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ABSTRACT

Investment in water purification technologies led to large mortality declines by helping eradicate typhoid fever and other waterborne diseases. This paper seeks to understand how these technologies affected human capital formation. We use typhoid fatality rates during early life as a proxy for water quality. To carry out the analysis, city-level data are merged with a unique dataset linking individuals between the 1900 and 1940 censuses. Parametric and semi-parametric estimates suggest that eradicating early-life exposure to typhoid fever would have increased earnings in later life by 1% and increased educational attainment by one month. Instrumenting for typhoid fever using the typhoid rates from cities that lie upstream produces similar results. A simple cost-benefit analysis indicates that the increase in earnings from eradicating typhoid fever was more than sufficient to offset the costs of eradication.

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I. INTRODUCTION

Poor water quality remains a major threat to human health. Approximately 780 million people do not have access to improved water sources, leaving them vulnerable to typhoid fever, cholera, and other waterborne diseases.[1] Each year 21.5 million persons contract typhoid fever while 5 million contract cholera.[2] Furthermore, diarrheal diseases alone account for 1.8 million deaths each year or 4.7 percent of deaths worldwide.[3]

There is a large economic literature analyzing the impact of water purification on disease rates and early-life health outcomes, notably infant mortality. Perhaps the central finding of this research is that water purification has large and diffuse health effects, accounting for roughly fifty percent of the decrease in U.S. mortality between 1900 and 1950 (Cutler and Miller 2005; Ferrie and Troesken 2008). While the extant literature has done a thorough job identifying and measuring the short-term health effects of improving water quality, economists have yet to identify the long-term economic effects of water purification. There is, in particular, no evidence on how drinking impure water in childhood impairs human capital attainment twenty to thirty years later, nor is there any evidence regarding labor market outcomes. Accordingly, our goal in

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[1] Estimates for access to improved water sources taken from UNICEF: http://www.unicef.org/wash/index_watersecurity.html

[2] Typhoid and Cholera estimates from CDC: http://www.cdc.gov/nczved/divisions/dfbmd/diseases/typhoid_fever/technical.html and http://www.cdc.gov/cholera/general/index.html respectively.

[3] 1.8 diarrheal deaths from WHO: http://www.who.int/water_sanitation_health/diseases/burden/en/

this paper is to analyze how early-life exposure to impure water affects adult outcomes, particularly in terms of educational attainment and income.

Our analysis is predicated on a linkage procedure that allows us to identify how exposure to contaminated water during the in utero, neonatal, and postnatal periods affects later life economic outcomes. We use typhoid fever fatality rates, a waterborne disease, as a proxy for water quality.[4] We link city-year level typhoid fatality rates to children in the 1900 Census, which is then linked to adult outcomes in the 1940 Census. Parametric and semi-parametric results indicate that the eradication of typhoid fever, which cities achieved by purifying their water, would have increased educational attainment by one month and increased earnings by about one percent.

Of course, one might be concerned that investing in water quality is correlated with unobserved variables that might also influence human capital formation. Given this, we implement an instrumental variables strategy. Because typhoid is a waterborne disease, cities that dump their sewage into a river will increase future typhoid rates for cities downstream. Using typhoid rates from the nearest upstream city as an instrument, we find results that are larger. Specifically, these results indicate that if typhoid had been eradicated, schooling would have increased by nine months and earnings would have increased by about nine percent. However, only the estimate for schooling is statistically

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[4] We justify the use of typhoid fever fatality rates as a proxy for water quality in section two.

significant. We also find some evidence that high typhoid rates during early-life impaired geographic mobility.

This paper complements the existing literature on the benefits to water purification. Culter and Miller (2005) show that the adoption of water purification technologies decreased total mortality by 13 percent, infant mortality by 46 percent, and child mortality by 50 percent. Furthermore, those of lower socioeconomic status might have been the primary beneficiaries to water purification efforts. Troesken (2004) shows that water filtration reduced typhoid rates among African Americans by 52 percent, but reduced white disease rates by only 16 percent. Currie et al. (2013) analyze birth records and water quality in New Jersey from 1997-2007. They find that exposure to contaminated water during pregnancy is associated with lower birth weights and higher incidence of premature birth for the children of less educated mothers.

As impressive as these short-term benefits are, the benefits to water purification are likely understated. A growing literature has shown that early-life exposure to disease and deprivation has adverse effects on adult health and economic outcomes, lowering educational attainment, earnings, and mortality (see Almond and Currie (2011) for a detailed overview). Because the diseases that accompany contaminated water are manifold and often severe in their consequences, it is reasonable to hypothesize that early-life exposure to contaminated water will have long-run effects. Consistent with the literature, we find that exposure to contaminated water decreased educational attainment and earnings. Our findings are particularly relevant for policymakers in the developing world. Many developing countries have yet to undertake efforts to purify their water, possibly because water purification is costly. Cutler and Miller (2005) estimate the social return to water purification to be 23 to 1. Our results indicate that the discounted increase in earnings alone was sufficient to offset the costs of water purification.

II. TYPHOID FEVER

II.a. Typhoid as an indicator of water quality

In this paper, our primary indicator of water quality is typhoid fever. Before the advent of formal water testing, typhoid fever was taken as an indicator of water quality among public health experts. For example, George F. Whipple argued that "the relation between [water quality and typhoid] is so close that the typhoid death-rate has been often used as an index of the quality of the water. Generally speaking . . . a very low death rate indicates a pure water, and a very high rate, contaminated water".[5] Similarly, a report on water quality in New York City in 1912 stated that "the death rate from typhoid fever is commonly taken as one index of the quality of a water supply."[6] This same report noted, however, that typhoid was an imperfect indicator of water quality because typhoid epidemics could sometimes be caused by milk, shellfish or other sources, and because the absence of typhoid did not guarantee the water in question was free from other pathogens that might cause diarrhea, cholera, or other diseases.

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[5] Whipple (1908), p. 228.

[6] *Engineering News*, May, 1913, p. 1087

While it is true that typhoid could be spread by means other than water, in the era before water treatment those sources of infection accounted for only a tiny fraction of all typhoid outbreaks (Troesken 2004; Whipple 1908, pp. 131-33). In addition, as explained below, typhoid was eradicated not through shellfish inspection or milk pasteurization but through improvements in water quality. It is well established in historical demography that water filtration and chlorination were by far the most important in the eradication of typhoid (Ferrie and Troesken 2005; Melosi 2000, pp. 138-47; Troesken 2004). As for the idea that typhoid did not fully reflect all possible pathogens in the water, typhoid fever rates were correlated with the death rate from cholera and diarrhea (Fuertes 1897).

To demonstrate that typhoid fatality rates are correlated with water quality, we take data from thirteen cities in North Carolina. This data reports typhoid fatality rates for whites and water bacteria counts for 41 city-year pairs. Regressing bacteria counts on typhoid fatality rates (see column one of Table 1) reveals a positive but insignificant relationship. However, collapsing this data at the city level and comparing the average typhoid rate by city to the city's average bacteria count reveals a strong positive relationship. The p-value is 0.051 or 0.007 depending on whether the observations are weighted by the number of years included in the sample. Because typhoid fatality rates vary from year to year, average typhoid rates are a better predictor of bacterial counts than instantaneous typhoid rates. This observation has implications for our empirical analysis below. In particular, instead of using typhoid rates from an individual's year of birth, we use average typhoid rates from the prenatal to neonatal period as a proxy for water quality during early life.

During the late nineteenth and early twentieth century, the waterborne disease that posed the most serious threat to American populations was typhoid fever—as of 1900, probably one of every three Americans would have contracted typhoid at one point in his or her life.[7] Typhoid was caused by the bacterium *Salmonella typhi*, and was typically contracted by drinking water tainted by the fecal wastes of infected individuals. A common transmission might have gone something like this. The family of a typhoid victim dumped the patient's waste into a cesspool or privy vault. If the vault was too shallow or had leaks, it seeped into underground water sources. In turn, if these water sources were not adequately filtered, people who drew their water from them contracted typhoid. Typhoid rates in a given city or region were, therefore, highly correlated with the quality and extensiveness of water and sewerage systems.[8]

II.b. Living and dying with typhoid

Once they entered the body, typhoid bacilli had a one to three week incubation period. During incubation, an infected individual experienced mild fatigue, loss of appetite, and minor muscle aches. After incubation, the victim experienced more severe symptoms: chills, coated tongue, nose bleeds, coughing, insomnia, nausea, and diarrhea. At its early stages, typhoid's symptoms often resembled those of respiratory diseases and pneumonia was often present. In nearly all cases, typhoid victims

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[7] Troesken (2004).

[8] This paragraph is based on George C. Whipple, *Typhoid Fever: Its Causes, Transmission, and Prevention*, New York: John Wiley & Sons, 1908, especially pp. 21-69.

experienced severe fever. Body temperatures could reach as high as 105º Fahrenheit.

Three weeks after incubation, the disease was at its worst. The patient was delirious, emaciated, and often had blood-tinged stools. One in five typhoid victims experienced a gastrointestinal hemorrhage. Internal hemorrhaging resulted when typhoid perforated the intestinal wall and sometimes continued on to attack the kidneys and liver. The risk of pulmonary complications, such as pneumonia and tuberculosis, was high at this time. The high fever associated with typhoid was so severe that about one-half of all victims experienced neuropsychiatric disorders at the peak of the disease. These disorders included encephalopathy (brain-swelling), nervous tremors and other Parkinson-like symptoms, abnormal behavior, babbling speech, confusion, and visual hallucinations. If, however, the patient survived all of this, the fever began to fall and a long period of recovery set in. It could take as long as four months to fully recover. Surprisingly, given the severity of typhoid's symptoms, 90 to 95 percent of its victims survived.[9]

That typhoid killed only 5 to 10 percent of its victims might lead one to wonder just how significant this disease could have been for human health and longevity. But typhoid's low case fatality rate understates the disease's true impact, because when typhoid did not kill you quickly and directly, it killed you slowly and indirectly.

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[9] Whipple (1908), Curschmann and Stengel (1902, pp. 37-42), Sedgwick (1902, pp. 166-68). See also, Troesken (2004, pp. 23-36).

A simple way to illustrate this last point is by looking at the results of a study conducted by Louis I. Dublin in 1915. Dublin followed 1,574 typhoid survivors over a three-year period. Comparing the mortality rates of typhoid survivors to the mortality rates of similarly-aged persons who had never suffered from typhoid, he found that during the first year after recovery, typhoid survivors were, on average, three times more likely to have died than those who had never been exposed to typhoid, and that in the second year after recovery, typhoid survivors were two times more likely to have died than non-typhoid survivors. By the third year after recovery, however, typhoid survivors did not face an elevated risk of mortality. The two biggest killers of typhoid survivors were tuberculosis (39 percent of all deaths) and heart failure (23 percent). Other prominent killers included kidney failure (8 percent) and pneumonia (7 percent).

More recently, Case and Paxson (2009) present econometric evidence that early-life exposure to diarrhea and typhoid fever impairs cognitive functioning later in life. This finding is particularly important for the results presented in this paper, which show that increased exposure to typhoid as a child is associated with lower incomes and reduced educational attainment in adulthood. Along the same lines, Almond et al. (2012) and Costa (2000) show early-life exposure to disease can raise the probability of contracting diabetes, heart disease, and other chronic health problems later in life.

II.c. The eradication of typhoid fever

For much of the nineteenth century, people believed typhoid arose spontaneously or spread through miasmas — miasmas were poisonous atmospheres thought to rise from swamps, decaying matter, and filth. In 1840, William Budd challenged these ideas, showing that typhoid spread through water and food. Budd recommended investment in public health infrastructure to halt the spread of typhoid. However, scientists who continued to espouse the idea that typhoid arose spontaneously, or spread through miasmas, vigorously attacked Budd and his new theory. Because of their attacks, Budd's recommendations were not soon implemented, and typhoid rates in Europe remained as high as 500 deaths per 100,000 persons. It took more than three decades for Budd's theories and recommendations to take hold in England. In 1875, the British government passed the Public Health Act and began improving its public health systems. Ten years later, typhoid rates in England had fallen 50 percent.[10]

With the development of Budd's ideas in particular, and the germ theory of disease in general, public health officials in America and Europe came to agree: to control typhoid, cities needed to assure purity of drinking water through filtration and chlorination, and through sanitary sewage disposal. The experience of Pittsburgh, Pennsylvania highlights the effectiveness of water filtration in controlling typhoid fever. Pittsburgh drew its water from the Allegheny and Monongahela Rivers. Upstream from the city, seventy-five municipalities dumped their raw and untreated sewerage into the rivers, leaving Pittsburgh's typhoid rate higher than any other major U.S. city. Pittsburgh held this distinction throughout the late nineteenth century. Then, in 1899, Pittsburgh voters approved a bond issue for the construction of a water filtration plant. Unfortunately,

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[10] Budd (1918) and Melosi (2008, pp. 1-42; 60-61; and 110-13).

political bickering delayed completion of the plant until 1907. Once the plant was in operation, though, typhoid rates improved, and by 1912, they equaled the average rate in America's five largest cities.[11]

As Figure 1 shows, in the years before the introduction of filtration, typhoid rates in Pittsburgh averaged about 100 deaths per 100,000. Within two years, filtration had reduced typhoid rates in Pittsburgh by roughly 75 percent. And through subsequent improvements and extensions in the city's water supply, typhoid rates were brought down to around 6 deaths per 100,000 by 1920. This represented a reduction of about 95 percent from pre-filtration levels. As impressive as the Pittsburgh example is, it represents a typical response of typhoid fever to filtration.[12]

Water filtration was not the only effective mechanism at decreasing typhoid fever. The other panels of Figure 1 show that typhoid fell following the introduction of chlorination in Detroit, and the extension of water intake cribs away from the shoreline in Cleveland. In all cities, the introduction of water purification technologies was followed by sharp reductions in the death rate from typhoid fever (Melosi, 2002; Ellms 1913; Cutler and Miller, 2005). The introduction of sewers also had an effect on mortality rates (Kestenbaum and Rosenthal, 2014; Beemer, Anderton, and Leonard, 2005; and Ferrie and Troesken, 2005). Because cities used different technologies to purify their water, and because implementation

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[11] For a survey of the effectiveness of water filtration (and other modes of improving water quality) in reducing typhoid rates, see Whipple (1908, pp. 228-66). On the Pittsburgh experience, see Troesken (2004, pp. 27 and 56).

[12] See Cutler and Miller (2005); Melosi (2008, pp. 136-48); Whipple (1908, pp. 228-72); Fuertes (1897); Sedgwick and MacNutt (1910).

dates are not reported consistently, we use typhoid as a proxy for clean water rather than these technologies themselves.

Some observers have argued that just looking at typhoid, as we have done here, understates the benefits of water filtration because eradicating typhoid has broad benefits. Specifically, eradicating typhoid affected mortality from a broad class of diseases and illnesses. The non-typhoid death rates that were the most responsive to improvements in water quality were infantile gastroenteritis (diarrhea), tuberculosis, pneumonia, influenza, bronchitis, heart disease, and kidney disease.[13]

The experience of Chicago nicely illustrates how improving water quality not only reduced deaths from typhoid fever but also a broad class of diseases not usually considered waterborne. From the late-nineteenth century onward, Chicago's primary water source was Lake Michigan. Unfortunately, Lake Michigan was also frequently polluted with sewage, which carried disease-causing pathogens. This pollution occurred because for much of the nineteenth century the city dumped its sewage directly into the lake, or into the Chicago River which flowed into the lake. Over the course of the nineteenth and early twentieth century, Chicago took two important steps in trying to prevent fecal pollution from entering the city's water mains. The first step occurred in 1893, when the city opened the Four-Mile water intake crib, the Sixty-eighth Street water intake crib, and permanently closured all shoreline sewage outlets.[14] The second step

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[13] Cutler and Miller (2005), Sedgwick and MacNutt (1910), Ferrie and Troesken (2008).

[14] For these projects and dates, see Chicago Bureau of Public Efficiency (1917); and *The Daily Inter-Ocean* (Chicago), January 1, 1894, p. 13.

occurred in 1917, when the city opened the Wilson Avenue water intake crib and completed its citywide chlorination of the public water supply.[15]

The completion of these projects corresponded with sharp drops in the city's death rate from typhoid fever. This can be seen in Figure 2, which plots typhoid rates in Chicago from 1865 to 1925. There are two vertical lines, each corresponding to the aforementioned technological improvements promoting water purity. Note in particular the dramatic effects of the Four Mile and Sixty-eight street water intake cribs and the closure of shoreline sewage outlets in 1893. Before 1893, typhoid rates averaged 73 deaths per 100,000, and death rates were often as high as 100 to 150. After 1893, death rates never rose above 50, and shortly after the opening of the Chicago drainage canal in 1900, rates never rose above 25. The installation and extension of chlorination around 1917 drove down typhoid rates still further until rates were hovering around 0 by the early 1920s.[16]

These improvements in water quality were also associated with large reductions in deaths from diseases other than just typhoid fever. This can be seen in the second panel of Figure 2, which plots the total death rate excluding deaths from typhoid fever. Again, the vertical lines correspond to the two regime changes in the city's water supply. The

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[15] See Cain (1977, pp. 57); *Municipal and County Engineering*, Vol. LVI, No. 1 (Jan.-June 1918), p. 6; Chicago Bureau of Public Efficiency (1917).

[16] The link between improvements in the city's water supply and reductions in typhoid rates did escape notice in the medical press. See the *Medical News,* November 21, 1896, p. 586; *The Daily Inter-Ocean* (Chicago), January 1, 1894, p. 13; and *Bulletin of the Chicago School of Sanitary Instruction* (Chicago Department of Public Health), Vol. XV, No. 9, Feb. 27, 1921, p. 34.

patterns are striking. Although death rates appear to be trending downward almost from the start of the time series, that trend is modest and highly variable. The two most prominent changes in the death rate are associated with improvements in the city's water supply. After the closure of shoreline sewage outlets and the opening of two new intake cribs in 1893, the total death rate quickly fell to 1500 per 100,000, and never again even remotely approached levels between 2000 and 2500, which were commonplace before 1893. Another sharp discontinuity is observed in 1917 when death rates fell to around 1100. The year 1917, moreover, coincides with the completion of the city's water chlorination system.

One might argue that the decline in non-typhoid deaths was the result of other public health investments. However, Cutler and Miller (2005) show that death rates from pneumonia, diphtheria, and meningitis fell following the adoption of water purification technologies. Specifically, they estimate that for every one typhoid fever death prevented by water purification there were four deaths from other causes that were also prevented. Ferrie and Troesken (2008) present similar, though somewhat stronger, evidence along these lines. The available evidence suggests that these diseases improved with water filtration because typhoid was a virulent disease that left a person vulnerable to secondary infections even if he or she survived its direct effects.

III. DATA

Given the large literature showing how early-life exposure to disease impairs human capital formation, and given the observation that typhoid had large and diffuse health effects, one expects that typhoid would have also had large and diffuse effects on economic and social outcomes. To identify these effects we combine city-year level typhoid fatality data with a linked sample of males from the 1900 and 1940 censuses.

We obtain typhoid fatality rates in the late nineteenth and early twentieth centuries for 75 cities. This data was transcribed from Whipple (1908) as well as the 10th annual Census mortality statistics. Figure 3 maps the cities used in our analysis. These cities tend to fall within the top 100 in terms of population. In 1900, they had an average population of 225,364 and a median population of 94,969. The cities are predominantly located in the Northeast and the Midwest but include all regions of the continental United States.

As a measure of early-life exposure to contaminated water, we average typhoid rates during the year of birth, the year before birth, and the year after birth. Figure 4 visually displays typhoid rates and the three-year moving average for Boston, New York, Philadelphia, and St. Louis between 1890 and 1910. Our analysis will focus on the three-year moving average. This has two advantages. First, because typhoid rates are volatile, the moving average provides a better proxy for average water quality. As shown in Table 1 and discussed in section two, typhoid rates averaged over several years are a better predictor of water bacterial counts than instantaneous typhoid rates. Second, the three-year moving average roughly corresponds with the prenatal, neonatal, and postnatal periods, which captures exposure during early life. Figure 5 plots the distribution of average typhoid rates during early life. The distribution is skewed right with a mean of 41.72 deaths per 100,000. The domain ranges from 10.39 deaths per 100,000 to 217.96 deaths per 100,000.

We merge this typhoid fatality data to linked micro data. This dataset links individuals observed in the 1940 and 1900 censuses that were born between 1889 and 1900. We restrict our analysis to males who, at the time of the 1900 census, were living in a city for which we have typhoid data. Because we treat the city of residence in 1900 as the birth city, we drop any individual that was born in a state other than their state of residence in 1900. We believe this assumption is reasonable given that the sample would be at most eleven years old in 1900.

Summary statistics are reported in Table 2. Age, education, income, homeownership status, and whether the individual moved from their birth city are taken from the 1940 census. These outcome variables are measured during peak earning years (ages 40-51). The percent of blacks is small because we are looking at individuals born in cities before the Great Migration. The average individual in our sample spent their early life in a city with an average typhoid rate of 42 deaths per 100,000.

IV. RESULTS

IV.a. OLS results

In Table 3 we estimate the relationship between early-life typhoid and adult outcomes using the following equation:

$$y_{ijk} = \alpha + \beta Typhoid_{jk} + \gamma \mathbf{1}[black_i] + birth\ city\ FE's \tag{1}$$
$$+\ birth\ year\ FE's + birth\ order\ FE's\ +\ \epsilon_i$$

where the outcome for individual i born in city j during year k is either years of schooling, ln(income), homeownership status, or mover/stayer status in 1940. Typhoid is the average typhoid rate during early life for individuals born in city j during birth year k, where early life is defined as the year before birth until the year after birth. We cluster standard errors at the birth-city level. Each regression includes fixed effects for each birth city, birth year, and birth order. Because outcomes are taken from the 1940 census, controlling for birth year automatically controls for age. We find that typhoid during early life decreases educational attainment and adult income, but we find no effect on homeownership status or geographic mobility (mover/stayer status). These results indicate that if typhoid were eradicated, years of schooling would have increased by nearly one month and income would have increased by one percent.

To illustrate that these results are driven by early-life exposure and not exposure during other ages we estimate a variant of equation (1) that includes typhoid rates during the following years: 7 to 5 years before birth; 4 to 2 years before birth; 2 to 4 years after birth; 5 to 7 years after birth, as well as our measure of early-life exposure (1 year before birth to 1 year after birth). Figure 6 plots the 95 percent confidence interval for these estimates. Consistent with Table 3, Figure 6 illustrates that early-life typhoid rates are associated with a decline in education and income in adulthood. No other periods are significant. Furthermore, the estimated relationship between early-life typhoid exposure and adult outcomes is similar to the estimates presented in Table 3. Although not presented in

Figure 6, the effect on homeownership status and mobility remains insignificant.

IV.b. Semi-parametric results

A concern with the analysis above is that it imposes a linear relationship on the data when the data might in fact be related in non-linear ways. To address this concern, we estimate the relationship between typhoid and adult outcomes semi-parametrically. Specifically, we estimate the following equation:

$$\begin{aligned} y_{jk} = \alpha + f\left(Typhoid_{jk}\right) + \beta\left[black_{jk}\right] + \gamma\left[birth\ order_{jk}\ \right] \qquad (2) \\ + birth\ city\ FE's\ +\ birth\ year\ FE's +\ \epsilon_{jk} \end{aligned}$$

this equation is similar to equation (1) except that it does not impose a linear relationship between early-life typhoid exposure and adult outcomes. We non-parametrically estimate the relationship between early-life typhoid exposure and adult outcomes using linear partial regression. However, this requires a strict ordering of early-life typhoid rates. We achieve this by collapsing the data at the city-year level.[17] Since we collapse at the city-year level, $black_{jk}$ becomes the percent of the cohort born in city j during year k that is black, and $birth\ order_{jk}$ becomes the average birth order for individuals born in city j during year k.

Figure 7 presents the non-parametric estimates of $f(Typhoid)$. Early-life exposure to typhoid decreases adult earnings and educational

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[17] Linear partial regression requires that we can sort typhoid rates from lowest to highest. If we did not collapse at the city-year level, then there would be many individuals with the same early-life typhoid rates, and the estimates would be sensitive to the sorting order.

attainment above the 10th percentile of the early-life typhoid distribution. Moreover the relationship is approximately linear. Moving from the top of the typhoid distribution to eradication would have increased educational attainment by one-third of a year and increased earnings by about four percent. There does, however, appear to be a positive relationship between zero and 20 deaths per 100,000, but this constitutes less than ten percent of our sample.[18] Overall then, it appears that the linear model adopted in section *IV.a.* is appropriate.

IV.c. Two-stage least squares results

One might be concerned that typhoid during early life is endogenous. For example, investment in water filtration might be correlated with unobservable investments that also increase human capital. To address this concern, we implement an instrumental variables strategy. This strategy builds on the following logic: because typhoid is a waterborne disease, cities that dump their sewage into a river will increase future typhoid rates for cities downstream. Additionally, the typhoid rates in cities upstream should be exogenous to human capital investments in the receiving city.

Eighteen of the 75 cities used in the previous analysis lie downstream from another city for which we have typhoid data. We confirm flow direction for each river using data from the United States

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[18] This could also be due to survivorship bias (see Bozzoli, Deaton, and Quintana-Domeque, 2009).

Geological Survey.[19] Cities that are upstream (the feeder cities) dump their sewage into the river. This increases the typhoid rates in cities downstream (the receiving city). Thus, we use typhoid rates in the feeder city an instrument for typhoid rates in the receiving city. Whether we should use contemporaneous typhoid rates or the rates lagged by one year depends on the distance between the two cities and the flow rate of the river. We find similar results regardless of whether we use the contemporaneous or lagged typhoid rate, but lagged typhoid rates produce a stronger first stage.

Table 4 presents our results using lagged typhoid rates in the feeder city as an instrument for typhoid rates in the receiving city. Lagged typhoid rates in the feeder city are a strong predictor of typhoid rates in the receiving city; an additional 100 deaths per 100,000 in the feeder city increases the typhoid death rate in the receiving city by 8 in the following year. The F-statistics associated with this estimate range from 517.81 to 671.12 and therefore suggest that lagged typhoid rates from the feeder city are a strong instrument. In the second stage we find that typhoid rates during early life decrease educational attainment and earnings, although only the first estimate is statistically significant at the five percent level. The estimate on earnings, while imprecisely estimated, is consistent with the OLS estimates presented in Table 3. These results indicate that the eradication of typhoid would have increased schooling by nine months. Table 4 also indicates that high typhoid rates during early life reduced

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[19] Specifically, we identified flow direction using the USGS/National Map Streamer tool. This information is available as a web app at: http://nationalmap.gov/streamer/webApp/welcome.html

mobility, i.e. the likelihood that the individual would reside in their birth city as an adult.

V. COST-BENEFIT ANALYSIS

The previous section illustrates that eradicating typhoid fever would have increased educational attainment by one to nine months and income by one to nine percent. These estimates raise the question of whether the net present value of the increase in wages was enough to offset the costs associated with eradicating typhoid fever. Cutler and Miller (2005) have analyzed the benefits of adopting water purification technologies using the value of a statistical life and find that the benefits outweigh the costs by a ratio of 23 to 1. In our analysis, we ignore the gains from additional life years and instead focus on whether the discounted increase in earnings would have been sufficient to cover the costs of eradicating typhoid fever.

To analyze the benefits from typhoid eradication, we need the following information: the probability that an individual survives to a given age with and without the intervention, average income by age with and without the intervention, and the number of individuals in a cohort who would benefit from the water infrastructure. To analyze the costs, we need to know the total costs of municipal water systems and how frequently these systems need to be replaced. Lastly, to compare the net present values, we need real interest rates.

The survival probability, S_a, is the probability that an individual survives to age a. We use the survival probabilities for males born in 1900 from the Social Security life tables. Cutler and Miller (2005) find that mortality fell by 13% after the introduction of clean water technologies. Accordingly, we adjust the 1900 survival probabilities to reflect this change. We use the 1940 census to obtain the wage profile for males. Specifically, we obtain average earnings by age using a local polynomial smooth for all males. For the counterfactual wage distribution, we scale these averages by one to nine percent, which corresponds to the OLS and IV estimates reported in Tables 3 and 4. Figure 8 plots the baseline and counterfactual survival probabilities as well as the baseline and counterfactual wages. Eradicating typhoid fever has two effects on wages. First, it increases the average wage. Second, it increases the probability that an individual will survive until that age.

We assume that the average cohort of males born in a city is 20,000, which is approximately the number of males born in Chicago in 1900.[20] Finally, to obtain the costs we use the numbers reported in Cutler and Miller (2005), which assumes that the average cost of the waterworks for a large city was 22.8 million dollars in 1940 and that the waterworks must be replaced every ten years.

The previous assumptions underestimate the gains from eradicating typhoid fever. First, we assume that female earnings were unaffected by typhoid. Second, we assume that the only benefit from

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[20] We obtain 20,000 by taking the number of males in Chicago that were age 0 in the IPUMS 5% sample of the 1900 census and multiplying it by 20.

reduced mortality was increasing the probability of receiving future earnings. Third, we assume that the entire waterworks must be replaced every ten years, when in reality many parts are likely to function for longer. Furthermore, we assume that the construction of the waterworks was necessary to eradicate typhoid fever, but one could argue that the marginal cost of chlorinating or filtering water was sufficient to eradicate typhoid fever.

We calculate the benefits to eradicating typhoid fever using equation three, where $S_a{}'$ is the counterfactual survival probability and $W_a{}'$ is the counterfactual wage. The waterworks lasts T years, N is the cohort size, and r is the real interest rate.

$$NPV = \sum_{i=0}^{T} \frac{N}{(1+r)^i} * \sum_{a=0}^{101} \frac{(S_a{}'W_a{}') - (S_a W_a)}{(1+r)^a} \tag{3}$$

Figure 9 graphs these benefits for various interest rates for both the OLS and IV counterfactual wages. The horizontal line corresponds to the cost of eradicating typhoid fever, 22.8 million in 1940 dollars. Figure 9 shows that for our OLS estimates and any real interest rate under seven percent, the increase in earnings alone was sufficient to offset the cost of eradicating typhoid fever. For our IV estimates, the break-even real interest rate increases to ten percent.

VI. DISCUSSION AND CONCLUSION

Between 1900 and 1940 mortality in the United States fell by nearly 40 percent. Approximately half of this decline was the result of investment in water purification technologies and the eradication of waterborne diseases such as typhoid fever. There have been a number of previous studies estimating the social rate of return to water purification measures, but all of these studies focus on the gains associated with reductions in mortality (e.g., Cutler Miller 2005; Ferrie and Troesken 2008). Yet because typhoid was such a virulent disease and had such a low case fatality rate, there is good reason to believe that its effects on morbidity and long-term human capital formation were substantial. Accordingly, in this paper, we explore how eliminating early-life exposure to typhoid fever affected economic outcomes in later life. Our laboratory consists of urban residents in large American cities during the late-nineteenth and early twentieth century.

In our analysis, we explore how early life exposure to typhoid fever (our primary indicatory of water quality) influenced later life outcomes in terms of income, educational attainment, home ownership, and geographic mobility. Using parametric, semi-parametric, and IV approaches, our results indicate that the eradication of typhoid fever, which cities achieved by adopting clean water technologies, would have increased educational attainment by one to nine months and earnings would have increased by between one and nine percent. A simple cost-benefit analysis reveals that the increase in earnings from eradicating typhoid fever was more than sufficient to offset the costs of eradication. When one considers that our calculations ignore the changes in mortality captured by Cutler and Miller (2005) and other researchers, the evidence that investments in water purification have very high rates of social return seems unassailable. These results have important policy implications for developing countries that have yet to adopt water purification technologies.

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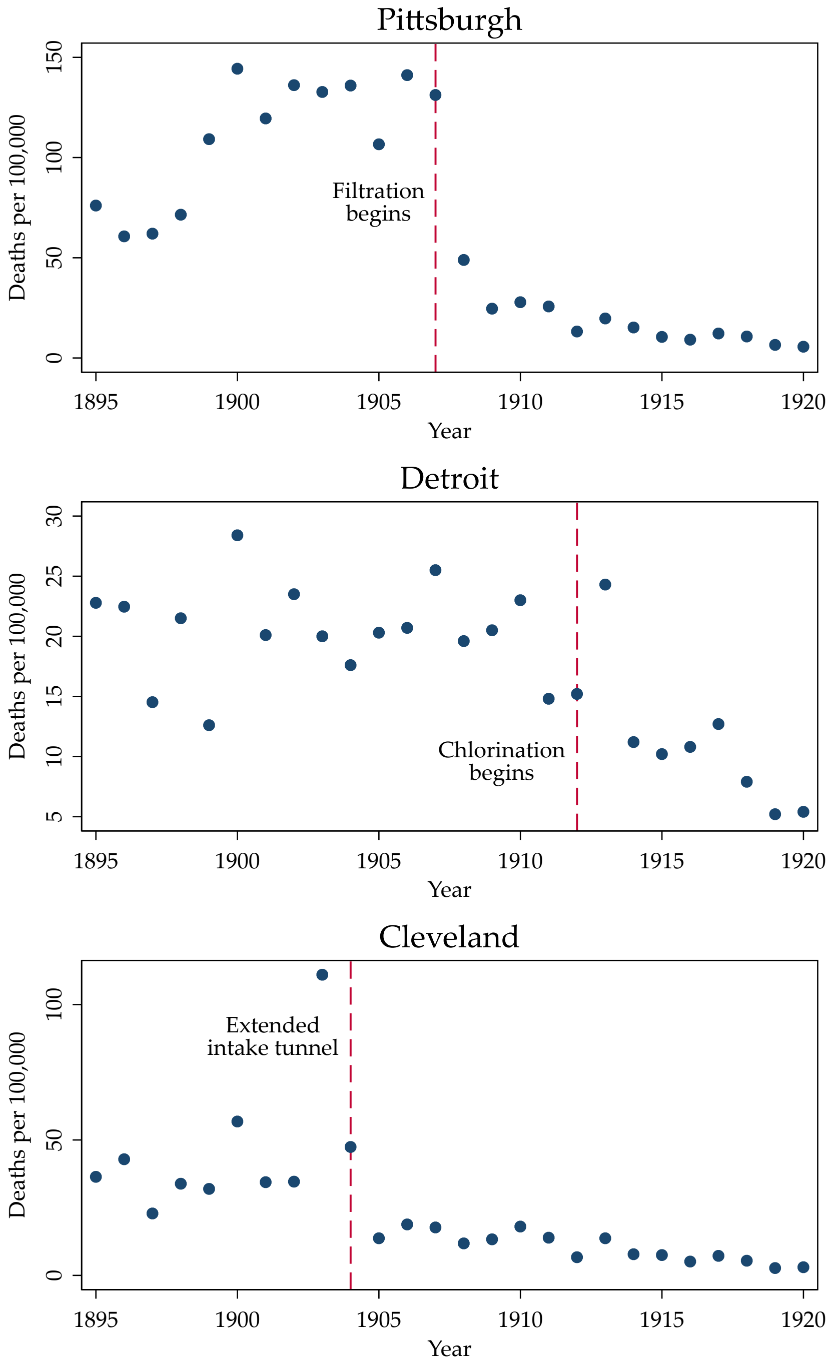
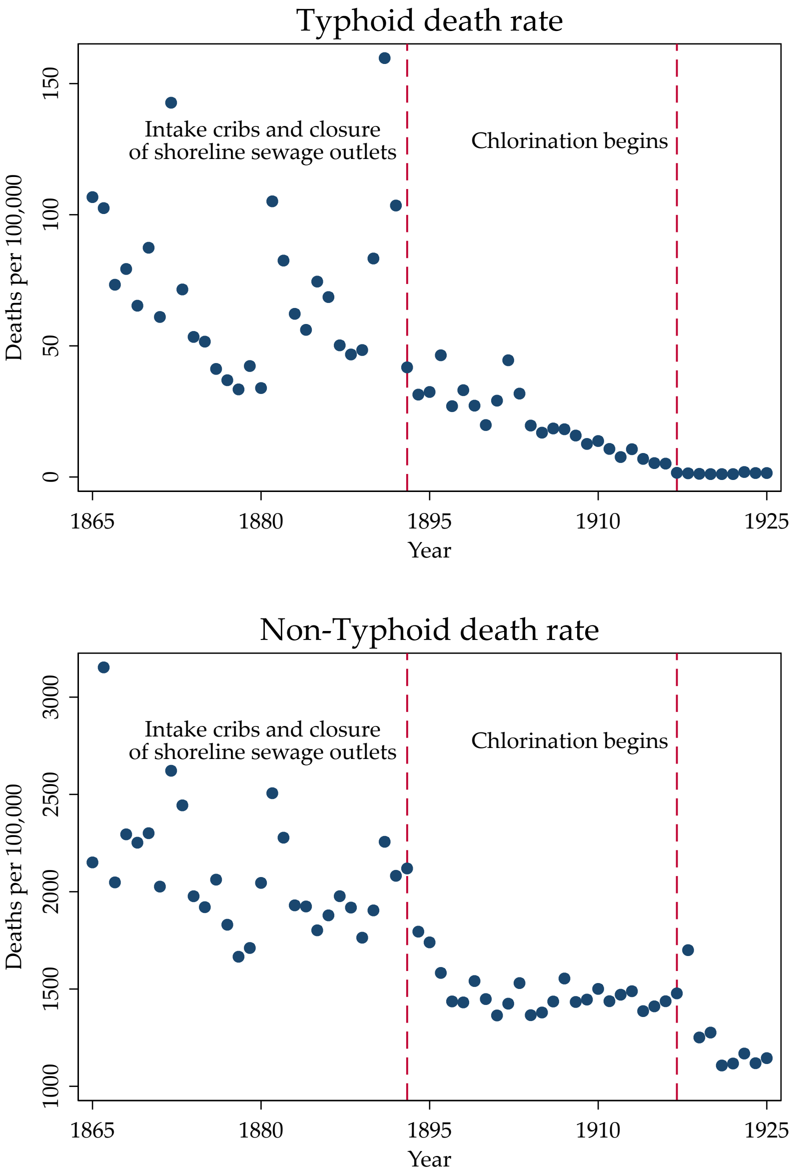
FIGURES AND TABLES

Figure 1: Typhoid death rates



Data from Whipple (1908) and the 10th annual census report on mortality statistics.

Figure 2: Death rates in Chicago



Data from Whipple (1908) and the 10th annual census report on mortality statistics.

Figure 3: Cities and rivers

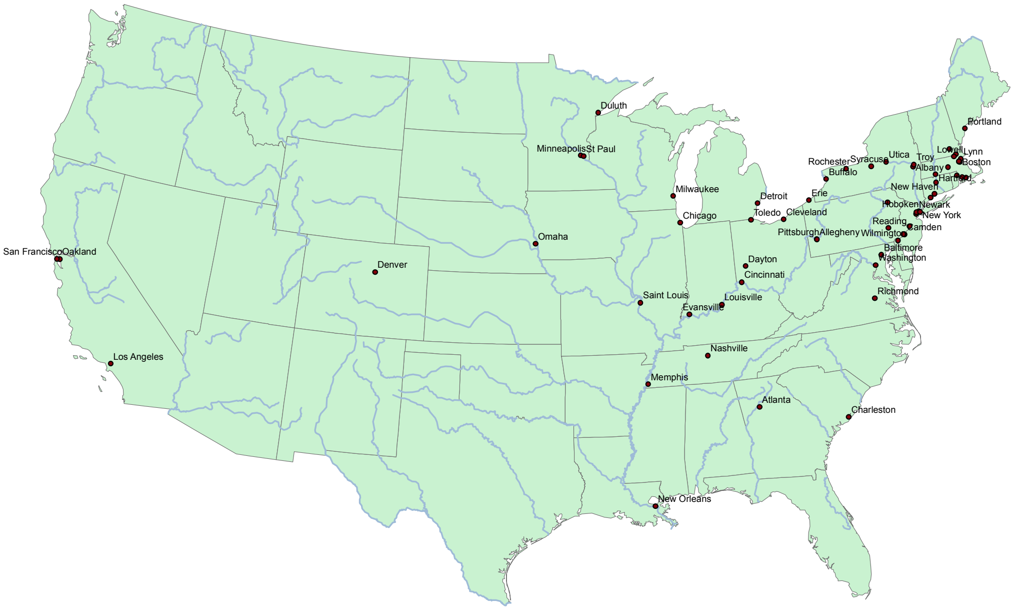
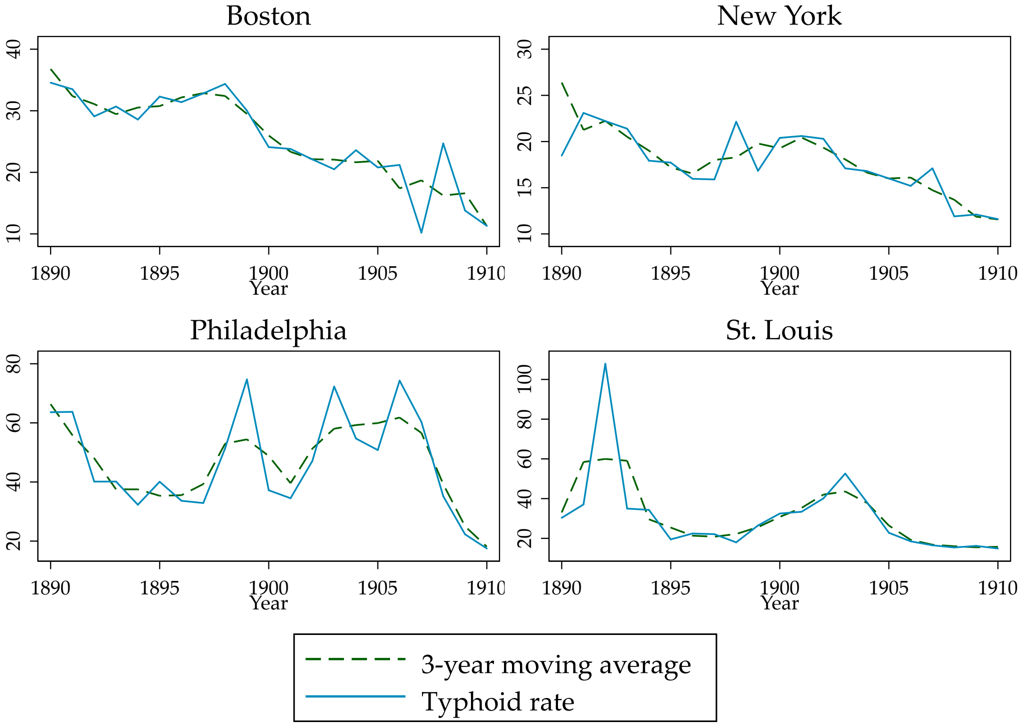
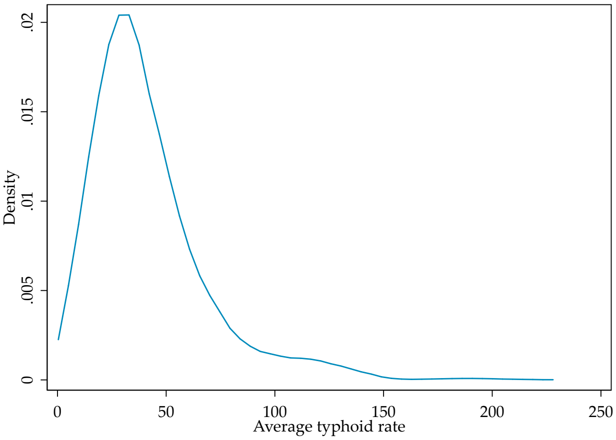


Figure 4: Typhoid rates



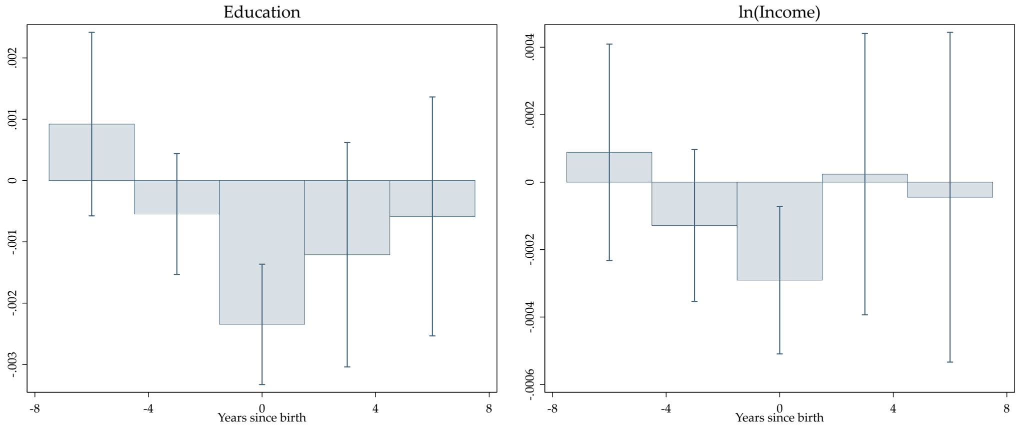
Notes: Data from Whipple (1908) and the 10th annual census report on mortality statistics. Typhoid fatality rate is the number of deaths per 100,000.

Figure 5: Distribution of typhoid rates during early life



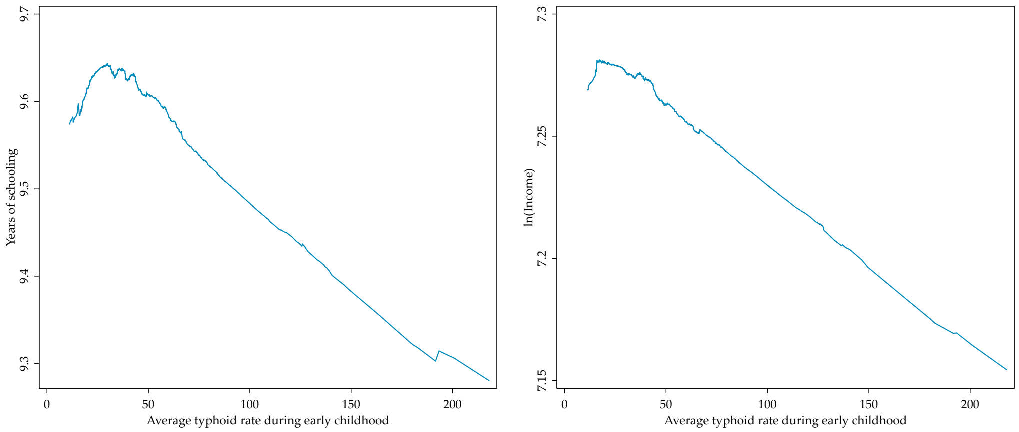
Notes: Average typhoid rate during early life is the average typhoid rate during the year before birth, the year of birth, and the year after birth. The average typhoid fatality rate is the number of deaths per 100,000.

Figure 6: The relationship between average typhoid rates at various stages and adult outcomes



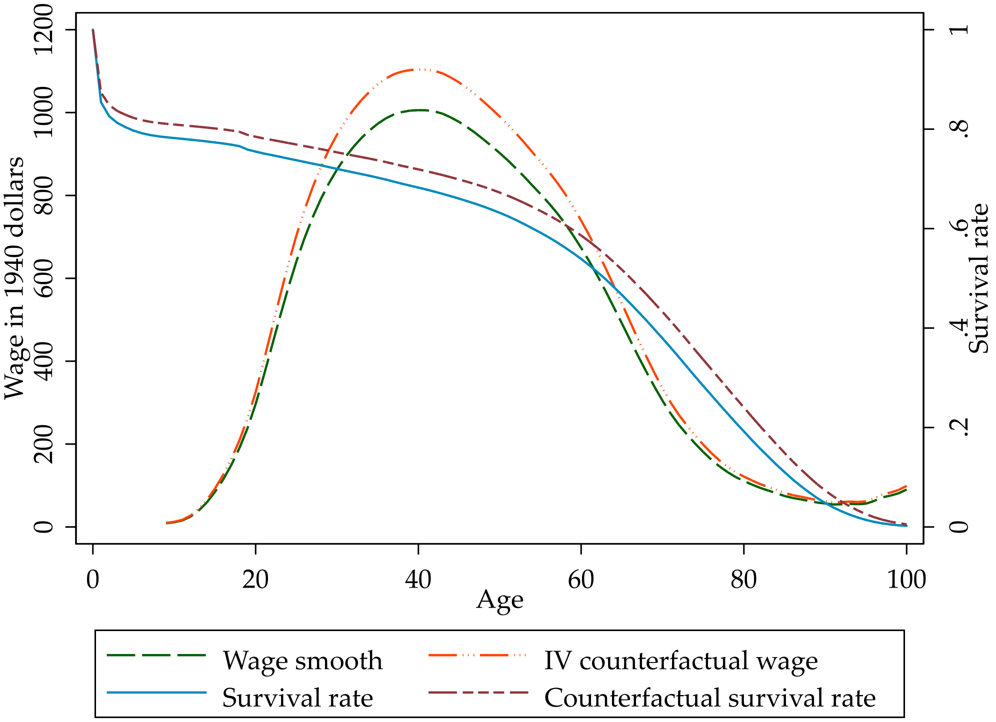
Notes: Each regression includes fixed effects for city of birth, year of birth, race, and birth order.

Figure 7: Semi-parametric estimates of the relationship between typhoid and adult outcomes



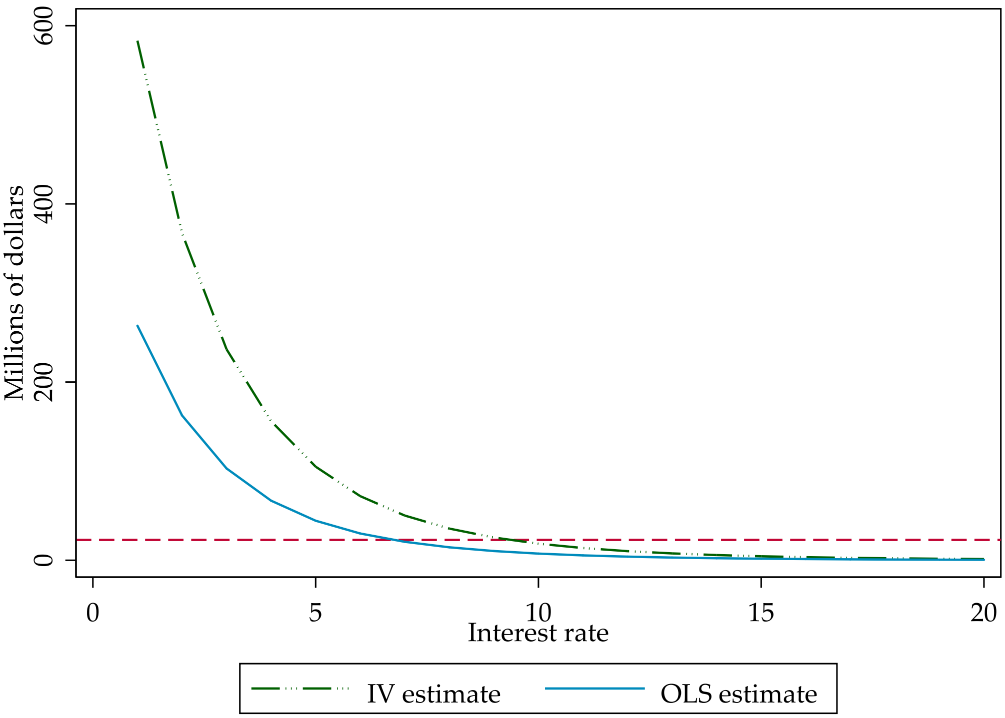
Notes: This figure presents the semi-parametric estimates from equation (2). The average typhoid rate during early life is the average typhoid rate during the year before birth, the year of birth, and the year after birth, and rate is the number of deaths per 100,000.

Figure 8: Earnings profile and survival curve



Notes: Survival rate obtained from Social Security Administration life tables for the 1900 male birth cohort. Wage obtained from IPUMS one percent sample of males in 1940. The counterfactual survival rate is adjusted using the estimated 13% decline in mortality rates reported in Cutler and Miller (2005). The IV counterfactual wage is adjusted using the 9% estimate from Table 4.

Figure 9: Net present value of typhoid eradication



Notes: The net present value of the benefits is obtained from equation (3) for various interest rates. The horizontal line corresponds to the estimated cost of the waterworks, 22.8 million dollars in 1940 (obtained from Cutler and Miller, 2005).

Table 1: Bacteria counts and typhoid rates

	Bacteria count	Mean bacteria count	Mean bacteria count
Typhoid fatality rate	21.8050		
	(14.4928)		
Mean typhoid fatality rate		18.1953*	18.9262***
		(8.3253)	(5.7220)
Constant	396.4265	907.6234	602.7608
	(793.3535)	(939.2506)	(692.9056)
Collapsed		Y	Y
Weighted			Y
Observations	41	13	13
R-squared	0.0662	0.0461	0.0757

Notes: Robust standard errors in parenthesis. In column one each observation is a city-year. In columns two and three each observation is the mean bacterial counts and mean typhoid rates by city. Column three weights each city by the number of years in the average. * p<.10; ** p<0.05; *** p<0.01

Table 2: Summary statistics

	Mean	SD	Min	Max	Observations
Age in 1940	45.09	3.38	40	51	189515
Education	9.47	3.16	0	17	184331
Income	1511.99	1302.85	0	5001	176821
Homeowner	0.48	0.50	0	1	153932
Moved from birth city	0.61	0.49	0	1	189515
Black	0.03	0.17	0	1	189515
Birth order	2.97	2.12	1	91	189515
Typhoid rate during early life	41.72	25.63	10.39	217.96	189515

Notes: Age, education, income, homeowner status, and whether the individual moved from their birth city are taken from the 1940 census. Birth order was reported in the 1900 census. Although the maximum of 91 is likely a typographical error, the 99th percentile of birth order, which is 10, is plausible. Typhoid rate during early life is the average typhoid rate in the birth city from one year before birth, the year of birth, and one year after birth.

Table 3: The relationship between typhoid and adult outcomes

	Years of schooling	ln(income)	Homeowner	Mover
Average typhoid rate during early childhood	-0.0022***	-0.0003**	-0.0000	-0.0001
	(0.0005)	(0.0001)	(0.0001)	(0.0001)
Black	-1.7273***	-0.7135***	-0.2424***	0.0294
	(0.1722)	(0.0295)	(0.0197)	(0.0256)
Birth year fixed effects	Y	Y	Y	Y
Birth city fixed effects	Y	Y	Y	Y
Birth order fixed effects	Y	Y	Y	Y
The average effect from eradicating typhoid†	0.0912***	0.0128**	0.0000	0.0041
	(0.0227)	(0.0050)	(0.0027)	(0.0047)
Observations	184331	141857	153932	189515
R-squared	0.053	0.038	0.039	0.238

Notes: Robust standard errors (clustered at the city level) reported in parentheses. * p<.10; ** p<0.05; *** p<0.01

† The average effect from eradicating typhoid is calculated by multiplying the negative of the coefficient by the average typhoid rate during early life (41.72 deaths per 100,000)

Table 4: 2SLS estimates of early-life typhoid on adult outcomes

	Years of schooling	ln(income)	Homeowner	Mover
Instrumented typhoid rate	-0.0189**	-0.0023	0.0014	-0.0025*
	(0.0091)	(0.0025)	(0.0016)	(0.0013)
Average effect from	0.7869**	0.0976	-0.0578	0.1037*
eradicating typhoid†	(0.3802)	(0.1035)	(0.0655)	(0.0562)
Observations	73496	56254	61398	76085
R-squared	0.048	0.042	0.032	0.088
First stage				
Lagged typhoid rate in	0.0872***	0.0921***	0.0883***	0.0881***
feeder city	(0.0035)	(0.0040)	(0.0038)	(0.0034)
F-statistic	628.124	517.813	542.895	671.12
Observations	73496	56254	61398	76085
R-squared	0.757	0.757	0.759	0.755

Notes: Robust standard errors reported in parenthesis. Each regression includes fixed effects for city of birth, year of birth, race, and birth order. * p<.10; ** p<0.05; *** p<0.01
† The average effect from eradicating typhoid is calculated by multiplying the negative of the coefficient by the average typhoid rate during early life (41.72 deaths per 100,000)