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Water infrastructure and health in U.S. cities☆

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ABSTRACT

Between 1900 and 1930 typhoid fever and other waterborne diseases were largely eradicated from U.S. cities. This achievement required a mix of technological, scientific, economic, and bureaucratic innovations. This article examines how the interaction of those forces influenced water and sanitary infrastructure provision during the 19th and early 20th centuries. I document a sharp link between infrastructure investments and declines in waterborne disease and discuss how that relationship informs the methodological approaches one should use to assess the impact of sanitary investments on urban development. Finally, I review the literature on the social returns to eliminating the threat of waterborne disease. The evidence suggests the benefits of infrastructure investment far exceeded the costs.

1. Introduction

Poor water quality remains a major threat to human health. As of 2019, 2.2 billion individuals lack access to safely managed drinking water, leaving them vulnerable to typhoid fever, cholera, and other water-related diseases.[1] Each year 11–21 million persons contract typhoid fever after consuming contaminated water and about 200,000 of those individuals die as a result. Additionally, 485,000 of the 1.6 million diarrheal deaths that occur each year are thought to be a direct result of contaminated water. These figures are despite a 2010 United Nations resolution recognizing clean drinking water and sanitation as human rights.[2]

Today residents in developed countries are largely insulated from these threats, but that was not always the case. The network of mains many rely on to safely transport water and waste were developed en masse during the 19th century. Before then, a typical urban resident obtained water from wells and pumps and disposed of human and household wastes in privy vaults and cesspools.[3] This arrangement frequently led to the contamination of local water supplies, leaving city dwellers susceptible to the same illnesses that continue to plague today's developing countries.

What lessons might developing countries take from the historical urban experience? The answer to this question is complicated, as the path that cities took to eliminate the threat of waterborne disease is not a perfect analog for the challenges associated with providing safe water and sanitation today. One of the more universal features is the reliance on large infrastructure investments. Thus, policymakers often turn to history in order to gain an understanding of the short and long-run social returns to improving water and sanitation.

This article examines how cities in the United States came to eliminate waterborne illness and the extent to which the costs associated with improving the sanitary environment were offset by health and productivity gains. The article highlights both the forces that shaped sanitary investment and how the implementation of these investments informs the set of methodological approaches one can use to quantify these returns. This provides a useful framework for researchers interested in understanding the impact of sanitary infrastructure on health and urban development.

The decision to focus on the U.S. experience is driven by space considerations. The technological, political, and economic innovations discussed in this paper are not uniquely American. It is also not the case

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[1] I use typhoid fever as a measure of the prevalence of waterborne illness as, at least during the period I study, typhoid fever is a consistently reported cause of death that is due almost entirely to the consumption of contaminated water.

[2] Statistics from un.org, who.int, and cdc.gov.

[3] Cisterns, ponds, and streams were among the first sources to become polluted (Blake, 1956, pg. 14).

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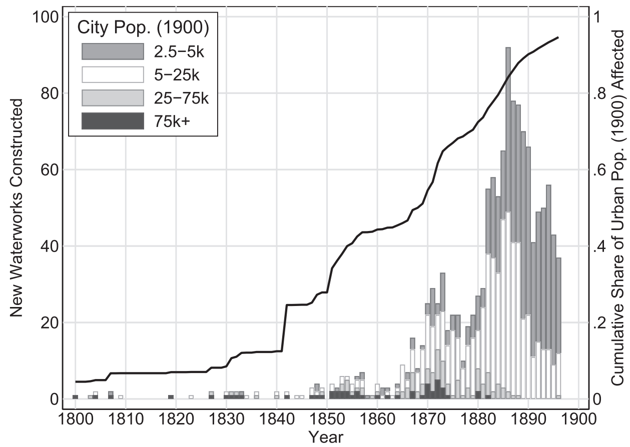


Data from Baker (1897). Populations are fixed as of the 1900 census. The population denominator used to calculate the cumulative share affected is the number of persons living in incorporated places with a population of 2500 or greater as of the 1900 census.

Fig. 1. Trends in U.S. Waterworks construction, 1800–1896.

that U.S. cities were uniquely susceptible to waterborne illness. However, a theme of this article is that historical features inform methodological choices and so it is necessary to provide an overview of the history. While many settings could be considered, a useful feature of the United States experience is that investments were heavily decentralized, occurring mostly at the local-level. A byproduct of decentralized investment is a substantial amount of variation in both the timing and types of investments that were made across U.S. cities, which is useful for generating well-identified evidence for a range of potential infrastructure solutions.

2. Causes and consequences of typhoid fever

For most of the 19th century Americans suffered from waterborne diseases in large numbers. We lack precise estimates of the scale of the problem because of incomplete and inaccurate vital statistics. Typhoid fever mortality offers the closest approximation since, at least until the early 20th century, typhoid fever deaths were due almost exclusively to contaminated water. We also 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. Building on this logic, Troesken (2004, p.47–49) estimates that 21–42% of Americans born in the mid to late 19th century would contract typhoid fever at some point during their life.[4] These estimates likely represent a lower bound as the varied and indistinct nature of typhoid fever's symptoms make it difficult to diagnose.[5]

The pervasiveness of waterborne disease in this period was due to inadequate water and waste transport. Most 19th century city dwellers relied on wells and pumps to access their water and privy vaults and cesspools to store their wastes. These waste receptacles were rarely watertight, and so nearby soil was often saturated with waste. If located near an underground well, then waste would saturate the soil and the water supply. Cesspools became increasingly prone to overflowing once households brought more water into the home. This was most problematic when waste flowed from the cesspool into a nearby well.[6]

It is now understood that preventing waterborne illness requires a mix of water and sewer infrastructure. Waterborne illnesses are typically spread by drinking water that is contaminated with the wastes of an infected individual. Thus, identifying an abundant source of clean water is a crucial first step. One solution might be to invest in infrastructure to transport uncontaminated water into the city. A second solution might be to purify existing water supplies either through filtration or chemical chlorination. A third, and often complementary solution, is to prevent contamination from occurring, either by treating sewage or diverting sewage away from water supplies.

Policymakers in the 19th century were often in an unfortunate situation where both the causes of waterborne disease and the solutions were not well understood. Sewage was recognized as dangerous, but until about 1880 the prevailing understanding was that disease transmission occurred through exposure to sewer gas rather than ingesting tainted water. Thus, sewage leeching into the water supply was seen as a nuisance but the sewer gas represented the real threat. While policymakers often recognized a need for infrastructure, few standard practices for safely transporting water and waste existed before the 1850s.

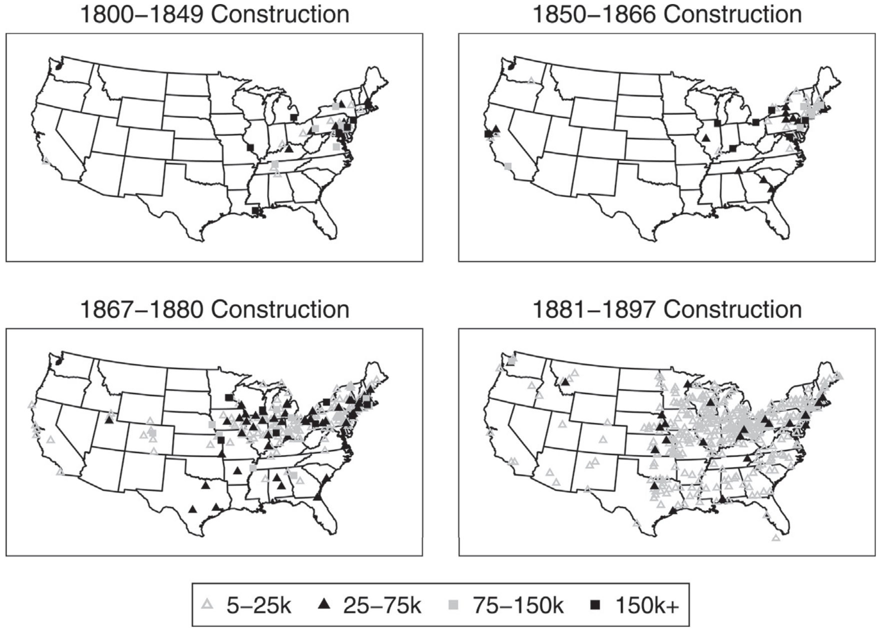
3. Evolution of infrastructure investment

Urban waterworks construction occurred in several phases. To fix ideas, Fig. 1 plots trends in waterworks construction among U.S. cities. The sample includes any incorporated place with a population of 2500 or more as of 1900. Each bar represents the number of waterworks constructed in a given year, with data on waterworks construction coming from Baker (1897). The solid black line represents the cumulative share of the 1900 urban population residing in cities that have a waterworks. The first phase lasted until roughly 1850. During that period, investment was concentrated among the largest cities and there was no clear temporal pattern. From 1850 to about 1866 the pace of construction increased as both large and medium sized cities start investing in waterworks. By 1866 about 50% of the urban population resided in a city that had at least started constructing a waterworks. From 1866 to

[4] 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 vol 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.

[5] 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, 1916; Whipple, 1908, pp. 96–97).

[6] For detailed accounts of epidemics that arose from cesspools and privies contaminating local wells, see Budd (1873), Sedgwick (1922), and Whipple (1908, Ch. VIII).



Year built data from Baker (1897). City populations correspond to population as of 1900 census.

Fig. 2. Diffusion of waterworks by city size, 1800–1896.

1880 the pace of construction increased again, largely due to investments in small cities. From 1880 to 1900 construction occurred almost exclusively among cities with populations smaller than 25,000 persons. By 1900 nearly 95% of residents in urban areas resided in a city with a waterworks.

The spatial diffusion of waterworks largely reflects underlying patterns of urbanization. Fig. 2 maps construction with each panel corresponding to one of the four phases mentioned above. The clustering of construction in the northeast is likely because the northeast urbanized earlier than other regions.[7] To this point, the top two panels indicate large and growing cities outside of the northeast (e.g., Chicago, Cleveland, New Orleans, Louisville, Nashville, and Richmond) were also among the first to invest.

While urbanization is an important driver, there is some evidence of investment spillovers from large cities to adjacent smaller cities. Before 1867, for instance, construction in smaller and medium sized cities (5-25k or 25-75k) appears almost exclusively among cities that are are proximate to large cities. The explanation for this pattern is an open question. One explanation is that small cities, having observed the success of investments made in adjacent larger cities, were motivated to replicate those investments. A second explanation might be that these small cities were connected to the same transportation networks that brought mains and other infrastructure to large cities, in turn lowering construction costs.[8]

One similarity between all four periods is that the primary motivation for investing in water and sewer infrastructure was to fight filth and fire. As population and density increased, cities quickly realized that their patchwork system of underground wells was inadequate. Wells were frequently contaminated, and even though residents lacked a scientific measure of water purity, when judged by the standards of taste, smell, and clarity, water quality was poor.[9] One idea that gradually arose from the miasmatic theory of disease was that cities needed an abundant supply of clean water to wash the streets and homes, which would in turn offer protection from disease. Cities also wanted water to fight fires (Anderson, 1981, pp. 87–95).[10] Bucket brigades struggled to contain fires in densely populated cities, but a waterworks offered a solution. Philadelphia was the first large city to build a municipal waterworks. Before its waterworks opened in 1801, it took 15 min for a bucket brigade to fill one fire engine. Once the waterworks opened, a fire engine could be filled in 90 s from a hose attached to a fireplug that was cut into a nearby wooden water main.

While the benefits of tapping into outside water sources were clear, bringing water into the city required finding solutions to a number of technological hurdles. If a city was lucky, their identified source would be at a higher elevation, and so water could be fed by gravity through a network of mains. If this was not the case, then water needed to be pumped into the network of mains. Early adopters implemented experimental solutions out of necessity. Sometimes that experimentation was successful. Other times, it only generated valuable lessons for future

[7] As of 1850, 30% of the population in the Northeast resided in urban areas, as compared to 10% in the Midwest, South, or West (Boustan et al., 2018, Fig. 22.1b). The midwest and west cross that 30% threshold in 1880 but the south would not cross that threshold until 1930. By 1900, 70% of residents in the northeast lived in urban areas, as compared to 40% in the west and midwest and 15% in the south.

[8] Feigenbaum and Muller (2016), for instance, show that proximity to a lead refinery is a strong predictor of whether a city invested in lead rather than iron water mains.

[9] One could improve water quality by boiling it, but this was a labor intensive task and it was not until the 1870s that households began to understand the benefits of private investments in household hygiene (Tomes, 1990; Mokyr and Stein, 1996; Mokyr, 2000). Antman (2020) notes that changes in tea consumption affected average water quality because consuming tea required boiled water. She finds that widespread tea consumption lowered mortality rates by about 1.4%, a lower bound estimate of the benefits of boiling water unless households completely replaced their water consumption with tea consumption.

[10] Of the 3341 waterworks that appear in Baker (1897), 120 only provided water for the purpose of fighting fire. Erie, PA; Lynchburg, VA, Batavia, NY and Danville, NY are four examples of cities that initially built a system to provide fire protection (Anderson, 1981, p. 90).

builders.[11] The experimentation phase would last until about 1850.

By 1850 key components of the supply chain were established and technological innovation started to gain momentum.[12] The first water mains were constructed out or bored wooden logs, which were difficult to work with, prone to rotting, and prone to leaking. 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 more frequent. Irregularities in the casting process and corrosion 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 lining pipes with other materials limited corrosion and increased the lifespan of a pipe by a factor of 2 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.

By 1866 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* (Melosi, 2008, Ch. 2). 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 lagged England, in part because it was less dense. But as American cities grew, so did the prevalence of filth and disease, which motivated Americans to commit dollars to address the problem (Melosi, 2008, Ch. 4). The experimentation among early adopters and subsequent innovations meant that by 1866 there was not only a desire to invest in infrastructure but also a clear understanding of what that investment should look like and what it might ultimately cost.

A complementary driver of investment after 1866 was an increase in state capacity among local governments. Prior to the 1840s, state governments were the most active branch of government, but much of that activity was financed by issuing debt (Wallis, 2000). The consequences of that arrangement were realized in the 1840s when several states defaulted on their debts. In response, many states reformed their constitutions, adopting rules that outlined the amount of debt that could be issued, the purposes for which debt could be issued, and how that debt would be repaid (Wallis, 2005).[13] Those reforms ushered in a reliance on local property taxes, and as argued in Wallis (2001), local government is well-suited to fund activity with property taxes since taxpayers can more easily observe the link between taxes and benefits. Thus, just as Americans found themselves willing to commit resources to building infrastructure, local governments found themselves in a position where they could tap into financial markets to fund those projects.

The 1880 transition to the fourth and final building regime marks the culmination of earlier forces. Chadwick's "Sanitary Idea" established the potential harm of environmental factors, but the germ theory of disease clarified why some interventions worked and others did not. The bacteriological revolution of the 1870s and 1880s solidified the standing of germ theory. The revolution had implications for public health, particularly after the discovery of the typhoid and cholera bacilli in 1880 and 1883, respectively. At this point, households and public officials understood the importance of clean water and safe sewage disposal. But identifying infrastructure as the solution was only half the battle, as infrastructure investments were still expensive. The public finance innovations following the 1840s state debt crisis bolstered the role of local government, but many municipalities (like the state governments prior to the 1840s) were quick to borrow and found themselves overextended following the Panic of 1873. This led to a wave of municipal defaults and another wave of constitutional reforms, which further restrained the ability to borrow. Perhaps because of their necessity, waterworks were one of the few purposes for which a local government could borrow beyond the legally established debt limit. Cutler and Miller (2006) argue that those reforms established the attractiveness of municipal debt, allowing even the smallest of cities to issue waterworks bonds at favorable interest rates.[14]

4. Eliminating typhoid fever in American cities

Typhoid fever death rates are a key metric for assessing the efficacy of clean water interventions during this period. As Whipple (1908, p.228) stated: *The relation between [water quality and typhoid death rates] is so close that the typhoid death-rate has been often used as an index of the quality of the water. Generally speaking, it is safe to do this; a very low death-rate indicates a pure water, and a very high rate, a contaminated water.* Typhoid fever mortality is an imperfect proxy because typhoid fever could be spread by other means, but at least until cities started tackling the issue of water quality, those other means only accounted for a small fraction of the overall death rate (Beach et al., 2016; Whipple, 1908). Because of this, and because of a lack of comprehensive bacteriological data, scholars have effectively settled on the use of typhoid fever mortality as a proxy for water quality.[15]

Fig. 3 provides an illustrative example of the relationship between water quality and typhoid fever. That figure plots annual typhoid deaths per 1000 persons in the neighboring cities of Newark and Jersey City. Both cities initially obtained their water from the heavily polluted Passaic River and typhoid fever mortality in the two cities was remarkably similar. Typhoid mortality fell by 60–70% in 1892 once Newark abandoned the Passaic River in favor of the Pequannock River. 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

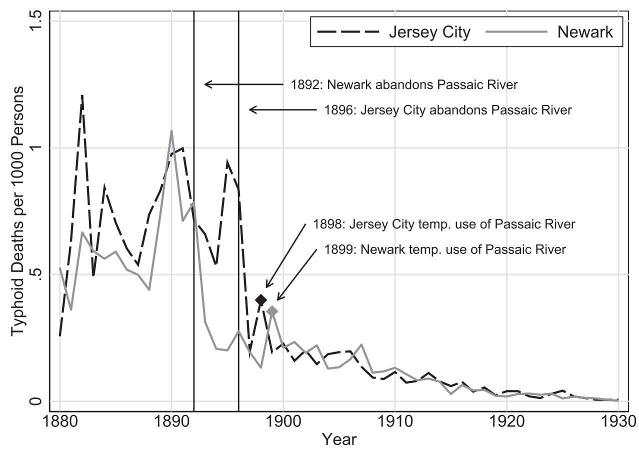
[11] The waterworks that opened in Philadelphia in 1801 relied on two steam engines to pump water from the Schuylkill River into wooden tanks. At that point, water could be gravity fed. The engines were expensive and unreliable, and when one of the engines broke down the supply of water was often shut off completely. The supply of water was so inadequate that Philadelphia started construction on a replacement waterworks in 1812 (Blake, 1956, pp. 18–44 and 78–99).

[12] Anderson (1981, pp. 10–34) offers an excellent summary on the supply of mains, pumps, and the supply of civil engineers throughout the 19th century.

[13] Whether self-imposed constraints are a credible commitment is an open question, since constitutions can be changed in the future, albeit at some cost. Evidence from Dove (2012) and Beach (2017) indicate that financial markets responded quickly and favorably to these constitutional reforms.

[14] One of the key pieces of evidence in favor of this hypothesis is the time series evidence on municipal borrowing. That series focuses on municipal bond yields in "New England", but after consulting the Upton (1892, pp. 857–861), it appears that those interest rates probably only correspond to municipalities in Massachusetts, which had an average bond yield lower than any other state. There is thus a need for additional evidence documenting how changes in the cost of borrowing affected construction.

[15] As Higgs and Booth (1979, p. 365) argue: *[the typhoid fever death rate] serves better than the available alternatives. Miles of mains (carrying water varying widely in its degree of contamination), miles of sewers (of varying materials, sizes, construction designs, and number of connections), house connections with the sewers (which include apartments equally with single-family dwellings), public expenditures for maintenance of the sewers and water works (necessary expenses being lumped with the highly variable graft) — none of these is a defensible measure of a city's sanitary condition.*



Typhoid deaths from 1880 to 1900 are from Whipple (1908) while mortality data 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.

Fig. 3. Typhoid patterns in neighboring cities, 1880–1930.

in Newark's typhoid mortality followed by an immediate reversal, but typhoid mortality rates in Jersey City were unaffected.

What is not shown in Fig. 3 is a number of subsequent interventions that did not have a meaningful effect on typhoid fever mortality. Jersey City changed its water source two more times: first in 1901 and again in 1904. Typhoid fever mortality was largely unresponsive to these changes, perhaps because the three sources were of similar quality. In 1908 Jersey City started chlorinating its water but there is little evidence of a decline in typhoid mortality relative to Newark. In 1924 both Newark and New Jersey started treating their sewage. Typhoid mortality is largely unresponsive, in part because at this point sewage disposal was not a threat to local water supplies and in part because typhoid fever had largely been eliminated in these cities. In the 5 years before Newark and Jersey City first abandoned the Passaic River, the average typhoid mortality was 0.74 deaths per 1000 persons, but in the five years before sewage treatment started, typhoid fever mortality in Newark and Jersey City averaged 0.03 deaths per 1000 persons. Thus, by the time sewage treatment occurred, typhoid fever mortality had already decreased by 96%.

Fig. 4 presents information for: Cleveland, Pittsburgh, St. Louis, and Washington DC. Four themes emerge when examining Figs. 3 and 4. First, there is usually one intervention that largely eliminates the threat of typhoid fever, although both the magnitude of the decline and the methods used to bring about that change vary from city to city.[16] Second, cities continued investing in water purification and sewage treatment, even though typhoid fever was no longer a major threat. Third, many cities invested in multiple interventions over a narrow time horizon, particularly after 1900. Fourth, the evidence suggests that in each of these cities the threat of typhoid fever was largely eliminated by 1920 and was practically eradicated by 1930.

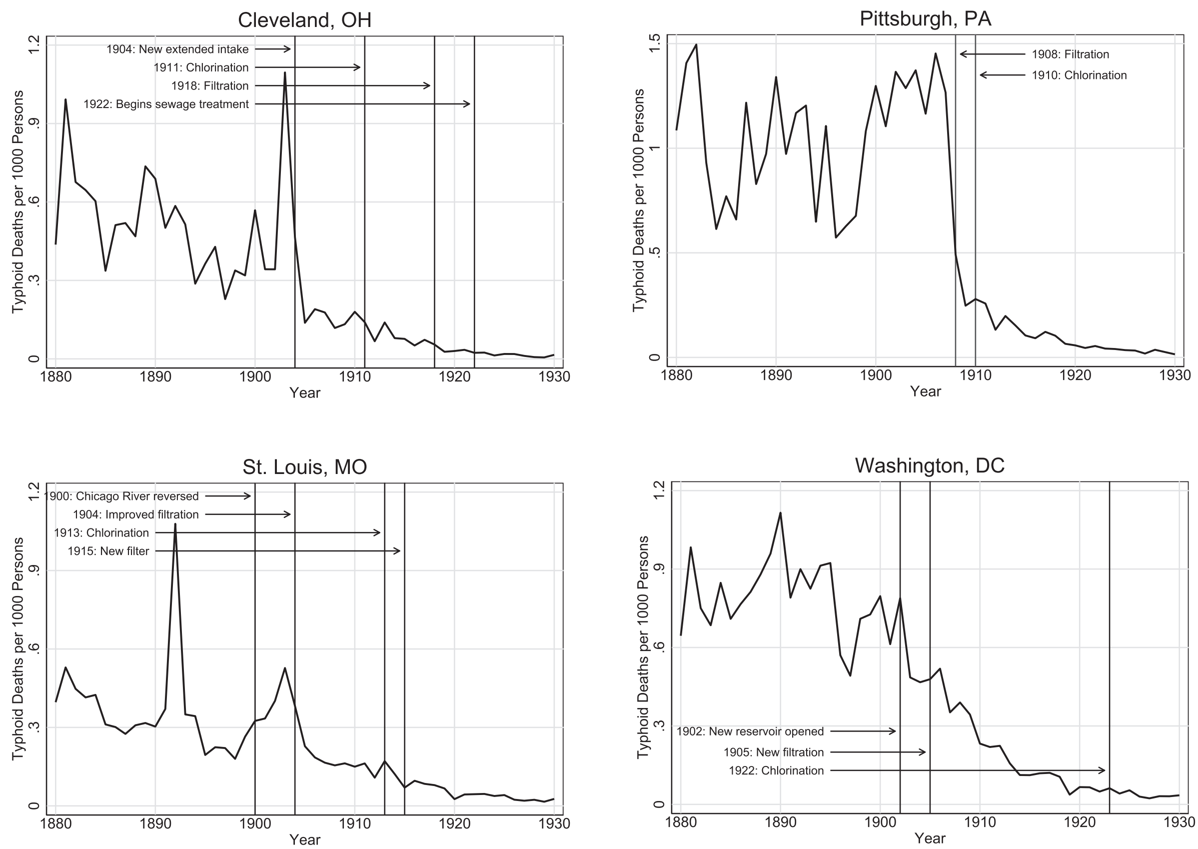
One puzzle is why cities employed more than one purification method when, theoretically at least, one successfully implemented technique should be sufficient to eliminate the threat of waterborne disease. This likely reflects a degree of complementarity between purification practices. For instance, a city might first invest in infrastructure to deliver water from a source that is unlikely to be tainted by sewage. But that city might also filter that water because of other amenity features (e.g., taste and clarity). Alternatively, since purification practices were still being perfected, a city might initially invest in filtration but only see limited success. Later, that city might choose to chlorinate their water to fully eliminate the threat of waterborne disease.

The most systematic evidence on the relationship between water purification and typhoid fever mortality comes from Beach et al. (2016). That paper constructs a panel of typhoid fever mortality rates and filtration dates for 61 cities spanning the years 1880–1920. The authors examine the impact of water filtration within a difference-in-differences framework and the results overwhelmingly suggest that typhoid fever mortality rates fell after a city started filtering its water. The authors also show that 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 after filtration begins.

One pattern in Figs. 3 and 4 seems to push back on the idea that typhoid fever was eliminated by improvements in the sanitary environment. In some cities typhoid fever mortality rates were declining before interventions were adopted while in other cities there is a sharp decline in typhoid fever following sanitary improvements but then we see decades of slow but continuous declines before typhoid is effectively eliminated. What explains the continuous declines in typhoid fever mortality? One interpretation is that continuous declines were driven by improvements in nutrition and income, which left individuals better equipped to fight disease. A second interpretation is that the continuous declines were driven by ongoing investment in water and sewer mains.

The efficacy of discrete water and sewage interventions depends on the share of households that are connected to the centralized network. New York City, for instance, started receiving clean water from the Croton Aqueduct in 1842 but many low-income households continued to rely on shallow (and polluted) wells because the cost of a water connection exceeded the perceived benefit (Glaeserand Poterba, 2020, p. 6). Glaeser & Poterba argue that waterborne disease rates in New York City 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. Kesztenbaum and Rosenthal (2017) provide more systematic evidence on diffusion, showing that high-income neighborhoods in Paris were among the first to receive sewer connections, which contributed to underlying health inequalities. Importantly, Kesztenbaum & Rosenthal (2017) show that connections were a continuous process: even 25 years after construction had started it was not uncommon to see neighborhoods where less than 60% of buildings were connected to the sewer network. Thus, continuous declines in waterborne disease might simply reflect

[16] One theme not depicted is the convergence in death rates among high and low socioeconomic status households once water quality is improved (Costa and Kahn, 2015; Kesztenbaum and Rosenthal, 2017; Troesken, 2004). The high baseline differences may be due to neighborhood-level differences in water quality and sewage disposal or it may a reflect a difference in household-level investments in disease prevention.



Typhoid deaths from 1880 to 1900 are from Whipple (1908) while mortality data 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.

Fig. 4. Four case studies on typhoid fever and water quality.

complementary—but often gradual—investments in mains and taps.[17]

Our understanding of the typical path to comprehensive access is incomplete because of a lack of infrastructure provision data. Data from The Union Army Project, which traced the evolution of water and sewer mains for 6 major cities, offers some insights into this question. Drawing on those data, Beach et al. (2019) estimate that, as of 1880, only 40–50% of households were connected to the centralized water system in Baltimore and Boston. Even in Philadelphia, which started building out its network in 1801, only 80% of households were connected to the network by 1880. Beach et al. (2019) and Troesken (2004) provide evidence that neighborhoods with large black shares were among the last to receive access. The extent to which this was due to racial discrimination or the willingness to pay story outlined by Glaeser and Poterba (2020) is an open question.

To summarize, before cities started investing in water and sewer infrastructure, urban residents paid a large health penalty for living in cities.[18] Cities eliminated the threat of waterborne disease with infrastructure investments, but the precise methods varied from city to city. Despite this, effective infrastructure investments generated sharp improvements in health. These investments came at a cost, however, and in the next section I try to assess whether the benefits outweigh the costs.

5. Quantifying the health benefits of sanitation

A skeptical reader might discard the idea that water purification generated large benefits on the basis that waterborne diseases, like typhoid fever, were not a major killer. The most comprehensive source on mortality during this period is the US Census Bureau's "Mortality Statistics" publications, which start in 1900.[19] The 1900 report covers over 300 cities. Among those cities, the average population was 78,000 and the crude mortality rate was 17.9 deaths per 1000 persons. The

[17] Cain and Rotella (2001) construct a panel of mortality and aggregate expenditures on water and sanitation for 48 cities spanning 1902–1929 and find strong evidence that sewer infrastructure expenditures were followed by declines in waterborne disease.

[18] Historically, that health penalty increased as a city became larger and more dense (Cain and Hong, 2009; Kesztenbaum and Rosenthal, 2011). Waterborne and other infectious diseases are one of the essential drivers of that health penalty. Other drivers included air pollution (Beach and Hanlon, 2018) and nutrition (McKeown, 1976; Fogel, 2004). See Costa (2015) for a longer-run perspective on health and economic development.

[19] 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 to 1900 reports with the new uniform classification standard.

leading cause of death was tuberculosis, which accounted for 10.8% of all deaths. Typhoid fever was the 15th largest killer, responsible for 2.4% of all deaths.

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 (Dublin, 1915). The two biggest killers of typhoid survivors were tuberculosis (39 percent of all deaths) and heart failure (23 percent). 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 Ferrie and Troesken (2008, pp. 7–8). 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. J.J. Reincke (Hamburg, Germany) who independently noted that, once their city started filtering its water, mortality rates declined by more than what could be explained by typhoid fever. In a pioneering study, Allen Hazen examined mortality patterns for 18 American cities in 1890 and 1900. Five of those cities improved their water quality over that period. Hazen's analysis, which we would now call a difference-in-differences analysis, indicated that total mortality rates in the treated cities declined by 4.4 deaths per 1000 persons while in the control cities mortality rates 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 cautiously concluded that the multiplier is "probably between 2 and 3" rather than the 4.26 that the exercise implies (Hazen, 1904, p. 153). Applying this multiplier to the statistics introduced above suggests that infrastructure investments could have lowered urban mortality rates by 7.2–9.6% (2.4% of which is the direct effect of eliminating typhoid fever).

Cutler and Miller (2005) is among the most famous papers on the health multiplier. That paper examines mortality patterns in 13 American cities following the adoption of clean water technologies. The authors argue that the timing of technology adoption was plausibly exogenous and thus one can assess the impact of water purification by using mortality patterns in late-adopting cities as a counterfactual for early-adopting cities. This methodology is similar in spirit to Hazen (1904), but Cutler and Miller (2005) include a wider set of controls to weaken the assumptions needed to interpret the results as causal. Mortality rates fell by about 40% between 1900 and 1940, and Cutler & Miller conclude that clean water technologies accounted for 38% of that decline.[20] As a point of comparison, applying Hazen's 2–3 multiplier to the 1900 mortality statistics, we would expect eliminating typhoid fever to explain 18–24% of the mortality decline. If we use Hazen's actual estimated treatment effect of 4.26, eliminating typhoid fever explains nearly 32% of the mortality decline.

Anderson et al. (2020) challenges the conclusions of Cutler and Miller (2005). Anderson et al. argue that the Cutler and Miller (2005) estimates are sensitive to correcting for transcription errors, the choice of population denominator, and other specification changes. Applying Anderson et al.'s preferred specification to the Cutler & Miller sample yields a point estimate that is roughly 50% smaller, suggesting that clean water technologies explain about 19% of the mortality decline. The authors extend Cutler and Miller (2005) to include 25 American cities and a broaderer set of public health interventions: water filtration, water chlorination, other clean water projects, sewage treatment, bacteriological standards for milk, and mandated tuberculin testing for cows. The authors adopt a difference-in-differences framework to assess which interventions contributed most to the mortality decline. The results are mixed. None of the interventions had a statistically significant effect on total mortality, and the only intervention to have a consistently negative and statistically significant effect on health is filtration, which is associated with declines in infant mortality and typhoid fever.

The evidence presented in Anderson et al. (2020) requires a nuanced interpretation. The paper finds little evidence to support a monocausal explanation of the mortality transition. This conclusion is consistent with the evidence and discussion in Section 4, which showed that: cities employed a number of different tools to improve water quality, there was often one intervention that was important for improving water quality, but the intervention that mattered varied from city to city. Because of this, it is not surprising that the authors find little evidence of one public health intervention driving the mortality decline.

One should hesitate to interpret Anderson et al. (2020) as evidence that improving water quality does not generate large improvements in health. Their methodology attempts to recover an average treatment effect for each intervention by leveraging variation in the year of adoption. To see why this is problematic, consider the impact of filtration. The evidence in Section 4 suggests that filtration was important for Pittsburgh but less important in places like Cleveland, which had largely eliminated the threat of waterborne disease through other means. 11 of the 17 cities that filter their water between 1900 and 1940 had already undertaken at least one other intervention between 1900 and the year of filtration.[21] If the authors extended their sample to 1950, then their estimates would be influenced by Chicago's decision to start filtering in 1947. But as early as 1930 typhoid fever mortality in Chicago had converged to 0.005 deaths per 1000 persons, a 99.2% decline from the 1880–1890 average, and so it's unclear what we learn by pooling Chicago with cities like Pittsburgh. In short, this empirical approach misses some of the historical nuances of infrastructure investment, which may explain some of the seemingly spurious results in the paper. For instance, the specification indicating that filtration lowered infant mortality by 11–13% also indicates that chlorination—a method still employed today— *increased* infant mortality by 8–9%.[22]

Obtaining causal estimates of the health multiplier is challenging. One issue is that cities often adopted various techniques within a few short years of each other. A second issue is that sometimes an intervention generates a large change in water quality, while in other settings the same intervention might not play a key role. Despite these challenges, two papers stand out as showing how a rich understanding of historical and institutional details can be leveraged to generate a convincing empirical design. The first paper is Ferrie and Troesken (2008) and the second paper is Alsan and Goldin (2019).

Ferrie and Troesken (2008) present a detailed history of Chicago as an illustrative example of the social returns to eliminating typhoid fever. By focusing on one city, the authors are able to offer a deep institutional understanding that informs their empirical analysis. The authors discuss three major changes in water infrastructure and sewerage and show that those interventions led to large changes in typhoid fever mortality but even larger changes in total mortality. Leaning on

[20] The original article states a decline of 43%. The 38% figure comes from an update that adjusts for some transcription errors in the underlying data set, see Cutler and Miller (2019). Cutler and Miller (2005) also presents results for infant mortality, with Table 5 suggesting that clean water interventions explained 74% of the infant mortality decline. Those infant mortality results are significantly smaller after correcting for transcription errors.

[21] I consider clean water projects, sewage treatment, and chlorination as alternative interventions. Technically, Tables 2 and 3 of their paper indicate that only 10 cities adopted an intervention before starting filtration, but that is because the authors don't list Washington DC's 1902 incorporation of water from a new reservoir as a clean water intervention.

[22] Interestingly, Anderson et al. (Forthcoming), which applies the same approach to 1906–1938 data tabulated by race, finds that chlorination lowered black infant mortality by 9% but had no effect on white infant mortality.

the idea that changes in typhoid mortality are driven almost entirely by improvements in sanitation, they then regress the all cause (minus typhoid) mortality rate on the typhoid mortality rate and some controls at the city level and the ward level. The ward-level evidence is perhaps the most convincing because it allows for the inclusion of time fixed effects to help account for broader changes in Chicago's health and economic environment. The results from that exercise suggest that the health multiplier associated with eliminating typhoid fever is somewhere between 2.3 and 5, which is remarkably close to Hazen's estimate of 4.26.

Alsan and Goldin (2019) offer some of the most convincing evidence that improving the sanitary environment generates large health effects for infants and children. The authors examine 60 Boston-area municipalities over the period 1880 to 1920. A feature of this setting is the plausibly exogenous arrival of infrastructure. Districts were forced to join the Metropolitan Sewage District and they could elect to receive water from the Metropolitan Water District, but the infrastructure's arrival was largely determined by geographical features such as terrain and distance. The authors 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. These findings highlight the importance of eliminating the contamination of water supplies, or what the authors refer to as the fecal-oral transmission channel. A second takeaway is that, in at least some settings, complementary investments were necessary to reduce mortality.

6. Aggregating costs and benefits

The previous section indicates that infrastructure investments were influential in eliminating waterborne disease but the effect of any one intervention depends on other external factors. In general, it seems that for each typhoid fever death that was prevented there were 2–5 deaths from other causes that were also prevented. This suggests that water improvements could explain anywhere from 20 to 40% of the mortality decline between 1900 and 1940.

What did the gains look like in a typical city? Drawing on the sample of registration cities introduced earlier, a typical city had a population of 78,000 in 1900 and experienced a typhoid death rate of about 0.4 deaths per 1000 persons. Relating this to our estimates of the multiplier suggests that a typical city could expect mortality rates to decline by anywhere from 1.2 to 2.4 deaths per 1000 persons after they eliminated the threat of waterborne disease. This translates into 93.6 to 187 lives saved each year. Assigning a monetary value to saving lives is often contentious, but Costa and Kahn (2004) estimate the value of a life in 1900 at 516,000 (2011 USD). This suggests that eliminating waterborne disease in a typical city generated 48.3 to 96.5 million dollars in benefits each year. Given the durability of infrastructure, a conservative assumption might be that the entire waterworks needs to be replaced every 25 years.[23] Assuming an interest rate of 6%, the net present value of these benefits would be between 666 million and 1.33 billion dollars (2011 USD).[24]

Were these gains large enough to offset the costs? Water and sewer investments were expensive, particularly since the costs were borne almost entirely by city residents. To fix ideas, note that in 2011 U.S. dollars the transcontinental railroad cost about 1.78 billion dollars or 50.8 dollars per capita. The Panama Canal cost 751 million dollars or about 8.5 dollars per capita. In contrast, Chicago's sanitary district cost 1.1 billion dollars, but when deflated relative to the population of Chicago, the cost was $653 per capita, New York City's Old Croton Aqueduct cost 336 million dollars or $1053 per-capita, and Louisiana's Owens River Valley Aqueduct cost 598 million dollars or about $1874 per capita (Troesken, 2015, p. 115). The above exercise suggests that the benefits accrued in the typical registration city would have been more than sufficient to offset investments of the scale of Chicago's sanitary district (1.1 billion) or New York City's old croton aqueduct (336 million), and that investment would continue to make financial sense so long as the cost of eliminating typhoid fever was lower than $8538 to $17,051 per capita.

While the value of lives saved offers a strong justification for investment, other benefits also help justify the cost of water and sewer infrastructure investment. For instance, health insults occurring during key periods of fetal development and in early childhood often have latent and lasting effects, including chronic health conditions and worse cognitive performance (Currie and Almond, 2011; Almond et al., 2018; Currie, 2020). Beach et al. (2016) examine the impact of early-life exposure to typhoid fever and their estimates suggest that cohorts born after typhoid fever had been eliminated would complete about 0.1 more years of schooling and see their annual income increase by 1.7–2.4%. A cost-benefit analysis indicates that, for larger cities, the discounted stream of future income was enough to offset the costs of eliminating typhoid fever. Those findings shed light on one productivity channel. Other channels include labor savings from no longer having to collect and store water or care for those suffering from the effects of waterborne illness. Sanitation is also an amenity that likely improved overall quality of life, although that benefit is harder to quantify.[25]

7. Conclusion

Between 1880 and 1930 American cities eliminated the threat of waterborne disease by investing in water and sewer infrastructure. This article reviewed the forces that guided those investments and the various tools used to improve the sanitary environment. The article assessed the impact of these investments on health. The evidence suggests that the economic value of eliminating waterborne disease far exceeded the cost of investment.

The arrival of safe water and sanitation in U.S. cities represents a large positive amenity shock and there are a number of areas that warrant future research. One promising area is in understanding a household's willingness to pay for these benefits, as it is likely that sanitary improvements were capitalized into rents and home values.[26] Recent research has shown that industrial air pollution in 19th century cities affected aggregate city growth and productivity (Hanlon, Forthcoming) as well as underlying segregation as high income households tried to move to neighborhoods that were upwind and thus relatively less polluted (Heblich et al., Forthcoming). It seems likely that changes to the sanitary environment would have generated similar effects. Finally, the move to piped water and sewage disposal also lowered the cost of engaging in household-level sanitary practices. The literature has not attempted to separate this channel from the "pure water" channel when assessing the impact on health, but understanding these complementarities seems particularly relevant for today's developing countries.

[23] One example of durability is Philadelphia's Fairmount waterworks, which was in operation from 1815 to 1909. A second example is offered by Flint, MI, which made national news in 2014 because toxic amounts of lead had leached from the city's lead pipes into the water supply. Those pipes were installed in 1897. For more on the harmful effects of lead water pipes, see (Troesken, 2006; Ferrie et al., 2012; Clay et al., 2014; Feigenbaum and Muller, 2016):

[24] Upton (1892, pp. 857–861) tabulates interest rates on outstanding debts for various state and local governments as of 1890. The average interest rate for municipalities with 4000 or more persons was 5.31%.

[25] Costa and Kahn (2017) show that newspapers in major cities were more likely to report on typhoid outbreaks *after* cities started cleaning up their water supplies, perhaps suggesting that the residents were no longer willing to accept that high disease rates were simply part of normal life.

[26] Ambrus et al. (2020) provides some insight on this mechanism. That paper argues that cholera epidemics introduced a sorting response that had persistent effects on home values.

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Declaration of competing interest

I, Brian Beach, have no conflicts of interest to disclose.

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