The Role of Public Health Improvements in Health Advances:
The 20th Century United States

David Cutler[1,2] and Grant Miller[1]

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Cartoon by Zim, 1919

“The present water closet system, with all its boasted advantages, is the worst that can generally be adopted, briefly because it is a most extravagant method of converting a mole-hill into a mountain. It merely removes the bulk of our excreta from our houses to choke our rivers with foul deposits and rot at our neighbors’ door. It introduces into our houses a most deadly enemy…”

–chemist quoted in the *Scientific American*, 1869

Abstract

Mortality rates in the US fell more rapidly during the late 19th and early 20th Centuries than any other period in American history. This decline coincided with an epidemiological transition and the disappearance of a mortality "penalty" associated with living in urban areas. There is little empirical evidence and much unresolved debate about what caused these improvements, however. This paper investigates the causal influence of clean water technologies – filtration and chlorination – on mortality in major cities during the early 20th Century. Plausibly exogenous variation in the timing and location of technology adoption is used to identify these effects, and the validity of this identifying assumption is examined in detail. We find that clean water was responsible for nearly half of the total mortality reduction in major cities, three-quarters of the infant mortality reduction, and nearly two-thirds of the child mortality reduction. Rough calculations suggest that the social rate of return to these technologies was greater than 23 to 1 with a cost per life-year saved by clean water of about $500 in 2003 dollars. Implications for developing countries are briefly considered.

David M. Cutler
Department of Economics
Harvard University
1875 Cambridge Street
Cambridge, MA 02138
(617) 496-5216
dcutler@harvard.edu
and NBER

Grant Miller
NBER
1050 Massachusetts Avenue
3rd Floor
Cambridge, MA 02138
(617) 868-3900
nmiller@fas.harvard.edu

Introduction

In the early 20th Century, mortality in the United States declined dramatically. Mortality rates fell by 40% from 1900 to 1940, an average decline of about 1% per year. Life expectancy at birth rose from 47 to 63. Together with the late 19th Century, no other documented period in American history witnessed such rapidly falling mortality rates. This decline in mortality was part of the 'epidemiological transition.' Nearly all of the mortality decline is accounted for by reductions in infectious disease, which today is only a small share of total mortality. It also coincides with the disappearance of the 'urban penalty' – the higher mortality rates observed in urban areas throughout the 19th Century.[1] Clearly potent forces outside of medical care were at work. But what were these forces?

Several explanations have been put forward. One posits that economic innovation and nutritional gains drove this change. (Fogel, 1994; McKeown, 1976) Fogel shows that mortality declines track reductions in chronic malnutrition as reflected by body-mass index (BMI).[2] McKeown argues for the importance of nutrition and living standard improvements in reducing mortality by ruling out other explanations.[3] A second explanation is that private actions taken by individuals and households to improve hygiene were a dominant factor explaining lower mortality. Health behavior campaigns were born in the late 19th and early 20th centuries, often targeting hand and food washing, the boiling of milk, and breastfeeding. (Ewbank and Preston, 1990) There is considerable variation in infant and child health related to mothers' education (Deaton and Paxson, 2001; Elo and Preston, 1996) – a relationship commonly thought to operate through health behaviors – and there is evidence of an effect of education on own mortality later in life. (Lleras-Muney, 2002) A third view stresses large-scale public health innovations

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[1] As late as 1900, life expectancy at birth for white males was 10 years greater in rural areas than in urban areas.

[2] Chronic malnutrition can be due either to a shortage of nutrients or excessive demands on them (often by either work or disease) and is commonly linked to immune system resilience.

[3] McKeown's evidence has been contested by numerous critics such as Simon Sretzer. (Szreter, 1988) There is also some evidence that the British mortality decline analyzed by McKeown was not unique when conpared to pre-industrial mortality fluctuations in Britain (Wrigley and Schofield, 1989), refuting his central thesis.

– including clean water technologies, sanitation, refuse management, milk pasteurization, and meat inspection – as the source of health improvement. (Meeker, 1972; Condran and Crimmins-Gardner, 1978; Preston and Haines, 1991) These explanations are not mutually exclusive, but it is important to discriminate amongst them. In formulating strategies to improve health in developing countries, it is essential to know the relative importance of nutritional gains, education campaigns, and major public health initiatives. Empirical research on these topics can aid development institutions in selecting interventions to improve health that have the greatest social returns.

Unlike the other two explanations, relatively little empirical work has examined major historical public health interventions. Existing evidence draws upon the link between municipal sanitation spending and mortality (Cain and Rotella, 2001), mortality decline in three 19th century French *départments* as water and sanitation infrastructure was built (Preston and van de Walle, 1978), concomitant changes in waterborne disease deaths and urban infrastructure (Condran and Crimmins-Gardner, 1978), racial differences in typhoid fever mortality following water filtration (Troesken, 2002), and the expansion of water and sewer infrasturcture across wards of Chicago (Ferrie and Troesken, 2004). All of this research shares common problems: it is difficult to rule out the influence of confounding factors,[4] and often the interventions themselves are difficult to pinpoint.[5]

Our paper responds to these problems by examining the introduction of a major class of discrete public health interventions – clean water technologies – in large American cities in the early 20th Century. Clean water technologies are likely the most important public health intervention of the 20th Century. In 1900, waterborne diseases accounted for nearly one quarter of reported infectious disease deaths in major cities. In the next few decades, waterborne disease mortality fell dramatically. The only disease killing more people at the turn of the century – tuberculosis – had already declined enormously by the time drugs to combat it were developed and widely distributed. We examine the importance of clean water using a difference-in-difference approach that exploits plausibly exogenous variation in the timing of water filtration and chlorination

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[4] Major urban infrastructure projects were often bundled with other municipal reforms, and they were often introduced in particular times of need.

adoption across cities. Importantly, we provide historical evidence and conduct several specification tests to support our identifying assumption of jointly exogenous variation in intervention timing and location.

We first estimate the impact of clean water on cause-specific and total mortality. We show that the introduction of water filtration and chlorination systems led to major reductions in mortality, explaining nearly half of the overall reduction in mortality between 1900 and 1936. Our results also suggest that clean water was responsible for three-quarters of the decline in infant mortality and nearly two-thirds of the decline in child mortality. The magnitude of these effects is striking. Clean water also appears to have led to the near eradication of typhoid fever, a waterborne scourge of the 19th and early 20th Centuries.

We next investigate behavioral responses to clean water. Our analyses lend some support to the notion of a multiplier effect of public health interventions: by increasing the returns to private health behaviors, public health interventions induce an increase in these private behaviors. We then approximate the rate of return to clean water investments. Water systems were expensive, but their benefits appear to have been substantially greater. Under conservative assumptions, we estimate the rate of return to clean water technologies to have been about 23 to 1 and the cost per life year saved to have been about $500 in 2003 dollars. Finally, we conclude by considering broad implications for developing countries today.

Public Health Advances in the Early 20th Century United States

Disease Environment and Theories of Illness

At the turn of the 20th Century, infectious diseases accounted for a large share of deaths in American cities. As Table 1 shows for the major cities studied in this paper (defined later), 44% of deaths were due to infectious diseases in 1900. By 1936, however, only about 18% of deaths were due to infectious disease. Although our analysis

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[5] Municipal water and sewer projects often spanned many decades.

begins in 1900 with the start of reliable annual mortality statistics, decennial census statistics clearly show that the striking mortality declines began before the turn of the century. The crude death rate during the 1850s has been estimated to have been about 22 per 1,000. (Meeker, 1972) This rate had fallen to about 18 by 1900 and declined to about 11 by 1940. (United States Census Office, 1902; United States Bureau of the Census, 1941)

Before the bacteriology revolution of the 1870s, the dominant view of contagious illnesses was the miasma theory of disease. This view essentially maintains that a variety of illnesses are the result of poisonous, malevolent vapors or “miasmas” that are offensive to the smell. (Duffy, 1990) The widespread acceptance of the miasma theory appears to have been based on Pavlovian learning. People exposed to foul odors were more likely to get sick, foul-smelling areas tended to have more sick people, and more people seemed to get sick during the summer seasons during which offensive odors were more common. This leap of logic from correlation to causation led to both successful and misdirected sanitary interventions. John Snow’s famous discovery of London’s contaminated well uncovered a direct causal relationship between dirty water and disease despite ignorance about the underlying disease mechanism. Consequently, concerns about the health effects of contaminated water and sewage solidified even before the underlying basis of disease was fully understood.

This understanding was not perfect, however. Many resources were also squandered on widespread ventilation campaigns and relatively ineffective quarantine initiatives. Even following the bacteriology revolution, a scientific understanding of infectious disease was slow to replace the miasma theory in public opinion. The large-scale provision of water to urban populations illustrates the mixed results of early understandings of disease.

Early Water Systems and Their Degradation

Municipal water supplies pre-dated a correct understanding of waterborne disease. The first large-scale municipal water system in the United States was built in Philadelphia at the dawn of the 19th Century. Benjamin Latrobe and colleagues completed the bulk of Philadelphia's water system in 1801, drawing water primarily from the Schuylkill River with supplemental water from Spring Mill. Many large cities subsequently followed in Philadelphia's footsteps, often after years or even decades of squabbling over water sources and the best means for tapping them. The tremendous Croton Aqueduct began serving New York in 1842, and in 1848, Boston celebrated the long-awaited arrival of water from Lake Cochituate (Long Pond).

Early municipal water systems did not prevent significant outbreaks of waterborne and related infectious diseases. During the 1870s and 1880s, many cities expanded or built new water and sewer systems, instituted systematic garbage collection, and began paving cobblestone roads with smoother materials to facilitate cleaning. However, a considerable amount of waste continued to be dumped into city streets; these wastes were generally swept or washed down drains and into sewers that ultimately emptied back into municipal water supplies. Water systems generally provided inadequate water or inadequate water pressure to wash streets and flush sewers on a regular basis. Moreover, because most sewer systems were only designed to carry storm water, they often became clogged because they lacked sufficient capacity (many were not more than 2.5 or 3 feet in diameter). (Duffy, 1990) Rapid population growth during the 19th Century greatly exacerbated these capacity problems. In addition to a large amount of waste introduced into sewers from city streets, the advent of water closets in the US in the 1870s added considerable strain to already overburdened sewers. The end result was often backflow from sewers into streets and gutters; some observers began referring to sewers as "elongated cesspools." (Duffy, 1990)

Perhaps the worst sort of backflow was the emptying of sewer systems directly into drinking water supplies. In the late 19th Century, the primary sewer outfalls of many American cities emptied upstream of river water intakes or directly into large water bodies (like the Great Lakes) in close proximity to water intakes. It is ironic that the cities with the most extensive sewer systems were often the ones with greatest potential to pollute their water sources. The few cities that addressed this problem early on also suffered from the dumping of untreated sewage by upstream communities. This phenomenon essentially reproduced "circular water systems" (a term referring to the common mixing of household privy vault and drinking well contents through the groundwater) on the municipal level. (Duffy, 1990)

A substantial mortality "penalty" to living in urban places therefore developed as American cities grew during the 19th Century.[6] (Haines, 2001) This can be seen in historical mortality statistics. In seven states with good data before 1900, urban mortality was 30% higher in cities than in rural areas in 1890. The gradient was much steeper for infants and children. In 1880, infant mortality was 140% higher in cities, and in 1890, mortality among children 1-4 was 94% higher. (Haines, 2001; United States Census Office, 1888)

Clean Water Technologies: Filtration and Chlorination

As city water quality deteriorated, new technologies to combat dirty water also emerged. Originally developed to combat turbidity, discoloration, and bad taste rather than disease, water filtration was first introduced into the United States in Poughkeepsie, New York in 1872.[7] However, historians report that it wasn't until the 1890s that truly effective filters began being used; the largest cities generally did not build filtration plants until after the turn of the 20th Century. In general, there were two major methods of filtration: slow sand filtration and rapid (or mechanical) filtration. Slow sand filtration is simply the large-scale pouring of untreated water into vats full of sand, gravel, and other porous matter. Gravity causes the water to settle through the filter. Particulate matter is strained out of the water, and bacteria is removed both by the sticky film of mud (called a "Schultsdeck" or "dirt cover" by the German scientists that espoused its benefits) that forms on the surface of the sand and by the oxidization that occurs as water passing through the filter comes into contact with air trapped between the particles of sand. (source: The Quest for Pure Water) Rapid filtration employs the same basic process but forces water into the sand using jets and passes it through the filter under pressure rather than letting gravity do the work. Additionally, rapid filters commonly

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[6] Historical data limitations make it difficult to pinpoint precisely when this mortality "penalty" first emerged.

[7] The first public water supply to be filtered was in Paisley, Scotland in 1804. (Melosi, 2000)

employed aluminum sulfate as a coagulant to aid in the forming of the protective film on the sand surface.

Although discovered to effectively remove bacteria from drinking water during the bacteriology revolution, filtration technologies did not remove all bacteria. Experiments with a large variety of disinfection techniques were seen as complements to filtration (or substitutes for them in some cases, depending on the clarity and amount of vegetable and particulate matter in a water source[8]). These techniques included exposure to ultraviolet rays, boiling, and treatment with ozone and compounds of copper, silver, and chlorine. (Baker, 1948). However, cost considerations and ease of use produced a clear winner: chlorine. The first large scale adoption of water chlorination occurred at the Boonton Reservoir of the Jersey City water works in 1908, and many cities quickly followed in subsequent years. Hypochlorite compounds were initially used, but they were shortly replaced at many water supplies with liquid chlorine, which was easier to administer and monitor.

In addition to the principal clean water technologies examined by this paper, some cities sought clean water through other means as well. In 1896, Jersey City abandoned the Passaic River as its water supply, instead turning to cleaner upland sources whose watersheds it could protect. (Blake, 1956) In 1900, Chicago completed its construction of the Chicago drainage canal, with which it successfully reversed the flow of the Chicago River, sending its wastewater down the Illinois and Mississippi Rivers rather than back into Lake Michigan – its water supply.[9] (Blake, 1956) In 1907, Chicago also shut-off its remaining sewer outfalls that emptied directly into Lake Michigan. (Melosi, 2000) In 1904, Cleveland extended its water intake tunnel four miles out into Lake Eerie to distance the intake from its sewer outfalls. (Melosi, 2000) Memphis chose never to take large quantities of water from the Mississippi River, instead drawing on deep groundwater for its population.

Sewage treatment technologies are of course also important for the provision of clean water. These range from early practices of dilution, straining, and oxidation to

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[8] Some saw an intermediate process like filtration as necessary for preventing other irregularities such as fish being delivered through infrastructure pipes into bathtubs.

more modern biological and chemical processes such as the "activated sludge process" and chlorination, respectively. However, modern technologies were not generally in widespread use in the United States until the 1930s and 1940s, so we cannot examine them in a meaningful way using the data we employ in our analyses. For the cities we examine, however, we do have knowledge of when basic sewage treatment technologies were introduced, so we can account for this in our empirical analyses.

Adoption of Clean Water Technologies

There was considerable variation in when cities adopted clean water technologies. Although some major cities such as Cincinnati, Philadelphia, and Pittsburgh began building large filtration plants around the turn of the century, others such as Chicago and Milwaukee waited many decades to do so. There was somewhat less variation in when water chlorination was adopted, however. Following the demonstration of chlorine's use for disinfection in 1908, most major cities began water chlorination within the next decade. Primary sewage treatment and sewage chlorination technologies were generally not used until later in the Century, which is why our analyses do not focus on them more. Figure 1 shows the cumulative number of our sample cities adopting clean water and sanitation technologies from 1900 to 1936.

Although probably not complete historical accidents, there was a large random component to the timing of clean water technology adoption in American cities. In general, early sanitarians fought uphill battles to persuade city councils to take action against poor water quality for many years or decades before such actions were finally taken. (Cutler and Miller, 2004) Matters were further complicated by differences in beliefs about the precise cause of disease despite the scientific advances of bacteriology and about the appropriateness of government involvement in water purification. Moreover, even as consensus about the need to begin filtering or disinfecting municipal water supplies emerged, partisan bickering about how it should be done (by the city directly or by private contract) and what specific technology would be adopted (slow or

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[9] St. Louis filed a historic suit against Chicago in federal court to block this action, but the suit failed after the discovery that water from further up the Mississippi River was dirtier than water entering from the

rapid sand filtration, for example) introduced additional hurdles to be cleared. Historical accounts therefore generally suggest that the precise year in which cities ultimately adopted clean water technologies was quite arbitrary.

The case of Philadelphia provides an illustrative example. (McCarthy, 1987) In 1885, the Philadelphia city council paid a prominent chemist from the University of Virginia to conduct a study of the quality of the city's water supplies. The study found Philadelphia's water quality to be good, but scrutiny by other scientists suggested that it actually varied enormously week to week, ranging from good to unfit for human consumption. Subsequent debate focused on moving the city's primary sewer outfalls from above water intake points to below them. Needless to say, this action did little to address upstream water contamination. Several famous experiments on filtration and water quality were conducted in subsequent years at Lawrence, MA by a group of scientists from MIT. Beginning in 1887, they demonstrated a causal effect of filtration on water quality. This did not simplify the choices facing Philadelphia, however, leaving it to decide between better confronting the sources of water pollution, abandoning its water supply and seeking a cleaner one via a long aqueduct, or purifying its water by filtration. Following a major cholera outbreak in Europe, the Philadelphia city council authorized the construction of an experimental filtration plant on the Schuylkill River in 1892. However, with the passing of the outbreak, the project was halted. In 1896, the director of the city's water bureau together with the health department's bacteriology department again pressed the city council to construct an experimental filtration plant. A bond issue to support its construction was eventually approved, but revised cost estimates much larger than the original ones again led to delay.

Consequently, the council again considered alternatives other than filtration of the existing water supply. A consortium calling itself the Schuylkill Valley Water Company proposed to develop a new water supply from the upper Schuylkill – complete with filtration plants – with a series of dams from Reading to Norristown. The city would pay the company for service over the next fifty years (an attractive time horizon for politicians in office at the time), at which point it would own the supply infrastructure. This plan was very nearly approved until a junior council member announced during a

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Illinois River. (Melosi, 2000)

council session in 1898 that he and other representatives had been offered bribes to vote in favor of the plan. This revelation was of course scandalous and resulted in an investigation that effectively ended the plan.

Following the demise of the Schuylkill Valley Water Company proposal, the director of the water bureau again submitted a report to the city council recommending slow sand filtration for most of the city's pumping stations and a mechanical filter for the remainder. By this time the city was on the verge of the 1900 elections, and political considerations were at the forefront. One of the former insiders of the Schuylkill Company deal introduced a bill supporting a new proposal by the Quaker City Water Company to increase the share of the city's water obtained from the Delaware River – and to filter this water. The proposal was naturally met with skepticism in light of the recent scandal, and the leading mayoral candidate opposed it. An alternative bill approving municipal construction of a new filtration system was then proposed but was subsequently defeated by Quaker Company supporters and other skeptics on a special council committee later dubbed "the typhoid thirteen." In the end, passage and implementation of a new plan for filtration ultimately had to wait until after the election of a new mayor in 1900. Because of the lengthy construction period, major population centers in Philadelphia didn't start receiving filtered water until late in decade.

The story of water politics in Philadelphia mirrors what occurred in most American cities. (Cutler and Miller, 2004) As a result, we take the precise timing of clean water technology adoption across cities to be largely exogenous. We turn next to the data that allow us to estimate the impact of these interventions on mortality.

Data and Sample Selection

To understand how clean water affected mortality, we need data on sanitary interventions matched to deaths by cause. There was no national system of death records in the United States prior to 1933, however. (Haines, 2001) Instead, we make use of the substantial data that was collected beginning in 1900 from an official "death registration area" comprised of ten states together with a number of "registration cities" outside of these states. (Haines, 2001) Annual mortality statistics collected in these areas by city, cause, and age were obtained from the Census Bureau's *Mortality Statistics* from 1900-1936.[10] We do not include years later than 1936 because a new data series begins in 1937. This is also a convenient end-point in time for our analysis because it immediately precedes the development of major antibiotics and more modern health care. The precise cause of all waterborne and diarrheal disease deaths is difficult to ascertain in the Census Bureau's statistics, and diarrheal disease categories are unfortunately reported inconsistently throughout the 1900-1936 series. However, typhoid fever, a marker for waterborne disease and important cause of death in its own right, is reported consistently throughout the series. In 1900, the ratio of diarrheal disease deaths to typhoid fever deaths in the cities studied was about 3:1. Summary statistics for total mortality, typhoid fever mortality, infant mortality, and child mortality are shown in Table 2.

We match these municipal-level mortality statistics to knowledge of where and when clean water technologies were in use according to historical engineering and urban planning periodicals. The most comprehensive sources are water system censuses published in the municipal engineering periodicals: two in the *Journal of the American Water Works Association* (in 1924 and 1932) and one in *Water Works Engineering* in 1943. Articles in these as well as other relevant periodicals including *American City* and *Engineering News* contain additional information. Several prominent historical texts on clean water also provide intervention dates. (Baker, 1948; Blake, 1956; Melosi, 2000)

Our selection of cities began with all municipalities of at least 100,000 population in 1900; more detail on these cities is available in the decennial censuses. A few smaller cities for which unusually good historical information is available were also included. We then sought four clean water intervention dates for each city: water filtration, water chlorination, primary sewage treatment, and sewage chlorination.[11] Because our empirical strategy relies heavily on the accuracy of intervention dates, we chose only to include those cities for which readily available published materials provide all four dates.

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[10] Available from authors upon request

[11] In many cases, readily available printed materials did not provide all four intervention dates for each city. Therefore, a number of phone calls requesting these dates were made directly to municipal water and sewage authorities. However, we ultimately question the precision of intervention dates obtained by telephone. In some cases, dates provided by municipal agencies conflicted with published dates; in other cases, the best answers given were of the "circa 1910" sort.

Our final sample is comprised of thirteen cities: Baltimore, Chicago, Cincinnati, Cleveland, Detroit, Jersey City, Louisville, Memphis, Milwaukee, New Orleans, Philadelphia, Pittsburgh, and St. Louis. Even by restricting our analyses to these cities, some measurement error undoubtedly remains. Cities did not always begin clean water interventions in an "all or nothing" manner from one year to the next. However, the dates we use correspond to the year in which the majority of municipal populations were first served by these interventions. Table 3 shows each intervention date for each city. It also makes plain why we cannot examine the impact of sewage treatment technologies – very few of the 13 cities had adopted these technologies by 1936.

Finally, data on demographic characteristics and literacy for these populations were obtained from the Census Bureau's decennial censuses, 1900-1940. Table 4 summarizes these demographic statistics. For years between decennial census years, values for these variables were estimated by linear interpolation.

Empirical Strategy

Given the importance of cumbersome political processes in determining the precise timing of clean water interventions in cities, our basic empirical strategy is to exploit this plausibly exogenous variation in intervention timing to identify the effects of clean water. We use a difference-in-difference approach to estimate the impact of clean water interventions. Specifically, we estimate equations for mortality in cities c and years t of the general form:

$$\begin{aligned}\ln(m_{c,t}) = {} & \alpha + \beta_1 \mathrm{Filter}_{c,t} + \beta_2 \mathrm{Chlorine}_{c,t} + \beta_3(\mathrm{Filter}_{c,t} * \mathrm{Chlorine}_{c,t}) + \\ & \delta_c + \mu_t + \gamma_c l_{c,t} + \sum \phi_d d_{d,c,t} + \sum \lambda_k \ln(m_{c,t-k}) + \varepsilon_{c,t}\end{aligned} \quad (1)$$

Mortality rates (m) are assumed to depend on indicators for water filtration and chlorination and their interaction, city and year fixed effects, city-specific linear time trends (l), demographic characteristics (d), and an error term (ε). Demographic characteristics specified are population age structure, sex, racial composition, and share of immigrants. We incorporate an interaction term between filtration and chlorination to test if the two technologies are substitutes ($\beta_3>0$) or complements ($\beta_3<0$).

Our dependent variables are variety of mortality measures including total mortality, infant mortality, child mortality, and cause-specific mortality due to a variety of diseases and conditions. It is difficult to determine which infectious diseases should respond to clean water technologies, however. Hiram Mills, a member of the Massachusetts state board of health, and J. J. Reincke, a health officer in Hamburg, Germany, independently observed a marked reduction in overall mortality, not just waterborne disease mortality, upon introduction of water filtration more than a century ago. (Sedgwick and MacNutt, 1910; Ewbank and Preston, 1990) The biological mechanism underpinning the so-called "Mills-Reincke phenomenon" would presumably be that contaminated water weakens the immune system, making one more susceptible to other contagions. The scope of the Mills-Reincke phenomenon should at least be limited to infectious diseases other than those directly transmitted by dirty water; chronic diseases such as cardiovascular disease and cancer should be less affected (at least initially). We therefore focus on water-borne causes of death and infectious diseases as a whole.

Our intervention variables capture the effect of clean water technologies on some, but not all, people in a city. While little good historical information is available, there is some suggestion that minority neighborhoods in urban areas to received piped water later than white neighborhoods. (Troesken, 2002) Our ignorance about the precise share of municipal populations receiving piped water in each year should not bias our results unless large-scale infrastructure improvement projects or a large number of citizen-initiated new household connections were timed to coincide precisely with the introduction of clean water technologies. This seems unlikely, and additional large and expensive infrastructure projects would have likely appeared in the municipal engineering periodicals that we searched for relevant intervention dates. Less than universal access to piped water suggests that we might have an underestimate of treatment effects.

Despite suggestive evidence from historical texts, a central concern with this approach is that cities may have begun filtering or chlorinating their water in response to specific events or factors such as a severe disease environment. Along these lines, relatively high mortality rates just before the introduction of clean water technologies could cause our estimates to capture a simple process of regression toward the mean. Alternatively, declining mortality rates in the years just prior to the adoption of clean water technologies might suggest that our estimates are confounded by secular mortality declines. We address these concerns in several ways. First, we include lags of mortality ($m_{c,t-k}$) as independent variables to account for differences pre-intervention mortality trends. Our results are not sensitive to this. In addition, we include leads of the intervention variables in some of our specifications. If the timing of these interventions is truly exogenous, mortality rates should not be higher or lower just before their introduction. Our results hold up to this test.

Results

We begin by illustrating our results with simple time trends. The charts in Figure 2 show typhoid fever mortality trends in each city in our sample, depicting the years in which clean water interventions were introduced. Despite considerable year-to-year volatility in typhoid mortality rates, these charts generally show that the adoption of clean water technologies were not preceded by increases in death rates. Particularly striking cases are Baltimore, Cincinnati, Philadelphia, and Pittsburgh. There does, however, appear to have been a slight pre-intervention dip in typhoid fever mortality in some cities shortly before clean water technologies were adopted. We pay careful attention to distinguishing pre-intervention declines in mortality from true program effects in our subsequent analyses. It is also possible that pre-program drops capture program effects resulting from the phase-in of technologies that occurred over several years in some cities.

Table 5 shows the results of estimating equation (1). Each column corresponds to a separate specification, with the dependent variable at the head of the column. Because the dependent variable is in logarithmic form, the coefficient estimates can be interpreted roughly as percent changes. The first row shows estimates of the effects of filtration on mortality. On average, filtration reduced typhoid fever mortality by 46%, total mortality by 16%, infant mortality (ages 0-1) by 43%, and child mortality (ages 1-4) by 46%. These are very large effects. The second row shows estimates of the chlorination effects, suggesting that chlorination alone had no detectable effect on mortality. The third row shows coefficient estimates for the interaction between filtration and chlorination. These coefficients are positive for typhoid fever mortality and total mortality, suggesting that filtration and chlorination were substitute technologies. We discuss the other coefficients below.

Taken together, Table 5 also suggests that filtration and chlorination were jointly important in reducing mortality. Their combined effects are shown in the third row from the bottom, and the corresponding F-statistic is shown immediately below. On average, filtration and chlorination together reduced typhoid fever mortality by 25%, total mortality by 13%, infant mortality by 46%, and child mortality by 50%.The result that filtration was more effective than chlorination is in some ways an artifact of the time period. Filtration technologies were developed before the health benefits of chlorination were first discovered in the United States, so major cities generally adopted filtration before chlorination. As a result, we have little mortality variation with which to identify the chlorination effect if the two technologies are largely substitutable. Another possible explanation for the results is that because it is so cheap, chlorination diffused very rapidly across cities after its first large-scale use, leaving less time variation with which to detect an effect.

The magnitude of these estimated effects is striking. In our sample of major cities, the reduction in mortality from 1900 to 1936 was about 30%. Our results suggest clean water technologies reduced mortality by 13% during this period, accounting for about 43% (13/30) of the total reduction.Infant and child mortality fell by 62% and 81% respectively in these cities during this period. Clean water appears to be responsible for 74% (46/62) of the infant mortality reduction and 62% (50/81) of the child mortality reduction. Similarly, clean water led to the near-eradication of typhoid fever.

The effect of clean water on total mortality is much larger than what can be accounted for by typhoid fever effects alone. Declines in typhoid fever due to clean water technologies account for only about 2% of the total mortality reduction during this period . Although total waterborne disease deaths are not reported consistently from 1900-1936, we suspect that they are roughly three times as large as typhoid fever mortality.[12] As a result, reductions in all waterborne diseases account for about 8% of the total mortality reduction. What of the remaining 35% attributable to clean water?

Table 6 presents regression results using the same specification with other causes of death as the dependent variable. Among the causes of death that are reported consistently from 1900-1936, the other diseases that respond to clean water are infectious diseases: pneumonia, tuberculosis, meningitis, and diphtheria/croup. As shown in the last column of Table 6, reductions in pneumonia, meningitis, tuberculosis, and diphtheria/croup account for 9%, 6%, 5%, and 4% of the total mortality reduction. Together with typhoid fever and an assumption about unobserved reductions in diarrhea and enteritis, we can identify specific causes of death for 32 percentage points of the 43% decline in total mortality attributable to clean water.

Importantly, clean water technologies have no effect on non-infectious disease mortality - in this case, cancer and diabetes (the last two rows of Table 6).[13] In both cases the coefficient estimates are substantially smaller than for infectious disease mortality, and the estimates are not statistically significant.

Specification Test

One test of our identifying assumption is if the coefficients on intervention lead dummy variables are different from zero. If we found positive coefficients on the lead dummy variables, we might worry that cities began purifying their water supplies in response to relatively high disease rates or that our estimates mistake a simple process of regression toward the mean for intervention effects. Negative coefficients might suggest that our estimates are confusing secular declines with clean water effects.

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[12] Using data from 1900 we calculate that the ratio of diarrhea and enteritis deaths to typhoid fever deaths is slightly less than 3:1. Given some assumptions, this ratio can be used to approximate changes in diarrhea and enteritis deaths from 1900 to 1936 despite the lack of consistent data.

[13] These are the only two chronic diseases reported consistently from 1900 to 1936.

The coefficients on the five-year lead dummy variables for filtration and chlorination are also shown in Table 5.[14] The coefficient estimates on the intervention lead dummy variables are either insignificantly different from zero or negative. The charts in Figure 2 depict why this is the case. In some of the cities there is evidence of mortality reductions a few years before the interventions. Nevertheless, there is an enormous decline in mortality in the year of the intervention. Furthermore, we coded intervention years to be the year in which the majority of city populations began benefiting although in many cases interventions were introduced over a period of several years.

Table 7 shows this result more formally. We parameterize the interventions by particular years on either side of the true year of introduction. There is a large abrupt drop in mortality in precisely the year of the intervention (time 0), even relative to one year prior to the true intervention (time -1). We thus do not believe that the results are simply capturing pre-existing trends.

The Effects of Clean Water over Time and Behavioral Responses

A central issue is whether the effects of clean water technologies increase or decrease over time. One might imagine an increasing effect if improvements in the disease environment take time to have a sustained impact on mortality or if there is learning over time in how to best use disinfection technologies. Growing effects over time could also be due to increases in complementary private health behaviors. Falling mortality rates increase the expected return to other health investments, possibly resulting in a multiplier effect due to intensified personal health practices. (Dow, Holmes, Philipson, and Sala-i-Martin, 1999; Murphy and Topel, 2003) Alternatively, the effects might become smaller over time if major public health interventions are substitutes for private preventive measures, effectively resulting in 'crowd out.' As the benefits of costly private prevention such as water-boiling or hand-washing fall, individuals might do them

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[14] The qualitative results are not sensitive to the choice of length of time before the onset of filtration and chlorination.

less. (Philipson, 2000) The mortality effects of clean water over time might also fall if those initially saved by interventions are weaker than the average member of the population. Because these weak 'marginal survivors' are more susceptible to other diseases, their mortality rate in subsequent years will be higher than that of the rest of the population.

To evaluate these competing explanations, we first estimate variants of the basic specification that include intervention dummy variables tracing out intervention effects 5 years and 9 years after filtration and chlorination were introduced.[15] Estimates for typhoid fever mortality and total mortality over time are shown in Table 8. The first column estimates a variant of our base regressions that includes 5 year intervention lag dummy variables. Separate estimates are shown for each intervention and its lag in the first rows, and joint intervention effects and their 5 year lag are shown at the bottom.

Our results suggest that the effects of typhoid fever mortality grew over time and perhaps resulted in the near-eradication of the disease observed by 1936. Clean water technologies jointly reduced typhoid fever by 26% initially and by another 65% after five years. Taken together, this is a reduction in typhoid mortality of more than 90%. The second column shows similar results that include both 5 year and 9 year intervention lags. Although more complicated intervention lag structures place greater demands on the data, the basic result of growing effects is similar with effects peaking after about 5 years. The third and fourth columns of Table 8 show the same results using total mortality as the dependent variable. Clean water initially reduced total mortality by 9%, with some small additional reduction in subsequent years. The general result of greater mortality declines over time is consistent with delayed intervention effects or learning over time, a personal health practice multiplier - and not with crowd-out or weak marginal survivors.

A second test of these theories is to look at intervention effects in different disease environments. The personal health practice multiplier theory predicts that private prevention will increase less - and mortality will therefore fall less - in more severe disease environments over time because their expected benefits are less than in healthier areas. The marginal survivor theory also predicts less clean water impact over time in harsher disease environments. Alternatively, the crowd-out theory predicts that mortality

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[15] The estimates presented are not sensitive to specific lag structure choices.

will fall more over time in harsh disease environments: costly private prevention should be crowded-out less in sicker areas because the benefits of private preventive behaviors fall less. Neither delayed intervention effects nor learning over time should result in heterogeneous clean water effects by disease environment.

To evaluate the predictions of these theories further, we constructed a dummy variable for high infectious disease cities in 1900 - cities in the top half of our distribution of infectious disease mortality rates. We then interact this dummy variable with interventions and their lags. The results are shown in Table 9. The bottom of the table shows that the interactions between clean water interventions and severe disease environments are jointly positive over time. The estimate of 0.12 in this first column implies that mortality rates in cities with more infectious disease rose by 12% over time relative to cities with less infectious disease. This finding does not support the predictions of the crowd-out theory – or at least does not support the notion that a crowd-out effect is dominant – nor is it consistent with delayed intervention effects or learning over time.

Together with more tenuous evidence that total mortality continued to decline after clean water technologies were adopted, our results are most consistent with the personal health practice multiplier theory: as public health interventions increased life-expectancy, the returns to personal health practices grew, inducing individuals to engage in them more. Table 10 summarizes this evidence.

Distributional Effects of Clean Water

The benefits of clean water could differ across the socioeconomic spectrum for a variety of different reasons. Because the poor are sicker than the rich on average, they might enjoy greater health improvements due to clean water. Alternatively, if the poor were less likely to have household connections to municipal water supplies, they might have benefited less from water filtration and chlorination.

Examining the distributional consequences of clean water empirically is difficult for several reasons. One is that good indicators of who was poor in historical census data are scarce. Income, assets, and consumption are difficult to infer, and other measures often used to identify the poor (such as occupation) are not comparable across decades because of the rapid rate of technological change. Furthermore, the best measures of socioeconomic status are only in decennial census data and are therefore not observed as frequently as annual mortality. We settle for using a measure of illiteracy contained in the decennial censuses at the municipal level through 1930.[16,17] We examine the effect of clean water technologies in cities that had varying degrees of literacy among their residents.

Table 11 shows results of our base specification with the addition of illiteracy and interaction terms between clean water interventions and illiteracy. Joint effects of filtration and chlorination are shown in the bottom row together with corresponding F-statistics. In general, the results are consistent with a steep illiteracy gradient in the impact of clean water on mortality, with larger mortality reductions for cities with more illiterate residents. This is consistent with a greater impact of clean water on the poor, but endogeneity cannot be ruled out in interpreting these results. Mortality changes might lead to changes in literacy, with greater mortality declines leading to more literacy. Because we find the opposite, we suspect that reverse-causation is not problematic in our analysis. We cannot distinguish between the possibility that the poor and illiterate benefited more from clean water and the possibility that those in cities with more poor and illiterate benefited more.

Social Rate of Return to Clean Water

Our estimates suggest that the benefits of clean water are quite large. Benefits alone do not justify interventions, however. Costs are important, too.

By itself, water chlorination is relatively inexpensive. The fixed-cost component of chlorination expenses is presumably not large (certainly not when compared to

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[16] More desirable measures such as years of schooling do not enter the decennial censuses until late in the time period investigated by this paper.

[17] We interpolate illiteracy between decennial census years.

filtration) because it does not require new facilities or infrastructure.[18] Chlorine disinfection does require careful monitoring, however, because of its highly toxic nature when concentrated. A rough estimate of annual variable costs associated with chlorination can be inferred from historical editions of the Census Bureau's *General Statistics of Cities*. Among cities in 1915 that chlorinated their water but did not employ other treatment processes, annual water treatment costs suggest the variable costs of chlorination in big cities to have been approximately $150,000 to $200,000 per year in 2003 dollars.[19] (United States Bureau of the Census, 1916) However, because our estimates suggest that chlorination alone did not significantly reduce mortality (possible because it was typically adopted shortly after filtration), we do not estimate a rate of return to water chlorination by itself.

It is not easy to pinpoint the costs of filtration using historical municipal finance statistics. To be conservative, we use the estimated value of *entire* municipal water systems making the assumption that these systems exist only to reduce mortality. We then need to determine how long a water system lasts. Again, we conservatively choose a horizon of 10 years, assuming that cities must rebuild their entire systems every 10 years. Because cities introduced clean water technologies around 1915, we use 1915 values of water systems in our calculations. In 2003 dollars, available information suggests that the mean big-city water system value in 1915 was just under $300 million. (United States Bureau of the Census, 1916)

Using these rough cost figures together with our estimates of the mortality benefits of clean water, Table 12 sketches some rough rate of return calculations to investment in clean water.[20] We first convert mortality reductions into life years saved and then value these life years saved in dollars. This dollar value of the benefits of clean water can then be compared to the costs incurred in producing them to yield a rough rate of return. The first row of the table shows our regression results indicating that clean water reduced mortality by an average of about 13% (with a 95% confidence interval ranging from about 4% to about 23%). Using the mean population of our cities in 1915

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[18] Chlorination devices are rather small and can be employed at any reservoir or distribution point in a water system.

[19] BLS on-line resources used to inflate 1915 dollars (http://www.bls.gov/cpi/home.htm#data).

(the average year by which a clean water technology had been adopted), the third row shows estimates of the mean number of lives saved by clean water per city each year; our point estimate is 1,484 lives. We convert lives saved annually into life-years saved by assuming that individuals saved by clean water would otherwise have died at age 27 (roughly half of life expectancy in 1915).[21] This assumption seems reasonable given that infectious diseases usually hit the very young and very old. Life expectancy at age 27 in 1915 was about 39 years, so we obtain average annual life years saved by multiplying the number of people saved by that 39 years. These estimates are shown in the fourth row of Table 12; on average, we calculate that clean water saved 57,922 life years per city each year.

The next task is to calculate a dollar value of benefits by attaching a dollar value to a year of life. Contemporary research on the value of life suggests that a reasonable dollar value of a life year today is about $100,000 on average. (Viscusi and Aldy, 2003) However, there is evidence that the value of life in the US has changed over time as income has grown. (Costa and Kahn, 2002) The elasticity of the value of life with respect to GNP per capita has been estimated to lie between 1.5 and 1.7. (Costa and Kahn, 2002) In 2003 dollars, GDP per capita has grown from $7,496 in 1930 to $37,600 in 2003, a real increase of about 500%.[22,23] The implied value of a life year in 1930 (in 2003 dollars) ranges from $11,723 to $13,280. We use the more conservative figure and assume that the value of life does not vary with age.

The total annual benefits are therefore a little less than $700 million per city. This is substantially greater than the $30 million amortized cost. As the second to last row of Table 12 shows, the rate-of-return estimate is 23 to 1, with a 95% confidence interval ranging from 7 to 40. Similarly, we obtain a point estimate for the cost per life year saved in 2003 dollars of $500 and a confidence interval ranging from $1,775 to $291.

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[20] We clearly make a number of simplifying assumptions which are conservative whenever possible. Specific details are available from the authors.

[21] Life tables can be found at http://www.demog.berkeley.edu/wilmoth/mortality/states.html, reprinted from life tables prepared by the Office of the Chief Actuary in the Social Security Administration.

[22] Reliable GDP figures are not available much further back than 1930. This figure may reasonably represent the period of interest because although taken from late in the period, GDP was of course low during the Depression.

[23] Numbers based on CPI data obtained from ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt, GDP data obtained from http://www.census.gov/prod/99pubs/99statab/sec31.pdf, and authors' calculations.

Even these estimates, large as they are, exclude benefits such as morbidity reductions and productivity gains. Nevertheless, they are tremendous.

Conclusion

Our results demonstrate the strikingly large and cost-beneficial role of clean water technologies in reducing mortality in the historical United States. The period examined was the era of most rapid mortality decline in documented American history, and clean water appears to have played as large a role as any force responsible for this rapid progress.

Although the historical United States surely differs from other contemporary contexts in important ways, clean water and adequate sanitation continue to be high on development agendas today.[24] Worldwide, roughly 1.1 billion people lack access to clean water and about 2.4 billion people do not have adequate sanitation. Cutting the share of people without suitable water and sanitation in half by 2015 is one of the ambitious objectives set by the Millennium Development Goals. The United Nations has declared the years 2005 - 2015 as the international decade for action on water, "Water for Life." The first international water decade, the 1980s, brought clean water to one billion new people and delivered new sanitation services to 770 million people worldwide. However, population growth and rapid urbanization have eroded these gains.

Much of the contemporary investment made in clean water has financed the construction of new water supply infrastructure. A reason commonly cited for the partial failure of these investments to achieve commensurate health returns is the relative neglect of sanitation. Although certainly not a substitute for appropriate investment in sanitation, our results from the historical United States suggest that inexpensive water disinfection technologies can have enormous health returns - returns that reach beyond reductions in waterborne disease - even in the absence of adequate sanitation services. In 2000, more than one-fifth of drinking water samples taken from existing water systems failed to meet

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[24] Information in this paragraph can be found at the Water and Sanitation Program (WSP) homepage: www.wsp.org

national quality standards for microbiological content and other pollutants.[25] (WHO and UNICEF, 2000) If the Mills-Reincke multiplier found in the historical United States[26] holds and only 1% of the roughly 1.7 million annual diarrheal disease deaths worldwide could be prevented by water disinfection, the corresponding social rate of return for one year alone would be about $160 billion.[27]

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[25] The true number is presumably much larger given that countries voluntarily reported these statistics. Ironically, developing countries also self-report that more than 90% of existing water supplies are adequately disinfected. (WHO and UNICEF, 2000)

[26] Our conservative estimate of the Mills-Reincke multiplier in the historical United States is about 3.

[27] In 2002, there were an estimated 1,767,326 diarrheal disease deaths worldwide. (WHO, 2003) An approximate social rate of return is calculated by taking 1% of these deaths, multiplying by 3 (the Mills-Reincke multiplier), assuming 30 life years lost per death, and valuing a life year at $100,000.

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Figure 1: Cumulative Number of Cities Adopting Technologies by Year

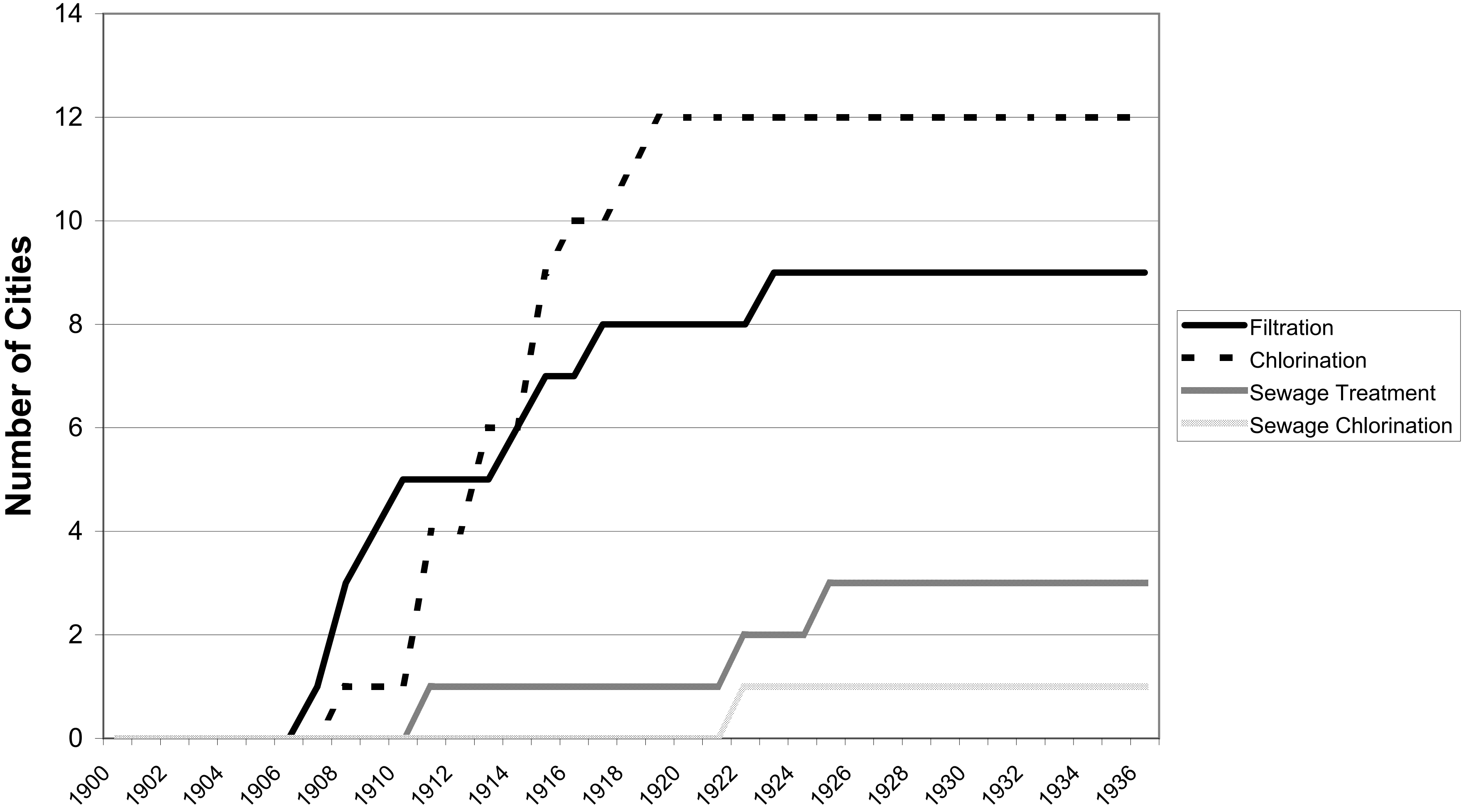
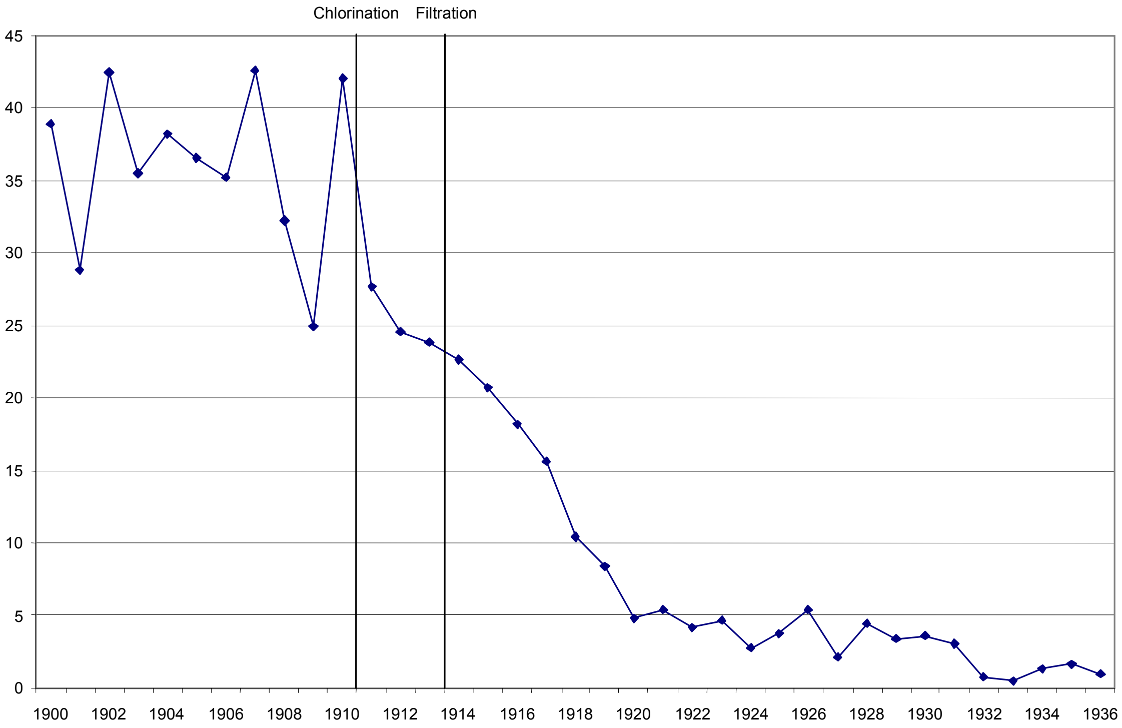
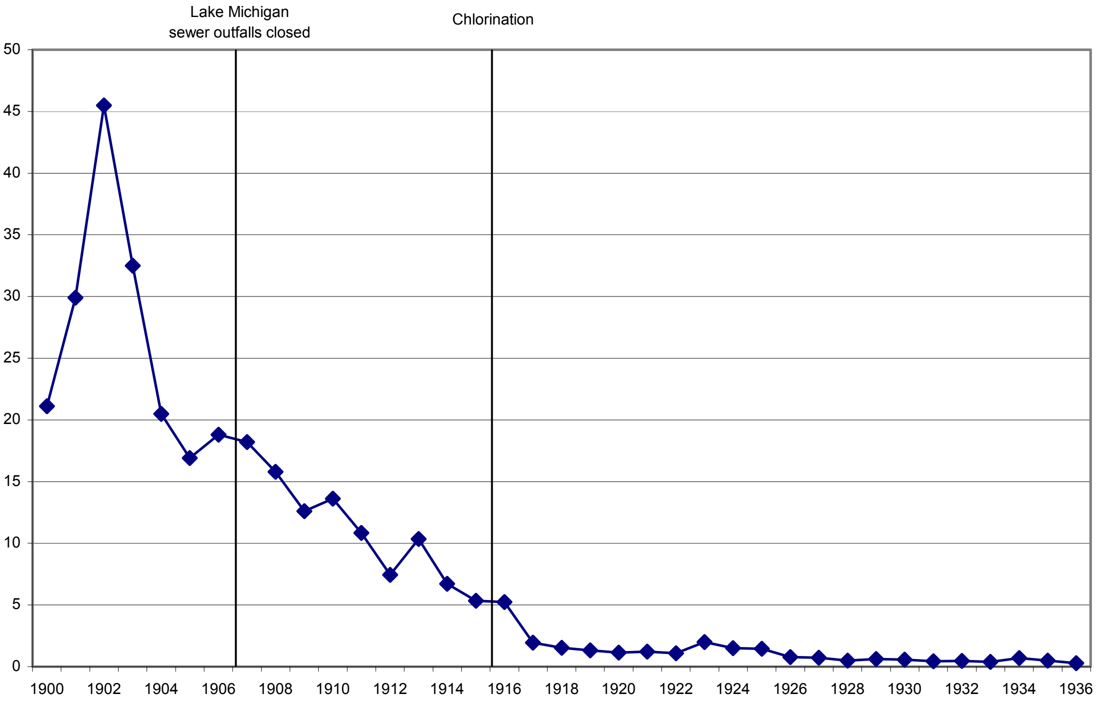


Figure 2: Typhoid Fever trends and Sanitary Interventions, 1900-1936

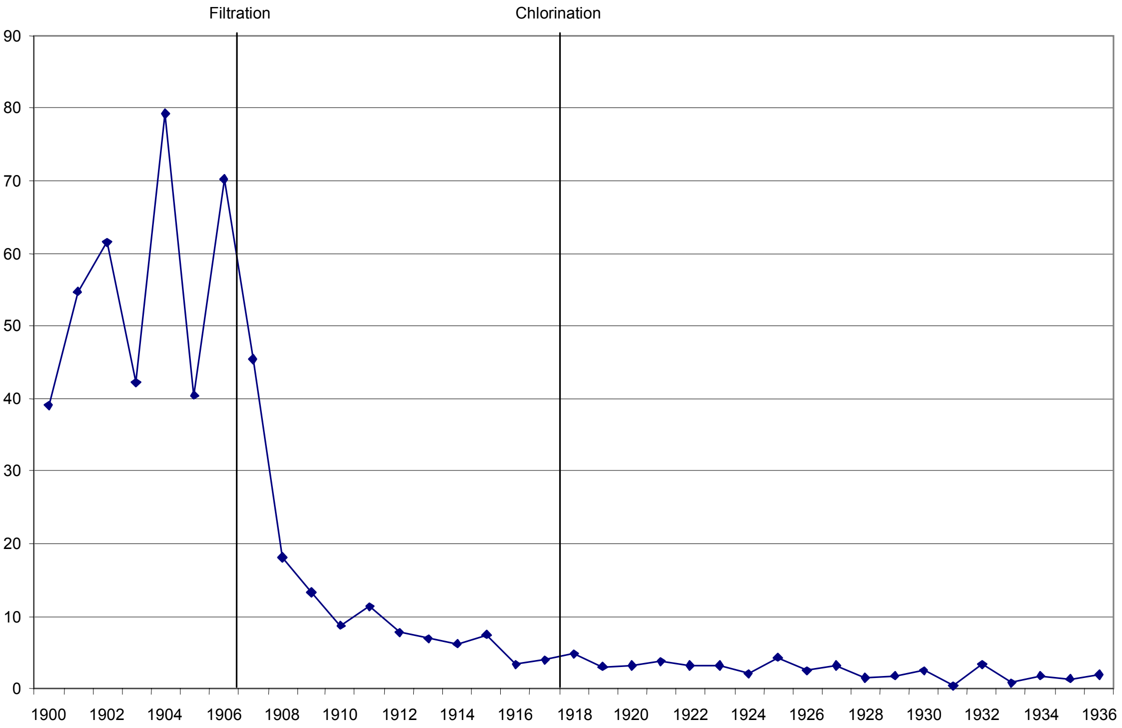
Baltimore Typhoid Fever Mortality per 100,000



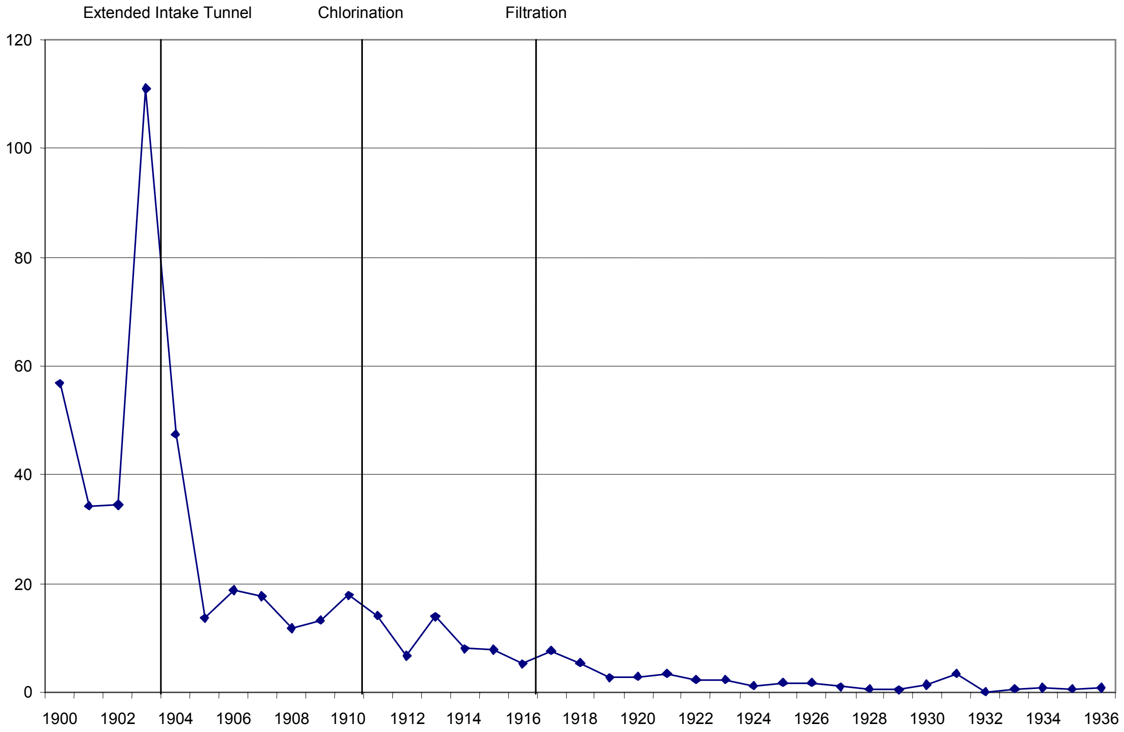
Chicago Typhoid Fever Mortality per 100,000



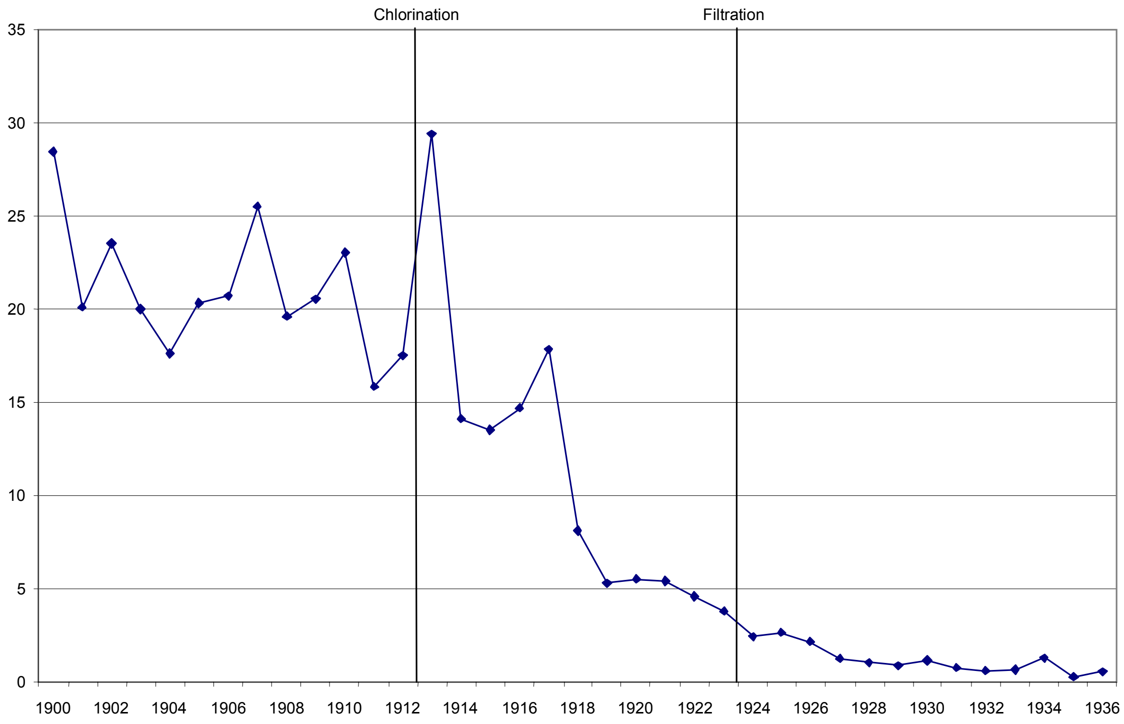
Cincinnati Typhoid Fever Mortality per 100,000



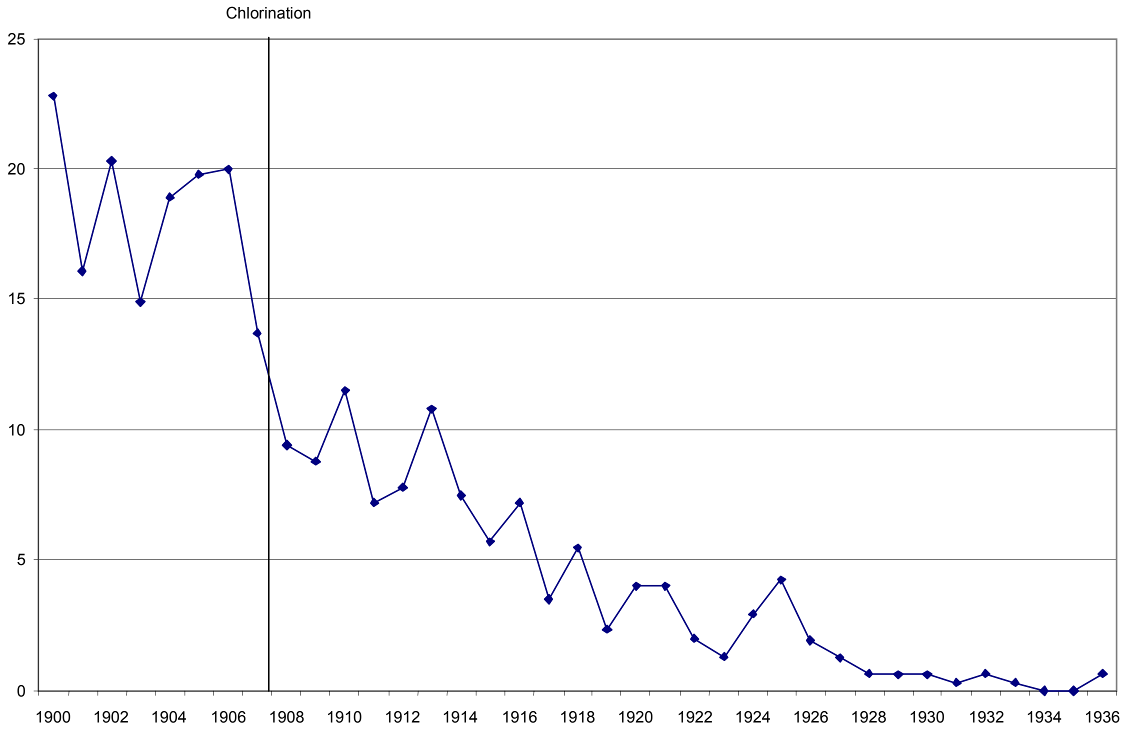
Cleveland Typhoid Fever Mortality per 100,000



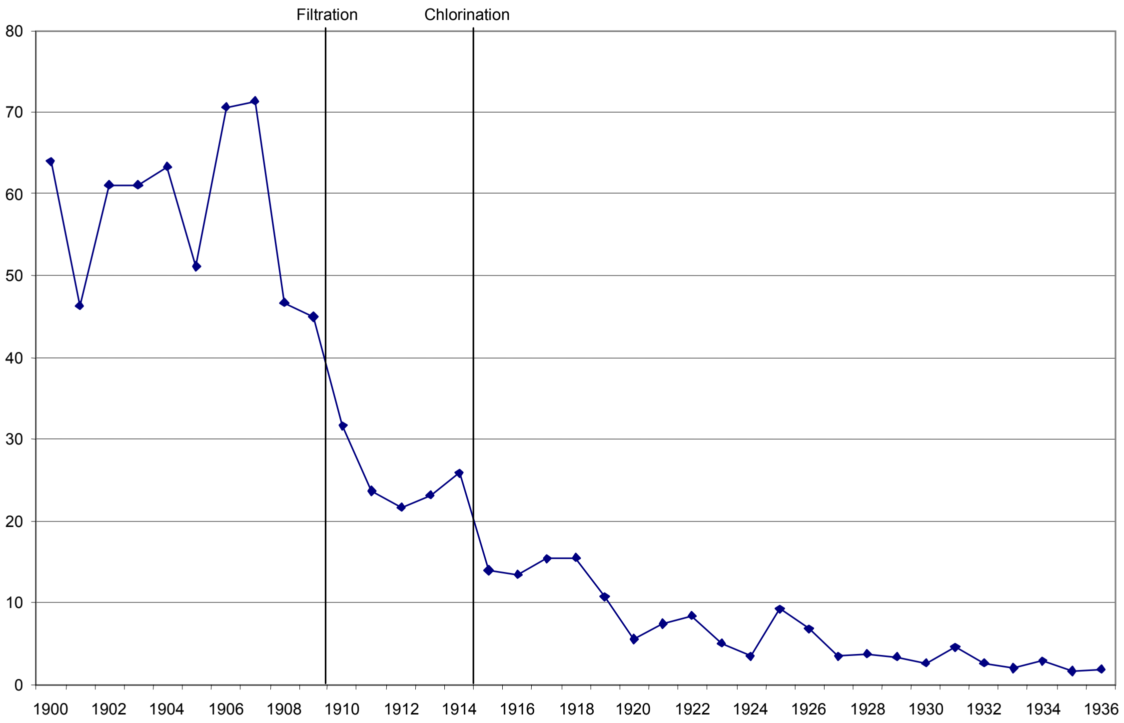
Detroit Typhoid Fever Mortality per 100,000



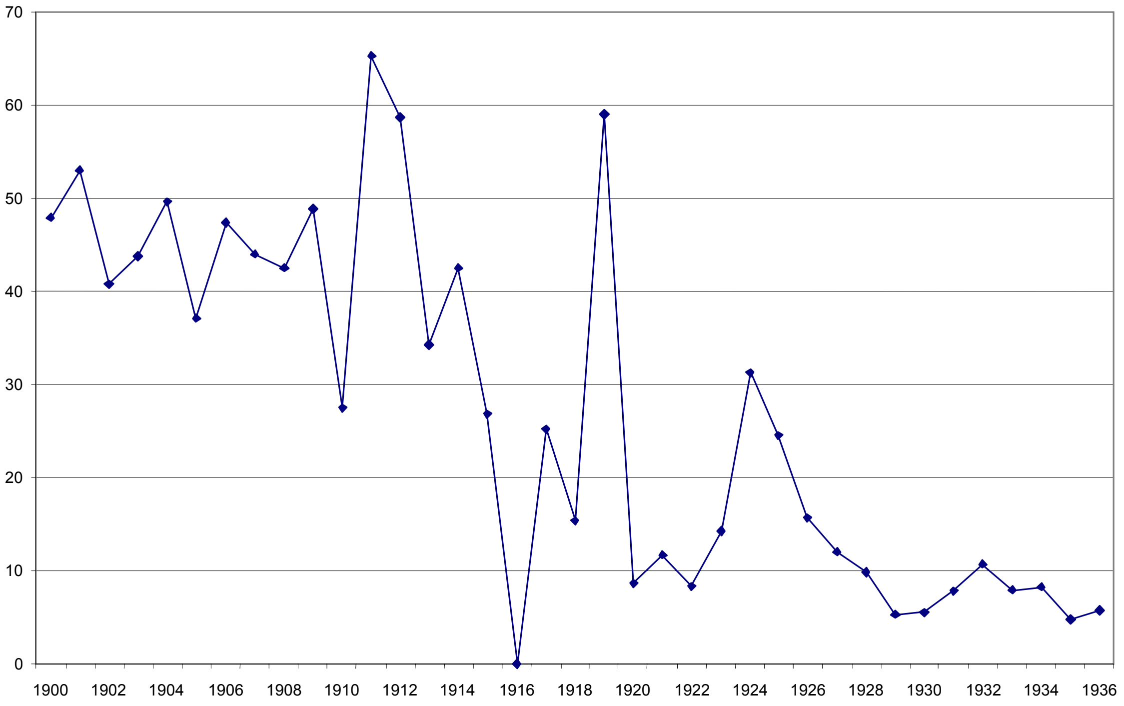
Jersey City Typhoid Fever Mortality per 100,000



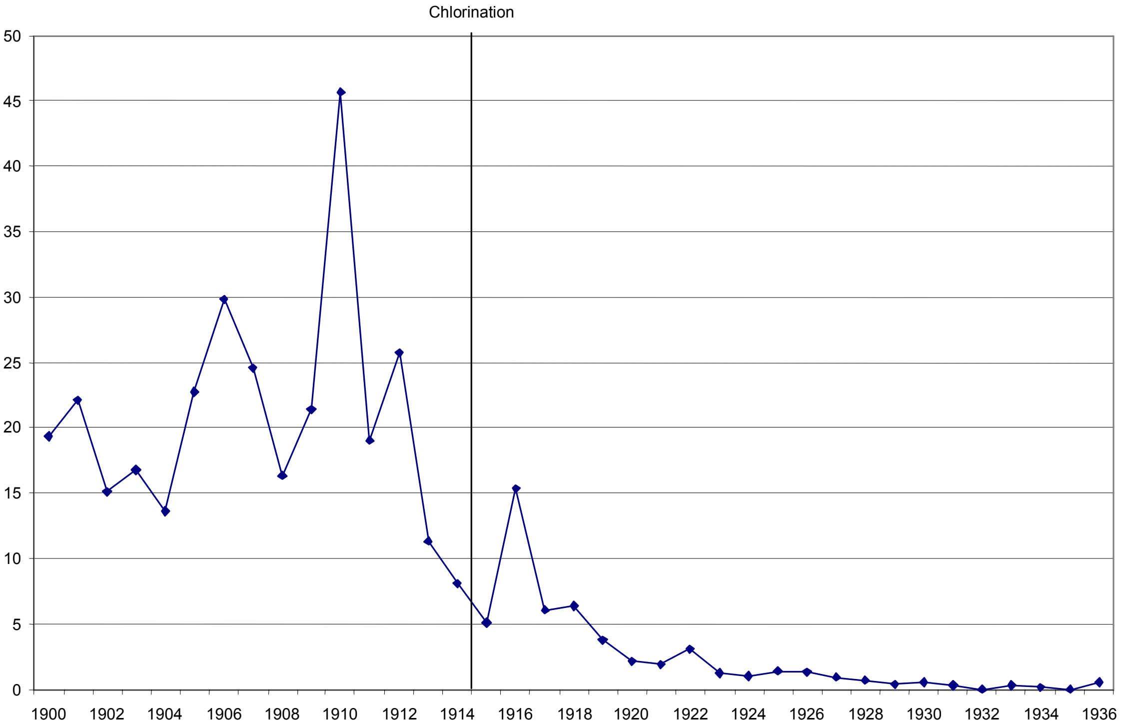
Louisville Typhoid Fever Mortality per 100,000



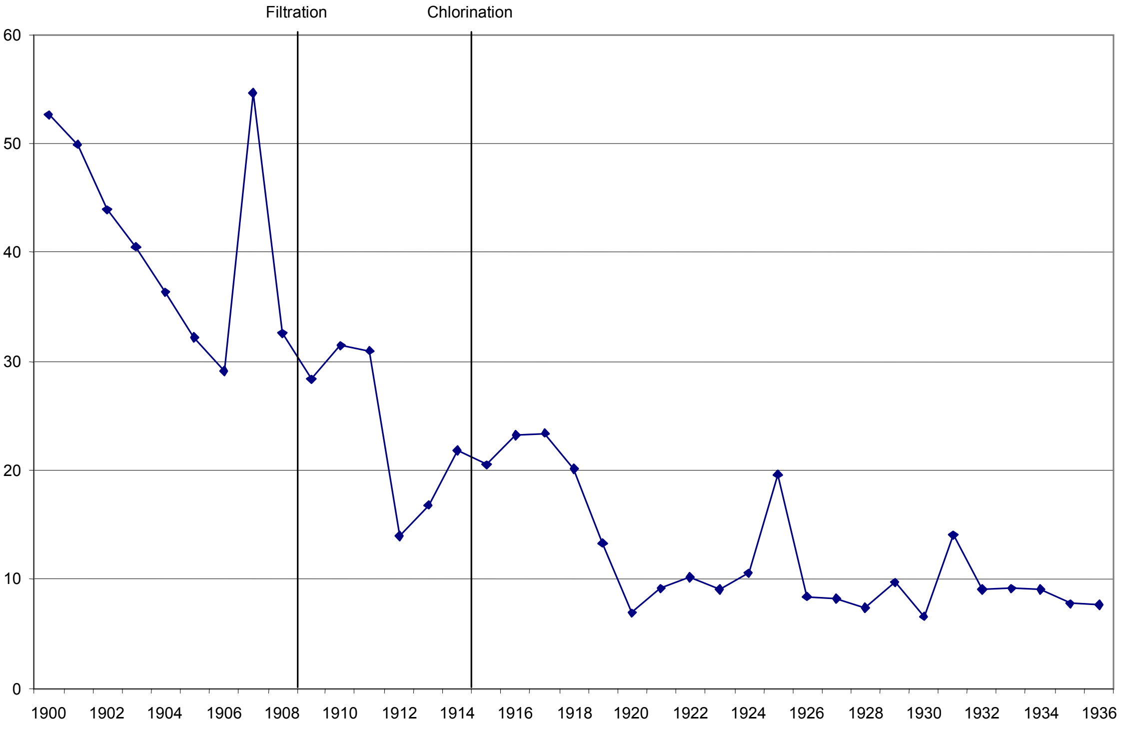
Memphis Typhoid Fever Mortality per 100,000



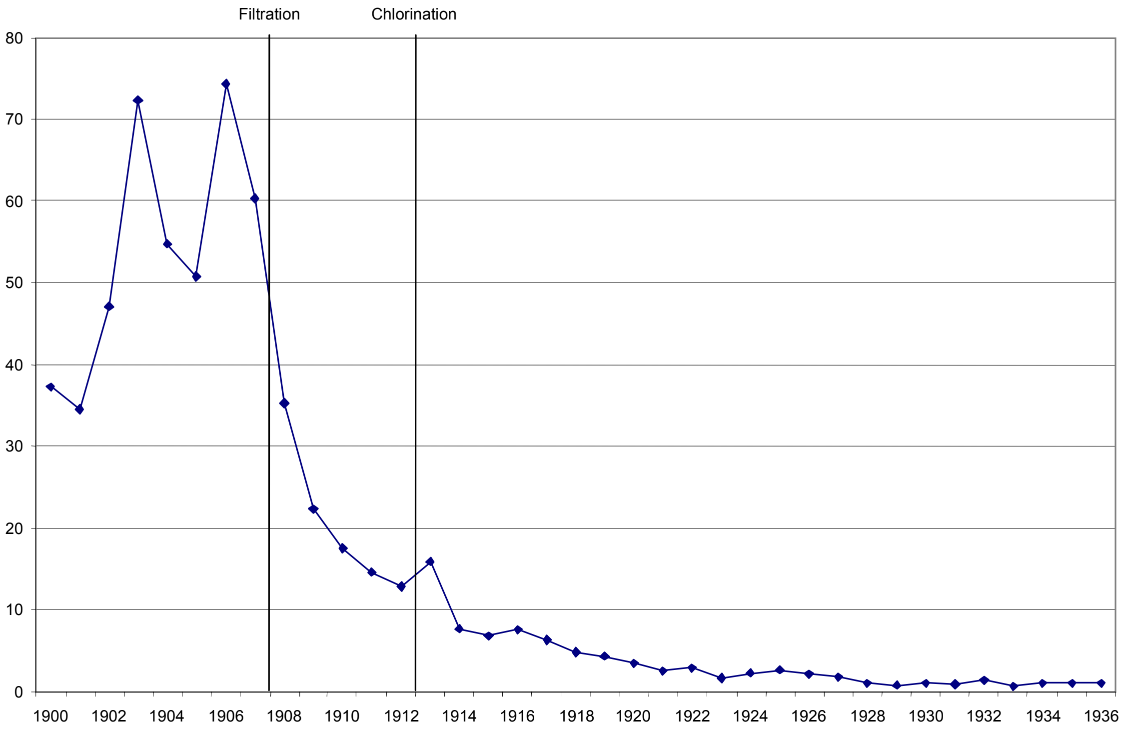
Milwaukee Typhoid Fever Mortality per 100,000



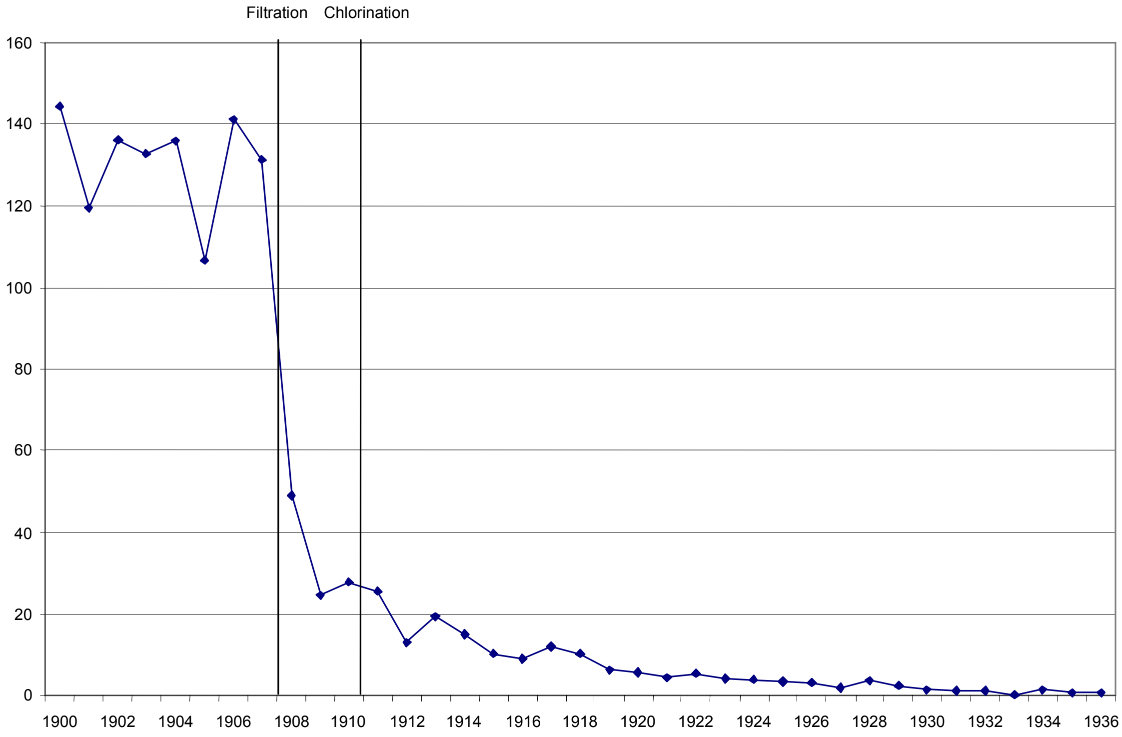
New Orleans Typhoid Fever Mortality per 100,000



Philadelphia Typhoid Fever Mortality per 100,000



Pittsburgh Typhoid Fever Mortality per 100,000



St. Louis Typhoid Fever Mortality per 100,000

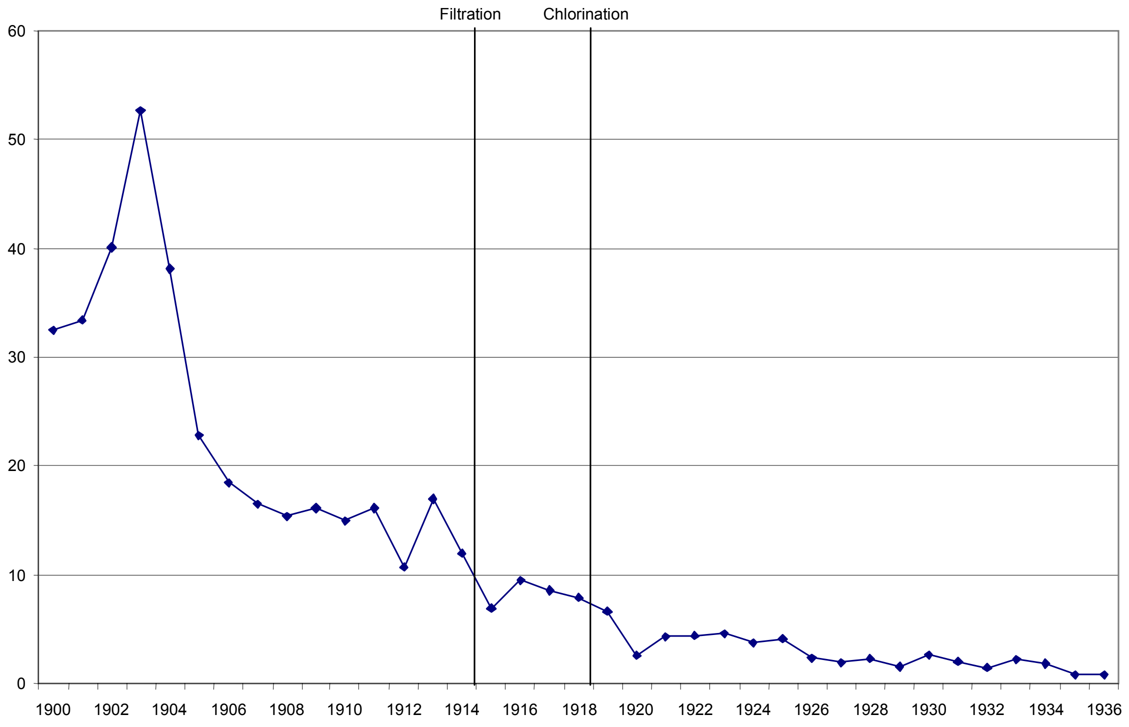


Table 1: Proportion of Deaths by Cause in Major Cities

	1900	1936
Major Infectious Diseases	39.3%	17.9%
Tuberculosis	11.1%	5.3%
Pneumonia	9.6%	9.3%
Diarrhea and Enteritis	7.0%	N/A
Typhoid Fever	2.4%	0.1%
Meningitis	2.4%	0.3%
Malaria	1.2%	0.1%
Smallpox	0.7%	0.0%
Influenza	0.7%	1.3%
Childhood Infectious Diseases	4.2%	0.5%
Measles	0.7%	0.0%
Scarlet Fever	0.5%	0.1%
Whooping Cough	0.6%	0.2%
Diphtheria and Croup	2.3%	0.1%

Note: All percentages are shares of total mortality

Source: United States Census Bureau’s Mortality Statistics, 1900-1936.

Table 2: The Evolution of Total, Infant, Child, and Typhoid Fever Mortality in Major Cities, 1900-1936

Deaths per 100,000

	1900		1920		1936	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Total Mortality	1,935	316	1,492	222	1,354	287
Infant Mortality	18,931	2,921	11,953	1,752	7,130	2,435
Child Mortality	2,818	1,360	1,260	167	522	267
Typhoid Fever Mortality	47	33	4	2	2	2

Source: United States Census Bureau's *Mortality Statistics*, 1900-1936.

Table 3: Clean Water Intervention Dates

	Water Filtration	Water Chlorination	Sewage Treatment	Sewage Chlorination
Baltimore, MD	1914	1911	1911	>1936
Chicago, IL	>1940	1916	1949	>1949
Cincinatti, OH	1907	1918	>1945	>1945
Cleveland, OH	1917	1911	1922	1922
Detroit, MI	1923	1913	1940	1940
Jersey City, NJ	1978	1908	>1945	>1945
Louisville, KY	1910	1915	1958	>1958
Memphis, TN	>1936	>1936	>1936	>1936
Milwaukee, WI	1939	1915	1925	1971
New Orleans, LA	1909	1915	>1945	>1945
Philadelphia, PA	1908	1913	>1945	>1945
Pittsburgh, PA	1908	1911	>1945	>1945
St. Louis, MO	1915	1919	>1945	>1945

Source: Water system censuses published in the *Journal of the American Water Works Association* (1924 and 1932) and *Water Works Engineering* (1943); various articles appearing in *American City*, *Engineering News*, *Journal of the American Water Works Association*, and *Water Works Engineering* (available upon request)

Table 4: Summary Demographic Statistics in Major Cities, 1900 and 1940

	1900		1940	
	Mean	Std Dev	Mean	Std Dev
Population	498,259	467,012	971,350	882,250
% Female	50.5%	1.3%	51.2%	1.1%
% Black	10.6%	14.1%	14.3%	10.8%
% Other Non-White	0.1%	0.0%	0.1%	0.0%
% Foreign Born	22.0%	10.0%	11.3%	7.1%
% Under 5	10.6%	1.0%	6.5%	0.4%
% Age 5-14	20.0%	1.1%	14.4%	0.8%
% Age 15-24	19.8%	1.0%	17.6%	1.0%
% Age 25-44	32.8%	1.4%	33.8%	1.4%
% Age 45-64	13.3%	0.9%	21.5%	1.4%
% Age 65+	3.2%	0.6%	6.3%	11.5%

Source: United States Census Office, *Twelfth Census of the United States, 1900;* United States Bureau of the Census, *Sixteenth Census of the United States, 1940.*

Table 5: Effect of Clean Water Technologies on Mortality

	Dependent Variable (ln form)			
	Typhoid Mortality Rate	Total Mortality Rate	Infant Mortality Rate	Child Mortality Rate
Filter	-0.46**	-0.16***	-0.43***	-0.46***
	(0.23)	(0.04)	(0.09)	(0.11)
Chlorinate	-0.11	-0.02	-0.08	-0.07
	(0.16)	(0.03)	(0.08)	(0.10)
Chlorinate*Filter	0.32**	0.05**	0.06	0.03
	(0.14)	(0.02)	(0.07)	(0.09)
ln(Population)	-0.19	-0.86***	2.78***	1.69**
	(1.49)	(0.23)	(0.66)	(0.77)
Begin Chlorination w/in 5 years	0.13	0.02	-0.05	0.00
	(0.10)	(0.01)	(0.06)	(0.07)
Begin Filtration w/in 5 years	0.17	-0.09***	-0.18***	-0.14**
	(0.17)	(0.03)	(0.05)	(0.06)
ln(Mortality-1)	0.02	0.01*	0.04*	-0.02
	(0.03)	(0.01)	(0.02)	(0.02)
ln(Mortality-2)	0.05*	0.02***	-0.01	-0.02
	(0.03)	(0.01)	(0.02)	(0.02)
ln(Mortality-3)	-0.17***	-0.01	-0.04**	-0.06***
	(0.03)	0.00	(0.02)	(0.02)
ln(Mortality-4)	0.06	-0.01*	-0.08***	-0.04***
	(0.03)	0.00	(0.02)	(0.02)
ln(Mortality-5)	0.02	-0.01*	-0.07***	-0.05***
	(0.03)	(0.01)	(0.02)	(0.02)
Joint Effect	-0.25*	-0.13***	-0.46***	-0.50***
(F-Statistic)	(2.55)	(7.75)	(10.31)	(7.97)
Total Mortality Change, 1900-1936	-96%	-30%	-62%	-81%
Share of Total Due to Clean Water	26%[‡]	43%	74%	62%
N	411.00	415.00	415.00	415.00
R^2	0.94	0.96	0.83	0.88

(Huber-White corrected standard errors in parentheses)

*p<0.1, **p<0.05, ***p<0.01

[‡] As shown in Table 9, clean water technologies explain almost all of the typhoid mortality decline when effects are allowed to vary over time

All specifications include sewage treatment and chlorination dummies, year and city dummies, city trends, and demographic characteristics including population share by gender, race, birth place, and age

Table 6: Other Cause-Specific Mortality Results

Dependent Variable (ln form)	Filter	Chlorinate	Filter*Chlorinate	N	R^2	Joint Share of Total Mortality Decline[‡‡]
<u>Infectious Diseases:</u>						
Pneumonia	-0.25*** (0.08)	-0.19** (0.08)	0.15** (0.06)	415	0.90	9%
Influenza	0.09 (0.17)	-0.15 (0.14)	-0.03 (0.13)	415	0.93	0%
Malaria	-0.42 (0.29)	-0.35 (0.25)	0.64*** (0.22)	309[‡]	0.95	0%
Small Pox	2.57 (2.63)	-1.13 (2.79)	1.74 (3.30)	95[‡]	0.91	0%
Measles	-0.63 (0.56)	-0.11 (0.46)	-0.10 (0.33)	396[‡]	0.52	0%
Scarlet Fever	0.16 (0.37)	-0.24 (0.37)	-0.15 (0.29)	413	0.71	0%
Whooping Cough	-0.06 (0.29)	0.36 (0.27)	-0.42* (0.22)	414	0.62	0%
Diphtheria	-0.64*** (0.21)	0.02 (0.19)	0.10 (0.15)	415	0.86	4%
Meningitis	-0.72*** (0.24)	0.02 (0.17)	0.00 (0.13)	415	0.89	6%
Tuberculosis	-0.09* (0.05)	-0.08* (0.04)	0.02 (0.03)	415	0.97	5%
<u>Chronic Diseases:</u>						
Cancer/Tumor	-0.03 (0.04)	-0.01 (0.04)	-0.02 (0.03)	415	0.98	0%
Diabetes	-0.12 (0.09)	0.08 (0.08)	-0.06 (0.07)	415	0.90	0%

(Huber-White corrected standard errors in parentheses)

*p<0.1, **p<0.05, ***p<0.01

[‡] Small samples due to exclusion of observations with zero values; regressions using mortality and ln(mortality) as the dependent variable yield similar results

[‡‡] As determined by joint effect of filtration and chlorination and associated F-statistics

All specifications include 5 year intervention leads, sewage treatment and chlorination dummies,
year and city dummies, city trends, and demographic characteristics including population share by gender,
race, birth place, and age

Table 7: Timing of Intervention Effects

	Dependent Variable (ln form)			
	Total Mortality Rate		Typhoid Mortality Rate	
True Intervention: Time 0	**Filter**	**Chlorinate**	**Filter**	**Chlorinate**
-4	-0.05*	0.01	0.37***	0.07
	(0.03)	(0.02)	(0.14)	(0.10)
-3	-0.07**	0.01	0.20	0.07
	(0.03)	(0.01)	(0.14)	(0.10)
-2	-0.06**	0.01	0.08	-0.06
	(0.03)	(0.01)	(0.11)	(0.09)
-1	-0.05**	0.01	-0.16	0.14
	(0.03)	(0.02)	(0.12)	(0.12)
0	-0.17***	-0.02	-0.59***	-0.11
	(0.04)	(0.03)	(0.22)	(0.16)
+1	-0.15***	-0.01	-0.58***	-0.15
	(0.04)	(0.03)	(0.21)	(0.14)
+2	-0.13***	-0.01	-0.45**	-0.05
	(0.04)	(0.02)	(0.21)	(0.15)
+3	-0.13***	0.01	-0.34	-0.09
	(0.04)	(0.02)	(0.21)	(0.15)
+4	-0.12***	0.01	-0.16	-0.04
	(0.04)	(0.03)	(0.23)	(0.15)

(Huber-White corrected standard errors in parentheses)

*p<0.1, **p<0.05, ***p<0.01

All specifications include 5 year intervention leads, 5 year intervention lags, sewage treatment and chlorination dummies, year and city dummies, city trends, and demographic characteristics including population share by gender, race, birth place, and age

Table 8: Mortality Results Over Time

	Dependent Variable (ln form)			
	Typhoid Mortality Rate		Total Mortality Rate	
Filter	-0.61***	-0.64	-0.14***	-0.12***
	(0.23)	(0.21)	(0.03)	(0.04)
Filter +5	-0.48***	-0.50	-0.04*	-0.03
	(0.12)	(0.13)	(0.02)	(0.02)
Filter +9		-0.25		0.03
		(0.11)		(0.02)
Chlorinate	-0.11	-0.16	-0.02	-0.02
	(0.16)	(0.16)	(0.03)	(0.03)
Chlorinate +5	-0.25**	-0.28	-0.05*	-0.05*
	(0.12)	(0.14)	(0.03)	(0.03)
Chlorinate +9		-0.24		0.01
		(0.12)		(0.02)
Chlorinate*Filter	0.47***	0.49	0.07***	0.07***
	(0.14)	(0.14)	(0.02)	(0.02)
Chlorinate*Filter +5	0.08	0.15	0.08***	0.06**
	(0.13)	(0.15)	(0.03)	(0.03)
Chlorinate*Filter +9		0.30		0.01
		(0.13)		(0.02)
Joint Effect	-0.26***	-0.31***	-0.09***	-0.08***
(F-Statistic)	(5.16)	(5.90)	(6.65)	(5.17)
Joint Effect +5	-0.65***	-0.63***	-0.01**	-0.02
(F-Statistic)	(6.95)	(6.32)	(3.09)	(1.99)
Joint Effect +9		-0.19*		0.04
(F-Statistic)		(2.50)		(1.25)
N	411.00	411.00	415.00	415.00
R^2	0.95	0.95	0.96	0.96

(Huber-White corrected standard errors in parentheses)

*p<0.1, **p<0.05, ***p<0.01

All specifications include sewage treatment and chlorination dummies, year and city dummies,
city trends, and demographic characteristics including population share by gender, race, birth place, and age

Table 9: Impact of Clean Water Technologies and Initial Disease Environment on Total Mortality

Dependent Variable: ln(Total Mortality Rate)

High Infectious Disease	0.06	(0.23)	0.06	(0.22)	-0.08	(0.25)
Filter	-0.10**	(0.04)	-0.12**	(0.05)	-0.11**	(0.05)
Filter*High Infect	-0.04	(0.04)	-0.06	(0.04)	-0.04	(0.04)
Filter +5	-0.01	(0.04)			-0.02	(0.04)
Filter*High Infect +5	0.00	(0.04)			0.03	(0.04)
Filter +9			0.00	(0.03)	0.04	(0.05)
Filter*High Infect +9			0.10***	(0.03)	0.06	(0.05)
Chlorinate	0.00	(0.03)	0.03	(0.03)	0.01	(0.03)
Chlorinate*High Infect	-0.06	(0.04)	-0.10**	(0.05)	-0.06	(0.04)
Chlorinate +5	-0.06*	(0.03)			-0.05	(0.04)
Chlorinate*High Infect +5	-0.02	(0.07)			-0.04	(0.07)
Chlorinate +9			-0.03	(0.02)	-0.03	(0.02)
Chlorinate*High Infect +9			0.11*	(0.06)	0.10*	(0.06)
Chlorinate*Filter	0.06*	(0.04)	0.03	(0.03)	0.06	(0.04)
Chlorinate*Filter*High Infect	0.01	(0.05)	0.09*	(0.05)	0.01	(0.05)
Chlorinate*Filter+5	0.00	(0.03)			-0.02	(0.04)
Chlorinate*Filter*High Infect +5	0.14**	(0.07)			0.14**	(0.07)
Chlorinate*Filter+9			-0.03	(0.03)	-0.05*	(0.03)
Chlorinate*Filter*High Infect +9			-0.02	(0.06)	0.01	(0.06)
Joint Effect	-0.04*	(2.30)	-0.06***	(4.52)	-0.04**	(2.69)
Joint Effect +5	-0.07	(1.53)			-0.09	(0.77)
Joint Effect +9			-0.06	(1.52)	-0.04*	(2.40)
Joint Effect*High Infect	-0.09	(1.02)	-0.07	(1.77)	-0.09	(1.01)
Joint Effect*High Infect +5	**0.12*** **	**(5.34)**			**0.13***	**(2.29)**
Joint Effect*High Infect +9			**0.20*** **	**(6.90)**	**0.17*** **	**(5.25)**
N	415		415		415	
R^2	0.96		0.96		0.96	

(Huber-White corrected standard errors and F-statistics in parentheses)

*p<0.1, **p<0.05, ***p<0.01

All specifications include sewage treatment and chlorination dummies, year and city dummies, city trends, and demographic characteristics including population share by gender, race, birth place, and age

Table 10: Clean Water Effects over Time - Hypotheses and Evidence Summary

Hypothesis:	Test 1: Lagged Time Effects	Test 2: Interactions with Disease Environment Severity
Learning over Time or Delayed Impact		
Prediction:	Negative Effect	Neither Positive nor Negative
Empirical Result:	Negative Effect	Positive Effect
Increased Complementary Private Health Behaviors		
Prediction:	***Negative Effect***	***Positive Effect***
Empirical Result:	***Negative Effect***	***Positive Effect***
Substitution or Crowd-out of Costly Private Prevention		
Prediction:	Positive Effect	Negative Effect
Empirical Result:	Negative Effect	Positive Effect
Weak Marginal Survivors		
Prediction:	Positive Effect	Positive Effect
Empirical Result:	Negative Effect	Positive Effect

Table 11: Distributional Effects of Clean Water

	Dependent Variable (ln form)			
	Typhoid Mortality Rate	Total Mortality Rate	Infant Mortality Rate	Child Mortality Rate
% Illiterate	-18.24	1.16	35.85***	28.97***
	(12.41)	(2.13)	(7.00)	(8.96)
Filter	-0.03	-0.18**	-0.16	-0.37
	(0.43)	(0.08)	(0.22)	(0.28)
Filter*% Illiterate	-11.03	0.14	-4.84	-1.49
	(8.24)	(1.22)	(5.36)	(5.53)
Chlorinate	1.13	-0.15	-0.36	-0.27
	(0.92)	(0.13)	(0.38)	(0.47)
Chlorinate*% Illiterate	-29.52	3.14	6.51	4.00
	(19.79)	(2.93)	(8.05)	(10.34)
Chlorinate*Filter	-0.07	0.32**	0.51	0.38
	(0.90)	(0.14)	(0.37)	(0.47)
Chlorinate*Filter*% Illiterate	7.08	-6.67**	-10.37	-8.49
	(19.46)	(3.00)	(8.15)	(10.27)
Joint Effect	1.03***	-0.01*	-0.01	-0.26
(F-Statistic)	(4.51)	(2.30)	(0.88)	(0.65)
Joint Effect*% Illiterate	-33.47***	-3.39***	-8.70**	-5.98
(F-Statistic)	-4.01	-4.20	-2.81	-0.74
N	337	337	337	337
R^2	0.95	0.96	0.80	0.81

(Huber-White corrected standard errors and F-statistics in parentheses)

*p<0.1, **p<0.05, ***p<0.01

All specifications include sewage treatment and chlorination dummies, year and city dummies, city trends, and demographic characteristics including population share by gender, race, birth place, and age

Table 12: Social Rate of Return Calculations

	Point Estimate	95% CI Low	95% CI High
% Mortality Reduction Due to Clean Water	0.1326	0.0373	0.2280
1915 Mortality Reduction per 100,000 Population	208	58	357
1915 Deaths Averted	1,484	418	2,551
1915 Life Years Saved	57,922	16,301	99,543
1915 Annual Benefits in Millions of 2003 Dollars	$679	$191	$1,167
1915 Annual Costs in Millions of 2003 Dollars	$29		
SOCIAL RATE OF RETURN	23:1	7:1	40:1
COST PER LIFE YEAR SAVED IN 2003 DOLLARS	$500	$1,775	$291