# Watersheds in Child Mortality: The Role of Effective Water and Sewerage Infrastructure, 1880–1920

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We explore the first period of sustained decline in child mortality in the United States and provide estimates of the independent and combined effects of clean water and effective sewerage systems on under-5 mortality. Our case is Massachusetts, 1880–1920, when authorities developed a sewerage and water district in the Boston area. We find the two interventions were complementary and together account for approximately one-third of the decline in log child mortality during the 41 years. Our findings are relevant to the developing world and suggest that a piecemeal approach to infrastructure investments is unlikely to significantly improve child health.

> The interactions of water, sanitation, and hygiene with health are multiple. On the most direct level, water can be the vehicle for the transmission of a large number of pathogens. Human faeces is a frequent source of pathogens in the water and the environment. . . . In fact, it is virtually impossible to have a safe water supply in the absence of good sanitation. (Dr. Margaret Chan, Director-General, World Health Organization [2013])

## I. Introduction

For much of the nineteenth century child mortality was the prime cause of short lifetimes at birth in the United States and much of Europe. In 1880 Massachusetts, for example, infant deaths were 20.4 percent of all deaths even though births were just 2.5 percent of the total population. Similarly, in 1900, infant deaths were 22.5 percent of all deaths, whereas births were 2.6 percent of the population. But change occurred swiftly and for reasons that often eluded contemporary observers and later researchers. From 1870 to 1930, life expectation conditional on reaching age 20 changed little, but infant mortality plummeted from around one in five to one in 16 white infants for the United States and Massachusetts, and deaths of noninfants under 5 years decreased by a factor of seven in Massachusetts (fig. 1).[1] Why the rapid change?

An extensive and important literature has explored the role of public health interventions in reducing the pathogenic environment of early twentieth-century cities in the United States and Europe and the concomitant decline of urban morbidity and mortality. Some researchers have emphasized the roles of public water and sewerage systems, whereas others have stressed additional public health factors. Analyses have been done both across and within cities. As impressive as these studies are, few can pinpoint a specific exogenous intervention. But the weight of the evidence is that cities began to clean up their acts in the early twentieth century.

Among the best identified of the research is that by Cutler and Miller (2005) on the impact of water chlorination and filtration on the death

[1] Child mortality means deaths to those less than 5 years of age and includes infant mortality. The "infant mortality rate" is the number of infants less than 1 year of age who died during a year divided by the number of births in that year. The historical literature on US infant mortality includes Cheney (1984), Preston and Haines (1991), Condran and Lentzner (2004), and Condran and Murphy (2008). Seminal contributions include Cain and Rotella (2001) on water and sewerage infrastructure by major city; Condran and Cheney (1982) on mortality changes within Philadelphia; Condran and Crimmins-Gardner (1978), demonstrating the importance of public works in the decrease of waterborne diseases; Ferrie and Troesken (2008) on clean water and a general decline of non-waterborne diseases; and Meeker (1972), a pioneering piece on waterborne disease and river spillovers. See also Beach et al. (2016) on long-run payoffs to water purification; Galiani, Gertler, and Schargrodsky (2005) on privatization of water services in Argentina; and Troesken (2001, 2002) on race-specific typhoid mortality and water provision. How cities began to clean up their acts in the early twentieth century is told in part by Cutler and Miller (2006), which emphasizes the growth of financial markets.
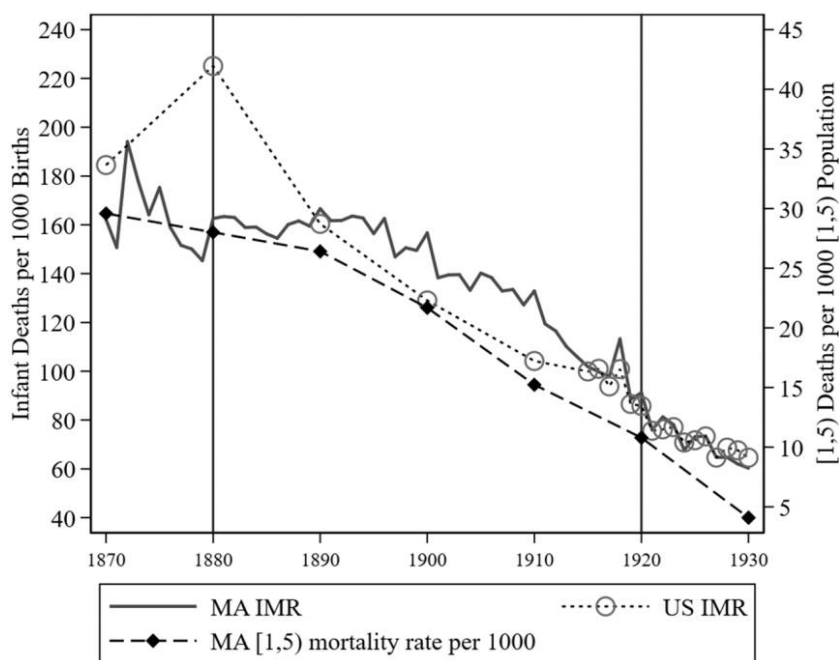
Fig. 1.—Infant and [1, 5] mortality in the United States and Massachusetts, 1870–1930. The US IMR series for 1870–1910 is probably less accurate than the Massachusetts series, which is at an annual frequency and from actual vital statistics data. See Haines (1998a) and Carter et al. (2006, 1–461). The right axis plots the death rate of those [1, 5) for Massachusetts based on the (yearly) registration reports and age-specific population counts from the federal decennial censuses. The US aggregate series for the children [1, 5) death rate begins in 1900.

rate from waterborne diseases across 13 US cities. Their estimates suggest that improved water quality accounted for 47 percent of the decline in log infant mortality from 1900 to 1936.[2] In addition to purer water, effective sewerage systems were installed across many US and European metropolitan areas, but their role in the mortality decline for children under 5 in the United States has yet to be rigorously assessed.[3]

Water and sewerage interventions interrupt different points on the fecal to oral transmission pathway. Sewerage reduces the fecal-oral transmis-

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[2] Cutler and Miller (2005, table 5) compute the decrease in the infant mortality rate due to clean water and sanitation to be 46 log points from 1900 to 1936 in their 13 cities. The total decrease was 98 log points (log[189.3/71.3], table 2), or 47 percent. Their paper reports a 74 percent change, but they have posted a correction.

[3] Cutler and Miller (2005) analyze two discrete water interventions, not sewerage. Research contributions on sanitation interventions and mortality include, but are not limited to, Brown and Guinnane (2018) on Bavaria, Kesztenbaum and Rosenthal (2014) on early twentieth-century Paris, Preston and van de Walle (1978) on nineteenth-century France, and Watson (2006) on US Indian reservations.

sion of pathogens by removing excrement from drinking water sources, reducing human contact with feces, and limiting exposure to the gastro-intestinal diseases transmitted by flies.[4] Clean water interventions remove impurities, making water safe for consumption and washing. Whether the improvements are substitutes or complements depends on their overall efficiency as well as the prevailing burden of disease. Technical complementarities between sewerage and water also existed. For instance, piped water was used to flush sewage down home drain pipes.

Our contribution to the impressive literature on public health and mortality is to provide an empirical examination, possibly the first, of the earliest sustained decline in child mortality in US history. Because we use data from the state that pioneered the collection of US vital statistics, our data are annual and include large and small municipalities for a period that predates national mortality statistics. Most important is that we exploit exogenous variation in both sewerage and water treatments and have information on mortality and cause of death for those under 5 years of age. We thus have exogenous variation in both water and sewerage treatments and examine their complementarity in the production of health using high-frequency and rich mortality data.

The estimation strategy exploits a mandate originating from the Massachusetts State Board of Health that all municipalities surrounding Boston join the Metropolitan Sewerage District (see Whipple 1917). We also rely on the fact that infrastructure rollout was based on technocratic considerations (such as the distance to various outfalls and terrain).[5] Unanticipated delays further staggered the rollout; thus infrastructure completion dates were not very predictable. Because of the negative externalities associated with upstream dumping of sewage, all municipalities located within the watershed area of the Boston Harbor were compelled by law to join (and pay for) the sewerage district. Although each could elect to receive water from the Metropolitan Water District, the timing of the intervention was beyond the control of any given municipality.

Our difference-in-differences estimates show that effective sewerage and safe water systems are complements in the production of child health, and their combination was a major factor contributing to the initial decline in child mortality in US history. Using our preferred specification, the combination of sewerage and safe water treatments lowered child (under-5) mortality by 26.6 log points (out of a 79.2 log point decline), or 33.6 per-

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[4] The aptly named "F-diagram" of fecal-oral disease transmission and control (Wagner and Lanoix 1958) demonstrates how feces can lead to disease transmission through the "5 F's": fingers, fluids (water supply), flies, fields/floor, and food (occasionally flooding is included). Even with clean water, feces can recontaminate water.

[5] We provide evidence in Sec. II.B and table B1 that intervention completion dates were determined largely by technical engineering factors, not political issues or health concerns.

cent. The treatments lowered infant mortality by 22.8 log points (out of a 47.7 log point decline), or by 48 percent. Each intervention in isolation had a small positive health effect, but their combination caused a powerful health improvement. As the financial and political powerhouse of the commonwealth, as well as the recipient of much of the downstream waste, Boston initiated the pure water and sewerage projects. In consequence, we exclude Boston from our analysis.

A variety of informal tests bolster our main findings about the complementarity of water and sewerage. These include (1) that our treatment and control municipalities show minor baseline differences in infant or child mortality (also in general health determinants or in outcome variable trends prior to the interventions), (2) a sharp and persistent shift in the evolution of infant or child mortality with the introduction of the two technologies that is not as prominent with the introduction of just one, and (3) the robustness of our results to time-varying municipality-level controls and various trends.

We provide further support of a causal interpretation by examining age- and cause-specific mortality (see also Galiani et al. 2005). Diseases related to the gastrointestinal system and those that require fecal to oral transmission are heavily affected by the introduction of the sewerage and safe water interventions in our analysis. However, deaths from non-waterborne diseases, such as tuberculosis, or among older children and adults, are not. The age-specific result is relevant because the less than 5-year-old population was most likely to succumb to gastrointestinal disease given their susceptibility to dehydration. In addition, the infrastructure improvements had larger impacts on children in municipalities that experienced more rapid population growth and had a higher fraction of certain foreign-born groups.

## II.  Mortality Decline and the Two Treatments: Historical Background

### A.  Infant and Child Mortality

Infant mortality data for the United States and Massachusetts start around 1850, no coincidence given the origins of US vital statistics collection.[6] For both series, as shown in figure 1, the infant mortality rate (IMR) begins its long-term descent starting in the late nineteenth and early twentieth centuries. The decrease in the mortality series of children 1–5 years old in

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[6]  See Haines (1979, 1998a) on the aggregate series, which is largely inferred from model life tables and also uses the 1900 and 1910 US population censuses on ever-born and surviving children. See Shattuck (1850) on the establishment of the commonwealth's vital statistics collection.

Massachusetts shows similar trends. We present the Massachusetts data that we construct from 1870 to 1930 because the US data begin in 1900. We refer in this paper to the death rate of those less than 5 years old as the child mortality rate (CMR).

Although the Massachusetts IMR series is highly volatile to around 1880, likely because of epidemics, the infant death rate clearly underwent a watershed event in the late 1890s. The rate fell from around 163/1,000 (1 in 6.14) in 1896 to 151/1,000 (1 in 6.62) in 1898 and then to around 91/1,000 (less than 1 in 10) by 1920.[7] To understand the initial period of decline, we focus our analysis of the Massachusetts data from 1880 to 1920. What enabled more babies and children in the commonwealth to escape death?

Several facts from the Massachusetts data provide clues regarding the cause of the initial decline in the mortality of those under 5 years. The first is that there was a decrease in the "urban penalty." The initial decrease was greater in the more urbanized areas of the commonwealth (fig. B1).[8] Another clue is that whatever enabled the youngest members of society to survive apparently had little mortality impact on older individuals. Infants and young children were primarily dying of diarrheal-related illnesses, whereas adults were succumbing mainly to pulmonary tuberculosis.[9]

We focus on a specific group of municipalities that experienced sharp changes to their water supply and sewerage systems. These cities and towns underwent a larger decrease in both CMR and IMR than occurred in the entire commonwealth during our analysis period, 1880–1920. These cities and towns also underwent a larger decrease than in comparable urban areas with no treatment. For example, CMR declined by 62 log points in our full sample of municipalities but by 79 log points in the 15 municipalities that received both treatments, compared with a 53 log point decrease in the sample that received no treatment.[10]

Our answer to what caused the initial decline in child mortality in Massachusetts is the radical change in water and sewage disposal and the protection of watersheds that provided purer water to the greater Boston area. An extensive public water and sewerage project created a large watershed area from which potable water could flow to homes and in which water would be protected from potentially polluting sewage that would be piped and pumped into the Boston Harbor. The area eligible to re-

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[7] The United Nations data (2005–10) on infant mortality list eight nations with a rate exceeding 100/1,000 (all under 127 and in Africa). See http://esa.un.org/unpd/wpp/Excel -Data/mortality.htm.

[8] Preston and Haines (1991) confirm the urban penalty. See also Glaeser (2014).

[9] In figs. B2–B5 we demonstrate the distribution of deaths by age and by broad categories for children under 5 and the seasonality of deaths from all causes.

[10] The unweighted sample is used and a 5-year average of log CMR is used at the start and at the end because of volatility.

ceive pure water contained more than one-third of the state's population at the time but included only cities and towns within a 10-mile radius of the Massachusetts State House in Boston. Even though much of the state was not directly affected by the water project, the commonwealth in 1886 began to protect all inland waterways and to employ water engineers who aided its cities and towns.[11]

## B.  The Creation of the Metropolitan Water
and Sewerage Districts

The Boston Metropolitan District had rapidly increasing population density in the post–Civil War era.[12] The immediate impetus behind the creation of the Metropolitan Sewerage District (MSD) came from complaints among Boston's wealthier citizens about the stench of sewage: "The first of a series of hearings was given by the sewerage commission at the City Hall. . . . It would appear in various parts of the district including most of the finest streets, the stench is terrible, often causing much sickness" (*Boston Medical and Surgical Journal* 1875, 79).

The sewage had two main sources. The direct outfalls from Boston dumped into the harbor: "As early as 1870, an aggregation of old sewers discharged by about seventy outlets into tide water, chiefly along the harbor front" (Metropolitan Sewerage Commission of Boston 1899, 5). The second was that surrounding municipalities discharged into the Mystic, Charles, and Neponset Rivers, which eventually emptied into the harbor. Thus, Boston was the terminus for the region's sewage. A joint engineering and medical commission was appointed in 1875 to devise a remedy.

The report of the 1875 Sewerage of Boston Commission (Chesbrough, Lane, and Folsom 1876) recommended a drainage system for Boston and its surrounding municipalities. Boston city authorities acted and, from 1877 to 1884, constructed a comprehensive system of sewage disposal works that discharged into the deep shipping channels off Moon Island (in Quincy Bay, Boston Harbor). Attention then shifted to sources of pollution beyond its immediate control, namely, the municipalities of the Neponset, Charles, and Mystic River Valleys that constituted the harbor's

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[11] Infant mortality also declined in Europe in the early twentieth century. In England and Wales the rate remained in the 150/1,000 range until around 1900, when it decreased to 130 and then to 100 by 1910. Woods, Watterson, and Woodward (1988, 1989) discuss the roles of clean water and proper sanitation, but not as the major causes.

[12] In 1898 the Metropolitan Sewerage District, with Boston, had 36 percent of the state's population and 55 percent of its total assessed valuation, but just 2.5 percent of its land area. The "district" included 23 towns: Arlington, Belmont, Brookline, Cambridge, Chelsea, Dedham, Everett, Hyde Park (became part of Boston), Lexington, Malden, Medford, Melrose, Milton, Newton, Quincy, Somerville, Stoneham, Wakefield, Waltham, Watertown, Winchester, Winthrop, and Woburn (Metropolitan Sewerage Commission of Boston 1899, 3).

immediate watershed area.[13] But the obvious problems of public works coordination across municipalities complicated the control of sewage.

In 1887, the Boston General Court instructed the State Board of Health to revisit the regional sewerage system for the MSD. The board was authorized to pick the included municipalities and to determine how the sewerage system would be constructed.[14] The report divided the district into separate sewerage systems by geographical features. The 1889 report suggested an additional outfall at Deer Island (near Winthrop in Boston Harbor) draining the northern Charles River Valley and the Mystic River Valley and intercepting sewers connecting the southern portion of the Charles River Valley to the outfall on Moon Island. The court approved recommendations by the board to drain the Neponset River Valley with a separate outfall off Nut Island (in Quincy Bay) in 1895 (fig. 2).

As mentioned above, completion dates were determined mainly by engineering considerations. Unanticipated delays further staggered the rollout. The engineers considered the proximity of the municipalities to the harbor (which was the location of the three major outlets) as well as elevation. A Cox hazard model (table B1) demonstrates that the timing of water and sewerage interventions was strongly affected by geographic features and not influenced significantly by pretreatment demographic characteristics of the municipality. The analysis provides further evidence that technocratic considerations, rather than immediate need, were paramount. The construction teams encountered numerous challenges, including quicksand and boulders, further delaying the completion of specific lines in an idiosyncratic manner.[15]

Coincidental with the construction of a regional sewerage district, Massachusetts took several steps to ensure a safe water supply. The Act Relative to the Pollution of Rivers, Streams and Ponds Used as Sources of

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[13] In addition to the immediate harbor watershed area of the Charles, Mystic, and Neponset River Valleys, the commonwealth paid for sewerage infrastructure in the towns of Clinton and Marlborough. Both are included in our main analytical sample but are dropped and moved to control municipalities in robustness checks (see table 5).

[14] The General Court of Massachusetts resolved that the engineers appointed to the Sewerage Commission were to "designate the cities and towns . . . which shall be tributary to and embraced by the district" and "determine and show, by suitable plans and maps, such trunk lines and main branches as it shall recommend to be constructed, with outlet" (Massachusetts State Board of Health 1889, 3–4).

[15] Timing to sewerage and water are modeled separately since distinct engineering factors affected each. Time to the interaction is difficult to model since many geographic considerations may have differentially affected the infrastructure timing. The Charles River System, begun in May 1890, was completed in spring 1892 despite "difficulties." It was the fastest to complete since it was an extension of the extant Boston system. The North Metropolitan System began the same time as the Charles River System but "was slower in progress and much later in its completion" since it required a new pumping station and other engineering challenges. The Neponset Valley System was mainly completed in 1897. The High-Level System was still in progress in 1899 (Metropolitan Sewerage Commission of Boston 1899, 15).

Fig. 2.—Metropolitan Sewerage District (circa 1899). Source: Metropolitan Sewerage Commission of Boston (1899). The rivers draining into the Boston Harbor (from north to south) include the Mystic, Charles, and Neponset. The red solid lines depict the North and South Metropolitan Districts, the dotted lines to Moon Island trace the trajectory of the Boston sewerage system, and the dotted line from Hyde Park to Nut Island demarcates the High-Level System. The district boundary is given in the map in blue.

Water Supply, passed in 1878, forbade persons and corporations from dumping human excrement or effluent into any pond, river, or stream used as a source of water supply (Secretary of the Commonwealth 1878, 133). But three of the most polluted rivers—the Merrimack, Connecticut, and Concord Rivers—were exempt from the law. They were heavily used by industry, and manufacturers objected to their protection.

In 1886, the General Court extended the State Board of Health oversight of all inland bodies of water and directed the board to offer advice to municipalities on water and sewerage and to employ engineers to aid

the process. The board was reorganized that year, and Hiram Mills, a hydraulic engineer, became chair of the Committee on Water Control and Sewerage. A resident of Lawrence, Mills established the Lawrence Experiment Station to test the filtration of tainted water, the first in the nation. Mills persuaded Lawrence to adopt a sand filter since its water supply was taken from the heavily polluted Merrimack River.[16]

In general, however, the State Board of Health eschewed filtration techniques for water purification, instead preferring that the water be derived from impounding reservoirs in which spring floodwaters were stored. The storage process clarified the water and killed off bacteria, which eventually starved or burst. The distinctive Massachusetts methods for providing pure water would soon be contrasted to those of other cities that, in the early twentieth century, began using the new filtration and chlorination techniques.

Because of the safe water strategy that Massachusetts adopted, population growth posed a serious threat to the water supply because growth inevitably led to encroachment on watersheds. The concern led to the passage of an act by the General Court in 1893 that paved the way for the creation of the Metropolitan Water District (MWD).[17]

In 1895, the Board of Health recommended the creation of reservoirs in Sudbury and Wachusett by taking water from the South Branch of the Nashua River and flooding the town of West Boylston (Whipple 1917). Large aqueducts would bring fresh water to a renovated Chestnut Hill Pumping Station, where it would be distributed through newly constructed iron main lines to municipalities in the MWD (fig. 3). Construction on the waterworks began soon after, and water started to flow to municipalities in January 1898.

Evidence that water quality improved after the intervention comes from a report of the Metropolitan Water Board. Bacteria, fungi, and other parasites were reduced from 351 per cubic centimeter in 1897 before the intervention to 192 per cubic centimeter in 1899.[18] Similar observations came from the Lawrence filter. The average number of bacterial counts per cubic centimeter fell from 10,800 to 110 after filtration in 1894 (*JAMA*

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[16] See Whipple (1917, chap. 4) on the reorganization of the board. Regarding the Lawrence filter, it has been pointed out that "the plans were not furnished by the Board, but by Mr. Hiram F. Mills [who] gave his services to the city and received no compensation for them. . . . He was Chief Engineer of the Essex Company [which] had created Lawrence" (American Society of Civil Engineers 1901, 318).

[17] The act stated, "The State Board of Health is hereby authorized and directed to investigate, consider and report upon the question of a water supply for the city of Boston and its suburbs within a radius of ten miles from the state house, and for such other cities and municipalities as in its opinion should be included in connection therewith" (Secretary of the Commonwealth 1893, 761). Before the establishment of the MWD, many sources (including lakes, ponds, private wells, and reservoirs) supplied water to the municipalities and their residents.

[18] Also, oxygen consumed fell by half during the same period (Sprague 1900, 39).

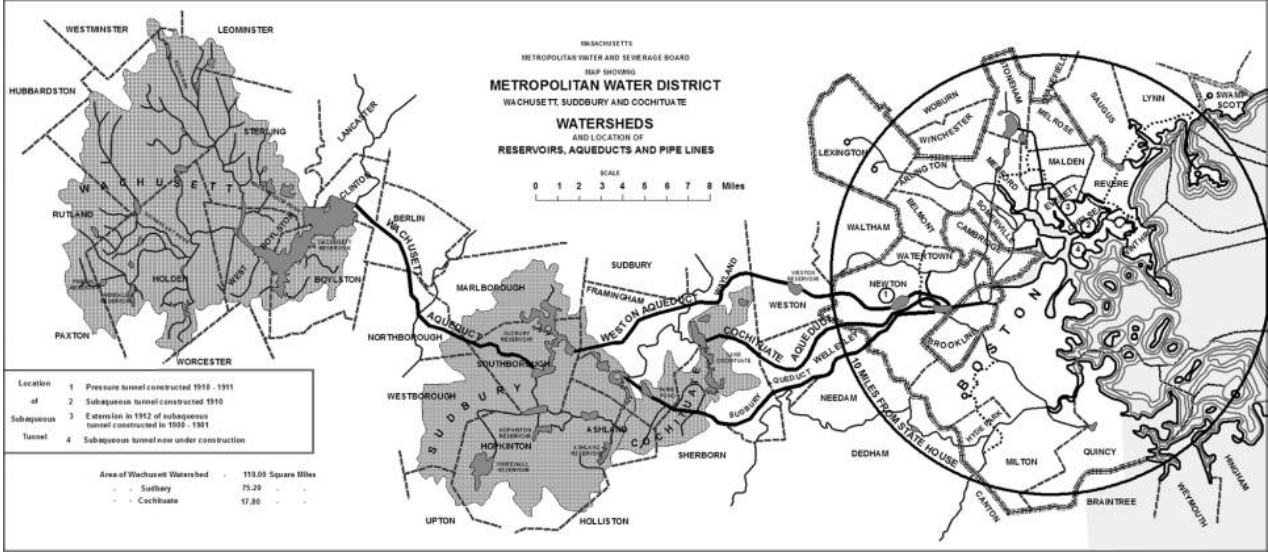Fig. 3.—Metropolitan Water District (circa 1910). Source: Engineering and Contracting (1914, p. 84). The circle gives the 10-mile radius from the State House that defined the eligible municipalities. Aqueducts (dark black lines) and a series of reservoirs (bodies of water labeled as such) were constructed to bring water from the south branch of the Nashua River to communities in and around Boston.

1903). But were these interventions responsible for the initial decline in child mortality in Massachusetts?

## III.    Estimating Equations and Empirical Results

### A.    *Empirical Strategy*

Our empirical analysis exploits the plausibly exogenous timing and geographic penetration of safe water and sewerage interventions. We assume that child mortality in municipalities with differentially timed access to clean water and sewerage would have evolved similarly in the absence of the interventions. The validity of that assumption is assessed below.

We use a difference-in-differences framework to estimate the impact of these interventions on population health. Specifically, we estimate

$$\log(\text{Outcome})_{it} = \alpha + \theta \text{Water}_{it} + \mu \text{Sewerage}_{it} + \gamma(\text{Water} \cdot \text{Sewerage})_{it}$$

$$+ \Omega X_{it} + \delta_t + \pi_i + \pi_i \cdot t_t + \varepsilon_{it}, \tag{1}$$

where $i$ is municipality and $t$ is year. Water and Sewerage are dummy variables indicating if a municipality had adopted the safe water (Water) and/or sewerage (Sewerage) intervention by year $t$. The interaction of safe water and sewerage assesses whether infrastructure investments are complements or substitutes. The coefficients are difference-in-differences estimates of the impact of the interventions on the outcome, and the sum is the combined effect of the interventions, conditional on municipality and time fixed effects, municipality-specific time trends, and a vector ($X$) of time- and municipality-varying demographic controls including (the log of) population density, percentage foreign-born, percentage male, and the percentage of females employed in manufacturing. The latter variable might be important if mothers who work in factories are less likely to breast-feed and if breast-fed infants are less likely to be exposed or succumb to diarrheal illness. In robustness tests, we include county-level time-varying covariates, such as dairy milk quality and a vector of dichotomous county-year fixed effects.

The main outcome of interest is the (log) under-5 mortality rate, although we also explore mortality rates at other ages (under-1, under-2, and over-5) and cause-specific mortality rates. The log outcome is preferred since a linear-in-levels specification constrains the mortality rate to decrease by the same amount each year across municipalities. Standard errors are clustered at the municipality level throughout the analysis since the water and sewerage treatments were at the municipality level. There are 60 clusters in our main analysis sample, and we describe their selection below.

The results from our analysis of equation (1) will show that the combination of safe water and sewage removal was an effective intervention for

reducing child mortality. Each intervention separately had much smaller effects. We augment the main estimating equation by including a series of leads and lags:

$$\log (\text{Outcome})_{it} = \alpha + \sum \theta_k \text{Water}_{ik} + \sum \mu_k \text{Sewerage}_{ik}$$
$$+ \sum \gamma_k (\text{Water}_{ik} \cdot \text{Sewerage}_{ik}) \qquad (2)$$
$$+ \Omega X_{it} + \delta_t + \pi_i + \pi_i \cdot t_t + \varepsilon_{it},$$

where $k$ is event time and spans the entire range of our 41-year analysis period. We group event time into 2-year bins surrounding the year immediately prior to the intervention.[19] That is, we include dummy variables for whether the sewerage, water, or their interaction (meaning both sewerage and water) will take effect in (or have been in effect for) 0–1 year, 2–3 years, and so on. Leads and lags before and after 9 years are coded as separate groups. The 2-year bins improve the precision of the estimates by increasing the number of observations used to estimate the lead and lag coefficients.

The intervention municipalities are represented in both the pre- and postintervention periods, and the analysis period is well balanced in terms of the number of treatment and control observations for all event years except the two extreme tails.[20] The coefficients from equation (2) give the dynamic response to the introduction of safe water and sewerage and their combination.[21]

## B. Intervention Dates and Sources

The dates of water and sewerage interventions are crucial to our empirical strategy. The treatment dates we use are when the main water and sewerage lines were completed for a given municipality rather than when homes and areas were linked to the system. In the case of water, the two

[19] We use the year prior to the connection as our reference period since municipalities were partially treated in the year of the connection. We thank an anonymous referee for the suggestion.
[20] There are 30 observations in each 2-year binned time to both sewerage and water that take the value of one, 50 in time to sewer, and 38 in time to water. Control municipalities (those that do not receive either intervention) are placed at $-1$ event time (i.e., the reference year). There are three observations for which the log of the outcome is missing in a year (Weston, 1904 and 1917, and Nahant, 1898). Weston is a control municipality. Because Nahant is an intervention municipality (and has a small population), we combine Nahant with Swampscott, which is adjacent to it and received the water intervention on the same date.
[21] In fig. B7, panel A, we extend the bins from 10 to 12 years before the intervention and from 10 to 16 years after the intervention, the limit of balanced event time. The patterns are similar to those provided in fig. 5 below, though the estimates, particularly in the earliest years of the analysis period, when smallpox and other vaccine-preventable disease epidemics afflicted various areas of the commonwealth, are noisier.

dates were largely coterminous. But that was not the case for sewerage, which we will also soon discuss. The strategy we use circumvents various endogeneity concerns, and it is supported by our event studies demonstrating that the effects of only water or sewerage did not have significant lagged effects.

We obtained the intervention dates mainly from annual reports of the State Board of Health, the Metropolitan Sewerage Commission, the Metropolitan Water District, and the Metropolitan Water and Sewerage Board.[22] We code a municipality as treated if a main sewerage or water pipe was linked to the municipality from the metropolitan system or if a local innovation was adopted at the request and expense of the Board of Health (see app. table A1 for the dates).[23]

None of our control municipalities is a pure control since attempts were made to improve water and sanitation across the commonwealth. If these efforts were successful, our estimates would be biased toward the null. But we have found limited evidence that water quality was greatly improved elsewhere except for Lawrence, which is part of the treatment group. Another instance was Springfield, which used water from the Ludlow Reservoir until 1910 when the water was deemed low-quality and then switched to using the Little River.[24] Control towns on the Connecticut River struggled to find clean water in other waterways and create reservoirs, but they lacked the coordination provided by the Board of Health in the Boston metropolitan area.

Municipality-level data on births are drawn from annual vital statistics registration reports of births, marriages, and deaths (Secretary of the Commonwealth, 1870–1920).[25] Although the annual reports prior to 1891 included deaths by age category for every municipality, between 1891 and 1897 the data were published at the county level only. But the cost-cutting decision was later reversed, and after 1897, deaths by age were reported for all counties and cities.[26]

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[22] All annual reports are available from Wright & Potter Printing Co., state printer.

[23] We consider three additional local interventions: the 1893 placement of a filter in Lawrence, the permission to take water from sources protected by the MWD (for Worcester in 1903 and Malden in 1904), and financing of sewerage infrastructure in Marlborough and Clinton because their effluent was a contaminant of the municipal water. In the robustness checks, we drop Lawrence, Marlborough, and Clinton. We also add them to the control group in another robustness check. These alternative approaches do not alter our main results.

[24] In robustness checks, we move Springfield to the treatment sample, though the decision to switch sources was endogenous to that municipality.

[25] The commonwealth tried to exclude stillbirths from the counts of births and deaths, but the concept of a stillbirth was ill defined. As late as 1915, the ambiguity was still unresolved: "Apparently, there is no precise definition of a stillbirth which the physicians or midwives are required to observe" (annual report, 18).

[26] Reporting was for incorporated cities with populations exceeding about 12,000 in 1895.

To establish a consistent measure of child mortality for our sample of municipalities during our analysis time period, we created a data set of child deaths from FamilySearch.org, which is a typescript of most information contained in the death records.[27] The same death certificates and death registries at the municipality level are the basis of both the Secretary of the Commonwealth's reports and the FamilySearch.org compilation.[28] The source includes deaths of young children for (almost) every year and for every municipality in our main sample. Stillbirths and early infant deaths were not reliably distinguished.[29] In compiling births, the Secretary of Commonwealth data tried to exclude stillbirths, whereas the FamilySearch.org data do not. To harmonize the two data sources, we chose to include stillbirths in both the numerator and denominator, since the definition was fluid during our period. Therefore, we add stillbirths to the official birth data. To construct the under-5 population, we subtract lagged deaths at infancy and other early ages from lagged births (app. A). In our robustness tests, we normalize under-5 deaths by total population (app. table B4).[30]

We also entered cause of death and grouped causes into major disease categories (such as ailments afflicting the gastrointestinal vs. the respiratory system and tuberculosis). These data allow us to probe whether deaths that, a priori, would be more responsive to sewerage and water interventions because of fecal-oral transmission declined more than deaths from communicable disease transmitted via alternative routes (i.e., respiratory droplets in tuberculosis). Graphs of the category of death data and deaths by age are in figures B2–B5.

Given the importance of clean milk for the health of babies and its role in the literature on IMR, we include data on the fraction of dairies at the municipality level that passed State Board of Health inspection.[31] The policy to inspect dairies and their milk started in 1905 and lasted until 1914, when the inspection authority devolved to the municipality level. For Suffolk County, milk was transported by refrigerated trains and tested for bacteria on arrival, in transit, and at stores. We define the milk market

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[27] Appendix C contains the search algorithm and the correlation between death rates from the vital registration reports and FamilySearch.org when overlap exists. In the handful of instances in which pages from registration pages were missing from FamilySearch.org, we checked Ancestry.org and occasionally could fill in missing values.

[28] Our definition of an infant death is that the death and birth years are the same. FamilySearch.org data list an infant death with the actual death date but give the birth year as the same as the death year if the infant was less than 1 year at death, even if the infant was born in the previous year. Therefore, we use the year at death, not birth.

[29] The concept of a live birth evolved over time. The common practice for our period was to count deaths of preterm fetuses as miscarriages and of fetuses more than 7 months' gestation as stillbirths. Many infant deaths that were categorized as stillbirths would have been live births that died during delivery.

[30] Results are also robust to normalizing under-5 deaths by total births.

[31] Data are mainly from 1905–14 annual reports of the State Board of Health. We also used the 1905–15 reports from the Health Department of the City of Boston.

at the county level and define milk purity as the percentage of dairies that passed inspection and the percentage of tested milk relatively free from bacteria.

The impact of lead water pipe materials, shown to be of importance to IMR in Clay, Troesken, and Haines (2014), is incorporated by using a cross section from 1897 of pipe materials by municipality.[32] Time-varying demographic features of municipalities, such as the percentage foreign-born, age and sex distribution, and percentage of females employed in manufacturing, are obtained from state and federal censuses, linearly interpolated every 5 years between censuses (app. A).

Our main sample is a panel of 60 commonwealth municipalities (excluding Boston) from 1880 to 1920. The sample contains all municipalities within the immediate harbor watershed area (about 12.5 miles from the Massachusetts State House) as well as municipalities outside the immediate Boston area that were incorporated cities as of 1895.[33] To this list, we add two coastal municipalities (Ipswich and Weymouth) and five (Attleboro, Clinton, Milford, Natick, and Peabody) with the largest 1880 populations among those that did not meet the other criteria.

In figure 4 we shade municipalities in the Boston metropolitan area by whether they received water (hatched), sewerage (cross-hatched), both (gray), or neither (white). Control municipalities are all in the commonwealth since Massachusetts was unique in its early collection of detailed birth and death records. Moreover, all municipalities in the commonwealth were exposed to other statewide Board of Health regulations, mentioned previously, that protected inland water.

## C. Results

### 1. Main Results

We first test whether there were preexisting differences in infant and child mortality, as well as other demographic variables, between municipalities that would eventually receive a safe water and sewerage treatment and those that would not. That is, we examine whether eventual participation in safe water, sewerage, or both interventions is correlated with covariates in 1880 and changes in our mortality measures of interest before the interventions were formally announced.[34] Table 1 presents these results.

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[32] Because time-varying data on lead pipes are not available, we test the robustness of our results to the inclusion of lead pipe status as of 1897. We find few differences.

[33] All sample municipalities are in Massachusetts because of its early vital statistics records. The Boston metropolitan area is frequently described as including all municipalities within 10 miles of the State House, but the sewerage district extended to those as far as 12.5 miles.

[34] This method is a reasonable way to assess baseline differences between groups, but it may not be fully consistent with the definitions of treatment and control that we exploit
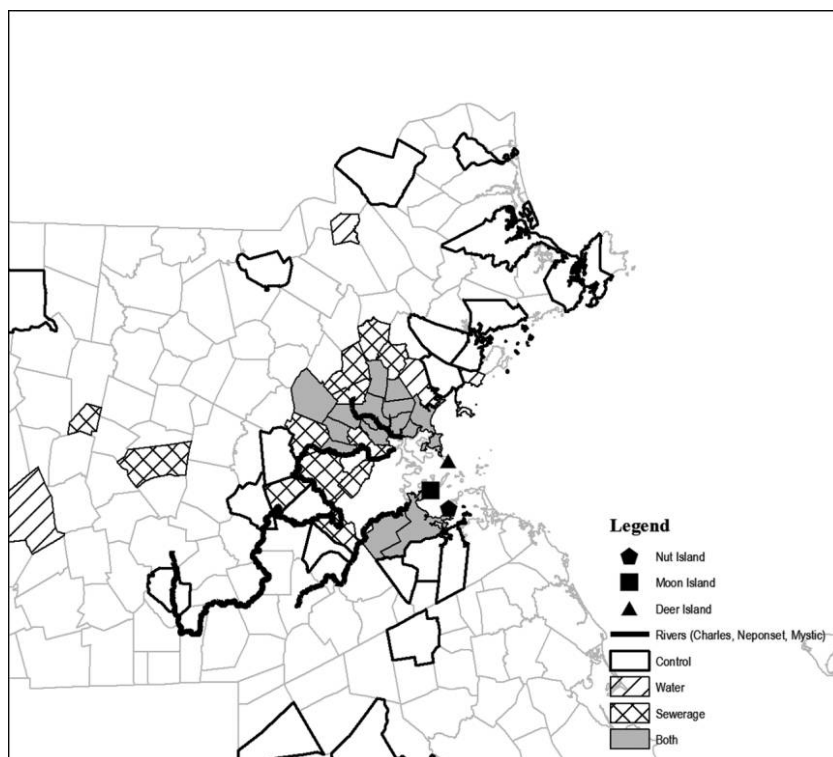
Fig. 4.—Safe water and sewerage treatments in the Boston metropolitan area

Column 1 of table 1 gives the mean health and demographic characteristics across the main sample. Column 2 presents differences between municipalities that improved water without the sewerage treatment and those that did neither. Column 3 repeats the exercise for sewerage, and column 4 gives the difference between municipalities that received both treatments versus neither. Columns 5–7 give differences between the treatment groups.

The results from rows 1–8 demonstrate that there are few highly significant baseline differences in demographics, the number of neighboring municipalities, and infant and child mortality across the intervention groups in 1880. Because some of the cities and towns outside the Boston metropolitan area were manufacturing hubs, the percentage of women

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since the regressions utilize both geographic and time variation in the rollout of the interventions. Nevertheless, large differences between the groups at baseline or in the years leading up to the interventions would be of concern. Two control municipalities (Westwood and Wellesley) were incorporated as towns shortly after 1880 and are therefore not in our baseline period.

TABLE 1
Baseline Municipality Characteristics and Trends in Outcome Variables

| | | Relative to No Intervention | | | | | |
| | All (1) | Safe Water Only (2) | Sewerage Only (3) | Both Interventions (4) | Difference (2 − 3) (5) | Difference (2 − 4) (6) | Difference (3 − 4) (7) |
| Characteristic | | | | | | | |
|---|---|---|---|---|---|---|---|
| Percentage foreign-born | 24.019 | 2.074 | 4.150* | −1.185 | −2.076 | 3.258 | 5.334*** |
| | [8.236] | (6.344) | (2.324) | (2.157) | (6.229) | (6.168) | (1.789) |
| Percentage male | 47.924 | −.320 | −.835 | .210 | .516 | −.529 | −1.045 |
| | [2.017] | (.906) | (.849) | (.620) | (1.125) | (.964) | (.910) |
| Log population density | .108 | .689 | .563* | .437 | .126 | .252 | .126 |
| | [.939] | (.606) | (.285) | (.326) | (.634) | (.654) | (.375) |
| Percentage female in manufacturing | 9.864 | 1.721 | −2.466 | −7.641*** | 4.187 | 9.362* | 5.175* |
| | [7.831] | (5.456) | (3.013) | (1.721) | (5.899) | (5.356) | (2.828) |
| Percentage female illiterate | 5.309 | −1.087 | .217 | −1.391 | −1.304 | .304 | 1.608* |
| | [3.448] | (1.502) | (1.068) | (.982) | (1.435) | (1.373) | (.877) |
| No. neighboring municipalities | 5.345 | −.483 | −.083 | −.349 | −.400 | −.133 | .267 |
| | [1.528] | (1.132) | (.499) | (.513) | (1.177) | (1.182) | (.605) |
| Log infant mortality rate | 4.974 | −.310 | −.134 | .029 | −.175 | −.339 | −.164* |
| | [.386] | (.330) | (.109) | (.103) | (.329) | (.327) | (.097) |
| Log under-5 mortality rate | 4.067 | −.055 | −.112 | .077 | .057 | −.131 | −.189* |
| | [.450] | (.281) | (.120) | (.135) | (.268) | (.275) | (.106) |
| Change in log infant mortality (1880–89) | .151 | .347 | −.014 | .004 | .361 | .343 | −.018 |
| | [.429] | (.234) | (.164) | (.133) | (.262) | (.243) | (.178) |
| Change in log under-5 mortality (1880–89) | .012 | .297 | .068 | .091 | .229 | .206 | −.024 |
| | [.418] | (.225) | (.138) | (.120) | (.229) | (.219) | (.126) |

Note.—Col. 1, rows 1–8, report average values for municipalities in 1880 with standard deviations in brackets. Cols. 2, 3, and 4 report coefficients from a single regression of the indicated characteristic on an indicator variable for eventual participation in sewerage, safe water, or both interventions. This categorization of the treatment differs from that in the regression analysis because the regression exploits variation across space and time, whereas this table gives the ex post treatment. The final two rows report coefficients for a similar regression, of the change in log infant mortality or child mortality between 1880 and 1889, the year of the report on the MSD put forth by the State Board of Health as legislated in 1887, on only water, only sewerage, or both in cols. 1–4. Standard deviations are in brackets. Robust standard errors are in parentheses.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

employed in manufacturing was generally lower in the municipalities that received infrastructure interventions (table 1, row 4) and the percentage foreign was 5.3 percentage points higher in municipalities that received only sewerage versus those that received both in the first year of the analysis (27.6 vs. 22.3 percent). However, directly adding the percentage of females working in manufacturing or the percentage foreign-born as a control or dropping the untreated group from the analysis (thus using only variation in the timing of interventions) does not significantly change our estimates, suggesting that baseline differences do not bias our results.

In the last two rows, we assess for differences in infant and child mortality rates between groups of municipalities that eventually received one or more interventions using data from 1880 and 1889, the year the State Board of Health issued its report on a sewerage system for the Charles and Mystic River Valleys. Note that in the 9 years prior to the interventions, the change in mortality rates was modest. In addition, whether a municipality eventually received safe water, sewerage, or both is not significantly correlated with the changing mortality pattern of young children prior to when the interventions were rolled out.

Our baseline estimates of the impact of the sewerage and water interventions, from estimating equation (1), are presented in table 2, panel A, for the 60 control and treatment cities and towns. The regressions are unweighted and contain municipality and year fixed effects, as well as municipality-specific linear trends and demographic controls, in every specification. By not weighting we are considering each city or town to be a separate experiment. We prefer this approach and directly model heterogeneity by population growth, a potential contaminant for the watershed areas (see table 3, panel B).

Columns 1 and 2 test whether the water or sewerage intervention had a significant impact on child mortality. These regressions provide estimates of the impact of one of the interventions neglecting the role of the other. The results suggest that the introduction of water (ignoring the role of sewerage) reduced child mortality by 12.6 log points and the introduction of sewerage (ignoring the role of water) reduced it by 12.3 log points. In column 3 we include both safe water and sewerage. Each estimate has the expected sign, but only sewerage is significant. Sewerage and water (in col. 4) taken together are economically and statistically significant. These regressions do not include the separate main effects and thereby consider the full treatment as the combination of sewerage and safe water (as in a fixed proportions production function).

We next test whether the two interventions are complements or substitutes by adding the interaction of the two in column 5. By including the main effects with the interaction term, the coefficient on water identifies the effect of having only water (similarly only sewerage), whereas the interaction tests if the two are complements or substitutes. The sum of the

TABLE 2
THE EFFECT OF SAFE WATER AND SEWERAGE ON CHILD MORTALITY

| | A. OUTCOME IS LOG CHILD MORTALITY RATE, MAIN SPECIFICATION | | | | | B. OUTCOME OR SPECIFICATION VARIES | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | | | | | Log Child Mortality | Child Mortality | | |
| | | | | | | County-Year Fixed Effects | Count Model | Weighted | Unweighted |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| Safe water | −.126 | | −.101 | | .109 | .119 | .089 | 1.497 | 5.571 |
| | (.080) | | (.078) | | (.079) | (.083) | (.055) | (3.243) | (4.258) |
| Sewerage | | −.123** | −.106** | | −.067 | −.073 | −.039 | −2.403 | −4.037 |
| | | (.047) | (.045) | | (.046) | (.062) | (.040) | (2.227) | (2.748) |
| Interaction of safe water and sewerage | | | | −.238*** | −.307*** | −.298*** | −.199** | −1.006 | −13.498** |
| | | | | (.081) | (.106) | (.111) | (.079) | (3.253) | (5.102) |
| Safe water + sewerage + interaction | | | | | −.266*** | −.252** | −.149** | −1.911 | −11.963*** |
| | | | | | $p = .006$ | $p = .025$ | $p = .029$ | $p = .581$ | $p = .008$ |
| Observations | 2,438 | 2,438 | 2,438 | 2,438 | 2,438 | 2,438 | 2,440 | 2,440 | 2,440 |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | County-Year | Yes | Yes | Yes |
| Municipality fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Demographics | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality-linear trends | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Adjusted $R^2$ | .655 | .656 | .656 | .658 | .658 | .642 | .144 | .789 | .663 |
| No. clusters | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |

NOTE.—OLS estimates of eq. (1) are shown except for col. 7, which reports coefficients from a negative binomial model. The sample spans 1880–1920 and includes 60 municipalities (Swampscott and Nahant are combined). The dependent variable is the log of the child mortality rate (in panel A), the number of child deaths (in col. 7 of panel B), and the child mortality rate (in cols. 8 and 9 of panel B). Safe water is an indicator variable equal to one during the year when municipal water or a water filter (in the case of Lawrence) was introduced. Sewerage is an indicator variable that equals one in the year a municipality was connected to the MSD or had a sewerage system financed by the commonwealth (in the case of Marlborough and Clinton). The interaction is an indicator variable that equals one in the first year both interventions are provided to a municipality. The $p$-value associated with the combination of the estimated effects of water, sewerage, and their interaction is shown below it. Demographic controls include percentage of the population that is foreign-born, percentage male, percentage females in manufacturing, and the log of population density.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

difference-in-differences coefficients reflects the full effect of implementing water and sewerage interventions.

Our evidence points to a strong complementarity between the two interventions and indicates that their combined effect reduced child mortality by 26.6 log points (and that much of the reduction is driven by the interaction term).[35] In table B2, we repeat the analysis focusing exclusively on infant and under-2 mortality. The results obtained are similar.[36]

Figure 5 uses equation (2) to map out the dynamic response to the introduction of the combination of the safe water and sewerage interventions. Panel A plots coefficients from a single regression. The outcome variable is the log of the child mortality rate. The graph on the left plots the event study coefficients on water, the middle graph plots sewerage coefficients, and that on the right plots the full effect of the interventions by adding together the coefficients on water, sewerage, and the interaction. Panel B also plots the total combined effect of the interventions for three different outcomes: the graph on the left plots the event study coefficients for (log) seasonal mortality (spring and summer), the middle plots the same for (log) gastrointestinal mortality, and the graph on the right plots the coefficients for a placebo outcome, the (log) mortality rate for those 5 years and older.[37]

All six of the event studies demonstrate that in the years preceding the intervention, conditions were neither systematically getting worse nor getting better. Comparing across the event studies in panel A demonstrates that water alone did not have an appreciable effect on child mortality, sewerage had a small effect, and the combination produced a rapid decline. The set of figures also weakens the notion that a lagged effect of sewerage or water could be driving the main results. The results in panel B indicate that the combination of interventions led to an immediate and persistent decrease in gastrointestinal and spring-summer mortality. The effects, moreover, increased with time, probably as a result of the spread of sewerage connections within the treated municipalities. The connection to safe water was more immediate.

[35] Our preferred estimation includes linear trends. We also report robustness to dropping such trends in table B3 and map out the dynamic response without trends in fig. B7, panel B. Adding the main effects to the interaction in col. 5 does not change the coefficient on the interaction significantly but does alter the main effects (without significantly increasing their standard errors). We interpret this as evidence that the interaction is the primary driver of the mortality reductions, though we would caution against the interpretation that the main interventions held no individual benefits, since even the "control" municipalities in our sample were receiving advice on water use and sewage control from the State Board of Health and there is some evidence that sewage control alone is important for child survival.

[36] The standard error of the combined effect increases somewhat.

[37] Twenty-one additional event studies are included in app. B: fig. B6 includes category-specific outcomes (seasonal and gastrointestinal mortality among under-5 children), mortality at other ages, and the placebo outcome of nonchild mortality. Figure B7, panel A, includes additional lead and lag periods, and panel B omits municipality linear trends.

**Panel A: Outcome is Log Child Mortality**



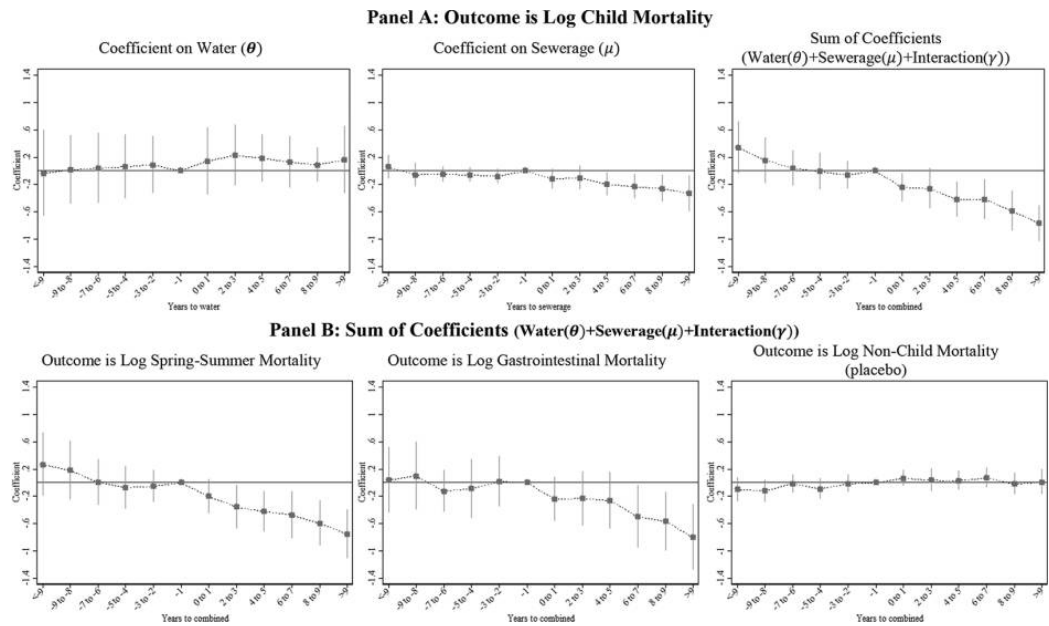**Panel B: Sum of Coefficients** (Water($\theta$)+Sewerage($\mu$)+Interaction($\gamma$))



FIG. 5.—Event studies of the effect of sewerage, water, and their combination on mortality by age and category of death. OLS estimates of equation (2) and their 95 percent confidence intervals are given. Panel A plots coefficients from one regression with the outcome log of child mortality, which includes the deaths of infants and young children [1, 5) years of age per 1,000 under-5 population. Reading from left to right are the coefficients on water ($\theta_k$), the coefficients on sewerage ($\mu_k$), and the sum of coefficients: Water ($\theta$) + Sewerage ($\mu$) + Interaction ($\gamma$). Plotted in panel B are the sum of coefficients: Water ($\theta$) + Sewerage ($\mu$) + Interaction ($\gamma$) using three different outcome variables (i.e., three different regressions): the log of the child mortality rate during the spring and summer, which is deaths during the months of April to September per 1,000 under-5 population; the log of the child mortality rate from gastrointestinal disease; and the log of the nonchild mortality, which is deaths of those 5 and above per 1,000 relevant population. See appendix A (variable definitions) and the text for further details. Standard errors are clustered at the municipality level.

Each of the municipalities was required to own its water pipes before the water intervention.[38] When the new source was available, water could immediately flow into residences. In fact, after the water was available the Metropolitan Water Board was alarmed by what they saw as rampant wastage, and their concern prompted the installation of water meters. Regarding sewerage, however, after the main trunk lines were connected to the outfalls in the harbor, branching lines within the municipality and some separate residences had to be connected. Although there was an immediate jump in the miles of local sewerage connected to the district (fig. B8), connections continued to increase as more neighborhoods were "drained." The need for connections within municipalities could account for the increased beneficial effect of the sewerage and combined treatment with time.

Thus, the time pattern of change we show in figure 5 accords well with the historical information about the safe water and sewerage projects and with the time course of disease. Since diarrhea is an acute disease, interventions that protect children from transmission should translate into a swift decline in mortality.

In table 2, panel B, we report results obtained using variations in our baseline specification. These alternative specifications vary by column heading. We assess the robustness of our results to county-year fixed effects (col. 6), the use of a count model (col. 7), and a linear-in-levels model specification both weighted (col. 8) and unweighted (col. 9). The results presented in panel B are generally consistent with those reported in panel A and demonstrate the failure of a piecemeal approach to infrastructure improvements. Weighting by the under-5 population attenuates our results; though as we show in table 3, this is likely due to smaller municipalities with higher population growth rates benefiting more from the combination of interventions.[39]

## 2.   Channels

How were young children affected by potentially contaminated water, and why did they benefit so greatly from both safe water and sewerage interventions? Most babies were not exclusively breast-fed throughout but were, instead, often fed a gruel that contained water, as were toddlers. Detailed information on breast-feeding practices from the extensive Children's Bureau Bulletins of the late 1910s and early 1920s shows that around half of all surviving infants were exclusively breast-fed at 6 months, about

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[38]  By law, municipalities had to own their water pipes, or purchase them from private providers if they did not already own them, to receive water from the MWD.

[39]  In addition, weighting by population can cause a populous outlier municipality to have undue influence on the results. See fig. B9.

a quarter were wholly bottle-fed at 6 months, and the rest were nurtured by a combination of the two methods (US Department of Labor, Children's Bureau 1923).[40] Women in low-income families who worked outside the home were less likely to breast-feed, although differences in breast-feeding practices by family income were not large. Furthermore, some women were not able to breast-feed independent of family income.

Even for women who did breast-feed, it was a common practice, later condoned and recommended by the Children's Bureau, to feed infants water. The advice often came with the admonition to boil water, but that was not always the case. "When the baby cries between feedings [at the breast] give him pure, warmed water without anything in it. Then let him alone" (US Department of Labor, Children's Bureau 1914, 50).[41] Even if babies were not deliberately given water, they were bathed in water that may have been polluted. Finally, flies landing on feces could have spread disease to milk or gruel that was fed to young children.

Evidence presented in table 3 on deaths by season and disease category bolsters the claim that the water and sewerage interventions greatly reduced gastrointestinal disease and improved the survival of children. The table begins with seasonal mortality since the prevalence of gastrointestinal disease increases in warmer months because of spoilage and flies, and the mortality rate conditional on infection rises as children more easily succumb to dehydration.[42] We find that the full effect of water and sewerage reduced deaths during the warmer months by 6.7 per 1,000 under-5 population as compared to fall-winter mortality by 5.1 per 1,000 under-5 population. In columns 3 and 4 we find that the full effect was greater for gastrointestinal mortality (4.4 per 1,000) than for respiratory mortality exclusive of tuberculosis (1.8 per 1,000).

In columns 5 and 6 we find no significant effect of the interventions on tuberculosis or on the nonchild mortality rate. Tuberculosis is generally transmitted through airborne droplets and should be less affected by water and sewerage interventions, though contaminated dairy products might have played a role in transmission during this period. Given that

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[40] See Apple (1997, table 9.1). Because babies who were not exclusively breast-fed died at higher rates than those who were, the fraction of survivors breast-fed at 6 months overstates the fraction breast-fed had none died. The Children's Bureau surveys were done in the late 1910s, but the sources in Apple (1997) and Wolf (2001) reveal similar breast-feeding percentages for earlier decades. Among the reasons offered by Wolf (p. 10) for low breast-feeding rates is that American women began to rely on artificial formulas before inexpensive ones were marketed. Although the reasons offered are not fully satisfactory, the decline of breast-feeding seems sound.

[41] Also, "Feed the baby one part milk and two parts water during the first month. . . . During the second and third months use one part milk and one part water. . . . After the fourth month give two parts milk and one part water" (US Department of Labor, Children's Bureau 1914, 51).

[42] We revert to a level specification since some of the categories (i.e., tuberculosis among children) have few deaths.

TABLE 3
THE EFFECT OF SAFE WATER AND SEWERAGE ON SPECIFIC CATEGORIES OF DEATH AND HETEROGENEOUS EFFECTS

| | A. CATEGORY OF DEATH | | | | | |
|---|---|---|---|---|---|---|
| | Spring-Summer (1) | Fall-Winter (2) | Gastrointestinal (3) | Respiratory (4) | Tuberculosis (5) | Nonchild Mortality Rate (6) |
| Safe water | 3.542 | 2.413 | 1.193 | 1.045 | .136 | −.021 |
| | (2.569) | (1.885) | (.783) | (.829) | (.527) | (.445) |
| Sewerage | −1.965 | −1.475 | −1.709 | .407 | −.195 | .346 |
| | (1.964) | (.983) | (1.241) | (.529) | (.308) | (.299) |
| Interaction of safe water and sewerage | −8.249** | −6.053*** | −3.883*** | −3.208*** | −.348 | .504 |
| | (3.088) | (2.229) | (1.158) | (1.056) | (.634) | (.574) |
| Safe water + sewerage + interaction | −6.672** | −5.114*** | −4.399*** | −1.756* | −.407 | .828 |
| | $p = .021$ | $p = .005$ | $p = .001$ | $p = .052$ | $p = .527$ | $p = .144$ |
| Observations | 2,440 | 2,440 | 2,440 | 2,440 | 2,440 | 2,440 |
| Adjusted $R^2$ | .651 | .449 | .631 | .324 | .233 | .616 |
| No. clusters | 60 | 60 | 60 | 60 | 60 | 60 |

|  | B. Heterogeneous Effects | | | | | |
|---|---|---|---|---|---|---|
|  | >50th Percentile Population Growth Rate (1880–1920) (1) | ≤50th Percentile Population Growth Rate (1880–1920) (2) | >50th Percentile British (1880) (3) | ≤50th Percentile British (1880) (4) | >50th Percentile Irish (1880) (5) | ≤50th Percentile Irish (1880) (6) |
| Safe water | .172 | .051 | .156 | .015 | .174** | .130 |
|  | (.106) | (.045) | (.093) | (.041) | (.083) | (.082) |
| Sewerage | −.028 | −.059 | −.029 | −.083 | −.027 | −.094 |
|  | (.067) | (.062) | (.057) | (.059) | (.055) | (.056) |
| Interaction of safe water and sewerage | −.348** | −.175 | −.285** | −.323** | −.502*** | −.184* |
|  | (.134) | (.197) | (.126) | (.134) | (.150) | (.093) |
| Safe water + sewerage + interaction | −.203* | −.183 | −.158 | −.391*** | −.355** | −.148 |
|  | $p = .065$ | $p = .399$ | $p = .187$ | $p = .002$ | $p = .010$ | $p = .146$ |
| Observations | 1,189 | 1,187 | 1,187 | 1,189 | 1,189 | 1,187 |
| Adjusted $R^2$ | .710 | .623 | .697 | .630 | .611 | .711 |
| No. clusters | 29 | 29 | 29 | 29 | 29 | 29 |

Note.—OLS estimates of eq. (1). The sample is unbalanced spanning the years 1880–1920 and includes the 60 sample municipalities when feasible. The dependent variables for panel A are category- and age-specific mortality rates: col. 1: spring-summer = child mortality rate constructed from deaths during the months of April to September; col 2: fall-winter = child mortality constructed from deaths during the months October to March; col. 3: gastrointestinal = child mortality from diseases that are associated with the gastrointestinal tract and/or are transmitted by fecal-oral route; col. 4: respiratory = child mortality from diseases that affect the lungs, exclusive of tuberculosis; col. 5: tuberculosis = child mortality from tuberculosis in all forms; and col. 6: nonchild mortality rate (over-5 mortality). For precise definitions and data sources, see app. A. The dependent variable for panel B is the log of the child mortality rate. The sample is described at the top of the column heading, with ≥50th percentile Irish denoting municipalities in the top 50th percentile of the percentage foreign who are Irish-born, in the baseline year of 1880. Other columns are defined similarly. Safe water is an indicator variable equal to one during the year in which municipal water or a water filter (in the case of Lawrence) was introduced. Sewerage is an indicator variable that equals one in the year a municipality was connected to the MSD or had a sewerage system built for it by the commonwealth (in the case of Marlborough and Clinton). The interaction is an indicator variable that equals one in the first year both interventions are provided to a municipality. Demographic controls included in every regression include percentage of the population that is foreign-born, percentage male, percentage females in manufacturing, and log population density. Also included are municipality and year fixed effects and municipality-specific linear trends. Standard errors are clustered at the municipality level.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

the overwhelming cause of death for adults at the time was pulmonary tuberculosis, we view these findings as supportive of the notion that safe water and sewerage interventions improved child survival by greatly reducing deaths from diseases affecting the gastrointestinal system.

## 3. Heterogeneous Effects

We investigate whether the impact of the infrastructure improvements depended on the percentage of foreign-born by municipality. We divide municipalities by the median percentage of various demographic groups in 1880 (the last US census before the interventions). Using the period prior to interventions obviates concerns about endogenous migration response to the interventions (though table 4 fails to demonstrate any significant migration response).

Our findings, presented in table 3, panel B, demonstrate that the full effects of water and sewerage had a significant effect on the mortality of children in certain municipalities. As alluded to above in the discussion of weighting, we find that effects of the interventions are largest and statistically significant only for municipalities that experienced the most rapid population growth during the analysis period (cols. 1 and 2). Municipalities with more foreign-born residents, especially those who lived in crowded and squalid conditions, would have had the most to gain from sewage removal and clean water interventions. But political economy considerations could have led the foreign-born enclaves to be excluded from the expansion of sewerage connections. But when we decompose the foreign population by major ethnic groups, we find that sewerage and water combined led to a 35.5 log point decline in child mortality for municipalities with more Irish-born inhabitants. These effects are much larger than are those for places with more foreign-born of British descent (full effect of 15.8 log points) and larger than places with fewer Irish, suggesting that a socially and economically marginalized group in the Boston area gained disproportionately from the public health investments.

We have presented evidence bolstering the notion that clean water and sewerage interventions together greatly reduced child mortality. But could the interventions have not directly improved health but, instead, changed the composition of the population? Higher-income persons and the health-conscious could have migrated to less odiferous and clean water places.

To examine the possibility of a composition effect we modify equation (1) and replace mortality rates with the percentage of the population that meets some demographic criteria. The analysis, given in table 4, columns 1–6, is estimated on a limited sample because of the availability of the dependent variable only in the quinquennial state and decennial federal censuses. Nevertheless, the results point in the direction that

TABLE 4
THE EFFECT OF SAFE WATER AND SANITATION ON THE COMPOSITION AND DEMOGRAPHIC FEATURES OF THE MUNICIPALITY

| | Percentage Foreign (1) | Percentage Male (2) | Percentage Females in Manufacturing (3) | Percentage Females Illiterate (4) | Percentage British (5) | Percentage Irish (6) | Log Total Population (7) | Log Total Births (8) | Log Foreign Births (9) |
|---|---|---|---|---|---|---|---|---|---|
| Safe water | −.020 | −.158 | −.256 | .104 | .390 | −.055 | .030 | .021 | .040 |
| | (.752) | (.753) | (.682) | (.432) | (.298) | (.399) | (.037) | (.039) | (.064) |
| Sewerage | .749 | −.450 | .541 | −.248 | −.011 | .753** | .070 | .048* | .070 |
| | (1.024) | (.577) | (.340) | (.269) | (.147) | (.319) | (.043) | (.027) | (.055) |
| Interaction of safe water and sewerage | −.667 | −.570 | .202 | .200 | −.188 | −.377 | −.051 | −.027 | −.041 |
| | (1.013) | (.835) | (.646) | (.524) | (.312) | (.436) | (.040) | (.053) | (.079) |
| Safe water + sewerage + interaction | .062 | −1.178 | .487 | .055 | .192 | .321 | .050 | .043 | .068 |
| | $p = .970$ | $p = .131$ | $p = .286$ | $p = .882$ | $p = .337$ | $p = .267$ | $p = .333$ | $p = .333$ | $p = .383$ |
| Observations | 535 | 535 | 535 | 535 | 535 | 535 | 535 | 2,440 | 2,440 |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Demographics | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality-linear trends | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Adjusted $R^2$ | .878 | .643 | .975 | .928 | .967 | .982 | .992 | .990 | .982 |
| No. clusters | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |

NOTE.—OLS estimates of eq. (1). The sample is unbalanced spanning 1880–1920 and includes the 60 sample municipalities. Each column is a separate regression with a different outcome variable. The outcome variables listed under the column numbers are derived from the Mass. and US censuses as described in app. A. Safe water is an indicator variable equal to one during the year in which municipal water or a water filter (in the case of Lawrence) was introduced. Sewerage is an indicator variable that equals one in the year a municipality was connected to the MSD or had a sewerage system built for it by the commonwealth (in the case of Marlborough and Clinton). The interaction represents an indicator variable that equals one in the first year both interventions are provided to a municipality simultaneously. Demographic control variables (percentage foreign-born, percentage male, percentage females in manufacturing, and log population density) exclude the outcome variable when applicable. Standard errors are clustered at the municipality level.

\* $p < .1$.
\*\* $p < .05$.
\*\*\* $p < .01$.

compositional changes are not a major explanation for our findings. An unusual exception is the positive correlation between the variation in the sewerage intervention and the percentage of Irish.

Another possibility is that changes in child mortality led to a decline in fertility or to migration. But we find no migration response to the interventions (col. 7). At the annual level, there does not appear to have been an immediate fertility response to the combination of the interventions in the general population (table 4, col. 8), consistent with a fairly stable fertility rate for the period (Haines 1998b).[43] There is, moreover, no statistically significant correlation between foreign births and the rollout of the interventions (col. 9).

## 4. Robustness

We assess the robustness of our results in table 5 and table B3 to adding further time-varying municipality-level controls, using different samples, changing the mode of statistical inference, and removing or adding various trends. We begin, in table 5, column 1, by adding a proxy for milk supply quality at the county level. Milk quality is measured imprecisely and does not reach statistical significance. In column 2 we control for the percentage of females who were illiterate since maternal education is known to be a strong predictor of child survival. But inclusion of the variable does not change the relevant point estimates.[44]

We also assess whether our results are driven by externalities among municipalities by including the share of neighboring municipalities with either sewerage or water interventions (those with both contribute to each separately). We find that controlling for spillover effects has no meaningful impact on the main results concerning the impact of pure water and sewerage for a given municipality.[45]

We next check the robustness of our results to varying the sample in ways that are meaningful to how it was selected. In column 4 we use only municipalities that eventually received at least one intervention, thus exploiting variation in time to the intervention only. The estimate of the combined effect is almost identical to that for the full sample, though with a

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[43] Infant survival and fertility are negatively correlated in developing countries today. Haines (1998b) notes that fertility in Massachusetts "had leveled off by the 1870s whereas the infant mortality rate did not commence its decline until the 1890s . . . but the birth rate then remained quite stable from the 1890s until the early 1920s, at which point fertility recommenced its decline until 1960" (238).

[44] Literacy is a poor predictor since most people had basic literacy in some language.

[45] In addition, we examined whether the combination of interventions by municipality is picking up the effect of upstream sewerage interventions. We find the combined effect in this specification (not shown) to be of similar magnitude (−0.250; standard error 0.098). We thank an anonymous referee for the suggestion.

TABLE 5
THE EFFECT OF SAFE WATER AND SEWERAGE ON LOG CHILD MORTALITY (Robustness)

| | Dairy Quality (1) | Female Literacy (2) | Externalities (3) | Treated Only (4) | Drop 3 Municipalities (5) | Move 3 Municipalities to Controls (6) | Move Springfield to Treated (7) |
|---|---|---|---|---|---|---|---|
| Safe water | .109 | .110 | .086 | .106 | .123 | .129 | .124* |
| | (.080) | (.085) | (.086) | (.103) | (.102) | (.101) | (.067) |
| Sewerage | −.066 | −.075 | −.100 | −.080 | −.048 | −.045 | −.068 |
| | (.045) | (.046) | (.061) | (.069) | (.049) | (.048) | (.045) |
| Interaction of safe water and sewerage | −.307*** | −.303*** | −.328** | −.297** | −.334*** | −.334*** | −.322*** |
| | (.106) | (.112) | (.129) | (.114) | (.121) | (.121) | (.102) |
| Safe water + sewerage + interaction | −.264*** | −.267*** | −.343*** | −.271* | −.259*** | −.250*** | −.265*** |
| | $p = .006$ | $p = .006$ | $p = .003$ | $p = .070$ | $p = .009$ | $p = .010$ | $p = .006$ |
| Observations | 2,438 | 2,438 | 2,438 | 1,269 | 2,315 | 2,438 | 2,438 |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Demographics | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality-linear trends | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| No. clusters | 60 | 60 | 60 | 31 | 57 | 60 | 60 |

NOTE.—OLS estimates of eq. (1). Each column is a separate regression. The sample specification varies across columns. Col. 1 adds the percentage of dairy milk at the county level that is high-quality (see app. A); col. 2 adds the percentage of females illiterate; col. 3 adds controls for the percentage of neighbors with sewerage or water or both; col. 4 limits the sample to only those municipalities that eventually received an intervention; col. 5 drops three municipalities: Lawrence (which had a filter) and Clinton and Marlborough (which had sewerage systems financed by the commonwealth); col. 6 treats Clinton, Marlborough, and Lawrence as controls; and col. 7 adds Springfield as a water intervention municipality. Safe water is an indicator variable equal to one during the year in which municipal water or a water filter (in the case of Lawrence) was introduced. Sewerage is an indicator variable that equals one in the year a municipality was connected to the MSD or had a sewerage system financed by the commonwealth (in the case of Marlborough and Clinton). The interaction is an indicator variable that equals one in the first year both interventions were provided to a municipality. Year and municipality fixed effects are included in every specification as are demographic variables (percentage of the city population that is foreign-born, percentage male, percentage females in manufacturing, and log population density). Standard errors are clustered at the municipality level.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

somewhat larger standard error. In column 5 we exclude three municipalities: Lawrence (which had a filter) and Marlborough and Clinton (whose sewerage systems were financed by the state). In column 6 we move the three municipalities to the control category. In both cases, the estimates of the combined effect are relatively unchanged (25.9 and 25.0 log point declines in mortality) and remain significant. In the last column of table 5, we consider Springfield as a treatment municipality because it improved its water supply during our analysis period. Changing the sample in these ways has little effect on our results.

In table B3, we use standard errors that correct for (col. 1) spatial correlation and (col. 2) a small number of clusters. The combined effect of water and sewerage remains highly significant. In the last set of robustness checks, we vary the included trends. In column 3 we add quadratic trends, in column 4 we add intervention-specific linear trends, in column 5 we add breaks in trends by intervention date, in column 6 we include trends by baseline demographic features of the municipality as well as distance from the State House, and in column 7 we exclude all trends. These robustness checks provide further support for the notion that municipalities were not chosen on the basis of patterns of survival of their youngest residents and are not particularly sensitive to various samples or specifications.

## IV.   Concluding Remarks

We find robust evidence that the pure water and sewerage treatments pioneered by far-sighted public servants and engineers in the commonwealth saved the lives of many infants and young children. These interventions must also have improved the health of and enhanced the quality of life for the citizens of the Greater Boston area even if they did not greatly reduce the nonchild death rate.[46]

Using our preferred specification, the combination of sewerage and safe water together lowered the child mortality rate by 26.6 log points or 33.6 percent of the total change in treatment municipalities. The combination also lowered the infant mortality rate by 22.8 log points or 48 percent of the total change in treatment municipalities, which is close to the 47 percent estimate from Cutler and Miller (2005) in their study of filtration and chlorination for a somewhat later period across 13 US cities.

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[46] These benefits came at a high future cost. The dumping of generally raw sewage into the Boston Harbor led it to be known, by the 1970s, as the "dirtiest harbor in America." A cleanup and the installation of a multi-billion-dollar sewage treatment facility on Deer Island changed its designation to the cleanest harbor in America and a "great American jewel" (http://www.mwra.state.ma.us/01news/2008/bhpenvironentalsuccess/bhpenvsuccess .htm).

Can we say that the benefits from the treatments were worth the cost? The question is a difficult one since there were many benefits and we focus on just one. If the only benefit was the reduction in child mortality, what was the cost of an averted death? We answer the question using data for 1910, about in the middle of the treatment period we consider. We produce hypothetical child deaths as of 1910 in the 15 municipalities (excluding Boston) that received both water and sewerage treatments.

In 1910, there were 36,801 children less than 5 years in these municipalities, and the deaths of 440 were averted in that year by the treatments. What about the cost? Since the benefit (averted deaths) is on an annual basis, the cost must be as well. We consider the cost only for the sewerage system since it was imposed on the municipalities. The total sewerage assessment for the 15 municipalities in 1910, which was to cover the interest and sinking fund on the project plus maintenance, was around $300,000.[47] Therefore, each death prevented per year came at a cost of $682, about equal to the annual earnings of a manufacturing worker.

But there were a great many other benefits from the projects. Illness must have declined for all and the quality of life was improved. In fact, the "stench" was what first sparked public activism to rid Boston of the sewage. The water project was also an expense, but it alone had little impact on child mortality and the creation of the watershed area was completely dependent on the removal of effluent. All towns had a water supply before the watershed project, but in many cases the water was of questionable purity because of sewage.

The answer we have offered for the first decline in child mortality differs from that of many contemporary observers in the early twentieth century and some who have contributed to the literature on the historical decline for the United States and Europe.[48] Yet a spate of research in economics has focused on clean water technologies and their influence on public health, particularly typhoid mortality.

The lessons from our historical study are clear. Without proper disposal of fecal material, the benefits of clean water technologies for the health of

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[47] Metropolitan Water and Sewerage Board, tenth annual report (1911, 52–53). Since there were around 337,000 people in these 15 towns in 1910, the annual cost per person was $0.89. Note that the impact on Boston is not considered.

[48] It is our sense that contemporary US observers writing around 1915 correctly deduced that many babies were dying because of impure milk and that their written works influenced a more recent literature. By the early twentieth century the initial decline in infant mortality we describe, which was largely due to clean water and effective sewerage systems, had already taken place. Lee (2007), e.g., stresses the role of clean milk but not clean water and sanitation. Condran and Lentzner (2004) conclude that many factors were at work, and Cheney (1984) puts the greatest weight on clean milk and the work of the Child Hygiene Bureau. Woods et al. (1988, 1989) in their informative work on Britain mention clean water but emphasize clean milk. On the prominence of milk in the contemporary literature, see the various US Department of Labor, Children's Bureau reports from the 1910s and 1920s and Whipple (1917, 58), which discusses infant mortality causes in the 1870s.

children are limited. Although the management of diarrheal illness has improved greatly since the early twentieth century, clean water and sanitation still pose daunting global challenges. According to UNICEF (2014), more than 700 million people lack ready access to improved sources of drinking water and some 2.5 billion people do not have an improved sanitation facility. Each day, an estimated 3,000 children under 5 years of age die because of diarrheal disease, and millions of school days are lost. Further, chronic exposure to fecal pathogens may lead to inflammatory changes in the gut that preclude the absorption of essential nutrients and that stunt height, retard cognitive development, and increase susceptibility to other diseases (Korpe and Petri 2012; Yu et al. 2016).[49]

Although health challenges in late nineteenth-century US cities were similar to those in modern-day developing nation cities, there are important differences. The clean water technology we investigate was primitive. It consisted of protecting watersheds rather than employing a later technology of chlorination, which has a more persistent germ-killing effect. Still, the impact of chlorination on health might be muted if systems for sewage disposal are not also in place.[50] Our findings accord with recent results from community-level water and sanitation infrastructure improvements in India. Together, the interventions were found to reduce diarrheal episodes by 30–50 percent (Duflo et al. 2015).

Finally, one may wonder why the commonwealth government was so foresighted and why municipalities agreed to raise taxes to prevent downstream pollution and protect the watersheds. Although a full account of political economy considerations is beyond the scope of our work, extensive writing on this important issue reveals the respect that politicians and the people gave to the water engineers and health officials who, in their writings, showed an understanding of the roles of unsafe water and sewage in spreading disease, even as miasmatic theories still abounded in the population. We quote Whipple (1917, 134) on these matters: "so great has been the confidence of the public in the ruling of the [State] Board [of Health] that its letters have come to have almost the force of law."

We have identified that the combination of safe water and sewerage interventions was responsible for much of the first sustained decrease in child mortality in the United States. Yet child mortality continued its long decline. Later in the Progressive Era, the purification of the milk supply, street cleaning, health stations, vaccinations, and nurse home visits re-

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[49] This constellation of symptoms resulting from fecal pathogen contamination is commonly referred to as "environmental enteropathy."

[50] Bhalotra et al. (2017) examined the recent rollout of a program in Mexico to chlorinate municipal water sources and found that the health benefits for young children to the clean water intervention were much stronger in places that had complementary sanitation infrastructure.

duced mortality.[51] Still later in the twentieth century, a host of medical technologies, including antibiotics, continued to lower infant and child death rates. Closer to the present, the use of neonatal intensive care units has spared many premature babies. Yet improving the lives of young children in much of the developing world still involves decreasing morbidity from diarrheal disease through a combination of safe water and sewerage system interventions just as it did during the first decline in the United States.

**Appendix A**

**Data Sources and Dates of Interventions**

*A. Data Sources*

*Vital statistics*: Information on births, total deaths, and deaths under 1 year of age (infant deaths) are from Secretary of the Commonwealth of Massachusetts, Report on Births, Marriages, and Deaths (available from Wright & Potter, state printer). Total deaths and total births are available annually for each municipality from 1870 to 1920. From 1870 to 1891, data on infant deaths are available for each municipality, but starting in 1891 and continuing through 1897, the Registration Reports give infant deaths by county but not by municipality. From 1897 to 1920, infant deaths are available for counties and only larger municipalities. For this reason, we obtained data on infant deaths from the original death registry, put into a searchable form by FamilySearch.org. The data were collected using an algorithm described in appendix C. We also extracted cause, exact age (to the day), and sex of the infant that died.

*Demographic variables*: From the Massachusetts state and federal censuses for 1875, 1880, 1885, 1890, 1895, 1900, 1905, 1910, 1915, and 1920.

*Water*: The dates are mainly taken from appendix number 1 of the 1909 Metropolitan Water and Sewerage Board Report.

*Sewerage*: Similar to the water district, a Metropolitan Sewerage System was constructed to remove effluent from municipalities into various outfall locations, described further in the text. The dates for the completion of the sewerage system are taken from several texts: The Main Drainage Works of Boston and Its Metropolitan Sewerage District, 1899; Metropolitan Water Board Legislation, 1895–1900; Metropolitan Sewerage Board Legislation, 1889–1900; Metropolitan Water and Sewerage Board Legislation, 1901–14; and Reports of the State Board of Health, the Metropolitan Sewerage Commission, the Metropolitan Water District, and the Metropolitan Water and Sewerage Board.

*Service pipe material*: Moses Nelson Baker, *The Manual of American Water-Works* (New York: Engineering News Publishing Co., 1897).

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[51] The funding of public health interventions in the 1920s has been identified as a factor reducing IMR. Moehling and Thomasson (2012) show that in the 1922–29 period, better public health, caused by the Sheppard-Towner Act matching grants to states, can account for 9–21 percent of the decrease in infant mortality.

*Dairy quality*: Annual State Board of Health Reports (1905–14) and City of Boston Board of Health Reports for 1905–7 and 1909–16.

## B.    Variable Definitions

*Total registered births*: Number of live births per municipality as recorded in the Annual Massachusetts Registration Reports on Births, Marriages, and Deaths; available at the state, county, and municipality levels, 1870–1920.

*Total deaths*: Number of deaths as recorded in the Annual Massachusetts Registration Reports on Births, Marriages, and Deaths; available at the state, county, and municipality levels, 1870–1920.

*Total infant deaths*: Infant death counts at the municipality level are compiled from FamilySearch.org and include all children less than 1 year of age.

*Infant mortality rate (IMR)*: Deaths of infants less than 1 year of age in a calendar year per 1,000 registered births in that year. Both the numerator and denominator include stillbirths in the main specification.

*Child mortality rate (CMR)*: Deaths of children [0, 5) years of age in a calendar year per 1,000 population [0, 5) years in the same calendar year. Data for the numerator were obtained from the FamilySearch website with a search algorithm similar to that described in appendix C except modified to include deaths among those 1–4 years of age. The denominator population under 5 years of age is the sum of total registered births + stillbirths + the population of those [1, 5) years for each municipality-year. Population [1, 5) years was calculated as the difference between lagged total births − lagged deaths (without stillbirths included) for age $a$ in period $k$ (in year $t$):

$$\text{Pop1--4}_{a,k} = \sum_{a=1}^{a=4}\left[\text{Births}^{t-a} - \left(\sum_{k=1}^{a}\text{Deaths}_{a-k}^{t-k}\right)\right].$$

*Nonchild mortality rate*: Noninfant mortality is calculated as total deaths in the population minus deaths of those under 5 years old divided by the nonchild population. The nonchild population is calculated as the total population minus contemporaneous infant births net of deaths (both births and deaths exclude stillbirths) and the [1, 5)-year-old population as calculated above.

*Log total births*: Log of total registered births excluding stillbirths.

*Log foreign births*: Log of foreign births (defined in registration report as both parents foreign-born) excluding stillbirths.

*Category-specific mortality*: Category-specific mortality was calculated as deaths of under-5 children per 1,000 population [0, 5). Gastrointestinal-related mortality includes symptoms consistent with an infection of gastrointestinal tract and pathogens transmitted via the fecal to oral route, including deaths from diarrhea, enteritis, colitis, cholera, typhoid, malnutrition/marasmus, and polio. Tuberculosis-related mortality included deaths from pulmonary tuberculosis, consumption, basilar meningitis (which in children is overwhelmingly due to tuberculosis), scrofula (tuberculosis of the neck), and Pott's disease (tuberculosis of the spine). Respiratory-related mortality includes death from diseases afflicting the lower respiratory tract (i.e., pneumonia), upper respiratory tract (i.e., bronchitis), pleural space (including effusions and pleurisy), and hyperreactive processes such as asthma.

*Spring-summer mortality*: Deaths of children under 5 during the warmer months (April to September) per 1,000 population [0, 5].

*Fall-winter mortality*: Deaths of children under 5 during the cooler months (October to March) per 1,000 population [0, 5].

*Water*: Indicator variable that takes a value of one in the year a municipality was supplied with water from the MWD of Boston or, if Lawrence, installed a filter.

*Sewerage*: Indicator variable that takes a value of one in the year the municipality was linked to the MSD of Boston or, if Marlborough or Clinton, had a sewerage system built by the commonwealth.

*Dairy quality*: The proportion of dairies in the county (except Suffolk) that do not contain "objectionable features." The number for Suffolk County is reported as the proportion of milk sold at stores with <500,000 bacteria per cubic centimeter. The years prior to the first year of available data by municipality are assigned the first available value and the years after the last available value are assigned the last value.

*Demographic and economic data*: Percentage female, foreign-born, females working in manufacturing, females illiterate, Irish, and British. Linearly interpolated between censuses.

*Log population density*: Population per square acre.

TABLE A1
Intervention Dates

| Municipality | Sewerage | Water | Municipality | Sewerage | Water |
|---|---|---|---|---|---|
| Arlington | 1895 | 1899 | Needham | | |
| Belmont | 1895 | 1898 | New Bedford | | |
| Beverly | | | Newburyport | | |
| Braintree | | | Newton | 1892 | |
| Brockton | | | North Adams | | |
| Brookline | 1892 | | Northampton | | |
| Cambridge | 1895 | | Peabody | | |
| Chelsea | 1895 | 1898 | Pittsfield | | |
| Chicopee | | | Quincy | 1899 | 1899 |
| Clinton | 1899 | | Randolph | | |
| Dedham | 1900 | | Reading | (1921) | |
| Everett | 1895 | 1898 | Revere | 1903 | 1898 |
| Fall River | | | Salem | | |
| Fitchburg | | | Saugus | | 1903 |
| Gloucester | | | Somerville | 1895 | 1898 |
| Haverhill | | | Springfield | | |
| Holyoke | | | Stoneham | 1897 | 1901 |
| Ipswich | | | Swampscott/Nahant | | 1899** |
| Lawrence | | 1893 | Taunton | | |
| Lexington | 1898* | 1902 | Wakefield | 1898* | |
| Lowell | | | Waltham | 1892 | |
| Lynn | | | Watertown | 1892 | 1898 |
| Malden | 1895 | 1898 | Wellesley | (1921) | |
| Marlborough | 1904 | | Weston | | |
| Marshfield | | | Westwood | | |
| Medford | 1895 | 1898 | Weymouth | | |
| Melrose | 1895 | 1898 | Winchester | 1895 | |
| Milford | | | Winthrop | 1895 | 1898 |
| Milton | 1898 | 1902 | Woburn | 1895 | |
| Natick | | | Worcester | | 1903 |

Source.—State Board of Health, the Metropolitan Sewerage Commission, the Metropolitan Water District, and the Metropolitan Water and Sewerage Board.

Note.—Parentheses denote dates outside our sample period.

* Only part of the town.

** Swampscott and Nahant are combined for purposes of the analysis.

## Appendix B

### Additional Tables and Figures

TABLE B1
Cox Hazard Model of Time to Interventions

|  | Water (1) | Sewerage (2) |
|---|---|---|
| Geographic features: |  |  |
| Distance to Wachusett Reservoir | .996 | .866*** |
|  | (.024) | (.044) |
| Distance to State House | .945* |  |
|  | (.029) |  |
| Distance to outlet |  | .836*** |
|  |  | (.058) |
| Elevation (meters) | .998 | 1.001 |
|  | (.002) | (.002) |
| Pretreatment demographics: |  |  |
| Log population density | 1.256 | 1.348 |
|  | (.337) | (.300) |
| Percentage male | 1.095 | .948 |
|  | (.151) | (.101) |
| Percentage foreign | .996 | 1.047 |
|  | (.050) | (.050) |
| Percentage female in manufacturing | .996 | .998 |
|  | (.063) | (.067) |
| Observations | 58 | 58 |

Note.—The sample includes 58 municipalities incorporated by 1880. Two control municipalities (Westwood and Wellesley), incorporated just after 1880, are dropped. Distance to State House defined the bounds of the MWD. Distance from outlet is the minimum distance to one of three sewerage outlets: Deer Island, Moon Island, and Nut Island. Distance from the Wachusett Reservoir is included in the timing to sewerage since Clinton and Marlborough sewerage systems were constructed to protect the municipal water supply. Pretreatment characteristics are from the 1880 census. Hazard ratios are reported with standard errors in parentheses. The period covered is 1880–1920.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

TABLE B2
Alternative Age-Specific Mortality Outcomes

| | A. Outcome Is Log Under-2 Mortality Rate | | | | | B. Outcome Is Log Infant Mortality Rate | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| Safe water | −.121 | | −.098 | | .065 | −.107 | | −.081 | | .039 |
| | (.075) | | (.073) | | (.045) | (.075) | | (.073) | | (.055) |
| Sewerage | | −.116** | −.099** | | −.069 | | −.127*** | −.113** | | −.091** |
| | | (.045) | (.043) | | (.044) | | (.046) | (.043) | | (.044) |
| Interaction of safe water and sewerage | | | | −.209** | −.239*** | | | | −.178** | −.175* |
| | | | | (.085) | (.084) | | | | (.087) | (.090) |
| Safe water + sewerage + interaction | | | | | −.242** | | | | | −.228** |
| | | | | | $p = .013$ | | | | | $p = .026$ |
| Observations | 2,431 | 2,431 | 2,431 | 2,431 | 2,431 | 2,424 | 2,424 | 2,424 | 2,424 | 2,424 |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Demographics | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality-linear trends | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Adjusted $R^2$ | .571 | .571 | .572 | .573 | .573 | .482 | .483 | .484 | .483 | .484 |
| No. clusters | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |

Note.—Ordinary least squares (OLS) estimates of eq. (1). The sample spans the years 1880–1920 and includes 60 municipalities (Swampscott and Nahant are combined). The dependent variable is the log of the under-2 mortality rate (in panel A) and the log of the infant mortality rate (in panel B). Safe water is an indicator variable equal to one during the year in which municipal water or a water filter (in the case of Lawrence) was introduced. Sewerage is an indicator variable that equals one in the year a municipality was connected to the MSD or had a sewerage system financed by the commonwealth (in the case of Marlborough and Clinton). The interaction is an indicator variable that equals one in the first year both interventions are provided to a municipality. The $p$-value associated with the combination of the estimated effects of water, sewerage, and their interaction is shown below it. Demographic controls include percentage of the population that is foreign-born, percentage male, percentage females involved in manufacturing, and the log of the population density.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

TABLE B3
The Effect of Safe Water and Sewerage on Log Child Mortality

| | Wild Bootstrap (1) | Conley Spatial (2) | Adding Quadratic Trends (3) | Trends by Intervention Type (4) | (4) + Trend Breaks (5) | Trend by Baseline Demographics (6) | No Trends (7) |
|---|---|---|---|---|---|---|---|
| Safe water | .109 | .109* | .091 | .119 | .101 | .061 | .087 |
| | $p = .27$ | (.057) | (.150) | (.079) | (.080) | (.050) | (.079) |
| Sewerage | −.067 | −.067* | −.015 | −.056 | −.061 | −.052 | −.074** |
| | $p = .12$ | (.037) | (.055) | (.045) | (.049) | (.044) | (.036) |
| Interaction of safe water and sewerage | −.307** | −.307*** | −.257 | −.319*** | −.305*** | −.215*** | −.201** |
| | $p = .032$ | (.067) | (.167) | (.104) | (.104) | (.073) | (.088) |
| Safe water + sewerage + interaction | −.266** | −.266*** | −.181* | −.257*** | −.266*** | −.206** | −.188*** |
| | $p = .01$ | (.055) | $p = .051$ | $p = .007$ | $p = .006$ | $p = .014$ | $p = .0003$ |
| Observations | 2,438 | 2,438 | 2,438 | 2,438 | 2,438 | 2,376 | 2,438 |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Demographics | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality-linear trends | Yes | Yes | Yes | No | No | No | No |
| No. clusters | 60 | 60 | 60 | 60 | 60 | 58 | 60 |

Note.—OLS estimates of eq. (1). Each column is a separate regression. The sample specification varies across columns. Col. 1 uses wild bootstrap standard errors (see Cameron, Gelbach, and Miller 2008); col. 2 uses Conley spatial standard errors with cutoffs of 10 kilometers; col. 3 adds quadratic trends; col. 4 adds trends by intervention type; col. 5 adds to the col. 4 specification trend breaks by intervention type; col. 6 adds trends by baseline demographics and distance to Boston (trend coefficients are not displayed because of space constraints, though none of the coefficients in cols. 4 and 5 are significant); and col. 7 drops municipality-level trends. Safe water is an indicator variable equal to one during the year in which municipal water or a water filter (in the case of Lawrence) was introduced. Sewerage is an indicator variable that equals one in the year a municipality was connected to the MSD or had a sewerage system financed by the commonwealth (in the case of Marlborough and Clinton). The interaction is an indicator variable that equals one in the first year both interventions were provided to a municipality. Year and municipality fixed effects are included in every specification as are demographic variables (percentage of the city population that is foreign-born, percentage male, percentage females in manufacturing, and log population density). Municipality-linear trends are included except when replaced with alternative trends or dropped from the analysis as indicated in the column heading. Standard errors are clustered at the municipality level.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

TABLE B4
POPULATION IN DENOMINATOR

| | A. OUTCOME IS LOG CHILD MORTALITY | | | | | B. OUTCOME IS LOG INFANT MORTALITY | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| Safe water | −.092 | | −.080 | | .048 | −.096 | | −.080 | | .062 |
| | (.066) | | (.066) | | (.053) | (.079) | | (.079) | | (.065) |
| Sewerage | | −.066 | −.052 | | −.029 | | −.081 | −.068 | | −.042 |
| | | (.050) | (.051) | | (.053) | | (.049) | (.049) | | (.051) |
| Interaction of safe water and sewerage | | | | −.156** | −.187** | | | | −.169* | −.208** |
| | | | | (.072) | (.077) | | | | (.090) | (.100) |
| Safe water + sewerage + interaction | | | | | −.168** | | | | | −.187* |
| | | | | | $p = .043$ | | | | | $p = .059$ |
| Observations | 2,438 | 2,438 | 2,438 | 2,438 | 2,438 | 2,424 | 2,424 | 2,424 | 2,424 | 2,424 |
| Year fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality fixed effects | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Demographics | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Municipality-linear trends | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Adjusted $R^2$ | .750 | .750 | .750 | .751 | .751 | .685 | .685 | .686 | .686 | .686 |
| No. clusters | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |

NOTE.—OLS estimates of eq. (1). The sample spans the years 1880–1920 and includes 60 municipalities (Swampscott and Nahant are combined). The dependent variable is the log of the child mortality rate normalized by total population instead of population under 5 (in panel A) and the log of the infant mortality rate also normalized by total population (in panel B). Safe water is an indicator variable equal to one during the year in which municipal water or a water filter (in the case of Lawrence) was introduced. Sewerage is an indicator variable that equals one in the year a municipality was connected to the MSD or had a sewerage system financed by the commonwealth (in the case of Marlborough and Clinton). The interaction is an indicator variable that equals one in the first year both interventions are provided to a municipality. The $p$-value associated with the combination of the estimated effects of water, sewerage, and their interaction is shown below it. Demographic controls include percentage of the population that is foreign-born, percentage male, percentage females involved in manufacturing, and the log of the population density.
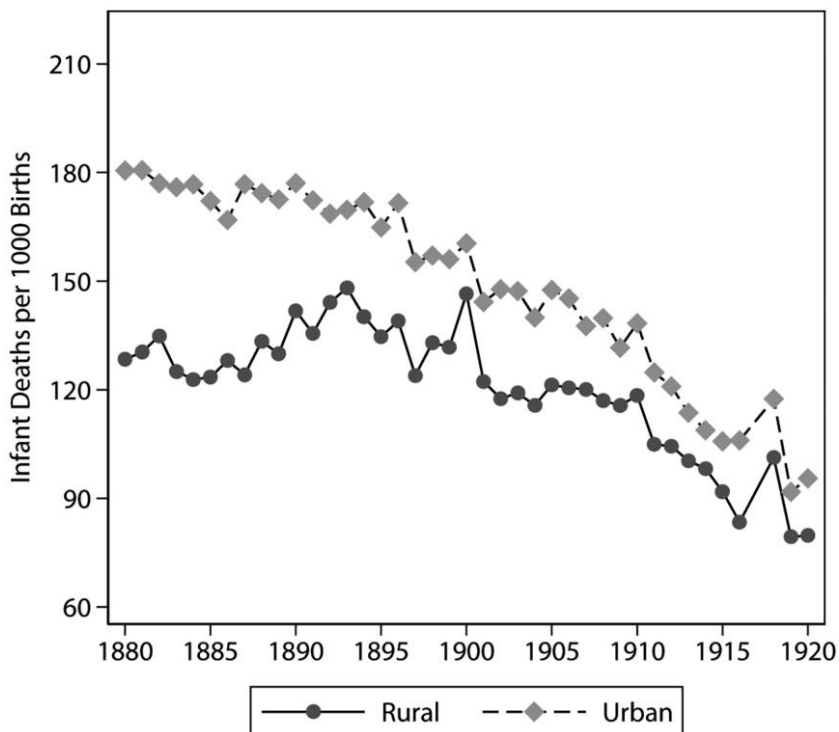
* $p < .1$.
** $p < .05$.
*** $p < .01$.

FIG. B1.—Urban and rural infant mortality rates, Massachusetts. Source: See appendix A. Urban is defined as the 32 largest municipalities in Massachusetts in the Registration Report of 1898. Rural is all other populations in each of the counties. The data are from the annual registration reports, and mortality rates are aggregates within the urban and rural designations.
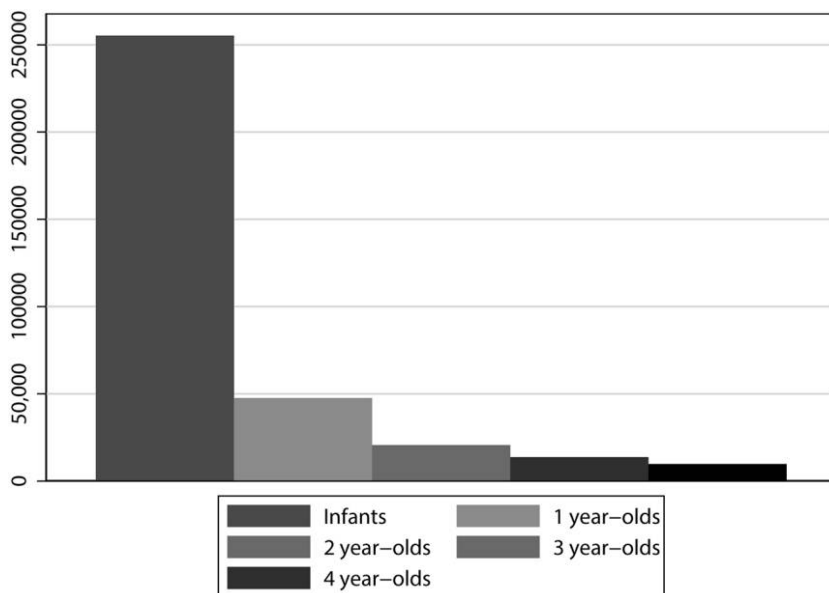
627

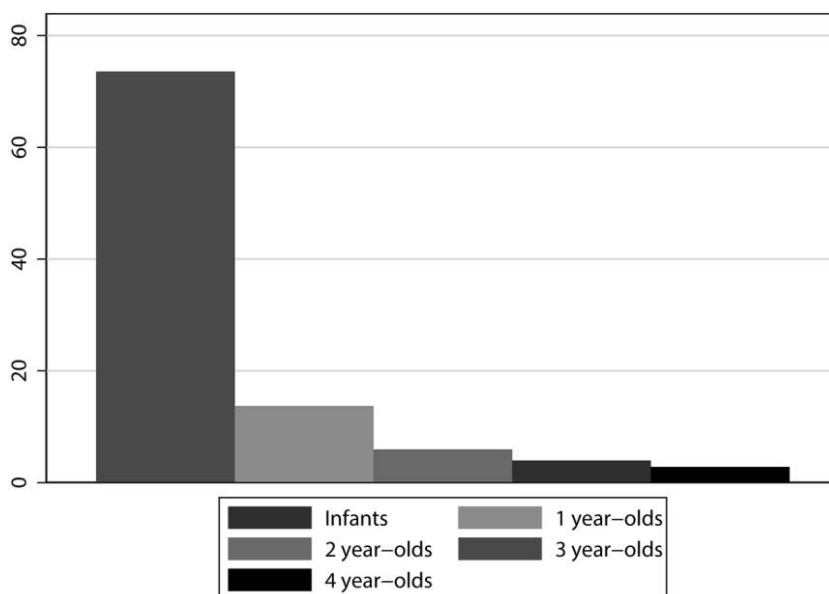Fɪɢ. B2.—Distribution of deaths by age, children under 5 (total)



Fɪɢ. B3.—Distribution of deaths by age, children under 5 (percent)

628
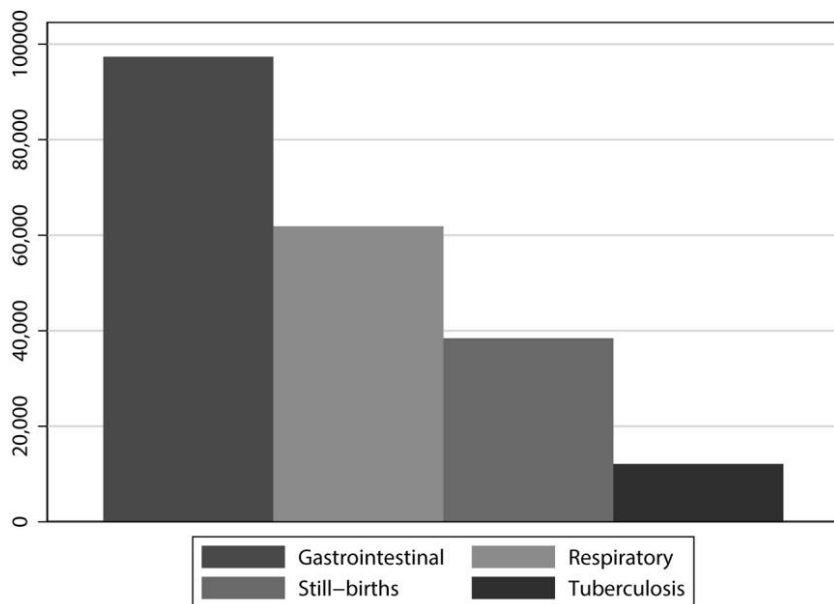
F‍ɪɢ. B4.—Distribution of deaths by category, children under 5
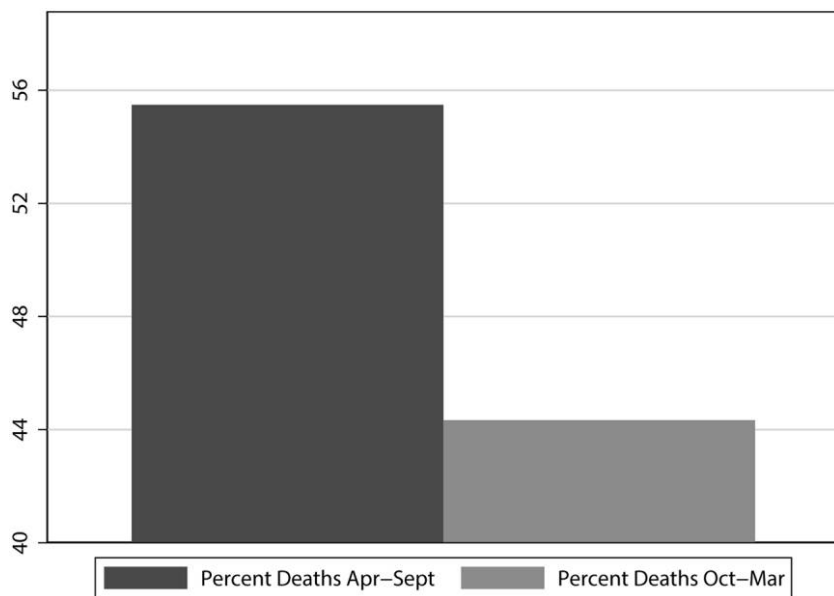


F‍ɪɢ. B5.—Distribution of deaths by seasons, children under 5
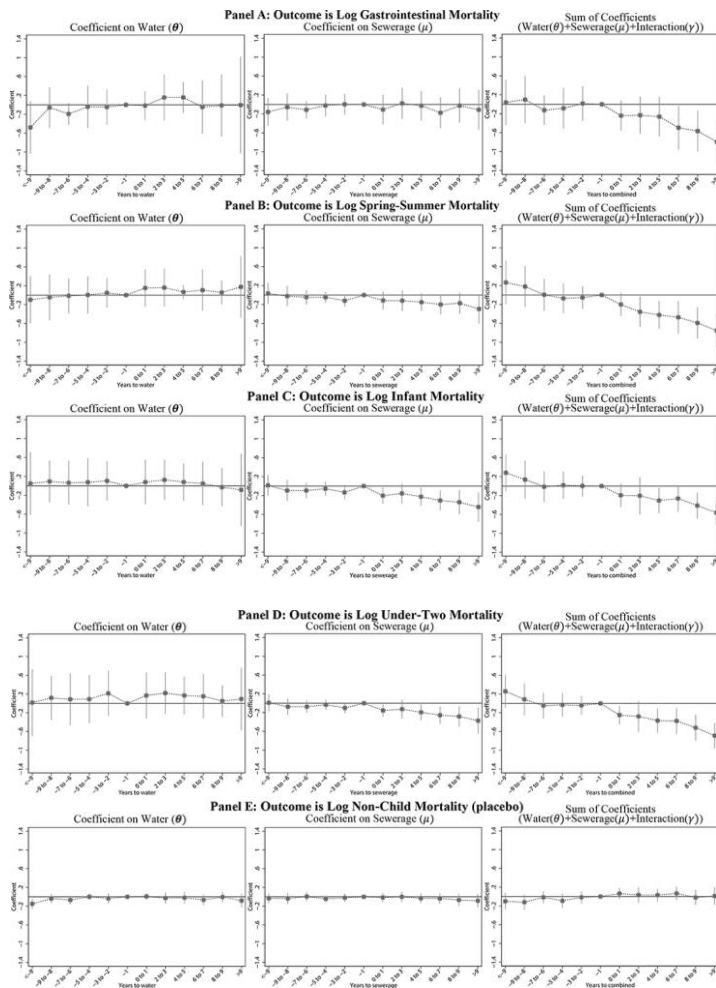
629

FIG. B6.—Event studies of the effect of sewerage, water, and their combination on mortality by category of death. OLS estimates of equation (2) and their 95 percent confidence intervals are given. Panel A plots coefficients from one regression with the outcome log of gastrointestinal-related mortality, which includes deaths involving the gastrointestinal tract and fecal-oral transmission, per 1,000 under-5 population. Reading from left to right are the coefficients on water ($\theta$), on sewerage ($\mu$), and on the sum of coefficients: Water ($\theta$) + Sewerage ($\mu$) + Interaction ($\gamma$). Panel B is similar to panel A; however, the outcome is the log of spring-summer mortality. Panel C reports coefficients for the outcome of log infant mortality, defined as infant deaths per 1,000 births; in panel D the outcome is the log of under-2 mortality; and in panel E the outcome is log nonchild mortality rate, deaths of those 5 and over per 1,000 5 and over population, which we consider a placebo outcome since adults more often succumbed to other diseases, such as tuberculosis. See appendix A (variable definitions) and text for further details. Standard errors are clustered at the municipality level.
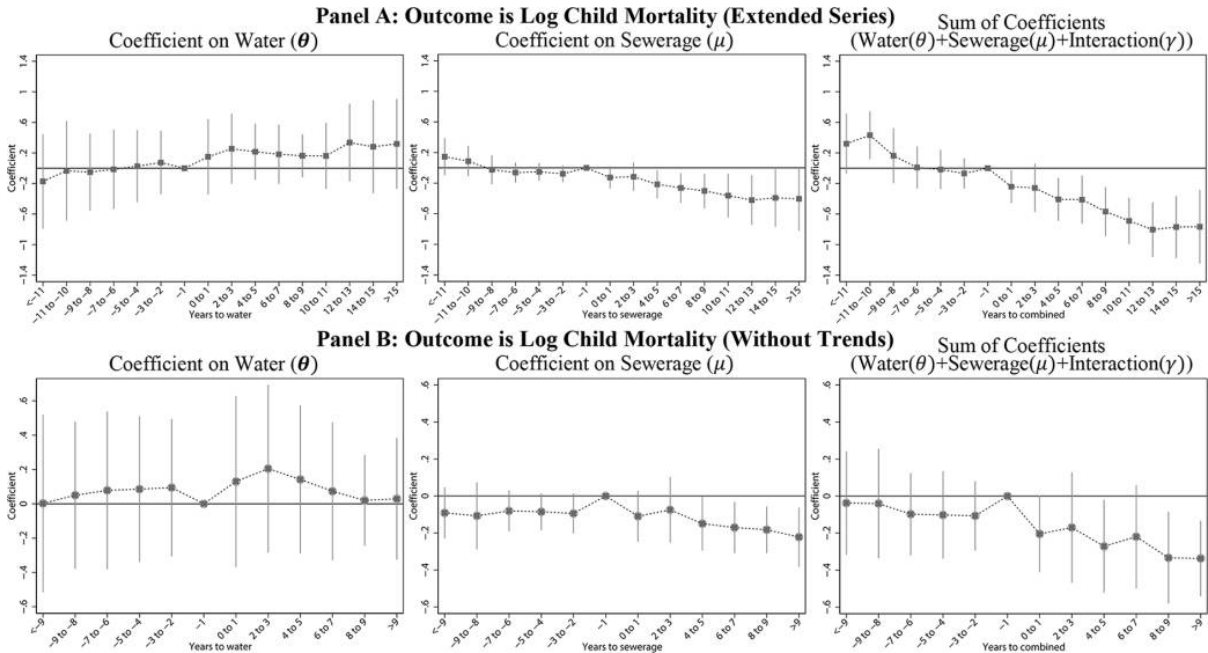
630

**Panel A: Outcome is Log Child Mortality (Extended Series)**

Coefficient on Water ($\theta$)    Coefficient on Sewerage ($\mu$)    Sum of Coefficients (Water($\theta$)+Sewerage($\mu$)+Interaction($\gamma$))

**Panel B: Outcome is Log Child Mortality (Without Trends)**

Coefficient on Water ($\theta$)    Coefficient on Sewerage ($\mu$)    Sum of Coefficients (Water($\theta$)+Sewerage($\mu$)+Interaction($\gamma$))



FIG. B7.—Event studies of the effect of interventions on mortality. OLS estimates of an extended version of equation (2) and their 95 percent confidence intervals are given. Panel A plots coefficients from one regression with the outcome log of child mortality, which includes the deaths of infants and young children [1, 5) years of age per 1,000 under-5 population. Reading from left to right are the coefficients on water ($\theta$), on sewerage ($\mu$), and on the sum of coefficients: Water ($\theta$) + Sewerage ($\mu$) + Interaction ($\gamma$). Panel B plots the same specification as in figure 5 of the main text without municipality-specific linear trends. Standard errors are clustered at the municipality level.
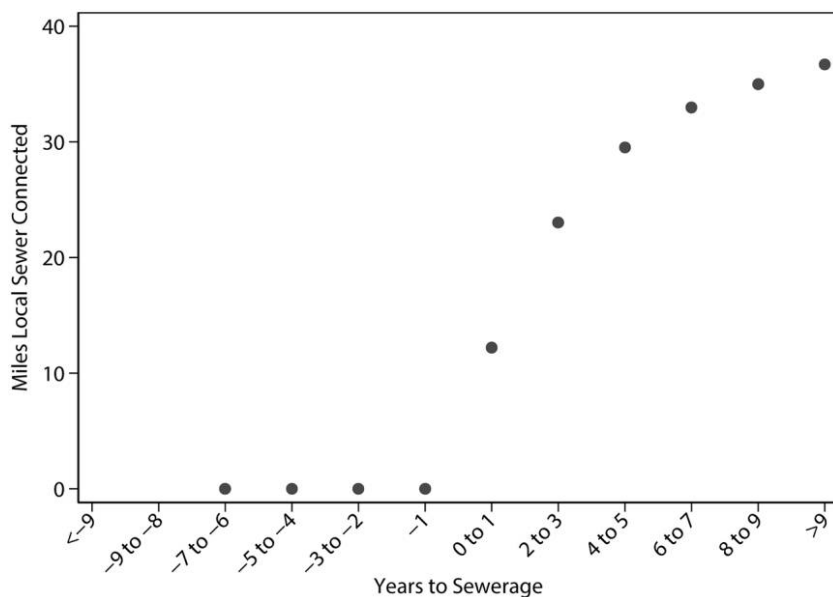
Fɪɢ. B8.—Miles of local sewers connected. Data are from the annual reports of the Metropolitan Sewerage Commission (1897–1901) and the annual reports of the Metropolitan Water and Sewerage Board (1902–19). The recurring table used to create these figures began in the 1897 published report. The sample is limited to the municipalities that receive water and sewerage or sewerage only (though not all municipalities that receive sewerage were included in the table). The average miles of local sewer connected to the sewerage district are plotted.
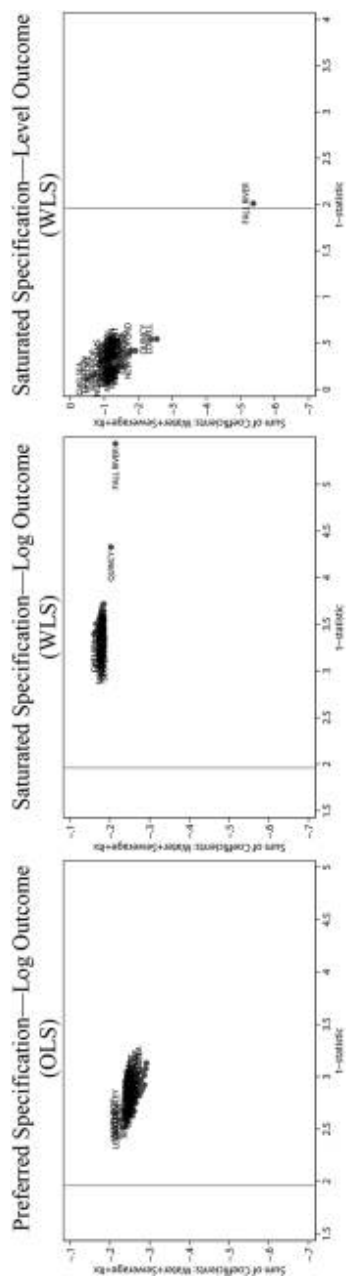
FIG. B9.—Leave one out estimates. The figure plots the full effect of water and sewerage leaving one municipality out at a time. The left column plots the combined coefficients using our preferred specification with log child mortality as the outcome variable and controlling for time-varying demographic variables, municipality and year fixed effects, and municipality linear trends. The middle column demonstrates the same specification including only intervention, municipality and year fixed effects, and weighting by the under-5 population. Although omitting Fall River would increase the statistical significance of the full effect when the outcome is logged, it would not change the magnitude of the estimates appreciably. In contrast, the right-most graph plots the linear-in-levels estimates from the same specification. The results suggest that Fall River has a large effect on both the magnitude and significance of the results.

**Appendix C**

### Use of the FamilySearch.org Data

*FamilySearch.org algorithm and data-cleaning procedure.*—We developed the following algorithm for generating a count of under-5 deaths using data from Family Search.org. For each municipality, we isolated each death report in which the estimated birth year matched the recorded death year (for infants) and used a similar procedure to isolate deaths of children dying at ages 1, 2, 3, and 4.

Two potential limitations exist to our use of the FamilySearch.org website. The website data are inputted on the basis of the actual death records, leaving the potential for data entry errors. FamilySearch.org has redundancy in record entry, and we have found, and corrected, instances of duplicate observations.

To systematically minimize the impact of duplicates, we create a flag indicator when multiple observations shared the same date of death and the first two letters of first and last names. Each flagged observation was then more closely examined. If all the following fields were identical or nearly so if a name was typed slightly differently (event date, decedent name, event place, father's names, and birthplace), we considered the entry a duplicate and removed it from the file. An example of a duplicate is as follows:

| unique_id | eventdate | name | first_name | last_name | eventplace | fathername | birthplace |
|---|---|---|---|---|---|---|---|
| 2837 | 04 Feb 1880 | Thomas Reely | th | re | Boston, MA | Cornelius | Boston |
| 1911 | 04 Feb 1880 | Thomas Reely or Keely | th | re | Boston, MA | Cornelius | Boston |

In total, we eliminated between two and 47 records per year with this methodology.

We identified other potential data errors during its original entry by the municipal authorities or onto the FamilySearch.org website by dropping all entries identified as child deaths that included an occupation or for which marital status was entered as married, divorced, or widowed.
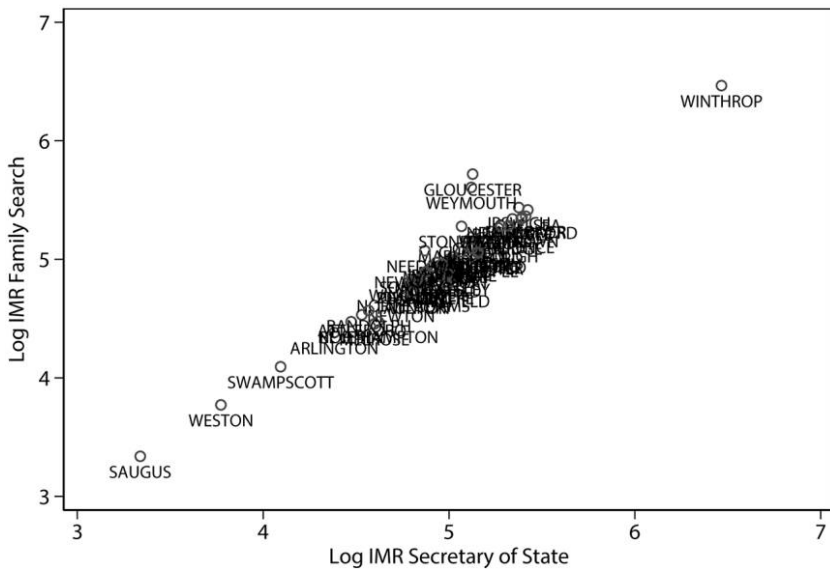
Fig. C1.—Correlation between FamilySearch and Secretary of State data across munic-ipalities. This figure gives the relationship between log infant mortality from FamilySearch (*y*-axis) versus the log infant mortality rate from the Secretary of State of the Common-wealth registration reports for the year 1885 when both sources reported municipality-level infant death data.
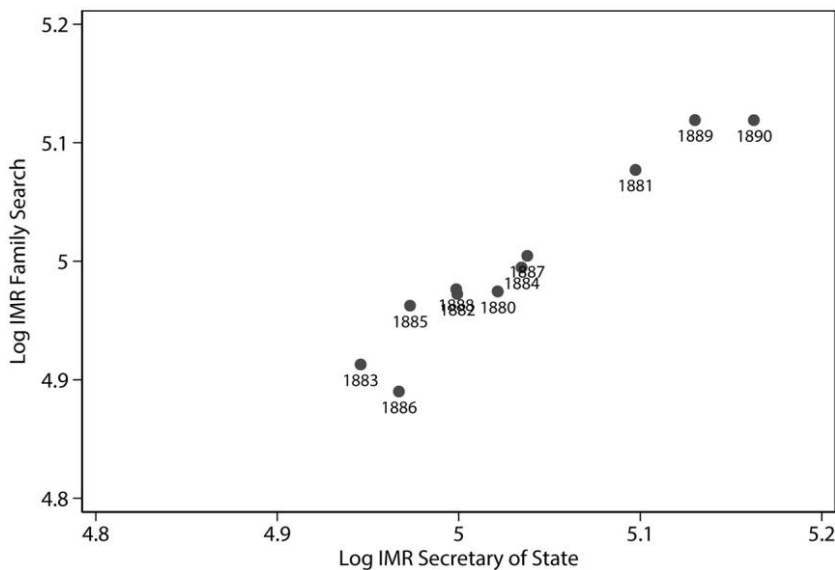


Fig. C2.—Correlation between FamilySearch and Secretary of State data across years. This figure gives the relationship between log infant mortality from FamilySearch (*y*-axis) versus the log infant mortality rate averaged across years from the Secretary of State of the Commonwealth registration reports, omitting the years when the latter resource reported only county-level infant death data.

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