Small-Scale Rural Water Supply, Typhoid Eradication, and Human Capital Development

Abstract

Small-scale water purification facilities are economically viable for developing countries with limited capital and skills and with a high proportion of rural population to supply safe drinking water. However, their effectiveness has been under-studied. Using the case of Korea in the 1960s, this study investigates the effects of small-scale water supply interventions on population health and human capital formation. By exploiting the timing and geographic variations in the installation of small-scale water facilities, we estimate that the intervention substantially reduced the incidence of typhoid fever, and that eliminating early-life exposure to typhoid fever was beneficial to human capital formation.

Keywords: small-scale water supply system, typhoid fever, early-life condition, human capital formation

JEL codes: I15, I25, O10, Q56, R11

1. Introduction

Approximately 800 million people, or one-ninth of the world's population, did not have access to safe drinking water in 2015 (World Health Organization, 2015). As a result, around 80% of the diseases in developing countries are waterborne ones, such as typhoid fever and cholera, which are generally caused by contaminated drinking water. Children, including fetuses, are especially vulnerable to these diseases. Therefore, providing safe drinking water is significant for preventing waterborne diseases and improving population health, particularly in developing countries.

Economic studies have revealed that clean water policies have been successful in the past. Around 1900, advanced countries such as the United States, Germany, the UK, and France began introducing large-scale water purification facilities in large cities. Using those historical experiences, previous studies have shown that such efforts significantly reduced mortality due to waterborne diseases (Alsan and Goldin, 2019; Beach et al., 2016; Brown, 1989; Cutler and Miller, 2005; Ferrie and Troesken, 2008; Kesztenbaum and Rosenthal, 2014; Preston and van de Walle, 1978; Szreter, 1988). It has also been suggested that such clean water policies are cost effective (Ferrie and Troesken, 2008; Watson, 2006; Hutton et al., 2004). Some studies have also investigated whether introducing water purification facilities were effective for human capital accumulation, measured by educational attainment and income in adulthood. Specifically, this beneficial effect was estimated to be greater when clean drinking water was provided in early life than in adulthood (Ao, 2018; Beach et al., 2016; Zhang and Xu, 2016). These findings highlight the economic validity of clean water policy.

The above historical experiences of advanced countries provide important implications for developing countries today. However, it is not as easy for today's developing countries to adopt such large-scale purification facilities as the advanced countries did in the early 20th century. Such water supply systems require sophisticated technology and significant capital investment, which is not practical in rural areas with small populations. Therefore, the introduction of small-scale purification facilities that require fewer skills and capital and can cover a small population economically, has been suggested for developing countries. In short, small-scale water chlorination facilities are more economically feasible for developing countries than large-scale ones. However, the feasibility of such small-scale facilities depends on their effectiveness in improving public health and human capital formation. Therefore, using the experience of Korea from 1960-1984, this study thus aims to investigate the long-term effects of introducing small-scale water chlorination systems in rural areas, which had been little explored in the literature.

To address the shortage of purified water in rural areas, the Korean government introduced small-scale water supply systems in the late 1960s by installing chlorine purifiers in villages' communal tap water facilities (Cho, 2013). This intervention improved rural residents' access to chlorinated water. Although each of the facilities covered extremely small populations, the adoption of this system greatly contributed to disease control, especially in areas considered vulnerable to waterborne diseases. Subsequently, throughout the early 1970s, Korea experienced a dramatic decrease in typhoid fever incidence and also observed a substantial increase in human capital and economic productivity, which have been considered key determinants of the rapid economic growth over that period. This study demonstrates how the introduction of small-scale water supply facilities improved public health and human capital formation in rural areas.

We use a difference-in-differences framework to estimate the causal effects of such small-scale water supply interventions on typhoid-fever incidence. Specifically, our estimation relies on the timing and regional variations in adopting the facilities. The key finding is that the introduction of small-scale water supply systems substantially lowered the incidence of typhoid fever within a few years. The estimates from our preferred specification, which controls for various local conditions, fixed effects, and time trends, suggest that the decrease in typhoid fever cases caused by small-scale water supply interventions accounts for approximately 30% of the total decline in this period. Additionally, using cohort studies, we find that early-life exposure to typhoid was detrimental to human capital formation in the long term. It is also estimated that the magnitude of the effects on educational attainment was more substantial for secondary education than for primary education and for females than males. We discuss that these results are closely associated with the education-labor transition and with the cognitive ability required for achieving a higher education level. Moreover, we develop a novel identification strategy to allay concerns of omitted variable bias, namely unobservable investments related to human capital formation. We use the humidity in summer to instrument for typhoid exposure in early life. The results from the instrumental variables identification strategy strengthen the ordinary least squares estimates with larger effects.

The rest of this paper is organized as follows. In Sections 2 and 3, we discuss the previous literature related to our study and the Korean background of water supply interventions after the Korean War, respectively. In Section 4, we estimate the effect of a small-scale water supply system on typhoid occurrence. In Section 5, we analyze the long-term effect of typhoid eradication on human capital development. In Section 6, we conclude and discuss the implications of the study from the perspective of development economics.

2. Literature Review

Many historical studies have revealed that the efforts toward providing safe drinking water were effective in improving population health. For instance, using the experience of the early 20th-century USA, Cutler and Miller (2005) demonstrate that typhoid mortality dropped by 25% in 13 cities after they adopted water purification facilities. Beach et al. (2016) show that water filtration reduced typhoid death rate by 17–48% during an earlier period (1880 to 1920) for 61 US cities. In addition, Ferrie and Troesken (2008) estimate that 35–56% of mortality reduction in Chicago from the late 19th century to the early 20th century can be attributed to water purification and the subsequent decrease in other types of infections. They further stress that the social rate of return on those investments far exceeded their cost.[1] Alsan and Goldin (2019) estimate that the introduction of sewerage significantly reduced child mortality in Massachusetts during 1880–1920.

There are also studies on the experiences of European countries. For example, Brown (1989) studies the case of German cities in 1890–1910 and finds that around 40% of the decline in childhood mortality over this period can be explained by the improvements in public water and sewer systems. Szreter (1988) re-analyses McKeown's (1979) research, pointing to the role of proper water supply and waste disposal systems in declining mortality during 1850–1914 in England and Wales. Preston and van de Walle (1978) attribute the decline in child mortality in 19th-century France to improved water supply and sewage disposal. In a similar vein, Kesztenbaum and Rosenthal (2014) identify the improvements in water infrastructure as the cause of an increase in life expectancy in Paris during 1880–1914.

The question is how the supply of safe drinking water can improve human capital formation. Many studies have argued that the control of diseases in early life is crucial for enhancing the level

[1] However, they only considered the estimated number of lives saved by eradicating typhoid fever, not the improvement in productivity due to the health gains. Therefore, they argue that for the conservative or lower bound estimates of the social rate of return.

of human capital because it can improve nutritional status and school attendance (Almond and Currie, 2011; Almond et al., 2018; Barker, 1998; Davis and Sandman, 2010; Fogel and Costa, 1997; Heckman, 2007). Specifically, the eradication of waterborne diseases improves the return of human capital investments by reducing the chronic disease burden and increasing the subsequent nutritional status (Arthi, 2018), which is substantiated by the theoretical discussions of Behrman and Deolalikar (1988) and Bleakley (2010a). Supporting this argument, some studies have empirically shown that the supply of safe drinking water and reduction in waterborne diseases as its consequence played an important role in improving human capital accumulation. For example, Beach et al. (2016) utilize typhoid mortality as an indicator of water quality, exploring how early-life exposure to typhoid fever can deteriorate later-life outcomes, such as educational attainment and income in adulthood. Targeting a similar period in the USA, Ao (2018) directly estimates the effects of introducing water filtration plants on school enrollment and adolescent labor participation. In addition, Zhang and Xu (2016) show the educational benefits to rural youth in China from a piped water treatment program in the 1980s. They find that the program increased the average school years by 1.1 years among rural youth.

3. Water Supply Interventions after the Korean War: Historical Background

In the 1950s and 1960s, the water supply in Korea was insufficient, as the Korean War destroyed most of the related infrastructure. The estimated damage caused by the war was the destruction of 30–90% of water purification plants, 5–10% of water pipes, and 60–80% of pumping stations (Cho, 2013).[2] Therefore, it was of paramount importance to recover from the

[2] The estimated damage in Seoul amounts to USD 28,785,000 in 1953 dollars (Cho et al., 2008).

ravages of war and develop water supply system techniques. Water supply facilities began to be gradually introduced from the early 1960s when the first national plan of economic development was established. During this period, the clean water supply was quantitatively expanded through the construction of large-scale piped waterworks (hereafter, large-scale waterworks) (Cho et al., 2008).[3]

Large-scale waterworks required high levels of technology and capital. Therefore, the central government strategically engaged in their expansion through a public corporation (the Korea Water Resources Corporation or K-Water).[4] These were mainly provided to urban cities and industrial areas since this water supply system was more economical for dense populations. This is because the high-density housing reduced the cost of the water supply per household (Choi and Lim, 2015). For these reasons, it was difficult to install large-scale waterworks in rural areas, which lead to a wide gap between urban cities and rural areas in piped-waterworks coverage (See Appendix Figure 1). As such, rural residents relied on traditionally dug wells or used water from natural springs. The wells on which the majority of the farmers depended on were shallow aquifers and were located in residential areas. Hence, they were likely contaminated by adjacent toilets, housing, and sewage (Cho, 2013). Since these water sources were used without being sterilized, residents were easily exposed to unsanitary conditions (Kim, 1992). This led to problems such as the frequent outbreaks of waterborne diseases.

To address these issues, from 1967, the government started the installation of small-scale water supply systems (hereafter, small-scale systems) in rural areas as a part of the local

[3] The water supply ratio rapidly increased from 20% in 1961 to 78.4% in 1990 according to the authors' calculation.

[4] The intervention through the public corporation (K-Water) enabled the government to directly engage in the water supply policy, while taking advantage of corporate instead of public finances (Koun, 2009).

community development policy.[5] Moreover, with the Five-Year Economic Development Plan and the New Village Movement in the early 1970s, small-scale water supply projects in rural areas had begun being promoted in earnest. Unlike the large-scale waterworks supplied by the central government and operated through the public corporation, the provision of small-scale systems was made under the guidance of the Ministry of Health and Human Services (now, the Ministry of Health and Welfare Affairs) with the participation of local residents. Specifically, villages from a city or county requested to receive the installation of a small-scale system and the New Village council in each city or county reviewed and set the budget allocation priorities (Cho, 2013).[6] With the active engagement of the demand side (i.e., residents of rural areas), the supply of small-scale systems increased rapidly throughout the nation in the 1970s and 1980s—especially, during the early 1970s (See Panel B of Figure 2).

There are several reasons why small-scale systems could be expanded particularly in the rural areas of Korea.[7] First, they were easy, fast, and cheap to install. Compared to the large-scale waterworks which were constructed over several years, small-scale systems only took around 6 months to be installed, having relatively low costs. Therefore, it was possible to immediately reflect the necessities of locals. Additionally, by using a small-scale system, the water was directly supplied from water tanks with chlorination disinfection. Hence, this system had the advantages of low maintenance costs and was easy to manage and operate compared to the filtration process used in large-scale waterworks. In sum, it was more desirable for rural residents to select these

[5] Cho (2013) discusses in detail the small-scale system in Korea, but with less emphasis on the quantitative analysis.

[6] The first priority rule of allocation was to install facilities in the area in which waterborne diseases had occurred, or which was considered vulnerable to waterborne diseases (Cho, 2013).

[7] We compare the characteristics of large-scale waterworks and small-scale system in Table A1 in Appendix A.

economical, reasonable, and small-sized on-site treatment systems that were also easy to install and maintain (Cho, 2013).

4. Small-Scale Water Supply and Reduction of Typhoid Fever Cases

4.1. Data and Key Variables

We collected district-year level aggregated data on typhoid incidence, large-scale waterworks, and small-scale systems to explore the impact of each water supply type. First, we relied on the *Statistical Yearbook* by each province and each district (for 1960–1969 and 1979–1984) and the *Yearbook of Public Health and Social Statistics* (for 1970–1978) to measure the severity of typhoid fever in each region by year. Second, data related to large-scale waterworks also come from the *Statistical Yearbook*. Specifically, we selectively hand-collected records on population, incidence of infectious diseases (mainly, typhoid fever and diphtheria), and waterworks supply population by year and district. Third, we exploited a record of small-scale systems compiled by the Ministry of Environment in 2009.[8] This record provides information on the names of facilities, addresses, installation year, capacities, resource of water, and methods of water processing.

From these sources, we construct district-year panel data from 1960 to 1984.[9] Since the information on typhoid incidence during 1960–1984 is consistently available only for the 114 districts shaded in Figure 1, our analyses below focus on these districts. The 114 districts cover around 73% of the total of the 156 administrative districts in 1980. However, our additional

[8] The data are available at http://www.me.go.kr/.

[9] The geographic units in this paper are city and county (*Si* and *Gun* in Korean). Due to the changes in administrative boundaries, we aggregated some cities and counties based on the 1980 administrative area codes. In Table A2 of Appendix A, we provide an example of *Changwon-Si* (city) of *Gyeonsangnam-Do* (*South Gyeongsang* province) to explain how we construct the aggregated city and county groups.

analysis in Appendix A shows that the selected districts are nationally representative in terms of typhoid fever.[10] The comparison between (urban) cities and (rural) counties is crucial in our study. The 114 districts consist of 25 cities (*Si* in Korean) and 89 counties (*Gun* in Korean). This geographic classification is mainly based on population size and urbanization.[11] The average population during our analysis period is 630,000 for cities and 140,000 for counties.

[Figure 1 Here]

Figure 2 shows the percent of sample districts that adopted each water supply technology (large-scale waterworks in Panel A and small-scale systems in Panel B) and the trends of typhoid fever incidence (Panel C) from 1960 to 1984 for the 114 sample districts. The first notable feature is the large gap in the large-scale waterworks between cities and counties: for example, 24 out of 25 cities had already adopted large-scale waterworks by 1963 but only 20 out of 89 counties had introduced this system. Second, the initial adoption of small-scale systems increased sharply from 1970-1972, particularly in counties, while large-scale waterworks were gradually introduced during the same period. Finally, there was a difference in typhoid incidence between city and county areas during the 1960s, and the incidences in both areas and their gap dramatically decreased throughout the 1970s.

[Figure 2 Here]

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[10] Figure A2 in Appendix A shows that the entire nation has similar trends with the sample regions. Therefore, we assume that our sample regions are representative for the Korean case.

[11] According to Article 5 of the Local Autonomy Act in 1973, "A *Si* or *Eup* shall be in an urban form in most parts and shall have a population of at least 50,000 for *Si* and 20,000 for *Eup*, respectively."

Interestingly, we can find that the period of rapid decline in typhoid fever coincides with the proliferation of small-scale systems in the early 1970s. Even though each of the facilities covered extremely small populations (less than 2,500 people according to the Water Supply and Waterworks Installation Act in Korea)[12], the adoption of these systems may have greatly contributed to waterborne disease control because the first priority of allocation was to install them in areas vulnerable to waterborne diseases (Cho, 2013). Therefore, the benefits of small-scale systems are both direct and indirect. The local residents in a village where a small-scale system was adopted could enjoy chlorinated drinking water free from the danger of waterborne diseases (direct benefit), while the neighboring villages where small-scale systems were not yet adopted could get the positive externality of the lowered threat of waterborne diseases (indirect benefit).[13] Therefore, the implementation of small-scale systems in a few villages can decrease the risk of waterborne diseases in the district (city or county) even if only an extremely low portion of local residents actually use the system. Figure A1 in Appendix shows the hypothetical penetration rates of small-scale systems were below 20% even in the last year of the sample period.[14] However, the penetration rates are not an appropriate measure for our study because they only consider the direct use of small-scale systems and cannot capture the indirect benefit (reduction of waterborne

[12] The Act mentions that a small-scale system is classified into 20–500 m^3/day for populations of 100-2,500 people and less than 20 m^3/day for populations of less than 100 people.

[13] The bacteria (*Salmonella enterica serotype Typhi* bacteria) are deposited in water or food by a human carrier and are then spread to other people (Cabral, 2010).

[14] 14 out of 89 counties initially adopted small-scale systems in 1971 and 29 counties adopted in 1972, which means 43 out of 89 counties (nearly 50% of total) initially introduced small-scale systems in these two years. However, in regard to penetration rates, there was only a less than 1% increase in 1971-72.

diseases in nearby villages) of the spatial spread of facilities.[15]

4.2. Transition of Typhoid Incidence

Here, we estimate the effects of a small-scale system on typhoid fever incidence. Our empirical analysis relies on a difference-in-differences approach by using variations across districts and years. A possible concern regarding this method is the differential trends on the outcome variable in the pre-treatment period. Specifically, there is a concern that districts might have begun to install water supply facilities in response to specific events, such as a high incidence of waterborne diseases. If the incidence was systematically high before the adoption of each system, this would cause our estimates to capture a mean-reversion. If it had been low, the secular trend of typhoid incidence likely confounds our estimates.

To verify the above concerns, we examine whether the trends of typhoid fever incidence were common across districts in the pre-treatment period. The idea is to compare typhoid incidence before and after the introduction of water supply facilities in each district. The estimation equation is as follows:

$$T_{jpt} = \sum_{k=-2}^{5} \beta_k D_{jt}^{k}(t - i_j = k) + X_{jt}'\Gamma + Z_{pt}'\mathrm{H} + \delta_j + \delta_t + time + \varepsilon_{jpt}, \qquad (1)$$

where T_{jpt} denotes the typhoid incidence per 100,000 residents in district j (of province p)

[15] A village is a smaller administrative unit than a city or county. One caveat of this study is that each small-scale system facility was installed for use in a village, but our unit of analysis (city and county) does not allow us to investigate the role of this system within the village. Hence, we use the information whether each district had begun small-scale system intervention to measure both direct and indirect effects. Previous studies also used this strategy when evaluating the treatment effect of water supply infrastructure (e.g., Cutler and Miller, 2005; Ferrie and Troesken, 2008; Beach et al., 2016; Alsan and Goldin, 2019).

during calendar year t. We define $D_{jt}^{k}(t - i_j = k)$ as dummy variables that indicate the years before or after the intervention, where i_j is the starting year of the intervention in district j.[16] Specifically, we control for the variables that indicate 1 and 2 years before intervention ($k = -2$ to -1), year of the intervention ($k = 0$), 1 to 4 years after intervention ($k = 1$ to 4), and 5 or more years after intervention ($k = 5$). We omit the dummy variable that indicates 3 or more years before the intervention ($k = -3$) as the reference group. Column vector X_{jt} includes year- and district-varying controls, namely population and weather-related variables such as summer averages of humidity and precipitation.[17] Z_{pt} represents a vector of the province-level time varying covariates, namely rice output, number of deaths, and number of primary schools by population.[18] We also controlled for year and district fixed effects, δ_t and δ_j, to eliminate potentially confounding year-specific changes and district-specific conditions, respectively. $time$ has province-specific linear time trends to reflect systematically different trends in typhoid fever

[16] In the case of capturing the intervention of large-scale waterworks, we construct the treatment variable as to detect a relatively large and sudden increase in the penetration rate, as Zhang and Xu (2016) did. We code a district in a particular year as being covered by the intervention based on two conditions: (1) initial intervention year is included in our analysis period or (2) initial intervention year is not identified during 1960–1984, but penetration rate increase by more than 10 percentage points compared to the previous year.

[17] We collected the variables-related meteorological conditions from the Korea Meteorological Administration. This dataset provides daily and monthly mean temperature, mean relative humidity, and accumulated precipitation according to weather stations that had existed during 1960-1984. However, not every district had weather stations in this period. For example, there were 64 weather stations in 1980. Thus, we need to interpolate weather variables for districts without weather stations for the sample periods. For this purpose, we first regress available weather stations' weather variables on various geographical information at weather station level, including latitude, longitude, elevation, the nearest distance from shoreline, and their interaction terms. Then, we plug the same control variables calculated for the centroid of each district into the estimated equations to interpolate weather information for all the districts. Using this method, we estimate monthly mean temperature, monthly mean humidity, and monthly accumulated precipitation by district for every month in the sample periods. In the empirical analysis, we use the averages for humidity from June to August, which reflects typhoid's characteristic that tends to be concentrated in the humid summer season in Korea, and the averages for temperature and precipitation from May to September in considering the rice cultivation period (Hong, 2017).

[18] The province-level variables of rice output, number of deaths, and number of primary schools are compiled from *Statistical Yearbook* of each province.

and other province-level economic conditions at the province level.[19] We cluster standard errors at the district level.

[Figure 3 Here]

Estimated coefficient $\widehat{\beta_k}$s, which measures how much the incidence rate of typhoid fever in each relative year k deviated from the rate of the 3 or more years before the intervention, is shown for 95% confidence intervals in Figure 3. We estimate the coefficients for urban cities and rural counties and for the intervention of the small-scale systems and large-scale waterworks separately. There is no significant result for large-scale waterworks, even after the intervention in both counties and cities (right-hand figures in Panels A and B). Moreover, the results for the small-scale system of the city sample also do not significantly deviate from 0 (left-hand figure in Panel B). Since cities rarely adopted small-scale systems, they were unlikely to benefit from them.

We expect that the effects of a small-scale system would be much larger in counties mostly consisting of rural towns. In the left-hand figure in Panel A, the coefficients on the leads are close to zero (x-axis $= -2$ to -1), supporting that the typhoid incidence rates were not systematically high or low right before rural counties adopted small-scale systems. The figure also shows that the coefficient significantly deviated from 0, starting from the time of introduction. For 4–5 years after the introduction, the rate of typhoid incidence declined to about 5 per 100,000 inhabitants. This strongly suggests that the intervention through small-scale systems substantially led to the decline of typhoid fever in rural areas. The effects, moreover, increased with time, probably as a result of

[19] One might suggest that we use district-specific linear trends. The results are robust for the inclusion of district-specific linear trends. The results are available upon request.

the additional installation of the small-scale systems in other villages within the counties.[20]

4.3. Treatment Effects of Small-Scale Water Supply on Typhoid Fever Incidence

Next, we estimate the average effects of small-scale system interventions on typhoid incidence. We rely again on a difference-in-differences approach as follows:

$$T_{jpt} = \beta Post_{jt} + X_{jt}'\Gamma + Z_{pt}'\mathrm{H} + \delta_j + \delta_t + time + \varepsilon_{jpt}, \tag{2}$$

where $Post_{jt}$ is a dummy variable that indicates where small-scale system had been introduced in county j in year t.[21] All other specifications are the same as in equation (1).

Table 1 summarizes the results of estimating equation (2).[22] All regressions control for year and district fixed effects. In Panel A, the results strongly suggest that small-scale system interventions reduced typhoid fever incidence during 1960–1984 in county regions. Column (4), which is our preferred specification, indicates that the typhoid incidence fell by approximately 3.194 per 100,000 inhabitants after a small-scale system was introduced. This accounts for 30.2% of the observed decline in the typhoid incidence rate (10.6 per 100,000 before and after the

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[20] In each county, the small-scale systems increased slightly right after the initial adoption in a village, but then increased substantially in subsequent years, especially in county areas. This suggests that more villages in each county rapidly adopted small-scale system facilities, and so the number of (direct and indirect) beneficiaries sharply increased after the first installation. Consequently, the effect of preventing typhoid fever cases seems to have increased over time.

[21] The installation of small-scale systems was expanded to other villages in each district after the first adoption in a village, particularly in county areas. Therefore, our definition of $Post_{jt}$ could underestimate the true effects of the small-scale system.

[22] The results for other control variables are available in Table A3 in Appendix A.

treatment in each county).[23] In column (5), we replace the variable of $time$ with district-specific linear time trends instead of province-specific trends to reflect systematically different trends in typhoid fever at the district level, independent of the installation of water supply facilities.[24]

In column (6), we add the interaction term $Post_{jt} \times T_j^{pre}$ to check whether areas with high infection rates benefited more from small-scale water supply intervention where T_j^{pre} is the 1960–1966 average typhoid incidence in district j (i.e., pre-intervention typhoid risk measure).[25] Because the variable for the pre-intervention typhoid risk is the demeaned value, the estimated coefficient of $Post_{jt} \times T_j^{pre}$ measures how much greater the effect of a small-scale system was on typhoid when pre-intervention typhoid risk was higher than average. The results show that the effects on the drop in typhoid cases were more substantial in the areas with greater pre-intervention typhoid risk. In Panel B, we apply the same regressions to the city sample and, as expected, the small-scale system interventions on average did not have much effect on urban cities. However, the decline in typhoid shown in Panel C of Figure 2 (solid line for city sample) can be explained by some high pre-intervention typhoid risk cities as reported in column (6).

[Table 1 Here]

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23 The magnitude in our analysis is approximately comparable to other studies' because the typhoid incidence in both Cutler and Miller (2005) and Beach et al. (2016) is calculated as the death rate from typhoid, while we use the incidence rate. Nevertheless, the evaluated effect in this study is similar with the previous studies. Cutler and Miller (2005) estimate that filtration and chlorination together reduced typhoid fever mortality by 25% (on page 11) and Beach et al. (2016) suggest that water filtration reduced typhoid death rates by between 17% and 47% depending on specifications (on page 49).

24 Although the results are similar to column (4), this is not our preferred specification because our data are at the district-year level and so the inclusion of district-specific trends capture a lot of variations in independent variables.

25 As stated in Section 3, small-scale system interventions started in 1967. Thus, we assume that the variable T_j^{pre} measures the initial condition of typhoid environment in district j.

We also conduct placebo tests in rural counties and Table 2 summarizes the results. First, the results of testing of different treatment timing instead of the initial adoption year are presented in columns (2) and (3). Both before and after three years of treatment, results are estimated to be statistically insignificant. In column (4), we replace the treatment variable with the introduction of large-scale waterworks instead of small-scale systems. From Figure 3, large-scale waterworks are thought not to have brought any significant benefit to counties. We find that large-scale waterworks were not effective in controlling typhoid fever in county regions, probably because they were constructed in more densely populated areas that were less typhoid-endemic. Finally, column (5) replaces the dependent variable with the diphtheriae incidence, which is not a waterborne disease and so would not be affected by increasing the safety of drinking water. Since the information on diphtheriae during 1960–1984 is consistently available for the 51 counties, it is perhaps useful to show that our main results hold for this subset of counties. Accordingly, we replicate our main analysis (restricting to the set of counties where diphtheriae information is available) in column (6). The results in columns (5)-(6) are in line with our expectations and highlight the significance of small-scale systems only for water-related diseases.[26]

[Table 2 Here]

5. Long-Term Effects on Human Capital Development

[26] In addition to water supply investments, sewage supply also plays a crucial role in public health (Alsan and Goldin, 2019). Nevertheless, the Korean case avoids the confounding effects from the sewage supply because sewage systems were implemented in large Korean cities starting in the late 1970s. As shown in Figure A3 in Appendix A, the supply ratio of sewage treatment was extremely low until the end of our analysis period. Therefore, the estimated effects in this study would be little influenced by the introduction of a sewage system.

Did the intervention and consequent improvement in the disease environment enhance human capital accumulation among populations? Many studies suggest that an improved environment is likely to lead to better human capital through various channels (Almond and Currie, 2011; Almond et al., 2018; Barker, 1998; Behrman and Deolalikar, 1988; Bleakley, 2010a; Davis and Sandman, 2010; Fogel and Costa, 1997; Heckman, 2007). They especially emphasize the significance of the exposure to any intervention in early life. However, some argue that the effects are not theoretically clear when children who benefited from the intervention decided to work rather attend school.[27] Since these opposing possibilities suggest that the effect on education is an empirical question, in the following sub-section, we analyze the effects of typhoid reduction through small-scale systems on educational attainment by tracking birth cohorts from the Korean population censuses.

5.1. Eliminating Typhoid as a Channel for Human Capital Formation

Typhoid fever is a bacterial infection caused by a specific type of *Salmonella* (Wain et al., 2015). Incidences of typhoid vary seasonally and usually occur during the humid season (Dewan et al., 2013; Sinha et al., 1999).[28] This disease is spread by drinking water contaminated with the feces of an infected person (Wain et al., 2015). During the incubation period of 6 to 30 days, typhoid bacilli causes mild symptoms such as fatigue, loss of appetite, and minor myalgias. After the incubation period, the symptoms become more severe and include diarrhea, coated tongue,

[27] For example, after small-scale system was adopted, children could be healthier because they were more likely to be free from waterborne disease. This might increase the returns to schooling with better academic performance, which was likely to lead to go to school. On the other hand, children who became healthier could be more productive in their workplace (Zhang and Xu, 2016; Ao, 2018; Pitt at al., 2012). In this case, the foregone earnings due to more time in school might be larger than before, which could cause the opposite decision on school enrollment (Ao, 2018; Bleakley, 2018; Pitt at al., 2012).

[28] In Korea, summer months (June to August) are the most humid. Every year, the Korea Center for Disease Control and Prevention (KCDC) requests that people be more careful in preventing typhoid during the summer season.

nosebleeds, coughing, insomnia, malaise, and chills. People with typhoid fever usually experience a sustained fever as high as 103˚-104˚ Fahrenheit (39˚-40˚ Celsius), and the disease is at its worst stage after three weeks of incubation. If victims survive all of this, their fever begins to fall and a long period of recovery sets in, which can take several months.

Despite the severity of the symptoms, fatalities from typhoid are less than 5% with treatment (Wain et al., 2015). However, typhoid's low death rate understates its true impact as discussed in detail by Beach et al. (2016). They argue that typhoid survivors have a higher risk of mortality, and pregnant women diagnosed with typhoid fever have an increased risk of both miscarriage and pre-term delivery.[29] In the economics literature, Ferrie and Troesken (2008) provide evidence that 35–56% of the reduction in mortalities in Chicago from the late 19th century to the early 20th century can be attributed to water purification and the subsequent eradication of diarrheal diseases and typhoid fever. More closely related to our paper, Case and Paxson (2009) show that early-life exposure to diarrhea and typhoid deteriorates cognitive ability in adulthood, and Beach et al. (2016) find that increased exposure to typhoid as a child is related to lower educational attainment. Accordingly, both typhoid itself and the energy used to fight typhoid may have lingering effects later in life. A high risk of typhoid during early life could influence human capital formation in the long-term since typhoid impairs maternal and infant health as noted above.[30]

[29] Moreover, Sinha et al. (1999) suggest that typhoid is a common and significant cause of morbidity in children under 5 years of age, arguing that the early-life period is the optimum age for typhoid treatment.

[30] Some may have concerns about survivorship bias (sample selection of relatively healthier individuals), which can be caused by increased infant mortality during the epidemic (Bozzoli et al., 2009). However, since our measure of typhoid fever is incidence-based (not deaths from typhoid) and typhoid fatalities are lower than 5% with treatment, we can avoid such selection bias.

5.2. Early-life Typhoid and Completed Education Level: Baseline Estimation

We construct synthetic cohort data from the 1995 (10% random sample), 2000 (10%), 2010 (10%), and 2015 (20%) censuses by creating cohort cells according to birth year, birth district, gender, and census year.[31] Considering the timing of finishing schooling, we limit the cohort samples to those who reached the ages of 30–54 in the years of the censuses. Then, we calculate cohort averages for the various outcome variables: final years of schooling, rate of completing primary school or higher, middle school or higher, and high school or higher.

Using cohort-level panel data, we estimate the effects of the exposure to typhoid risk early in life. Following the approach of Beach et al. (2016), we employ three-year average typhoid incidence rates during early life, the year of birth, the year before birth, and the year after birth. Recalling their argument, this method offers two advantages. First, the moving average provides a better proxy for average typhoid risk when considering the volatile nature of typhoid. Second, the three-year moving average includes prenatal, neonatal, and infant periods, which captures early-life exposure (Beach et al., 2016). Because typhoid data are available during 1960-1984, and we include typhoid incidences in the year before birth and the year after birth, we restrict our analysis to those who were born between 1961-1983.[32] The descriptive statistics for educational outcomes, early-life typhoid rates, and other variables are reported in Table A4 in Appendix A.

We estimate how early-life typhoid influences educational attainment using the following

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[31] Deaton (1985) states the benefits of tracking cohorts through independent cross-sections. Cohort means can be used as a panel structure, which complements attrition bias and can be stretched to a long-time horizon. The geographic unit employed in this analysis should be the place of birth, since individuals with matching early life conditions would be problematic to be analyzed by current residence because of selective migration. The Microdata Integrated Service (MDIS) of Statistics Korea provides birth district information only for the 1995, 2000, 2010, and 2015 Korean population censuses through authorization (https://mdis.kostat.go.kr/).

[32] Since typhoid incidences in 1959 and 1985 are not available, cohorts who were born in 1960 and 1984 are excluded.

equation:

$$y_{jtk} = \alpha + \beta TA_{jt} + X_{jt}'\Gamma + \delta_{t\times k} + \delta_j + time + \varepsilon_{jtk}, \tag{3}$$

where y_{jtk} is the average of final education level among the cohorts born in district j in year t and surveyed in census year k. TA_{jt} is the average typhoid rate during early life for cohorts born in district j in year t. Column vector X_{jt} includes year and region-varying controls, namely population (district-year level) and average rice output per capita during early life (i.e., the three years of prenatal, neonatal and infant periods), average number of deaths per capita during early life, and number of primary schools per capita at age six (province-year level). $\delta_{t\times k}$ is the interaction of year-of-birth dummies and census-year dummies.[33] δ_j represents place-of-birth district fixed effects. $time$ is the province-specific time control, defined as the interaction of birth-province dummies with birth year linear trends.[34] The square root of the sample size of each cohort is used as regression weight. We cluster standard errors at the birth-district level.

In Table 3, we report the results of the ordinary least squares (OLS) estimation for male and female samples, respectively. The estimated coefficients $\hat{\beta}$ suggest that typhoid during early life generally decreases educational attainment. These results indicate that eliminating typhoid would increase years of schooling by 0.0206 years ($= 0.0015 \times 13.73$; or same as 0.25 months $=$ 0.0206×12) for male and 0.0316 years ($= 0.0023 \times 13.73$; or same as 0.38 months$=$

[33] Because outcomes are taken from each census, controlling birth year times automatically controls for age.

[34] One might suggest that we use district-specific linear trends. The results are not robust for the inclusion of district-specific linear trends. This is perhaps because our data are at the district-year level and so the inclusion of district-specific trends captures a lot of variations in district-year level typhoid rates.

0.0316×12) for female.[35] In addition, the magnitude of the benefit becomes substantially greater when the cohort average completion rate of higher-level education is used as the dependent variable. Given the structure of education in Korea (see Table A5 in Appendix A), most cohorts over our analysis period were not influenced by the compulsory education law for middle or high schools.[36] Therefore, entering middle or high school depended on household decisions. In this case, the positive effects of typhoid eradication would play a key role. Further, a higher cognitive ability is required to attend and complete higher education. The results above therefore suggest that childhood exposure to the intervention might significantly improve cognitive ability.

Another notable feature in Table 3 is the magnitude of the benefits, which are almost double for the female sample compared to the male one. The theoretical mechanism explaining the gender gap is provided by Pitt et al. (2012). They find that males have a comparative advantage in "brawn" development and females a comparative advantage in brain development. Since boys' "brawn" grows more when they experience interventions that can augment health, this increases the opportunity cost of education for boys. Thus, public-health interventions are more likely less beneficial to men regarding additional schooling, compared to women.

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[35] We calculate the average effect from eliminating typhoid by multiplying the coefficient for average typhoid rate during early life before small-scale system intervention by - 13.73, where 13.73 is the average typhoid incidence rate that cohorts in our sample were exposed to during their early life (three-year average typhoid incidence rates during early life: the year of birth, the year before birth, and the year after birth). The magnitude of estimated coefficient $\hat{\beta}$ is similar with that of Beach et al. (2016). When they regress years of schooling (only for male) on average typhoid death rates during early life, the estimated result is -0.0022 (Table 4 on page 60), which is close to our results -0.0016 (for male sample) and -0.0023 (for female sample) in Table 3. However, the average effect from eliminating typhoid is smaller in our study because of the smaller average typhoid incidence rate before intervention (13.73) compared to that in the late nineteenth century US cities (41.72 in Table 3 on page 59).

[36] The attendance rates of elementary school-aged children were over 96% in 1959 due to the "Compulsory Education Six-year Plan" from 1954 to 1959. However, the implementation of the Compulsory Education Law for middle schools had begun in 1992. Therefore, only those born after 1979 might have been affected by the Compulsory Education Law when they reached middle-school age. When we subsequently check the robustness by excluding the cohorts born after 1979 from the analysis, the results are similar and available upon request.

[Table 3 Here]

To check whether these results are driven by early-life, we test the effects of exposure to typhoid rates in other stages of life as well as our definition of early life (one year before to one year after birth). Specifically, we conduct the baseline estimation replacing the average typhoid rates (TA_{jt}) with 6 to 4 years before birth, 4 to 2 years before birth, 2 to 4 years after birth, and 4 to 6 years after birth. For a consistent comparison, we restrict our sample to cohorts that can be linked to lagged and forwarded typhoid data. Specifically, to match typhoid rates of 6 years before birth and 6 years after birth, we need to analyze only cohorts born from 1966 to 1978 since we have typhoid data from 1960 to 1984. In Figure 4, the capped spikes indicating 95 percent confidence intervals show that the effects of early-life (one year before to one year after birth) typhoid rates have the largest magnitudes and are statistically significant. Other periods are not statistically significant.

[Figure 4 Here]

5.3. IV Estimation

Some may be concerned that average typhoid rates during early life are systematically related to other unobservable confounding factors. For example, typhoid decline might be correlated with variables of other infrastructure (e.g., hospitals) that we cannot observe and that also enhance educational attainment and effect the disease environment. Thus, our ordinary least squares estimation has potential over-estimation problems in evaluating typhoid reduction through small-scale interventions. To address this endogeneity issue, we instrument the typhoid rate with summer humidity.[37]

As noted in Section 5.3, typhoid fever tends to be concentrated in the humid season, especially in summer months (June to August) in the case of Korea. In Section 4, we show that average humidity in the summer is positively correlated with typhoid incidence (Table A3 in Appendix A). To investigate such a relationship in a consistent setting with early-life exposure, we propose the first-stage specification to be of the form:

$$TA_{jt} = \pi_1 + \pi_2 H_{jt} + W_{jt}'\Phi + X_{jt}'\psi + \theta_t + \theta_j + time + \nu_{jt}, \tag{4}$$

where TA_{jt} is the average typhoid rate during early life for cohorts born in district j in year t. H_{jt} is the average of summer months' (from June to September) humidity during the year of birth, the year before birth, and the year after birth.[38] X_{jt}' is the same as in equation (3). θ_t is a set of birth-year fixed effects and θ_j is a set of birth-district fixed effects. $time$ is the province-specific time control, defined as the interaction of birth-province dummies with birth year linear trends. We cluster standard errors at the birth-district level.

In addition, we include a vector of early life weather-related controls, W_{jt}, to address a concern that humid conditions are likely correlated with crop yields, which may indirectly influence human capital formation via improved nutritional intake. For example, Deschênes and

[37] Beach et al. (2016) also use the 2SLS approach by instrumenting for typhoid fever using typhoid rates in cities upstream.

[38] The method of constructing the summer humidity variable is discussed in footnote 17 in Section 4.2.

Greenstone (2007) find the positive linear relationship between temperature and agriculture output in the US during 1970-2000. Schlenker and Roberts (2009) argue that crop yields increase as the temperature increases until some threshold value; after which, the increase in temperature has a negative impact on crop yields. In the Korean case, Hong (2017) shows that temperatures during the rice cultivation period are positively correlated with rice yields but precipitation is negatively associated with rice outputs during 1981-2012.[39] Therefore, considering the importance of temperature and precipitation on agriculture outputs (and considering the distinctiveness of Korea), we need to partial out this mechanism, independent of the effect of humidity. Specifically, to exclude the "nutrition channel" in the reduced-form relationship between summer humidity and human capital development, we additionally control for three-year moving averages, which reflects early-life exposure, of temperature and precipitation from May to September.[40]

Table 4 presents the first-stage relationship using early-life summer humidity as an instrument for early-life typhoid rates across different regression specifications. We find that our instrument is a strong predictor of typhoid rates during early life. The F-statistics are estimated between 5.14 and 7.08, which suggests that early-life summer humidity is not a weak instrument. Additionally, typhoid rates driven by summer humidity should be exogenous to human capital investments. We assume that early-life summer humidity affects people's education only through waterborne disease environments, weather conditions during rice cultivation periods and other variables

[39] In Korea, the critical growth period of rice (hereafter rice cultivation period) is between May to September (Hong, 2017).

[40] Summer temperature and precipitation may also be related to typhoid. However, their strong relationship with conditions during the rice cultivation period can cause a violation of exclusion restriction (i.e., temperature and precipitation during the rice cultivation period affect rice yields according to the previous studies). Thus, we instrument for typhoid using only summer humidity. Moreover, in Table 4, when we include temperature and precipitation in the first-stage specification, only humidity is statistically significant.

including province-year level rice yields and district and year fixed effects.[41]

In Table 5, we summarize the results of the instrumental variable estimation. We report OLS results in columns (1) and (3) for comparison purposes. Our IV estimates support the results from OLS estimates that show early-life typhoid rates have detrimental impacts on educational attainment. Columns (2) and (4) show that the effect of early-life typhoid is negative and statistically significant at conventional levels for years of schooling, probability of completing middle school, and probability of completing high school. Although some results from IV strategy are imprecisely estimated with larger standard errors than OLS, the estimates have the same sign and much larger magnitudes in absolute values than OLS estimates. For example, these results indicate that eliminating typhoid would have increased schooling by one month.

6. Concluding Remarks

In developing countries, 660 million people are suffering from water shortages (World Health Organization, 2015). Particularly, the water supply ratio is less than 30% in the least developed countries. Consequently, around 80% of diseases in developing countries are waterborne diseases caused by contaminated water and inadequate sanitation systems. Therefore, for developing countries, which have relatively low economic levels and environmental awareness, it is important to introduce appropriate water supply technologies that do not require large amounts of capital and

[41] Aside from waterborne diseases, there are some noteworthy studies linking variations in weather conditions and later education. For example, Maccini and Yang (2009) show that higher early-life rainfall provides better health, schooling, and socioeconomic status for women in Indonesia. They explain the results with the underlying mechanism of rainfall's effects on crop output (and thus increase in income and food availability). However, we can address the concern by conditioning on related variables as explained above. Also, Barreca (2010) finds that cohorts born in malaria-ideal temperatures in the U.S. South (circa 1910) had lower education, instrumenting for malaria using warmer and wetter weather. Since malaria was not widespread in Korea compared to tropical and subtropical regions, the effects of weather conditions on malaria would be minimal.

are simple to apply. From this perspective, small-scale water supply systems are useful for developing countries with poor infrastructures and financial bases since these treatment systems are easy to install and require low costs compared with large-scale piped waterworks.

Until the 1960s, rural areas in Korea faced similar economic environments and disease incidence to developing countries today. With small-scale water supply interventions, Korea overcame this problem in a short period. Based on this experience, we explored the extent to which the interventions protected against the outbreak of waterborne diseases. Using hand-collected district-year level data, we estimated that the introduction of small-scale water supply systems in rural areas reduced the incidence of typhoid fever by between 27% and 30%. Further, we found evidence that the intervention and subsequent improvement in disease incidence played a crucial role in long-term human capital accumulation. Specifically, the magnitude of the benefits is estimated to be larger for higher-level education and is almost double for females compared to males. These results are closely related to education-labor transition, the enhanced cognitive ability through intervention, and the gender division of labor. Moreover, we applied a novel identification strategy to address potential endogeneity issues (for instance, investments related to both typhoid and human capital formation) by instrumenting for typhoid exposure at early life using summer humidity. The instrumental variables identification strategy produced results approximately three times larger.

The Korean case is unique since policies that target rural areas with sufficient time lapse allowing researchers to evaluate the direct short-term and indirect long-term effects simultaneously are scarce. Moreover, when one considers the success of small-scale water supply interventions and the rapid economic growth of Korea over the analyzed period, the experience of Korea has important policy implications for developing countries that require feasible water supply systems.

Appendix A. Figures and Tables

[Table A1 Here]

[Table A2 Here]

[Table A3 Here]

[Table A4 Here]

[Table A5 Here]

[Figure A1 Here]

[Figure A2 Here]

[Figure A3 Here]

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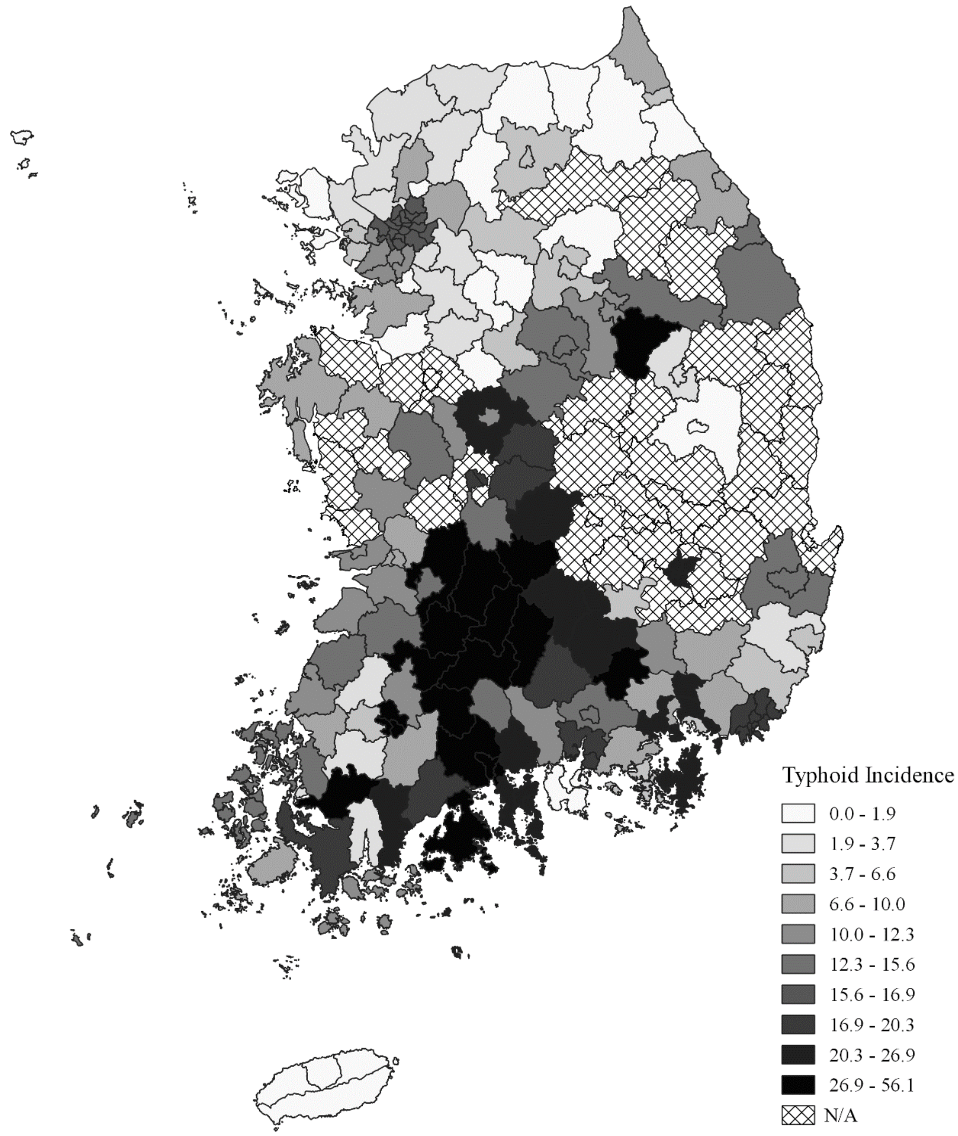
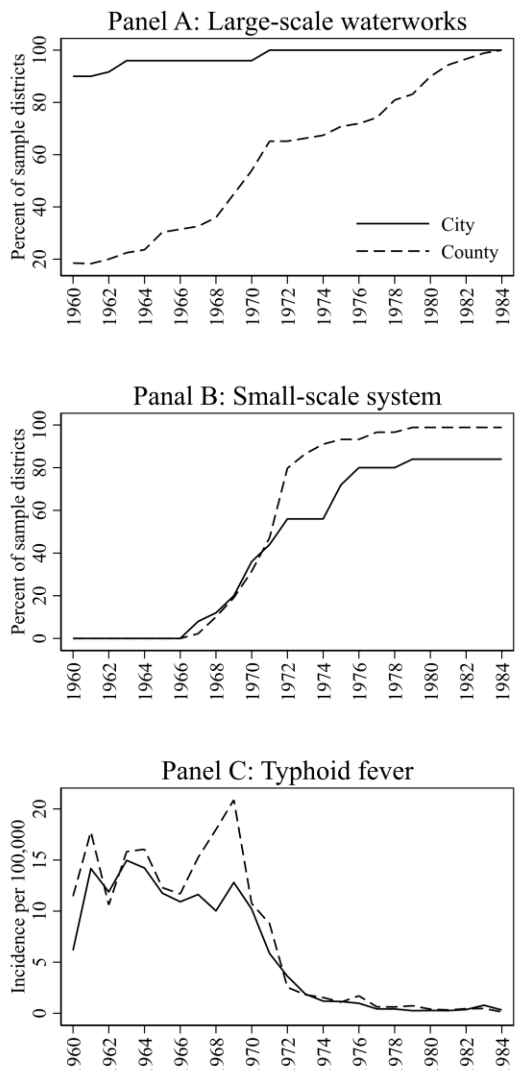
Figures and Tables

Figure 1. Regional Disparity in Typhoid Incidence Prior to Small-Scale Water Supply Intervention



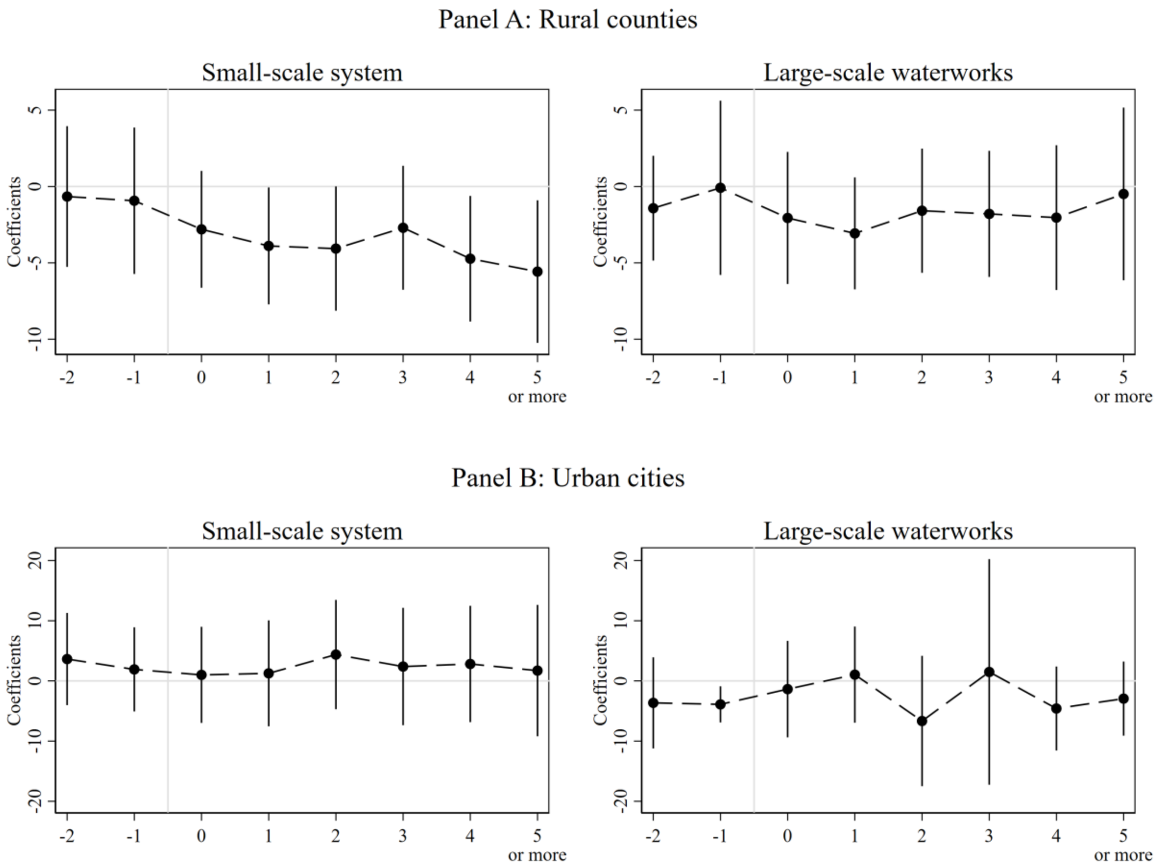
Notes: The regional boundary is based on the 1980 administrative area codes. The typhoid risk (1960–1966 average) is matched with the 1980 administrative map. The grid-marked districts are excluded from the analysis because typhoid data are not consistently available during the analysis period. The sample covers around 73% (114 out of 156) of the country.

Figure 2. Trends of Large-Scale Waterworks, Small-Scale System, and Typhoid Fever in Sample Districts, 1960–1984



Notes: Panels A and B show the percent of sample regions that adopted each water supply technology. Panel C shows the trends of typhoid fever incidence per 100,000 residents. City and county are divided based on 1980 administrative area code. The number of cities and counties is 25 and 89, respectively. The sample covers around 73% (114 out of 156) of the country.

Figure 3. Estimated Impact of Water Supply Interventions on Typhoid Fever for the Years Before, During, and After Adoption



Notes: We conducted the regressions in equation (1). We depicted the estimated coefficients β_k against the relative year of initial adoption with the 95 confidence intervals. City and county are divided based on 1980 administrative area code. In Panel A, the number of counties is 89 for small-scale systems and 56 for large-scale waterworks. In Panel B, the number of cities is 21 for small-scale systems and 12 for large-scale waterworks. The range spikes show the confidence intervals at 95 percent level of statistical significance. Standard errors are clustered at the district level.

Table 1. Estimated Effect of Small-scale Water Supply Intervention on Typhoid Fever
Dependent variable: Typhoid incidence per 100,000

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: County sample						
Independent variables						
Post	-3.096**	-2.867**	-3.076**	-3.194**	-3.395**	-3.332**
	(1.327)	(1.308)	(1.355)	(1.378)	(1.446)	(1.399)
Post × Pre-intervention typhoid						-0.701***
						(0.052)
Number of districts	89	89	89	89	89	89
Observations	2,206	2,206	2,206	2,206	2,206	2,206
Panel B: City sample						
Independent variables						
Post	0.361	-0.064	-0.354	-0.536	0.675	-0.454
	(2.231)	(2.374)	(2.335)	(2.277)	(2.379)	(2.420)
Post × Pre-intervention typhoid						-0.436*
						(0.224)
Number of districts	25	25	25	25	25	25
Observations	614	614	614	614	614	614
Additional controls						
District-year level:						
Population		✓	✓	✓	✓	✓
Summer humidity		✓	✓	✓	✓	✓
Province-year level:						
Rice output			✓	✓	✓	✓
Number of deaths			✓	✓	✓	✓
Number of primary schools			✓	✓	✓	✓
Province-specific trends				✓		✓
District-specific trends					✓	

Notes: We conducted the regressions in equation (2). Only the estimated coefficient for the dummy variable of small-scale system was reported in the table. We additively controlled variables. To control the effects caused by weather condition population size, we include year and district-varying summer humidity and population in column (2). In column (3), we include a vector of province-level time varying covariates. Additionally, we contain province-specific linear time trends in column (4) and district-specific linear time trends in column (5) to alleviate concerns that small-scale system facilities were introduced in response to region-specific differential trends. In column (6), we add the interaction term of pre-intervention typhoid incidence to check whether areas with high infection rates benefited more from small-scale water supply intervention. A single asterisk denotes statistical significance at the 90% level of confidence, double 95%, and triple 99%. Standard errors are clustered at the district level.

Table 2. Estimated Effect of Treatment: Falsification Check
Dependent variable: Typhoid incidence per 100,000

		Alternative Timing		Alternative Treatment	Alternative Outcome	Typhoid & with the sample used for column (5)
	Baseline	-3 Years	+3 Years	Large-scale waterworks	Diphtheriae	
	(1)	(2)	(3)	(4)	(5)	(6)
Independent variable						
Treatment	-3.194**	-0.841	-0.936	0.927	0.226	-2.440*
	(1.378)	(1.879)	(0.880)	(1.356)	(0.268)	(1.246)
Number of districts	89	89	89	89	51	51
Observations	2,206	2,206	2,206	2,206	1,272	1,272

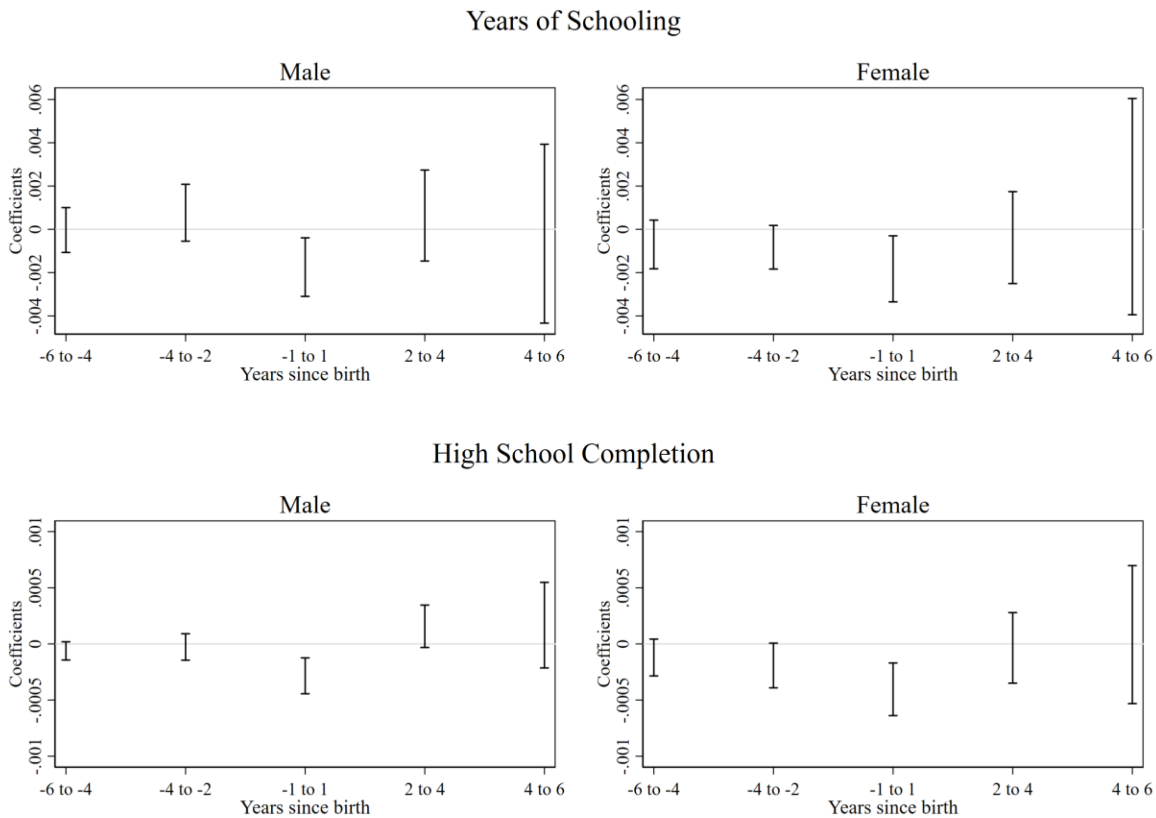
Notes: We conducted the regressions in equation (2). Columns (1) and (2) are reported for comparison purposes. The results of testing of different treatment timing instead of the real initial adoption year are presented in columns (2) and (3). In column (4), we replace the treatment variable with the introduction of large-scale water-works instead of that of a small-scale system. Column (5) replaces the dependent variable with the diphtheriae incidence, which is not a waterborne disease. A single asterisk denotes statistical significance at the 90% level of confidence, double 95%, and triple 99%. Standard errors are clustered at the district level.

Table 3. Average Typhoid Rates during Early Life and Final Education Level: Ordinary Least Squares Estimation

Dependent variables:	Years of schooling	Primary school completion	Middle school completion	High school completion
	(1)	(2)	(3)	(4)
Panel A: Male sample				
Independent variable				
Average typhoid during early life	-0.0015***	-0.0000	-0.0001***	-0.0003***
	(0.0005)	(0.0000)	(0.0000)	(0.0001)
Average effect of elimination	0.0206	0.0000	0.0014	0.0041
Percent of sample mean	0.1560	0.0000	0.1420	0.4554
Panel B: Female sample				
Independent variable				
Average typhoid during early life	-0.0023***	-0.0000	-0.0002***	-0.0006***
	(0.0006)	(0.0000)	(0.0001)	(0.0001)
Average effect of elimination	0.0316	0.0000	0.0027	0.0082
Percent of sample mean	0.2512	0.0000	0.2867	0.9487
Additional controls				
Rice output	✓	✓	✓	✓
Number of deaths	✓	✓	✓	✓
Number of primary schools	✓	✓	✓	✓
Birth province-specific trends	✓	✓	✓	✓
Number of districts	89	89	89	89
Observations	5,061	5,061	5,061	5,061

Notes: We conducted the regressions of equation (3). The square root of the sample size of each cohort in the underlying microdata is used as regression weights. A single asterisk denotes statistical significance at the 90% level of confidence, double 95%, and triple 99%. Standard errors are clustered at the birth-district level.

Figure 4. Relationship between Average Typhoid Rates and Final Education Level Depending on the Timing of Exposure



Notes: We conduct the baseline estimation replacing the average typhoid rates with 6 to 4 years before birth, 4 to 2 years before birth, 2 to 4 years after birth, and 4 to 6 years after birth. For consistent comparison, we restrict our sample to cohorts that can be linked to lagged and forwarded typhoid data. Specifically, to match typhoid rates of 6 years before birth and 6 years after birth, we analyze only with cohorts born from 1966 to 1978 since we have typhoid data from 1960 to 1984. The capped spikes are indicating 95 percent confidence intervals. Standard errors are clustered at the birth-district level.

Table 4. First-stages of Two-stage Least Squares Strategy

Dependent variable: Average typhoid rate during early life

	(1)	(2)	(3)	(4)	(5)
Independent variables					
Summer humidity	0.1012**	0.0906**	0.0728**	0.0757***	0.0676**
	(0.0412)	(0.0347)	(0.0321)	(0.0285)	(0.0279)
F-statistics	6.03	6.81	5.14	7.08	5.86
Additional controls					
Population		✓	✓	✓	✓
Rice output		✓	✓	✓	✓
Number of deaths		✓	✓	✓	✓
Birth province-specific trends			✓	✓	✓
Rice cultivation period (May to September) weathers					
Temperature				✓	✓
Precipitation				✓	✓
Temperature × Precipitation					✓
Number of districts	89	89	89	89	89
Observations	5,061	5,061	5,061	5,061	5,061

Notes: We conducted the regressions in equation (4). Only the estimated coefficient for the summer humidity was reported in the table. We additively controlled variables. A single asterisk denotes statistical significance at the 90% level of confidence, double 95%, and triple 99%. Standard errors are clustered at the district level.

Table 5. Average Typhoid Rates during Early Life and Final Education Level: Two-Stage Least Squares Estimation

Independent variable: Average typhoid rate during early life

Samples:	Male		Female	
Estimating models:	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)
Dependent variables				
Years of schooling	-0.0015***	-0.0065*	-0.0023***	-0.0066*
	(0.0005)	(0.0037)	(0.0006)	(0.0038)
Primary school completion	-0.0000	-0.0000	-0.0000	0.0001
	(0.0000)	(0.0001)	(0.0000)	(0.0001)
Middle school completion	-0.0001***	-0.0004	-0.0002***	-0.0010**
	(0.0000)	(0.0003)	(0.0001)	(0.0004)
High school completion	-0.0003***	-0.0011*	-0.0006***	-0.0019**
	(0.0001)	(0.0006)	(0.0001)	(0.0008)
Additional controls				
Rice output	✓	✓	✓	✓
Number of deaths	✓	✓	✓	✓
Number of primary schools	✓	✓	✓	✓
Birth province-specific trends	✓	✓	✓	✓
Rice cultivation period (May to September) weathers:				
Temperature		✓		✓
Precipitation		✓		✓
Number of districts	89	89	89	89
Observations	5,061	5,061	5,061	5,061

Notes: The square root of the sample size of each cohort in the underlying microdata is used as regression weights. A single asterisk denotes statistical significance at the 90% level of confidence, double 95%, and triple 99%. Standard errors are clustered at the birth-district level.

Table A1. Comparison of Characteristics between Water Treatment Systems

	Large-scale waterworks	Small-scale system
Source of water	river or reservoir	underground water or valley water
Treatment technology	both filtration and chlorination process	only chlorine disinfection (≈90%)
Capacity	avg 24,000m^3/day	avg 50m^3/day
Construction period	several years	5–6 months

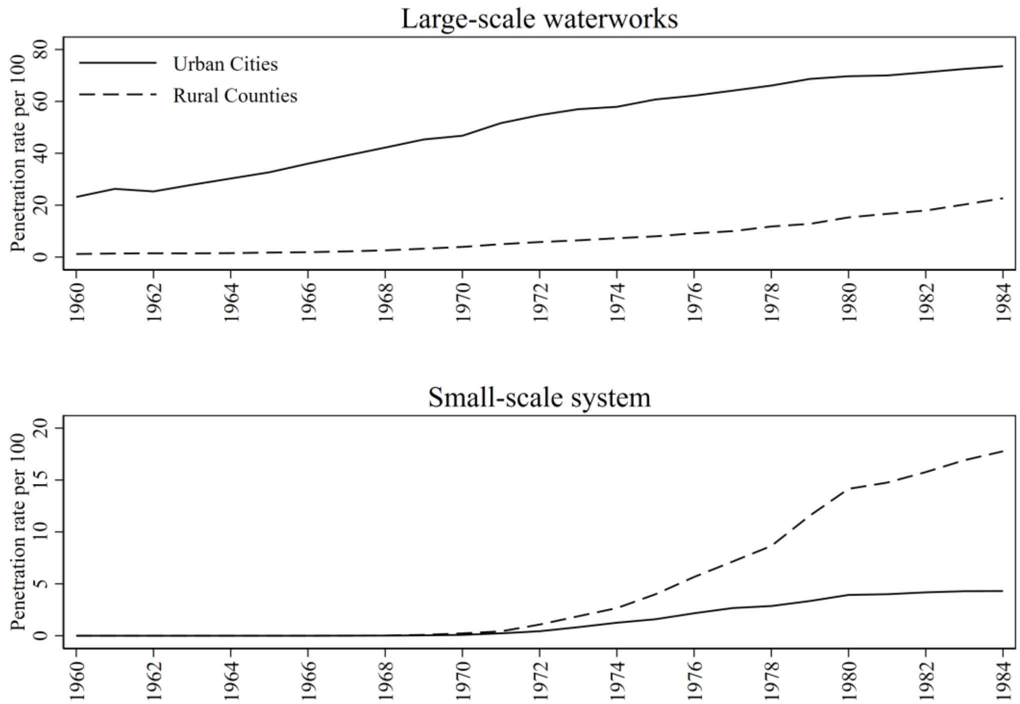
Sources: The information on small-scale supply system comes from Cho (2013); information for large-scale waterworks comes from the Ministry of Environment.

Table A2. Example of Administrative Area Change

Name of Area	Brief History of Area Change	1980 Administrative Area/Code
Masan-Si	Parts of *Changwon-Gun* were incorporated into *Masan-Si* in 1973. Former *Changwon-Gun* parts incorporated into *Masan-Si* were separated as *Changwon-Si* in 1980. Parts of *Changwon-Si* were incorporated into *Masan-Si* in 1983. Parts of *Changwon-Gun* were incorporated into *Masan-Si* in 1995. *Masan-Si* was incorporated into *Changwon-Si* in 2010.	*Changwon-Si*/3811
Jinhae-Si	Parts of *Changwon-Gun* were incorporated into *Jinhae-Si* in 1973. Parts of *Changwon-Si* were incorporated into *Jinhae-Si* in 1983. *Jinhae-Si* was incorporated into *Changwon-Si* in 2010.	*Changwon-Si*/3811
Changwon-Si	*Changwon-Si* was newly created based on parts of *Masan-Si* in 1980. Parts of *Changwon-Gun* were into *Changwon-Si* in 1995. *Masan-Si* and *Jinhae-Si* were incorporated into *Changwon-Si* in 2010.	*Changwon-Si*/3811
Changwon-Gun	Parts of *Changwon-Gun* were incorporated into *Masan-Si* and *Jinhae-Si* in 1973. *Changwon-Gun* was incorporated into *Changwon-Si* and *Masan-Si* in 1995 with demolition.	*Changwon-Si*/3811

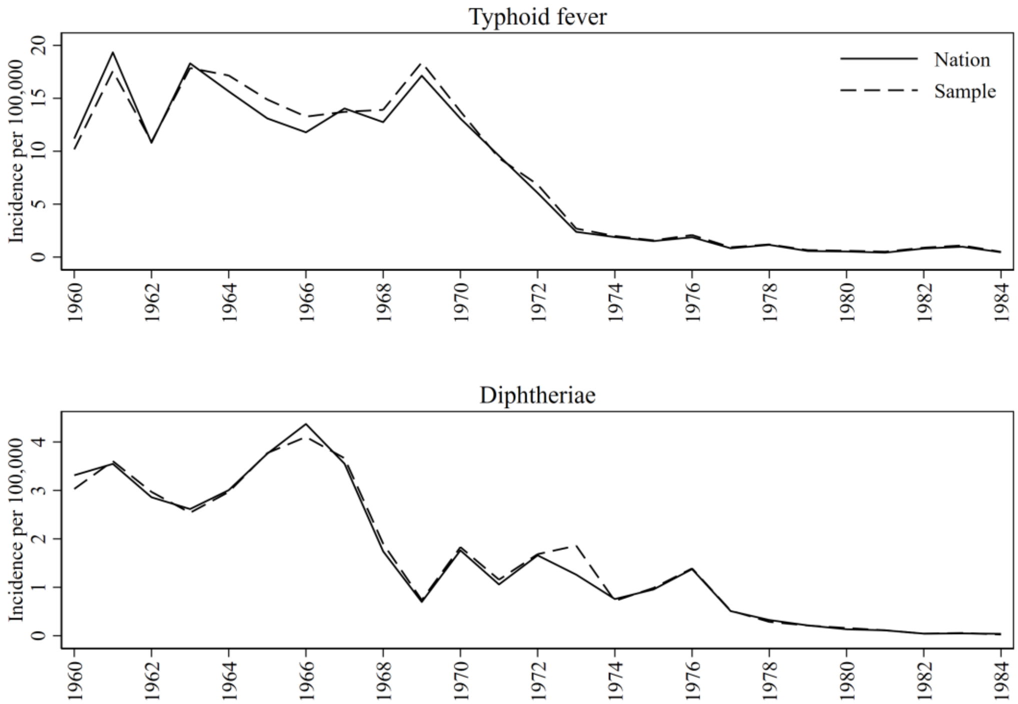
Note: We merged four areas (*Masan-Si*, *Jinhae-Si*, *Changwon*-Si, and *Changwon-Gun*) into *Changwon-Si* because their boundaries changed over time. Since the proportion of city areas (*Masan-Si*, *Jinhae-Si*, and *Changwon-Si*) was larger than that of county areas (*Changwon-Gun*) and *Changwon-Si* was the most urbanized area among them, *Changwon-Si* was chosen to represent this aggregated area group. Even if *Changwon-Gun* was a county area during our analysis period (1960–1984), it is converted to a city area because of the aggregation.

Figure A1. Trends of Penetration Rates of Large-Scale Waterworks and Small-Scale System, 1960-1984



Notes: The penetration rate for large-scale waterworks is the number who were able to use per 100 populations. The number of users are not provided for small-scale systems. To estimate how many people would have benefitted from small-scale facilities in each district, we used a pseudo-penetration rate by applying the facts in the Water Supply and Waterworks Installation Act in Korea: (capacity per day × 5) / population ×100. City and county are divided based on 1980 administrative area code. The number of cities and counties is 25 and 89, respectively. The sample covers around 73% (114 out of 156) of the country.

Figure A2. Trends of Typhoid Fever and Diphtheriae in the Whole Nation and Sample Districts, 1960-1984



Notes: Solid lines are the trends of whole nation and dashed lines are those of 114 sample districts.

Table A3. Baseline Estimation Results with Other Controls

Dependent variable: Typhoid incidence per 100,000

	Coef.	Clustered SE
Independent variable		
Post	-3.194**	1.378
Additional controls		
District-year level controls		
Thousand population	-0.013***	0.005
Summer humidity average	0.893**	0.405
Province-year level controls		
Rice output per pop	-0.001	0.001
Number of deaths per pop	-0.023**	0.010
Number of primary schools per pop	-4.253*	2.172
Number of districts	89	
Observations	2,206	

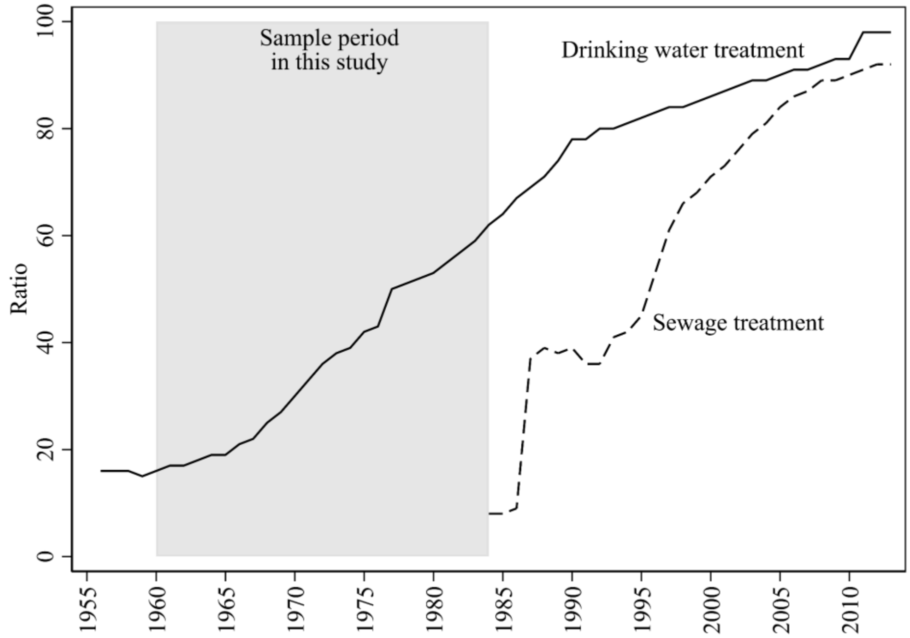
Notes: This table shows the results of the baseline regression of equation (2) corresponding to the column (4) of Table 1.

Table A4. Summary Statistics

	Mean	SD
Male sample		
Years of schooling	13.201	0.626
Primary school completion	0.990	0.012
Middle school completion	0.967	0.029
High school completion	0.904	0.066
Female sample		
Years of schooling	12.570	0.967
Primary school completion	0.991	0.010
Middle school completion	0.958	0.045
High school completion	0.868	0.119
Typhoid rate during early life	9.323	13.604
Typhoid rate during early life before 1967	13.731	16.250
Age	39.348	6.638
Summer mean humidity during early life	81.808	23.313
Rice cultivation period mean temperature during early life	22.478	3.279
Rice cultivation period accumulated precipitation during early life	275.396	193.262
Population in birth year	141042.270	72213.290
Rice output during early life per 10,000	1894.369	827.148
Number of deaths during early life per 10,000	106.653	49.974
Number of primary schools after 6 years of birth per 10,000	2.834	0.942
Number of districts	89	
Observations	5,061	

Notes: This table reports descriptive statistics on variables related to empirical analysis.

Figure A3. Supply Ratio of Drinking Water Treatment and Sewage Treatment



Notes: Drinking water treatment only refers to the large-scale waterworks in this study.

Table A5. Education Structure in Korea

Educational stage	Primary Education						Secondary Education					
School system	Elementary School						Middle School			High School		
Grade	1	2	3	4	5	6	1	2	3	1	2	3
Age	7	8	9	10	11	12	13	14	15	16	17	18

Notes: Children in Korea typically go to elementary school from age 7, middle school from age 13, and high school from age 16. Even though compulsory education for elementary school was completed in 1971, the attendance rate of elementary schooling aged children was over 96% in 1959 due to the "Compulsory education six-year plan" from 1954 to 1959. Compulsory education law for middle school was enacted in 1985. However, it was implemented only in remote islands or mountain regions until 1992. Complete compulsory education in rural areas that corresponds to our analyzed regions began only in 1992.