0109***
	(0.001)	(0.001)	(0.001)	(0.001)
No lead x	0.0021*	0.0025**	0.0023	0.0025
time	(0.001)	(0.001)	(0.002)	(0.002)
Mixed lead x	-0.0002	-0.0000	0.0017	0.0020
time	(0.001)	(0.001)	(0.002)	(0.002)
No lead x			0.0063***	0.0070***
time x 1(pH>7.3)			(0.002)	(0.002)
Mixed lead x			0.0039*	0.0040**
time x 1(pH>7.3)			(0.002)	(0.002)
Lead only x			0.0045**	0.0046**
time x 1(pH>7.3)			(0.002)	(0.002)
Controls	N	Y	N	Y
City FE	Y	Y	Y	Y
Observations	974	974	974	974
R-squared	0.817	0.827	0.822	0.833

Notes: The omitted category is lead-only. 1(pH> 7.3) is an indicator variable that is 1 if pH is greater than 7.3 and 0 otherwise. The specifications in columns 2 and 4 include regional fixed effects, and city population quartile fixed effects. Demographic and other controls are fraction foreign born, fraction white, fraction women of ages 20-40, state temperature and state precipitation. A constant was estimated but not reported. The baseline year is 1900. The panel covers 240 cities and is unbalanced. The number is greater than the largest number of cities in Table 6, because some cities appear in earlier years but not in later years. Heteroskedastic robust standard errors are shown 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: Historical water sources were identified using Baker (1897) The Manual of American Water Works; United States Geological Survey (1934) The Industrial Utility of Public Water Supplies in the United States, 1932; city websites, which sometimes have histories of the water utility; and other sources. pH and hardness of the historical water sources are primarily taken from United States Geological Survey (1954) The Industrial Utility of Public Water Supplies in the United States, 1952 or from The Water Encyclopedia (Van Der Leeden 1990), which report the acidity and hardness of the raw intake water for many water systems in the early 1950s and 1980s. Supplemental information was drawn from USGS reports. Data and detailed notes on source data for water characteristics of the cities are available online at http://www.heinz.cmu.edu/~kclay/research.html

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."[55] 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.

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