Water and Waste: A History of Reluctant Policymaking in U.S. Cities

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In its 2021 report card on U.S. infrastructure, the American Society of Civil Engineers assigned a C- to U.S. drinking water systems and a D+ to U.S. wastewater systems. These low rankings reflect that most systems are currently operating at both their designed maximum capacity and the end of their usable life. A 2018 survey found that about 16% of U.S. water mains are beyond their usable life and that, on average, a water main breaks every two minutes.[1] The situation is also deteriorating quickly. The frequency of main breaks increased by 27% between 2012 and 2018. For cast iron pipes, which many cities installed 50-100 years ago, the break rate increased by 43% between 2012 and 2018.

Water and waste systems are among the most crucial pieces of urban infrastructure, but the current state of neglect is far from puzzling. Many people remain perplexed as to why a country as rich as the United States would allow its infrastructure to fall into disrepair. The situation is less puzzling, however, once one recognizes that the history of urban water and waste management in the United States has always been more reactive than proactive. Early investments in U.S. water systems typically occurred after a city outgrew its local sources, not before. When scientific advances offered definitive proof of the dangers and origins of waterborne disease and when technological solutions to obtaining clean water were available, cities were still slow to purify their water supplies.

Lead water mains are an important and illustrative example. Perhaps the most prominent contemporary critic on the state of U.S. water and waste infrastructure is President Biden, who has tried to secure funding to replace the lead pipes that serve homes and schools.[2] Many cities relied on lead service lines because they were durable and easy to work with.[3] We now know that no amount of lead exposure is safe, particularly for children. Historical observers knew that lead was toxic, although

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[1] Folkman "Main Break Rates". This survey covers both the United States and Canada, but 90% of the survey responses come from U.S. municipalities.

[2] Lead exposure is harmful for health and cognitive development. In a March 31, 2021 speech, the president proposes replacing 100% of the nation's lead pipes and service lines, noting that "[we have] a chance to protect our children, help them learn and thrive. We can't delay. We can't delay another minute. It's long past due." A similar theme emerged in his address to congress following his 100th day in office, where on the issue of lead pipe replacement he said that it is "beyond time" to act.

[3] Troesken and Beeson "Significance."

they had a more incomplete understanding of the extent to which lead pipes threatened health. By 1920 it was understood that water-lead levels could be lowered by altering the chemistry of water supplies, and yet the first national water-lead standard would not be set until 1975. Lead water crises in Washington, DC (2001) and Flint, MI (2014) illustrated the delicate water chemistry balance that is necessary to keep lead pipes "safe." National coverage of these crises highlighted the desirability of prioritizing lead replacement, but even today somewhere between 9 and 10 million American homes continue to rely on lead water pipes, leaving many vulnerable to another public health emergency.

This chapter provides an overview of water and waste management in the United States throughout the 19th and early 20th centuries. The 19th century marks a turning point for water access and sewage disposal in the United States. Today, most Americans rely on treatment plants, pumping stations, and an immense network of mains to safely transport water and waste. Many of those key infrastructure investments were made in the 19th century, and the chapter describes the forces that helped shape those investments. With those infrastructure investments in place, there was an era of policy-oriented changes concerning whether waterworks should be publicly or privately managed and the role of health or environmental standards. These decisions had implications for the broader public health environment, which I discuss. The main theme to emerge is that both infrastructure provision and environmental standards are better classified as reactive in the sense that key aspects of water and waste management in U.S. cities tend to lag changes in scientific, economic, or bureaucratic forces.

The chapter contains four main parts. The next section describes the disease environment that arose from a reliance on wells and pumps to obtain water and cesspools and privy vaults to dispose of human and household waste. This is followed by an overview of the timing of infrastructure investments, which I broadly classify into three phases: early experimentation, early diffusion, and proliferation. Particular attention is paid to the scientific, technological, and bureaucratic innovations that encouraged cities to invest earlier, however, aside from a few innovators, most cities tended to delay acting, even when well-developed (but costly) solutions existed. A discussion of how cities came to control typhoid fever and other waterborne diseases and highlights where these benefits fit relative to the broader mortality transition is then presented. This is followed by a discussion of the consequences of 19th century decisions to invest in lead pipes, which provides an illustrative example of how cities struggled to enact environmental standards.

Waterborne Disease as a Barrier for Growth

In the United States, the process of urbanization started around 1820 in the Northeast.[4] In 1820 about 10% of Northeast residents lived in urban areas (towns with 2,500 or more residents). That figure steadily increased over the next 100 years, reaching nearly 80% in 1920. Population density was slower to increase, with the biggest increases occurring in the northeast between 1880 and 1960. The West and the Midwest urbanized second while the South lagged. By 1850, 30% of the population in the Northeast resided in urban areas, as compared to 10% in the Midwest, South, or West. The Midwest and West crossed the 30% threshold in 1880 but the south would not cross that threshold until 1930.

As cities grew they quickly discovered that local water sources either delivered an insufficient quantity or were increasingly likely to become polluted with industrial or human waste.[5] Most 19th century urbanites obtained their water from local sources, such as wells, lakes, rivers, streams, and springs. Human and household wastes were often stored in cesspools and privy vaults, which were not necessarily problematic if they were watertight and frequently emptied. But 19th century waste receptacles were rarely watertight and nearby soil was often saturated with waste. When receptacles were located near an underground well, then leaking waste could saturate both the soil and the water supply. This type of contamination was one of the common modes of transmission for typhoid fever and other waterborne illnesses.[6] In some cities the rivers that provided drinking water were also a natural place to deposit sewage and industrial waste, in turn contaminating the drinking water for residents that were unfortunate enough to reside in towns downstream.

Allowing sewage to leech into the water supply left city dwellers vulnerable to typhoid fever.[7] Typhoid fever is caused by ingesting the bacterium *Salmonella* Typhi. In its early stages, typhoid's symptoms often resembled those of respiratory diseases and pneumonia was often present. Nearly all cases experienced severe fever, with body temperatures reaching as high as 105° F (40.6° C). Three weeks after incubation, the disease was at its worst. The patient was delirious, emaciated, and often

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[4] Boustan, Buntin, and Hearey "Urbanization." See in particular Figures 22.1b and 22.2b, which depict long-run urbanization patterns in the United States.

[5] These themes are fairly universal, but Blake *Water for cities* is a useful reference. Chapter 1 in particular offers a detailed description of the challenges in Philadelphia. One idea that emerges from that description is how households would collect and store water in cisterns and how dust and cinders would spoil water such that it was not even suitable for washing clothes.

[6] For detailed accounts of epidemics that arose from cesspools and privies contaminating local wells, see Budd "Typhoid Fever," which synthesizes some of his earlier work arguing that typhoid fever was waterborne, Sedgwick "Principles," and chapter VIII of Whipple *Typhoid Fever*.

[7] This paragraph draws heavily from Beach, Ferrie, Saavedra, Troesken "Typhoid Fever," Whipple *Typhoid Fever*, pp. 23-36 of Troesken *Water, Race, and Disease*, and Curschmann "Typhoid Fever."

had blood-tinged stools. One-in-five victims experienced a gastrointestinal hemorrhage. Internal hemorrhaging resulted when typhoid perforated the intestinal wall and sometimes continued on to attack the kidneys and liver. The risk of pulmonary complications, such as pneumonia and tuberculosis, was high. Roughly half of all victims experienced neuropsychiatric disorders, including brain-swelling, Parkinson-like tremors, confusion, or hallucinations. Despite the severity of these symptoms, 90-95% of individuals would survive the initial infection, although recovery could take up to four months, and survivors often faced an elevated mortality risk that lingered for years.

We lack precise estimates of the health costs that resulted from inadequate infrastructure, but the available evidence suggests that the cost was large. We know that the case fatality rate of typhoid fever during this time was between 5 and 10%. Thus, for every observed typhoid fever death there were likely 9 to 19 other individuals that contracted typhoid fever and survived. We also know that at least until the early 20th century, typhoid fever deaths were due almost exclusively to contaminated water. Building on this logic, Werner Troesken estimates that 21-42% of Americans born in the mid to late 19th century would have contracted typhoid fever at some point during their life.[8] These estimates likely represent a lower bound as the varied and indistinct nature of typhoid fever's symptoms make it difficult to diagnose.[9]

Contemporary observers understood that cities were unhealthy places to live, but throughout the 19th century the origins of disease were not well understood. Sewage was recognized as dangerous, but it was commonly thought that disease transmission occurred through exposure to sewer gas rather than ingesting tainted water. Thus, sewage leaching into the water supply was seen as a nuisance but the sewer gas represented the real threat. It was not until the 1880s that we started to accept that it was, in fact, the other way around.

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[8] Troesken *Water, Race, and Disease* pp. 47-49. As far as I can tell, Troesken's calculation includes all residents, as typhoid fever existed in urban and rural areas. In 1890, the typhoid fever death rate among cities in the registration area was 3.9 deaths per 1000 persons, while the death rate in rural areas of those states was 3.13 deaths per 1000 persons (Vital Statistics, 1890 Volume 1, pg. 270). Among cities with a population of 100,000 or more the typhoid fever death rate was 5.33 deaths per 1000 persons.

[9] One distinguishable symptom is the development of rose-colored spots on the patient's abdomen, but those spots present in fewer than one-third of all cases. Without those spots, it was difficult to distinguish between typhoid, respiratory diseases, and malaria. Jordan "Purification" and Whipple *Typhoid Fever,* pp. 96-97.

Evolution of Infrastructure Investment

This section provides an overview of infrastructure investment among U.S. cities. I categorize investment patterns into three broad categories: the experimental phase (1800-1850), the early diffusion phase (1850-1880), and the proliferation phase (1880-1900). During the experimental phase investments occurred almost exclusively among the largest cities. This is because large cities invested out of necessity to combat filth and fire. The efforts of early adopters increased collective understanding of the technological aspects of transporting water. While this worked to reduce the uncertainty of investment, during the early diffusion phase investments were still concentrated among larger cities that were responding to the challenges of population growth. By 1880 the increased acceptance of the germ theory of disease meant that cities had a new scientific basis by which to judge the quality of their drinking water supplies. This higher standard led larger cities to improve the quality of the water that was being transported through earlier infrastructure investments. At the same time, rapid diffusion of waterworks infrastructure took place in smaller cities and larger towns.

Figure 1 reinforces this interpretation by plotting the diffusion of waterworks construction by city size. Cities are categorized based on their population as of 1900. I restrict attention to incorporated places with a population of 2,500 or more as measured in the 1900 census and information on the year a waterworks was built comes from Moses Baker's 1897 *Manual of the American Waterworks*.[10] Before 1850, construction occurs almost exclusively among the largest cities in the United States. After 1850 the pace of construction increases among large and medium sized cities. By 1880 nearly every major U.S. city has a waterworks. While we see some investment among small cities and towns starting around 1870, the pace of investment increases dramatically after 1880. Between 1880 and 1897 the share of small cities (populations between 5,000 and 25,000 in 1900) increased from 30% to about 90%. Among small towns (populations between 2,500 and 5000), about 10% had a waterworks by 1880 but by 1897 roughly 75% of these small towns would have a waterworks.

These patterns of infrastructure investment span key periods of U.S. urban development. Joel Tarr categorizes U.S. urban development from 1790 to 1920 into two broad periods.[11] Tarr refers to

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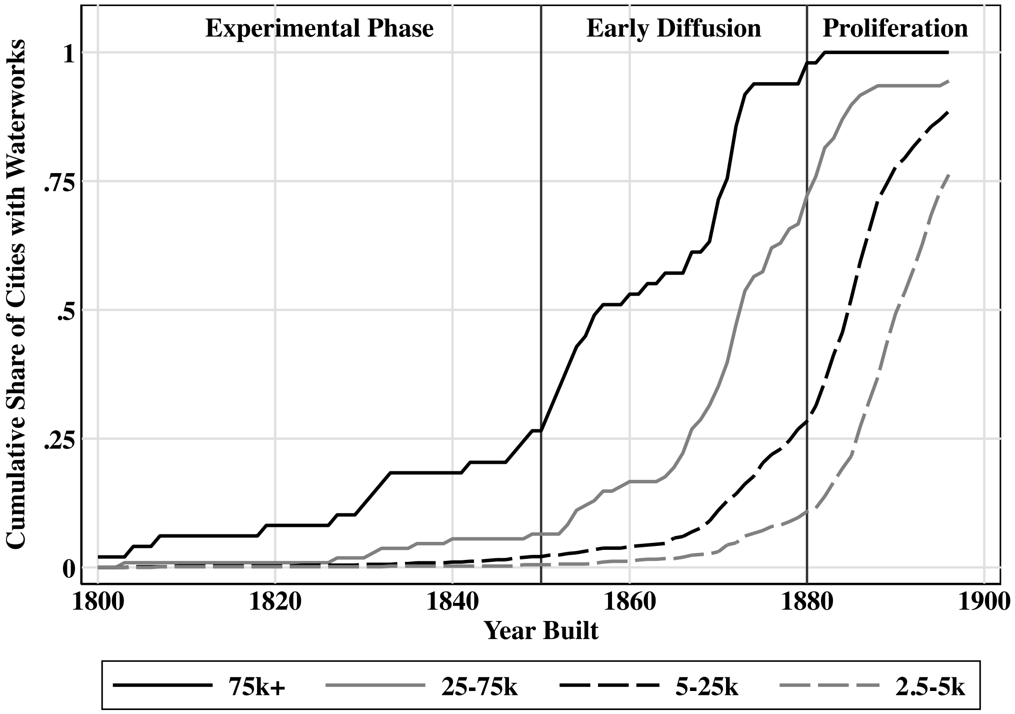
[10] The construction of a waterworks may have provided a foundation for future population growth, an issue I touch on later. It is thus helpful to think of the following thresholds as offering the following crude categorization of relative city sizes: major cities, medium-sized cities, small cities, and large towns.

[11] The remainder of this paragraph summarizes main themes from these periods of urban development. Those themes re discussed more formally in Tarr "Evolution," "The City," and elsewhere. The brevity of the discussion does not quite capture the remarkable amount of innovation, experimentation, and learning that was occurring, and so I encourage unfamiliar readers to engage with these articles.

the period spanning 1790 to 1870 as "The Walking City," a term capturing the idea that during this period cities were compact out of necessity (most residents walked to work). Here the compactness of a city meant that cities quickly felt the strain of population growth. This period saw a number of important technological developments to overcome these challenges. The development of horse and mule-powered streetcars made it feasible for wealthier residents to separate their place of residence from their place of work. At the same time, sanitary infrastructure, fire hydrants, and improved construction methods helped cities overcome factors that would otherwise limit a city's ability to continue to grow.

Figure 1: Diffusion of Waterworks Construction by City Size in 1900



Notes: Population is measured as of the 1900 census. Denominator corresponds to all incorporated places within the same population bins. Data on year built from Baker's 1897 *Manual of the American Waterworks*. There are 49 cities with a population over 75,000; 108 cities with a population between 25,000 and 75,000; 666 cities with a population between 5,000 and 25,000; and 754 cities with a population between 2,500 and 5000. These population cutoffs correspond to roughly the 97th, 90th, and 50th percentiles.

The "networked city" emerges between 1870 and 1920, as utilities (sanitary and otherwise) and transit systems became more centralized, with a push to connect households and businesses to these networks. A crucial benefit of networking is its automated service. A reliable supply of water, electricity, and waste disposal paved the way for a wide array of modern conveniences (e.g., flush toilets, washing machines, refrigerators, modern stove, and heating). In *The Rise and Fall of American Growth*, Robert Gordon argues that these urban networks are responsible for a substantial transformation in standard of living that will never be repeated. Networks, and the conveniences that followed, facilitated intense urbanization among the largest cities, and with that came some experimentation with urban form (e.g., business/commercial districts and streetcar suburbs). Since this chapter is focused on the adoption of one form of technology (water and sewer infrastructure), when I discuss the patterns of infrastructure adoption after 1870 I will be referring to the opposite side of the city-size distribution, as this is when infrastructure is adopted among large towns.

The Experimental Phase (1800-1850)

During the experimental phase the 50 largest U.S. cities were the most likely to begin constructing a waterworks. This is understandable. As cities grow, nearby ponds and streams quickly become polluted. At best, pollution is a harmless disamenity, affecting the taste, smell, or clarity of the water. At worst, contaminated water becomes a vector for disease, undermining public health.

Despite a limited understanding of the precise causes of waterborne disease, many cities identified water and sewer infrastructure as a solution. Philadelphia offers a paradigmatic example. Yellow fever ravaged the city in 1793, killing an estimated 5000 residents, with another 20,000 fleeing the city to protect themselves. These numbers are substantial, as Philadelphia's population in the 1790 census is recorded at 44,096. Yellow fever is spread through mosquito bites, although Carlos Finlay would not present his mosquito-vector hypothesis until 1881 and it would take another 20 years before Walter Reed's work confirmed Finlay's theory. Thus, in 1793, when the prevailing wisdom was that disease originated from foul air, it was suggested that Philadelphia could protect itself from yellow fever by cleansing its streets, houses, and clothes. This recommendation required an abundant supply of water that was pure, at least when judged by its clarity and smell. Philadelphia rose to this challenge and became the first large city to build a municipal waterworks in 1801.[12]

Bringing water into the city required finding solutions to a number of technological hurdles. To improve water quality, most cities looked to transport water from a source that is unlikely to be polluted. Thus, the city had to find a way to transport water in a cost-effective way. If a city was lucky,

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[12] Blake *Water for Cities* pp. 8-17 and Ch. 2.

their identified source would be at a higher elevation, and so the water could be fed by gravity. If this was not the case, then a typical solution would involve pumping water into a storage tank, at which point it could then be fed by gravity. In this situation, a city would need to invest in storage tanks and pumps that could reliably lift the water needed to fill those tanks. Water ultimately needs to be distributed across the city, which necessitated investment in mains that could transport water without rupturing from the pressure.

Early adopters implemented experimental solutions out of necessity, but those experiments were not always successful. The waterworks that opened in Philadelphia in 1801 was designed by Benjamin Latrobe and relied on two steam engines to pump water from the Schuylkill River into wooden tanks. At that point, water was gravity-fed to the rest of the city through a network of wooden mains. The waterworks opened in 1801, but it suffered from a number of problems. The engines were expensive to run and frequently broke down. When one engine broke down, the supply of water was often shut off completely. Even when the engines were running, the supply of water was often inadequate. Growing frustration with the first waterworks motivated the Philadelphia to start construction on a replacement waterworks in 1812. Philadelphia's second waterworks, The Fairmount Waterworks, was more successful, opening in 1815 and continuing to operate until 1909.

New York City's history illustrates that technology was not the only experimental area. Aaron Burr founded The Manhattan Company in 1799 and received the exclusive right to supply water to New York City. The company's charter allowed for surplus capital to be used for banking transactions, which was Burr's primary interest. Consequently, instead of bringing water from outside the city, the company dug a series of wells and used the surplus funds to start the Manhattan Bank, which became the Chase Manhattan Bank in 1955 and J.P. Morgan Chase in 2000. New York City continued to suffer the consequences of poor water quality for several decades. By around 1830 it was recognized that the Croton River offered a solution to New York City's water problems, but transporting water into the city was an engineering feat that ultimately involved a dam and a 41-mile aqueduct. It was not until 1842 that New Yorkers started to gain access to the purer water from the Croton River. Even then, health improvements were limited because many households felt the costs of connecting to this source outweighed the benefits.[13]

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[13] Glaeser and Poterba "Infrastructure Investment."

While New York City is an extreme example, cities experimented with administrative arrangements throughout the 19th century. Towards the end of the 20th century, however, there was a push for waterworks to be a public enterprise. New waterworks were increasingly likely to be publicly owned and existing private works were municipalized en masse between 1890 and 1920.

Scientific Advances and Early Diffusion (1850-1880)

The experimental phase lasted until roughly 1850, when key components of the supply chain were increasingly established and technological innovation started to gain momentum.[14] Consider, for instance, water mains. The first mains were constructed out of bored wooden logs, which were difficult to work with, prone to rotting, and prone to leaking. Rotting affected the taste of the water and compromised the integrity of the system. Leaking either meant a large repair bill, particularly if the main had to be dug up, or a lot of wasted water. Iron pipes were preferable, but they were expensive as they were typically imported from England. Domestic suppliers gradually appeared and after 1820 the use of cast iron became much more frequent. Irregularities in the casting process and corrosion from water exposure affected the strength and lifespan of iron pipes. The development of the vertical casting technique in 1845 allowed for a more uniform cast, and in the 1850s manufacturers learned that they could fight corrosion by lining pipes with other materials, and that doing so increased the lifespan of a pipe by a factor of two or more. Pumping technology, another crucial input, improved substantially in the 1860s with the refinement of the Worthington Pump and the Holly Rotary Pump. Those pumps were more reliable and offered more uniform pressure, which meant that cities did not need to rely on reservoirs or water towers, in turn lowering the cost of construction.

These technological advances arrived just as smaller cities started to recognize the benefits of infrastructure investment. The “Sanitary Idea” that epidemic disease results from environmental conditions rather than personal morality started to gain momentum following Chadwick's 1842 report: *An Inquiry into the Sanitary Condition of the Labouring Population of Great Britain*.[15] As the Sanitary Idea took hold in England, it was increasingly seen as the government's responsibility to supply water and remove waste. The United States' enthusiasm for infrastructure investment lagged behind that of

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[14] Anderson “Diffusion” pp. 10-34 offers an excellent summary on the supply of mains, pumps, and the supply of civil engineers throughout the 19th century.

[15] Melosi *Sanitary city*, Ch. 4.

England, in part because it had a lower population density. But as American cities grew, so did the prevalence of filth and disease, which motivated Americans to commit dollars to address the issue.[16]

As cities invested in water infrastructure, they quickly found themselves facing a new problem: waste disposal. Once running water was available, daily water consumption increased from about 2-3 gallons per capita to 50-100 gallons per capita.[17] Water consumption increased even further once water closets started to be installed. The problem, as Tarr notes, was that cities did not invest in water and sewer infrastructure simultaneously and existing disposal methods (cesspools and privy vaults) were not designed to handle the increased capacity.[18] Despite an incomplete understanding of disease transmission, overflowing cesspools and privy vaults were recognized as a threat to public health, forcing action. The first U.S. municipal sewers appeared in Brooklyn (1855), Chicago (1856), and Jersey City (1859). While we lack comprehensive data on sewer construction, the inherent complementarity between water and sewer infrastructure suggests that the pace of sewer construction likely mirrored waterworks construction but with a lag to account for when existing waste systems became overwhelmed.

American engineers were in the fortunate position that many of the technological challenges associated with building a sewer network had already been solved in England. As in England, most systems were designed to transport wastewater and storm water away from the city and preferably to a nearby waterway. Smaller cities had less of a need for storm-water diversion, and so they tended to build sewer networks that were dedicated to waste disposal. At the time, it was thought that the churning of rivers and streams purified water and the rudimentary chemical testing of the time seemed to confirm that idea.[19] Bacterial science would refute the self-purification idea in the 1880s and 1890s, but by then large cities would have already made substantial infrastructure investments. The durability of these investments meant that this design choice would impact a city's approach to wastewater treatment once cities were held accountable for the pollution they deposited into waterways.

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[16] Melosi, *Sanitary city*.

[17] Tarr *Ultimate Sink*, pg. 114.

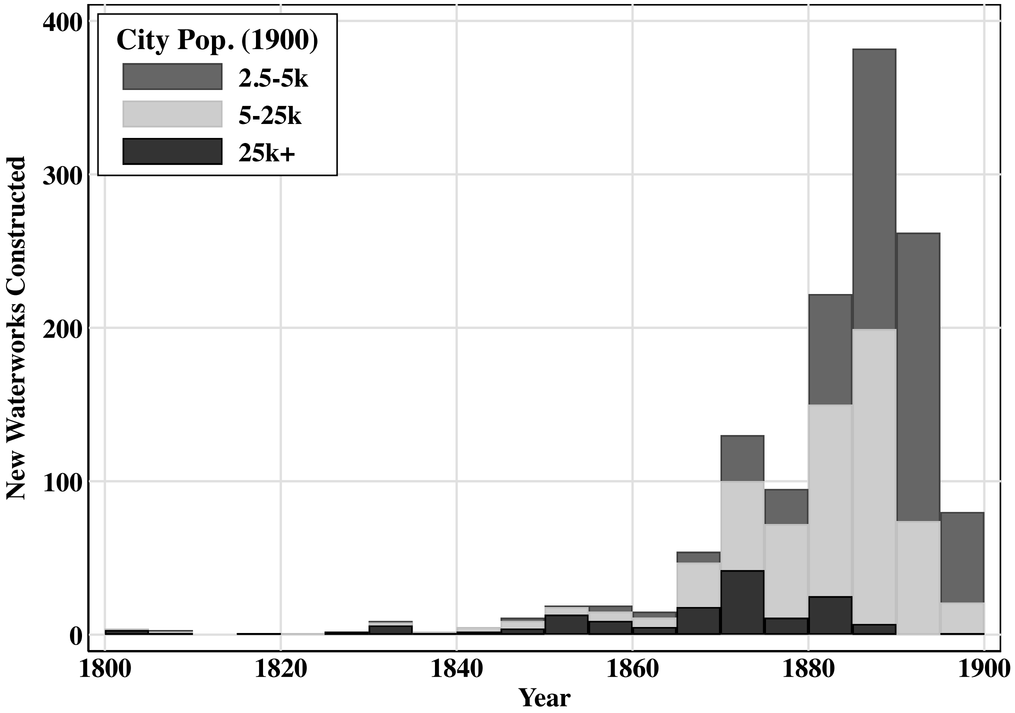
[18] New York faced a particularly interesting challenge. When households abandoned their contaminated wells in favor of the Croton water, the city's water table started to rise, resulting in flooded cellars. New York City Municipal Gazette, Volumes 1-41, p. 311; Documents of the Board of Aldermen of the City of New-York Volume 10, Part 2, 1844. This type of flooding likely had unfortunate implications for the cesspool and privy vault waste collection arrangement.

[19] Tarr *Ultimate Sink*, pg. 136.

Proliferation (1880-1900)

The pace of waterworks construction increased dramatically in the final decades of the 19th century. Figure 2 provides a sense of the scale of these investments by plotting, by city size, the number of waterworks constructed in each five-year bin. In some ways the patterns in Figure 2 are predictable. Since there are far more small cities than there are large cities, it is not surprising that the solid black bars are much smaller in magnitude or that from 1800-1860 it was rare to see more than 20 waterworks being constructed in any given five-year period. Even so, it is striking to see the pace of construction increase in the final decades of the 19th century, topping out at nearly 400 waterworks constructed between 1885 and 1890.

Figure 2: New Waterworks Construction by City Size and Year



Notes: Population is measured as of the 1900 census. Data on year built from Baker's 1897 *Manual of the American Waterworks*. There are 157 cities with a population over 25,000; 666 cities with a population between 5,000 and 25,000; and 754 cities with a population between 2,500 and 5000. These population cutoffs correspond to roughly the 90th and 50th percentiles for incorporated places with more than 2,500 residents in 1900.

One conclusion to take from Figure 2 is that the forces that drove smaller municipalities to invest in the final decades of the 19th century differed from the forces at play prior to 1880. As discussed above, investment before 1880 was typically the result of cities outgrowing local water supplies and needing to find a way to access higher quality and abundant quantities of water. It is hard to imagine that so many large towns (2,500-5,000 persons) and small cities (5,000-25,000 persons) simultaneously outgrew their waterworks in such a brief period of time. This seems particularly true once one recognizes that larger cities (25,000 or more persons) did not outgrow their local water supplies all at once. If we assume that year of construction offers a rough approximation for when cities outgrew their supplies, Figure 2 indicates that some large cities outgrew their local supplies as early as 1800 while other large cities did not outgrow their local supplies until nearly 1900.

What explains the seemingly coordinated wave of investments among smaller cities and larger towns after 1880? David Cutler and Grant Miller argue that there was pent up demand for waterworks and that the wave of investments after 1880 reflect public finance innovations that allowed cities to raise the capital to construct a waterworks.[20] Their argument is that the Panic of 1873 generated a wave of municipal defaults, which motivated the adoption of constitutional reforms to restrain borrowing, but waterworks were one of the few purposes for which a local government could borrow beyond the legally established debt limit. Those reforms established the attractiveness of municipal debt, allowing even the smallest of cities to issue waterworks bonds at favorable interest rates. One of the key pieces of evidence offered in favor of this hypothesis is time series evidence on municipal borrowing in New England from Jacob Upton's "Report on Wealth, Debt, and Taxation at the Eleventh Census, 1890." But those interest rates are based primarily on municipalities in Massachusetts, which had an average bond yield lower than any other state.[21] There is thus a need for additional evidence relating the public finance innovations, municipal borrowing costs, and waterworks construction.

Despite a need for more evidence linking those constitutional reforms to borrowing costs, it seems likely that municipalities were able to finance late 19th century waterworks investments at favorable terms.[22] Municipal water bonds are often tied to tangible assets that can be seized (and easily redeployed) in the event of bankruptcy. But bankruptcy is unlikely since waterworks are often profitable, raising more than enough revenue to offset operating costs and debt repayment. In some cases, waterworks generated enough revenue to service other debts as well. The revenue stream is also reliable. Demand for piped water rarely decreased during this period, particularly in growing cities.

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[20] Cutler and Miller "Water"

[21] Upton "Report," pp. 857-861.

[22] The following discussion is based off of information from Lawrence Chamberlain's 1911 book, *The Principles of Bond Investment*.

The business of delivering water is not labor intensive and they key input (the water that enters the pipe) is virtually costless. These features suggest that financial markets might have viewed municipal water bonds favorably, regardless of the existence of constraints on other types of borrowing.

While the above discussion indicates that small municipalities *could* borrow to construct waterworks in the late 19th century, it does not answer the question of *why* small cities and large towns across the country made these investments effectively all at once. Unfortunately, we lack a precise explanation for this phenomenon. This phase of investment, as with the adoption of other technologies, is the natural next step as waterworks construction diffused from larger to smaller cities. Adoption was likely stimulated by both greater demand for clean water as individuals gained a better understanding of the causes of disease and lower construction costs as building techniques became more standardized. The fixed costs of construction likely mattered more for smaller cities, which were more limited in their ability to spread those costs across any households. To the extent that waterworks were profitable, it seems likely that cities, constrained by their ability to borrow for other purposes, might have built a waterworks hoping that it might help raise revenue for other purposes. Finally, it seems plausible that smaller municipalities invested in waterworks to help establish their legitimacy. As Chamberlain (pg. 197) notes:

> The amount and character of property owned by any municipal or quasi-municipal corporation, especially in the less settled Southwest and West, and especially when the population is a matter of hundreds or scant thousands, have an important bearing upon the permanency of the settlement… Nothing else makes for stability and security like a good waterworks, operated and owned by the municipal corporation.

Letty Anderson also cites "boosterism" as a distinct driver of investment, as smaller towns competed for people and industry.[23] Vancouver, British Columbia is one city that invested in public health services in order to attract additional residents.[24]

Controlling Waterborne Disease

Improvements in water and sewer infrastructure helped cities control waterborne disease. Figure 3 provides an illustrative example. The neighboring cities of Newark and Jersey City initially obtained their water from the heavily polluted Passaic River and, as the figure indicates, typhoid fever mortality in the two cities was remarkably similar. In 1892, Newark abandoned the Passaic River in favor of the

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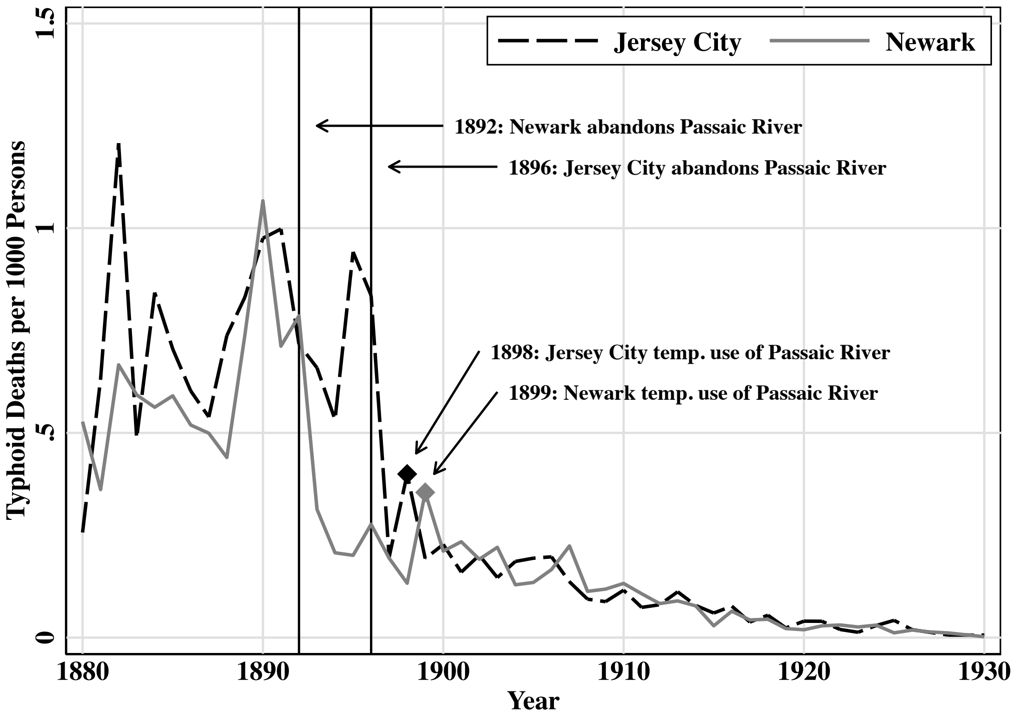
[23] Anderson "Hard Choices" and "Diffusion."

[24] Andrews "Best Advertisement."

Pequannock River and its typhoid fever mortality rate fell by 60-70%. Typhoid fever mortality rates in Jersey City remained at the higher rate until 1896 when Jersey City also abandoned the Passaic River. As in Newark, Jersey City's typhoid mortality rate fell by roughly 70% after changing water sources. In 1898, when Jersey City temporarily augmented its supply with previously abandoned sources on the Passaic River, there was a sharp and temporary uptick in typhoid fever rates in Jersey City but not Newark. A similar situation occurred in 1899 when a cold spell decreased the supply of water from the Pequannock River and Newark was forced to rely on the Passaic River. Again, we see a sharp increase in Newark's typhoid mortality followed by an immediate reversal, but typhoid mortality rates in Jersey City were unaffected.

Figure 3: Typhoid Patterns in Neighboring Cities, 1880-1930



Notes: Typhoid deaths from 1880 to 1900 are from Whipple (1908) while deaths from 1900 to 1930 are from various issues of the U.S. mortality statistics. Population is from the census and is linearly interpolated between census years.

The patterns illustrated in Figure 3 reflect complementary infrastructure investments that were made decades earlier. The waterworks that Jersey City and Newark built to draw from the Passaic River were built in 1852 and 1867, but key components of those waterworks (such as mains and taps) were not abandoned when the cities switched sources. The network of mains that transported water throughout each city, which was developed over several decades, could transport water from any source. Thus, once the Passaic River water was flushed from the mains and replaced with a purer source, any resident with a pre-existing access to the city water would benefit from consuming relatively uncontaminated water. This helps explain the sharp decline in the overall typhoid fever mortality rate observed in Figure 3, but it also highlights how a switch to a purer source might generate smaller health improvements in cities with a less-developed network of mains.

The above discussion offers a preview of three themes that I develop in the remainder of this section. The first theme is that it was important for cities to improve their water quality, which cities could do by: transporting water from an untainted source, building a filtration plant, or building a chlorination plant. The first two options were the costliest, and many cities appear to have delayed action until the first experiments with chlorination illustrated that contaminated water sources could become safe water sources at a very low price. The second theme is that infrastructure is an important complementary component. Compared to the adoption of water purification technologies, we know much less about infrastructure access. Here I discuss whether privately-owned and publicly-owned waterworks faced different incentives to extend access and improve water quality. I also discuss evidence supporting the idea that majority Black neighborhoods were among the last to receive infrastructure access. The final theme is that improving water quality played an important role in eliminating waterborne disease from American cities, and so this section concludes by placing the mortality improvements associated with water purification in a broader perspective.

Purifying Contaminated Sources

In the 1890s it would be established that, when it came to eliminating the threat of waterborne illness, water filtration systems were an effective and viable substitute to obtaining water from untainted sources. In the United States, this lesson originated in Lawrence, MA, which has the distinction of being the first U.S. city to filter its water for the purposes of controlling waterborne disease.

For 19th century textile towns like Lawrence, rivers were an important resource that served multiple purposes. First, rivers offer an abundant source of energy that could be used to power textile mills. Second, rivers provided an easy solution for removing human and industrial wastes: simply deposit the wastes into the river and allow it to flow downstream. Finally, if other sources were unavailable, a town could also obtain its drinking water from the river, ideally from a point that lies upstream from sewage and other waste outflows.

Unfortunately for the residents of Lawrence, the water entering the city's river intakes was heavily polluted from sewage and other waste. Health officials attributed at least part of the blame to the neighboring city of Lowell (located 10 miles upstream). As one Lawrence health official put it: "Whenever [typhoid fever] has appeared in Lowell we have noticed the appearance of it here in less than three weeks, and always in a more violent form than in Lowell."[25] The situation was not much better in Lowell, as until about 1893, it also relied on the Merrimack River for all three uses, and Merrimack water that entered Lowell's mains was also contaminated.

The health situation in Lawrence and Lowell degraded rapidly after about 1887. Figure 4 illustrates the scale of the issue by plotting annual typhoid rates in Lawrence, Lowell, and Manchester (NH), another textile town located along the Merrimack river. Manchester's typhoid fever rate was often lower than Lawrence and Lowell, likely reflecting some combination its location, which was further upstream, and its reliance on a nearby lake for its drinking water. From 1883 to 1886 annual typhoid rates in Lawrence and Lowell averaged 0.52 and 0.69 deaths per 1000 persons, while in Manchester the annual rate was 0.46 deaths per 1000 persons. Typhoid fever mortality rates in Lawrence and Lowell nearly doubled in 1897 and remained elevated for several years while Manchester's typhoid fever mortality held constant. The situation in Lawrence and Lowell was at its worst during the 1890-1891 typhoid epidemic. While the epidemic would not arrive in Lowell until September, 1890 was already shaping up to be a particularly deadly year. Between January and August of 1890, typhoid fever killed 0.64 of every 1000 residents of Lowell, a 30% increase relative to 1889. But between September and December, the cumulative death rate would increase by 0.94 deaths per 1000 residents, a 154% increase in deaths relative to September to December of 1889.[26] As was often the case with typhoid fever, when Lowell suffered, so did Lawrence. The epidemic arrived in Lawrence towards the end of October and lingered until the spring of 1891. Because of the lagged arrival the vast majority of typhoid deaths in Lawrence occurred in early 1891, which is why the epidemic appears less pronounced in Figure 4.

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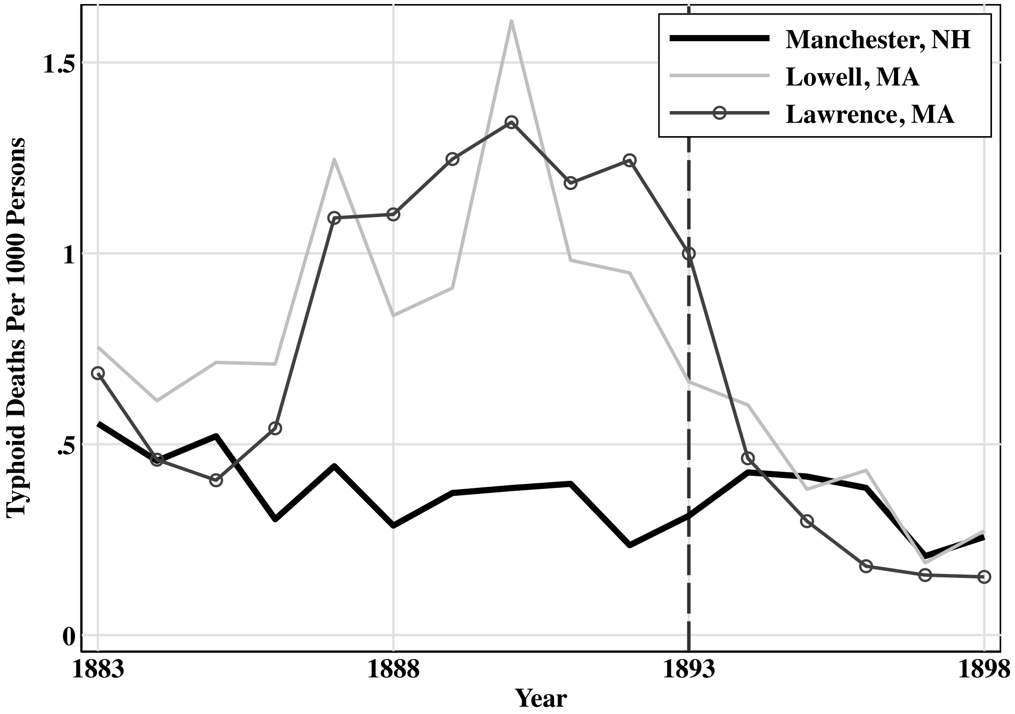
[25] Sixteenth Annual Report of the Board of Health of the City of Lawrence, Massachusetts (1893), 7.

[26] Monthly tabulations taken from Sedgwick 1891 Report on the Sanitary Condition of Water Supply of Lowell. Note that total typhoid mortality from these reports is slightly lower than what appears in the annual health reports, which explains the slight discrepancy between these figures and the data presented in Figure 4.

Figure 4: Typhoid Patterns along Merrimack River



Notes: Typhoid deaths from Whipple (1908). Population is from the census and is linearly interpolated between census years. The vertical line at 1893 marks the opening of Lawrence's water filtration plant. 1894 is the first full year of operation.

The 1890-1891 typhoid epidemic proved to be a turning point for water management in Lowell and Lawrence. In December 1890 the Lowell water board enlisted the help of the prominent public health scholar William Sedgwick to ascertain whether the Merrimack River was responsible for the epidemic. Sedgwick's investigation not only convincingly demonstrated that the Merrimack river water was harmful for human health, he also managed to trace the origins of the epidemic to an outbreak of typhoid in North Chelmsford, whose waste entered the Merrimack river roughly 2.5 miles upstream from Lowell's intake crib. Sedgwick's summary contains only the following sentence: "In view of all the foregoing facts I find myself compelled to report to your Honorable Board my firm conviction that there is danger, both constant and grave, in the water of the Merrimack River at

Lowell."[27] At this point, the evidence was overwhelming and Lawrence and Lowell accepted that it was their responsibility to find a way to protect their residents from typhoid fever.

Lowell's solution was to abandon the Merrimack in favor of water from a driven-well system located away from the river. Driven wells are quite deep and unlikely to be contaminated. The location of Lowell's wells was determined by the experiments of Sedgwick and others. Lowell's transition to driven wells started in 1893 and by 1896 the city was no longer supplying drinking water from the Merrimack river.[28] As Figure 4 indicates, as Lowell increased its reliance on the driven-well system, its typhoid fever death rate quickly converged to the lower rate of Manchester.

Lawrence's solution involved the development of a filtration system.[29] The Massachusetts Board of Health constructed an experimental filtration station at Lawrence in 1886. Early experiments showed that sewage could be filtered from water supplies, but the filtration rate was too slow such that it was infeasible to filter the entire water supply. Sedgwick's findings on the 1890-1891 typhoid epidemic illustrated the urgency of finding a way to successfully filter Lawrence's water supplies. The state board of health scaled up their filtration experiments, and after identifying a successful solution, the board advised Lawrence on how to filter its water. Construction started in 1892 and the plant opened on September 20, 1893. The efficacy of the filtration plant is illustrated in Figure 4. In 1894, the first year of continuous operation, Lawrence's typhoid fever mortality rate converges to that of Manchester for the first time in nine years. But from 1895 to 1898, Lawrence's typhoid fever mortality rate is consistently lower than Manchester's rate.

The evidence underpinning the idea that filtration can successfully eliminate the threat of typhoid fever extends well beyond Lawrence. Typhoid rates fell following the adoption of new filtration practices in Zurich, Switzerland (1886), Hamburg, Germany (1892), Albany, NY (1889), and elsewhere.[30] In one suburb of Paris, typhoid morbidity and mortality was cut in half once it started receiving filtered water in 1905, and water samples showed a decline from 238,000 to 170 bacteria per

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[27] Sedgwick "Sanitary Condition" pg. 53.

[28] Lowell still relied on the Merrimack River to supply water for the purposes of fighting fires, although that water was transported through a separate network. A large fire in 1903 required the city to draw on water from both sources and an unfortunate check valve malfunction allowed the river water to flow into the city's drinking water mains, in turn generated a small outbreak of typhoid fever, see Harrington "Epidemic" for more.

[29] The following paragraph is based off of Hiram Mills' 1895 report "The filtration of the water supply of the city of Lawrence and its results," which appeared in the 27th volume of the Annual report of the State Board of Health of Massachusetts. Mills was the chief engineer at the Lawrence experimental pumping station.

[30] Whipple *Typhoid Fever*, pp. 235-247.

c.c. after filtration.[31] While the type of analysis available to contemporary observers was mostly limited to a comparison of means (before vs. after treatment), more modern empirical techniques continue to confirm the idea that water filtration reduces typhoid fever mortality.[32] This more modern analysis also shows that the typhoid epidemics (defined as a year with mortality above 0.5 or 0.75 deaths per 1000 persons, the 75th and 90th percentile of the data) are about 20-30% less likely to occur when a city filters its water supplies.[33]

While Lawrence offered compelling evidence on the benefits of slow sand filtration as well as a blueprint for a successful model, it was not enough to spur widespread investment. Many large cities relied on rivers and lakes for their water and were thus subject to the same disease environment as Lawrence. As of 1905, a full decade after Lawrence illustrated that typhoid fever was preventable, only about 20% of large cities that drew their water from lakes, rivers, and streams filtered their water.

A likely explanation for this slow adoption is cost. Pittsburgh (PA), for instance, recognized that a filtration plant would solve its typhoid fever problem. Pittsburgh, like Lawrence, drew its water from rivers and suffered from high typhoid rates because of the amount of sewage that was dumped upstream. The city approved the construction of a filtration plant in 1899, but construction was delayed for several years as politicians fought over the allocation of the sizable amount of funds. If the cost of a filtration plant was deemed prohibitive, officials may have delayed acting in hopes that a cheaper option might soon arrive. The 1890s, after all, saw considerable innovation in the field of water filtration.[34]

The experience with chlorination offers further evidence that cities may have delayed their filtration investments because of cost concerns. Jersey City, NJ became the first U.S. city to continuously treat their water with chlorine in 1908. The chlorination plant was constructed because of a legal battle, not because Jersey City was suffering from high waterborne disease rates (See Figure 3).[35] Jersey City awarded a contract to impound water from the Rockaway River, but the contract specified that the water be "pure and wholesome and free from pollution deleterious for drinking and domestic purposes." There was thus a concern that because a filtration plant was not built that the water had the potential to be polluted, and thus the company had failed to fulfill the contract. The

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[31] Whipple *Typhoid Fever,* pg. 244.

[32] See Beach et al. "Typhoid Fever" and Anderson et al "Contribution of Public Health"

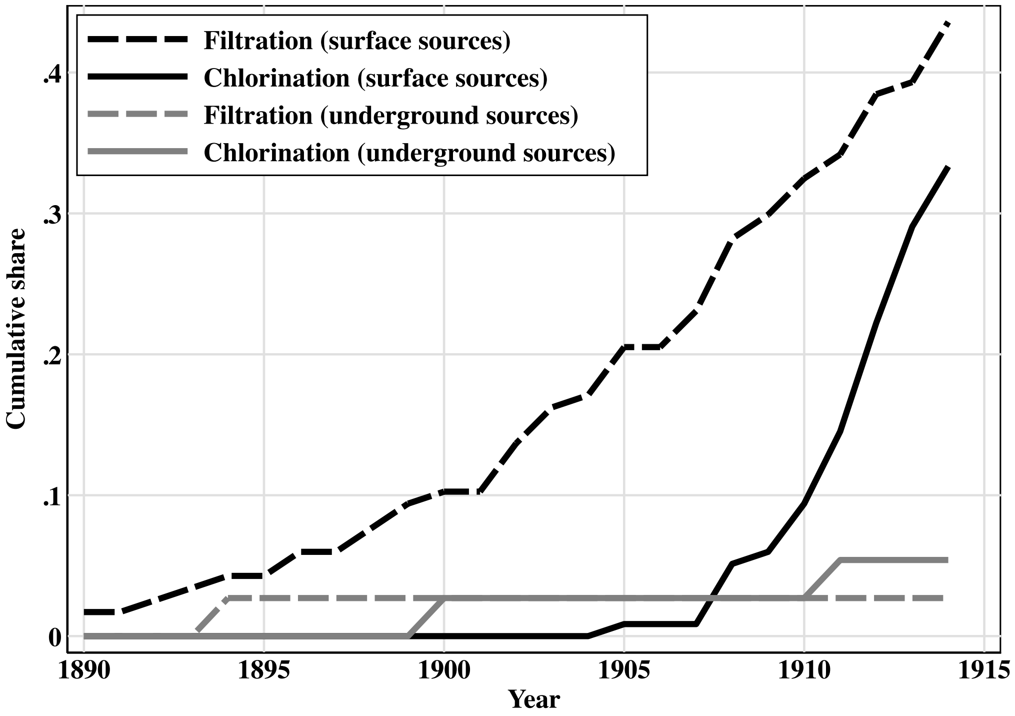
[33] Beach et al. "Typhoid Fever"

[34] Baker *Quest*

[35] The following discussion is based off of Baker *Quest*, pp. 336-339 and the citations within.

chlorination plant allowed the company to fulfill the contract, as early tests had showed the efficacy of chemical chlorination. The plant was built at a cost of $20,456 with an annual operating expense of $2,100. In contrast, diverting sewage would have cost several hundred thousand dollars.

Figure 5: Water Purification Adoption by Water Source



Notes: Sample restricted to cities with an estimated population of 30,000 or more as of 1915. Data on water source, filtration, and chlorination are form the 1915 General Statistics of Cities. Filtration includes: sedimentation, coagulation, slow sand filtration (i.e., the process used in Lawrence, MA), and mechanical filtration. The data do not distinguish between intermittent and continuous use. A city is classified as using surface water sources if they draw any of their water from: rivers, streams, lakes, ponds, creeks, or brooks.

Figure 5 plots the adoption of filtration and chlorination among large and medium-sized cities. The sample of cities is restricted to those with an estimated population of 30,000 or more as of 1915. A city is said to rely on surface water sources if any of their water comes from rivers, streams, lakes, ponds, creeks, or brooks. Underground sources are cities whose water originates from deep wells. All of this information, as well as information about the year a city started filtering or chlorinating its water comes from the 1915 general statistics of cities. The first takeaway from Figure 5 is that while cities were slow to build large filtration plants, even after the 1893 Lawrence experiment, they were much quicker to build chlorination plants once the benefits of that process were understood. As of

1910 about 10% of our sample of cities had started chlorinating its water supply, but by 1914 that figure would approach 35%. The second takeaway is that investment in filtration and chlorination was concentrated among cities that relied on easily-contaminated surface water sources. This is not particularly surprising, but given its low cost one might expect cities that relied on underground sources to invest in chlorination as a form of insurance against waterborne disease. That chlorination adoption was concentrated among cities that relied on surface sources provides further support for the idea that investment in filtration was slow because of cost concerns.

Infrastructure Access

Infrastructure access did not come all at once. Even among some of the largest cities in the United States, it was uncommon to see universal access to running water and flush toilets by 1940.[36] Charleston (SC) is an extreme example where only 63% of households had access to running water and only 44.4% of households had access to a flush toilet. More racially segregated cities had lower connection rates (94% vs 98% for running water and 81% vs 90% for flush toilet access).[37] Segregated cities tended to build waterworks earlier, but were slower to eliminate typhoid fever. These patterns are consistent with segregated cities building waterworks that excluded neighborhoods with larger Black shares. Since segregated cities lagged in their ability to control waterborne disease, it appears that cities may have been reluctant to make the final wave of investments where the benefits would have disproportionately benefited Black households.

When households lack connections to pure sources of water, there is potential for residents to draw on contaminated sources, undermining public health. This issue is discussed extensively in Lawrence Board of Health reports. For example, the 1899 report notes: "The fact that, in spite of repeated warnings, Canal water is occasionally drank by the mill employees and that water from different wells around the city is constantly used, may account for these sporadic cases."[38] The efficacy of New York City's Croton Aqueduct was undermined by many low-income households continuing to rely on shallow (and polluted) wells because the cost of a water connection exceeded the perceived benefit. As Edward Glaeser and James Poterba argue, New York City's waterborne disease rates

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[36] Beach et al. "Segregation"
[37] Beach et al. "Segregation"
[38] Twenty First Annual Report of the Board of Health of the City of Lawrence, Massachusetts (1899), 13.

remained elevated until 1866, when it was established that homeowners could be fined for failing to connect to water and sewer systems, which incentivized connections in low-income neighborhoods.[39]

By the end of the 19th century, a question would arise as to whether public ownership was necessary for eliminating the threat of waterborne disease. The ownership debate tended to focus on two issues. The first related to water quality, as there was a concern that private firms would underinvest in water purification technologies. The second was whether private firms faced enough of an incentive to extend access to lower income households and neighborhoods.

Economic theory offers mixed support for how ownership regimes relate to these motivations. Profit-maximizing firms face an incentive to deliver a quality product at the lowest possible cost. But waterworks, like other utilities, involve large fixed costs (mains and pumps), and so it is often the case that natural monopolies can deliver services at a lower cost than several small firms. With private provision we would expect less competition, with higher prices and inefficiently low levels of provision. The issue of provision is further complicated by disease spillovers: water and sewer infrastructure is most valuable when if offers protection from waterborne illness. But that type of protection often requires widespread access, and private firms are often unwilling to provide access to households or neighborhoods where the stream of revenues exceeds the cost of provision. Publicly-owned firms can charge lower prices and offset any losses with tax revenues, but whether that translates to more equitable access likely depends on political motivations.

Any explanation of the municipalization movement must reconcile two key facts. First, why did cities municipalize waterworks but allow other gas and electric companies to stay private? Second, why is it that the municipalization movement was concentrated between 1890 and 1920?

Waterborne disease spillovers seem to be the natural answer. By 1890 it was understood that water and waste transport, unlike gas or electricity transport, generate positive externalities by protecting the household that purchases the services as well as the household's neighbors or anyone else that they might interact with. If the goal is to help control waterborne disease, then a publicly owned firm may face a greater incentive to extend the network to outlying neighborhoods, even if the cost of those investments exceeds the stream of revenues. Scott Masten provides evidence consistent

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[39] Glaeser and Poterba "Infrastructure Investment"

with this interpretation, showing that public ownership was more common when the city was more dispersed (lower mains per square mile or lower population per square mile).[40]

The externality explanation of this movement is somewhat incomplete. First, there is little empirical support for the idea that publicly owned firms prioritized public health more than privately owned firms did. A study by Werner Troesken shows that private water companies were more likely to invest in filters and that typhoid fever rates did not change once private water companies were municipalized.[41] Troesken and Rick Geddes note that earlier legal disagreements over issues like fire hydrant rentals, market entry, and franchise revocation are a strong predictor of municipalization.[42] The authors suggest that these legal difficulties undermined the city's ability to commit to a contract, with this contract uncertainty providing an incentive for private firms to underinvest, and that underinvestment provided a justification for municipalization. This argument is ultimately about the threat of expropriation. Electric and gas utilities also face expropriation risk, and so if this institutional argument is correct then it must be the case that gas and electric utilities faced fewer legal difficulties and so the expropriation risk was simply more salient for privately owned water companies. This is plausible, as the public interest aspects of water delivery (fire hydrants to prevent fires and the monitoring of water quality to ensure that the water was safe) may have made contracting with private waterworks more difficult, although direct evidence supporting this hypothesis is needed.

Water and the mortality transition

Between 1880 and 1940, American cities underwent two large and seemingly related changes. First, there was a dramatic improvement in health. A child born in the United States in 1880 could expect to live to age 40, whereas a child born in 1940 could expect to live to age 64.[43] Second, water quality improved. While 20-40% of Americans born in the late 19th century would contract typhoid fever at some point during their life, typhoid fever was largely eliminated from American cities by about 1930.[44]

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[40] Masten "Public Utility Ownership"

[41] Troesken "Typhoid Rates"

[42] Troesken and Geddes "Municipalizing"

[43] Haines "Ethnic Differences" Table 8.

[44] Estimates on contracting typhoid fever from pp. 47-49 of Troesken *Water, Race, and Disease*. See Beach et al. "Segregation," particularly Figure 1 for direct evidence that typhoid fever was largely eliminated from major cities by 1930.

The threat of typhoid fever was eliminated by purifying water supplies, and so a natural question is whether water purification efforts played a key role in the health transition.

At first glance, it would appear that the improvements in health between 1880 and 1940 are too large to be explained by eliminating typhoid fever. Our most reliable source for mortality statistics is the US Census Bureau's "Mortality Statistics" publications, which start in 1900.[45] According to the 1900 report, typhoid fever was the 15th largest killer, responsible for 2.4% of all deaths. The census mortality schedules provide a comprehensive snapshot of mortality in census years after 1850, although the quality of the underlying data is likely lower. According to the 1880 report (Volume 12), typhoid fever accounted for about 3% of all deaths.[46] Taking the 3% number and recognizing that mortality fell by about 40% between 1880 and 1940, then one crude estimate is that eliminating typhoid fever can explain about 7.5% of the mortality decline.

What the above exercise misses is the virulence of typhoid fever, which often left survivors susceptible to other threats. A Met Life report showed that, relative to those that had not contracted typhoid, mortality risk among survivors was three times higher in the year following recovery and two times higher in the second year following recovery.[47] The two biggest killers of typhoid survivors were tuberculosis (39% of all deaths) and heart failure (23%). The modern medical literature has shown that typhoid fever can cause substantial and lingering damage to the heart, liver, kidneys, and broader circulatory and nervous systems.[48] This damage, particularly when the scope for medical intervention was limited, suggests that the ultimate health impact of typhoid fever extends beyond its seemingly low case fatality rate.

The health multiplier associated with eliminating typhoid fever is often referred to as the Mills-Reincke Phenomenon. The name originates from chief engineer Hiram Mills (Lawrence, MA) and Dr.

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[45] Those reports include information for "Registration" cities and states, i.e., those that conform to a common reporting standard. Registration states and cities are those with laws requiring that mortality statistics be collected. In contrast to England, which standardized and mandated the reporting of deaths in 1846, the United States left this decision to state and local governments. Several large cities and states passed mandatory reporting laws by 1900, and in that year the Census Bureau worked with those registration areas to establish uniform reporting standards. The result of this was the adoption of a standardized death certificate and the international classification standard, as well as the distribution of "The Manual of International Classification of Causes of Death," which cross referenced terms appearing in causes of death from 1890 and 1900 reports with the new uniform classification standard.

[46] The rate among the 50 largest cities was 1.7% while the rate for the rest of the country was 3.6%. This may reflect that the largest cities had already made some progress in preventing the contamination of water supplies by 1880, error due to differential misdiagnosis, or competing risks in urban areas (the idea that the typhoid fever death rate would have been higher if deaths weren't crowded out by other infectious diseases, like tuberculosis, which may have killed first).

[47] Dublin "Typhoid"

[48] Ferrie and Troesken "Water and Chicago" pp. 7-8 offer a nice discussion of this literature.

J.J. Reincke (Hamburg, Germany) who independently noted that after their cities started filtering their water in 1893, mortality rates declined by more than what could be explained by typhoid fever. In Lawrence, typhoid fever mortality declined by 0.95 deaths per 1000 persons in the five years following filtration relative to the five years before, but total mortality declined by 4.45 deaths per 1000 persons. A similar comparison in Hamburg shows a relative decline in typhoid mortality of 0.4 deaths per 1000 persons and a decline in total mortality of 6.3 deaths per 1000 persons.[49]

One concern with the above comparisons is that any estimate of the multiplier effect will be biased upward if cities that purified their water supplies also made other sanitary improvements. The idea of a valid counterfactual is one that we still struggle with today. In 1904, Allen Hazen's solution was to implement what we would now call a difference-in-differences methodology: comparing mortality patterns in cities that purified their water supplies to mortality patterns in similarly situated cities that did not change their water supply.[50] Hazen obtained mortality data for 18 American cities in 1890 and 1900; five improved their water quality while 13 did not. The data indicate that total mortality in the treated cities declined by 4.4 deaths per 1000 persons while in the control cities mortality declined by 1.37 deaths per 1000 persons. This yields a treatment effect of 3.03 deaths per 1000 persons, 0.71 of which is accounted for by the direct effects of typhoid fever. Hazen is somewhat cautious in his interpretation, opting to conclude that the multiplier is "probably between 2 and 3" rather than the 4.26 that the exercise implies. Joseph Ferrie and Werner Troesken provide an in-depth analysis of Chicago in the spirit of this earlier work.[51] Their estimates suggest that the health multiplier associated with eliminating typhoid fever is somewhere between 2.3 and 5. Applying these multipliers to the back-of-the-envelope calculation introduced above suggests that 7.5% of the mortality decline can be explained by the direct effects of eliminating typhoid fever and an additional 15-37.5% of the decline can be explained by the indirect effects of eliminating typhoid fever.

The precise contribution of water and sanitary improvements to the mortality transition remains an open question. Cutler and Miller attempted to answer this question by examining the change in infant and overall mortality rates following the adoption of a clean water technology (e.g. water filtration or water chlorination).[52] They conclude that clean water interventions explain about half of the mortality transition. D. Mark Anderson, Kerwin Charles, and Daniel Rees revisit this

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[49] Hazen "Purification"
[50] Hazen "Purification"
[51] Ferrie and Troesken "Water and Chicago"
[52] Cutler and Miller "Role"

question with a larger sample of cities and a broader set of public health interventions.[53] Their results do not support the idea that any specific intervention was a major driver of the mortality transition. Marcella Alsan and Claudia Goldin take a slightly different approach, examining the role of sanitary infrastructure in 60 Boston-area municipalities.[54] They find evidence that clean water and safe sewerage (independently) improved health, but once a district had access to both pieces of infrastructure there was a much larger effect: together, these interventions explain about 33% of the decline in child mortality and 48% of the decline in infant mortality during this period.

In some ways, the conflicting results in this literature are due to the fact that the question is methodologically challenging. One issue is that infrastructure or access is an important variable that interacts with improvements to the water supply. The experiences of Lawrence, New York, and many other cities have illustrated that, unless water and sewer connections are universal, there is potential for water and sanitation investments to be undermined by individuals drinking from contaminated sources. Despite its importance, infrastructure is typically an omitted variable because of a lack of data. A second issue is that cities invested in a range of technologies (clean water projects, sewerage, filtration, and chlorination). Sometimes those investments should be thought of as substitutes while other times they should be thought of as complements, and a small set of those investments should probably be ignored because they failed to generate meaningful improvements in water quality, as was the case with Jersey City's chlorination plant which is better thought of as offering insurance against future contamination.

On the Use of Lead Water Pipes

A general theme from the previous sections is that larger cities made water and sanitary investments in response to the challenges of urban and economic growth. While a major goal was to obtain large quantities of pure water, municipalities were reluctant to invest in filtration plants, despite an understanding that these would make a city’s water supply much safer for human consumption. In this section we will see another aspect of water infrastructure where municipalities have been reluctant to make necessary investments despite a clear understanding of the health benefits: the removal of lead service lines.

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[53] Anderson et al. “Re-e

[54] Alsan and Goldin “Watersheds”

When it came to water delivery, most large cities opted to install lead service lines. Werner Troesken and Patricia Beeson examine water infrastructure decisions among a sample of 797 towns and cities and find that 26% of municipalities had infrastructure networks that contained only lead water lines, while an additional 17% of their sample used lead pipes alongside other materials (such as galvanized iron).[55] Among the 16 largest cities (those with a population of 300,000 or more as of 1900), only one built a water infrastructure network without lead service lines. Eight of those cities used only lead lines. For cities with a population between 30,000 and 300,000, 72% of cities used lead exclusively (51%) or in part (21%).

Lead was one of the most expensive materials to work with, but those initial costs were often offset by two factors. First, lead pipes are malleable, which helped save on labor costs, particularly when it was necessary to work around existing infrastructure. Second, lead pipes were durable, as they were highly resistant to internal and external corrosion. Durability was important because it minimized the number of times that a water main would need to be serviced or replaced because of pipe failure. Unfortunately, the same properties that motivated cities to choose lead also ensured that lead water pipes would become a long-lasting threat to public health. Lead's ability to resist internal corrosion meant that lead pipes were particularly desirable in areas that had corrosive water. But corrosive water also prevents the natural accumulation of mineral deposits inside the pipe. Without those mineral deposits there is no internal barrier to prevent lead from leaching into water supplies. Thus, when a city with corrosive water invests in lead water pipes, they ultimately invest in a durable form of infrastructure that facilitates lead poisoning.

Why have municipalities been so reluctant to replace their lead pipes? The answer to this question is twofold. First, as we will see in the following sections, lead poisoning was difficult to diagnose and so it was easy to misinterpret a lack of evidence as proof that lead water pipes were dangerous. The second part of the story is a general theme in urban development: path dependence, which refers to the durability of historical events and decision-making. Land use patterns and buildings offer a classic example. When buildings are constructed, their form reflects the conditions at the time of construction. But since buildings are durable, those construction choices become "locked in," influencing land use patterns for decades to come. The inefficiency of this arrangement is often on full display when an earthquake or fire destroys entire city blocks and the re-constructed blocks take

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[55] Troesken and Beeson "Significance." The sample of towns is derived from Union Army recruits.

on a markedly new form.[56] The choice to install lead pipes reflects the conditions of the time, namely a lack of appreciation for lead water pipes to kill. Like other forms of durable capital, that decision became locked in due to high replacement costs, which is why many U.S. municipalities continue to use an inferior technology.[57]

Quantifying the Dangers of Lead Pipes

Today, we are well aware of the dangers of lead poisoning. Lead is a cumulative toxin and high levels of exposure can be fatal. Lead poisoning is often difficult to diagnose because its symptoms are nondescript and varied, as lead can affect any of the body's organ systems. At high levels of exposure, a victim might develop a blue line along their gums or experience paralysis resulting in wrist or foot drop. At lower levels of exposure, symptoms might include headache, abdominal pain, diarrhea or constipation, fatigue, memory loss, or hearing loss. Exposure can cause cognitive deficits, resulting in lower IQ and a range of behavioral issues, like aggression, hyperactivity, and reduced impulse control.[58]

A recent literature in economic history has shown that infants paid a large mortality penalty whenever cities chose to use lead water pipes. Troesken examines a set of Massachusetts towns as of 1900 and shows that infant mortality rates were about 25-50% higher on average in towns that relied on lead pipes. The effects were even larger in towns with newer pipes and more acidic water, two factors that increase the probability of lead leaching.[59] Karen Clay, Werner Troesken, and Michael Haines examine a broader set of cities and longer time frame. Their data on water acidity is much more detailed, allowing them to provide an interesting counterfactual. By examining only cities that relied on lead service pipes, the authors isolate the impact of water acidity and ask how infant mortality rates would have varied if water flowing through the pipes had different chemical properties. Their

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[56] Siodla "Clean State" Hornbeck and Keniston "Creative Destruction."

[57] Lead water pipes are not the only part of water supply that exhibit path dependence. Frost "Water Technology" and Frost and Shanahan "Domesticating Water" offer a more thorough treatment of this theme.

[58] Bruan et al. "Exposures," Burns et al. "Lifetime," Loeber et al. "Findings," and Marcus et al. "Lead."

[59] Troesken "Lead water pipes."

results indicate that reasonable changes in water chemistry would have lowered infant mortality rates by 7 to 33%, and that this penalty persisted until about 1920.[60]

The impact of high water-lead levels also appears to extend beyond infant mortality. Joseph Ferrie, Karen Rolf, and Troesken document a link between high water-lead levels and cognitive impairment. They examine a sample of World War II enlistees and show that performance on the Army General Classification Test was about one-third of a standard deviation lower among enlistees originating in cities with lead pipes and more acidic water (a pH of 6 rather than 7).[61] James Feigenbaum and Christopher Muller show that elevated water-lead levels increased homicide rates, which is consistent with the link between lead exposure and conduct problems discussed earlier.[62] While the transmission mechanism is different, these findings are consistent with other studies on the social consequences of lead exposure.[63]

Evaluating Regulatory Responsiveness

Given the scale of the issues associated with plumbosolvency, it is surprising how often the topic was ignored by contemporary observers. Consider, for instance, the work of Moses Nelson Baker. Baker was an influential figure in civil engineering, particularly when it came to the topic of drinking water. His Manual of the American Waterworks remains one of the definitive references for understanding how American cities came to invest in water infrastructure, and as associate editor of "Engineering News" Baker oversaw the publication of several articles advancing our understanding of how to control waterborne disease. Baker's 1948 book, *The Quest for Pure Water*, tells the history of water purification, providing a detailed history of how various technologies and techniques came to be adopted as well as their implications for public health. The book offers a seemingly comprehensive history, consisting of 22 chapters spread across 466 pages. But the book never mentions plumbosolvency (the ability of water to dissolve lead) or lead poisoning. The closest mention is a single footnote where Baker clarifies that the city of Birmingham (England) treats its water with lime "to prevent action of the soft water on lead service pipes of the distribution system."[64] This was not

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[60] Clay et al. "Lead and mortality."

[61] Ferrie et al. "Cognitive."

[62] Feigenbaum and Muller "Lead"

[63] On the link between lead exposure and cognition, see: Reyes "Environmental Policy" and "Antisocial," Schnaas et al,. "Reduced Intellectual Development," Aizer et al "Test Scores," Aizer and Currie "Juvenile Delinquency," and Canfield et al "Intellectual impairment."

[64] Baker *Quest*, pg. 262

an uncommon or uniquely British practice. A 1932 survey on U.S. water supplies includes an entry on pH adjustment, noting that: "It is therefore becoming increasingly common to give a final treatment, usually with lime, to bring the pH and calcium content of the water within a range that will insure freedom from corrosion of the mains and service lines."[65] The omission of how cities came to implement this practice thus seems glaring, particularly since Chapter 18 of the book is dedicated to "water softening," a form of water chemistry that can increase plumbosolvency.

It is unfair to single out Baker for ignoring the issue of lead poisoning. George A. Johnson published a 50-page summary of present-day filtration practices in the inaugural issue of the Journal of the American Waterworks Association (JAWWA). That article briefly discusses the issue of pipe corrosion, but the discussion is focused on the seemingly superficial aspects of the "red water plague" -- the tendency of corrosive water to impart a reddish-brown color on the drinking water. There is no mention of whether dissolving metals in drinking water is harmful for health in Johnson's article or in the recorded discussion of his paper, which included comments from notable figures such as George C. Whipple (co-founder of the Harvard School of Public Health) and George Fuller (who designed and built the first water chlorination plant, which served as a model for other cities). The first JAWWA article to mention lead poisoning is a 1917 summary of experiments in Lowell, MA, which sought to reduce corrosion. This is perhaps not surprising, as the question of plumbosolvency was debated more extensively (and decades earlier) in Massachusetts, where many wanted to be assured that the action of local water sources on lead service pipes were not a major threat.[66] Massachusetts, however, was something of an outlier. The first federal guidelines regarding lead concentrations do not appear until 1925, and while some cities attempted to prohibit or restrict the use of lead pipes circa 1920, there is evidence that lead pipes continued to be installed for several decades.[67] Chicago, for instance, is said to have the most lead service lines in the country, likely reflecting that it's plumbing code mandated the installation of lead service lines until 1986 when Congress banned that practice.[68]

Troesken argues that many contemporary observers underestimated the dangers of lead pipes because it was difficult to generate compelling evidence showing that lead pipes weren't safe.[69] Part of

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[65] USGS 1932 pg. 25

[66] See, for instance, "Service Pipes" in volume 6 of the Journal of the New England Waterworks Association, Blake *Water for cities,* pp. 253-254, and Troesken *Great Lead.*

[67] Rabin "Lead Industry."

[68] https://www.chicagotribune.com/news/environment/ct-chicago-lead-pipe-replacement-bill-20210528-lvcdbk7kjjhctptjk4v2rqokua-story.html

[69] Troeksen *Great Lead.*

this is because health officials were looking for evidence in the wrong place but another contributing factor is the complex nature of the water chemistry. On the first issue, most early studies on plumbosolvency examined the health of adults, but adults are less sensitive to lead poisoning, it was infants that bore the largest burden.[70] Thus, any analysis that does not consider infants and children would underestimate the relationship between water-lead levels and mortality. As to the second issue, lead pipes were installed in areas with highly acidic, neutral, and highly alkaline waters. Any statistical analysis that does not account for the role of water chemistry, while also including observations from cities with neutral waters, would be biased towards finding no relationship between lead pipe use and health. Indeed, it was common to point to the experience of cities with neutral waters as proof that lead pipes were safe.[71]

The legal concept of negligence offers a useful framework for understanding how cities have approached the issue of plumbosolvency. A negligence claim involves four elements: duty of care, breach of duty, causation, and damages. Working our way backwards, the above evidence clearly indicates that the damages condition is satisfied, as consuming water that contains lead is harmful for health and cognitive development. Further, the causation condition is satisfied because when lead pipes are used to transport drinking water, there is potential for lead to leach into the water. Duty of care and breach of duty are more complicated. For the duty of care condition to be satisfied, there must be a legal expectation regarding the safety of the water that is being delivered to consumers, i.e., that the water is reasonably safe with respect to disease or poisons. Assuming for the moment that this expectation exists, then it is necessary to show that the water supplier's actions (such as the continued use of lead pipes) or inaction (a failure to treat the water to reduce plumbosolvency) breached that duty. A breach would occur if the water supplier knowingly supplied water containing dangerous levels of lead or if the supplier acted (or failed to act) in a way that clearly differed from what a "reasonable" person in the same situation would have done.

In a strict legal sense, most water suppliers were not negligent in their handling of plumbosolvency, which explains why it has taken so long to remediate the issue. Courts held the opinion that consumers were responsible for the safety of water once it entered their service lines and that the water supplied through the mains was safe.[72] This was not particularly misguided, since the water in the mains cycles much more frequently than water in service lines, meaning that most of the

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[70] Troesken "Lead water pipes" and Clay et al. "Lead and Mortality."

[71] Troesken *Great Lead.*

[72] Troesken *Great Lead*, Ch. 7.

leaching of lead occurs in service lines. Moreover, there must be a point where the ownership and responsibility of the water is transferred from the supplier to the consumer, and the point where the water exits the main (often after passing through a meter, so that the consumer can be charged for their usage) is a natural option. Unfortunately, this legal opinion means that a "reasonable" supplier of water would not be inclined to incur the large cost of replacing their lead pipes with a suitable alternative (such as iron) nor would they face strong incentives to alter the chemistry to their water, which would have helped protect consumers by limiting the leaching of lead from service lines.

It is easy to forgive the initial installation of lead pipes, particularly before 1900. Although, despite a more limited understanding of water chemistry and plumbosolvency, it was widely understood that in at least some settings lead would leach into water supplies. It was also understood that lead, when consumed in large doses, was dangerous. The problem was that most thought that water-lead levels were not high enough to be dangerous, although Troesken's review of historical reports indicates that it was not uncommon to observe water-lead levels that were several hundred and even one thousand times higher than modern EPA guidelines.[73] However, by 1900 there were salient examples of lead poisoning.

Given the expense associated with installing water pipes, it is also understandable why a city might prefer to wait to replace them. By the turn of the 20th century it was increasingly understood that water chemistry could be altered to decrease the corrosiveness of water supplies, and in turn lower water-lead levels.[74] This presented a lower cost alternative: by altering the water's acidity levels municipalities could continue to use lead service lines while reducing the risk of lead poisoning. As in the case of water purification, most municipalities opted for the low-cost solution. Many Americans continue to rely on lead pipes, due to their durability and the low-cost of altering the acidity of the water to bring it into compliance with EPA standards. However, as the water crises in Washington DC (2001) and Flint MI (2014) have shown us, those that rely on lead service lines remain at risk for experiencing a public health crisis, should a municipality fail to get the water chemistry correct.

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[73] Troesken *Great Lead*

[74] (Donaldson, 1924, Weston, 1920)

Conclusion

The history of U.S. water and waste management is best summarized as a history of reluctant policymaking. The 19th and early 20th centuries saw the emergence of pumping stations, treatment plants, and an immense network of mains to safely transport water and waste. The abandonment of cesspools, privy vaults for waste containment and cisterns, pumps, and shallow wells for water delivery brought about a large increase in living standards. First, in terms of health, as urbanites became much less exposed to waterborne illness, and second in terms of labor savings. While the gains are impressive, this chapter highlights the general reluctance associated with making these investments. As scientific understanding of the origins of waterborne illness improved, cities did not rush to bring purer water to their inhabitants. Filtration plants presented an opportunity to purify existing sources, and yet few cities made those investments. Only with chlorination, a low-cost solution, did we see rapid adoption of purification technology. Today, somewhere between 6 and 10 million lead service lines remain in use in the United States.[75] Lead poisoning became a salient issue after the 2014 Flint Water Crisis, even though the potential for lead service lines to kill was appreciated as early 1900. Despite this, it remained legal to install lead service lines until 1986. Given the importance of water and waste systems for health, the cost of inaction is best measured by morbidity and mortality.

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[75] https://www.epa.gov/ground-water-and-drinking-water/lead-service-line-replacement

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