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The effect of water filtration on cholera mortality☆

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ABSTRACT

This paper examines how water filtration and distribution helped reduce mortality during a cholera outbreak. Using household water contract records and individual mortality data, I analyze the impact of filtered water with an event study approach. The results show that having access to filtered water at home greatly reduced the risk of death. This suggests that water filtration and distribution were key public health measures in lowering mortality from waterborne diseases in the 19th and early 20th centuries. Improvements in urban water systems could have played a major role in the decline of cholera outbreaks and mortality during this period.

1. Introduction

This paper investigates how having filtered water at home affected mortality during a cholera outbreak in Sweden. Using water contract data and individual death records, I analyze this question using an event-study approach. The results show that households with filtered water before the outbreak had much lower death rates during the outbreak than those without. The findings suggest that water filtration could almost completely remove the risk of dying from cholera.

How water improvements affected mortality during the 19th century is part of the historical narrative surrounding the “urban mortality transition” (Ferrie and Troesken, 2008; Cutler et al., 2006). This period was marked by sharp urban death rate declines and coinciding with significant investments in public health improvements and economic development (Preston, 1975; Mckeown et al., 1975). A long-standing academic debate concerns the relative contributions to mortality decline of public health investments compared to other factors related to economic development (Fogel, 1997; Steckel, 1999). The productivity of public health interventions is also relevant for countries struggling to provide a clean water supply in urban environments today.

Over 2 billion people globally lack access to clean water, with urban populations facing an urgent need for safe water resources as cities continue to grow (WHO, 2021). Recent data shows that the number of urban residents without safely managed drinking water has increased by more than 50 percent since 2000, a trend that could accelerate with the ongoing impacts of climate change and rapid urbanization (UN, 2024). Understanding the direct health benefits of clean water systems, such as filtration and piped distribution, may help to prioritize resource allocation in areas most at risk for waterborne diseases like cholera.

Cholera is still a significant public health risk in areas with poor water infrastructure (WHO, 2024). The clear connection between water quality and cholera contagion makes the setting of this study a unique opportunity to evaluate the effectiveness of water filtration and distribution on waterborne disease mortality. Moreover, the setting provides a clean context for studying the effect of the technologies on mortality since no other significant public health efforts were introduced simultaneously.

I have assembled a detailed dataset with address-level information on water access and mortality from archival sources to study this question. The effect of in-house filtered water on mortality is estimated by interacting information on the partial roll-out of a water distribution system in Stockholm with the cholera outbreak. This naturally leads to an event-study approach, tracing monthly changes in mortality rates

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across addresses with and without filtered water, which additionally allows me to test for pre-treatment trends and post-treatment dynamic effects after the outbreak.

The role of clean water infrastructure in reducing urban mortality has been an essential topic in economic and public health history. Cutler and Miller (2005) demonstrated that clean water technologies accounted for nearly half of the reduction in mortality in U.S. cities in the early 20th century, an estimate that positioned water infrastructure as a cornerstone of urban health. However, recent work by Anderson et al. (2022) revisited this claim and found that clean water's influence on total mortality was less significant than previously thought.[1] These revisions have spurred a renewed focus on clarifying the conditions and diseases for which water improvements prove most effective.

Many empirical studies on historical water filtration have focused on typhoid mortality, a bacterial waterborne disease. These findings demonstrate marked reductions in typhoid-related mortality following water filtration (Beach et al., 2016; Anderson et al., 2022; Cutler and Miller, 2005). In contrast, research linking water filtration to cholera mortality remains sparse despite cholera's significant historical mortality burden in urban settings. This gap is partly because cholera outbreaks largely subsided by the early 20th century. Few countries have reliable vital statistics so far back in time, making it challenging to empirically evaluate water filtration's direct effect on cholera mortality.[2] This study addresses this gap by focusing on a single cholera outbreak to examine water filtration's effectiveness against mortality in a high-density urban setting. My findings complement earlier results by showing that more generally, water filtration protects against bacterial waterborne diseases.

The literature also highlights the potential for complementarities between health technologies in reducing disease burden. Alsan and Goldin (2019) finds that water improvement and sewerage were only effective when implemented together. Similarly, Kesztenbaum and Rosenthal (2017) shows that a sewerage system reduced mortality in a context where pressurized water already existed. My results extend this discussion by showing that water filtration alone was highly effective during a cholera outbreak, even without large-scale sewerage infrastructure.

2. Background

During the 1850s, the crude mortality rate in Stockholm was often well above 30 per 1000 residents. As for many major European cities, Stockholm had a high infant mortality rate and twice the national average mortality rate. During this time, four out of ten children born in Stockholm did not survive to see their first birthday. Life expectancy at birth followed the high infant mortality rate, approximately 20 years for men and 26 for women (Lindberg, 1980). Poverty was high, sanitation was poor, and housing construction did not keep pace with the growing population.

One reason for the poor disease environment was the lack of access to clean water. The inhabitants relied on wells and nearby lakes for their daily drinking and washing water supply. There were more than 300 private and 27 public wells then, but the water quality and reliability during summer were generally poor (Cronström, 1986). The local health commission examined the public wells in 1867, and only 6 out of 27 wells were deemed moderately suitable to drink from; they recommended against drinking from the rest.[3]

The poor water quality could have partly resulted from inadequate sewerage infrastructure. Sewage and wastewater were mainly transported through street ditches. These ditches allowed for ground infiltration and the release of waste into surrounding lakes. Calls for city-wide investments in water and sanitation infrastructure were frequent during the 1850s, but the costs were deemed too high (Hansen, 1897). To balance the high costs of water and sewerage infrastructure with the poor health situation and unsanitary environment in Stockholm, city officials gave priority to water cleaning and distribution.[4]

A slow filtration water cleaning facility, inspired by the newest plants in the UK was built, starting in 1858, and a city-wide piped distribution system took form.[5] In 1861, filtered tap water was available to some of the inhabitants of Stockholm. The most central parts of Stockholm were the first with access to piped water, but the rest of Stockholm soon followed.[6] In 1866, around 26 percent of the population had access to in-house filtered water. The piped water was also used intensively. Water consumption increased during the studied period (see, Fig. 1) such that in 1872, daily per-user consumption was approximately 60 l, which can be compared to approximately 180 l today.[7]

2.1. Cholera

Cholera is a highly contagious and potentially lethal bacterial disease. Although records indicate that cholera has existed for a long time, pandemics were unknown before the early 19th century. During the 19th and early 20th centuries, cholera claimed millions of lives in recurring pandemics spreading throughout nearly the entire world (see Online Appendix Table A1).

Once infected, the body can produce up to 20 l of diarrhea a day, rapidly leading to acute dehydration and a lethal imbalance of electrolytes. During the 19th century, cholera's case fatality rate (CFR)

[1] Adjustments were related to data input errors, intervention date decisions, and the choice of population metrics to calculate mortality rates. The latter was paramount, with the revised analysis showing water filtration's impact as statistically insignificant and a mere quarter of what was initially claimed (although they did confirm substantial reductions in typhoid mortality). Cutler and Miller (2022) replied to these new findings and argued that their results on total mortality were largely unaffected by the corrections of Anderson et al. (2022). However, given the corrections, they recognize that their child mortality estimate became attenuated.

[2] Ambrus et al. (2020) find that cholera-affected areas had lower house prices, also over the long run. Ferrie and Troesken (2008) use data from the 1850s and forward but does not specifically consider cholera.

[3] These results were based primarily on the levels of organic compounds and water hardness, the metrics used at this time to assess water quality. The commission urged the public not to use well water for drinking but to rely on the piped water available in many parts of the city. Information on this assessment was retrieved from the city archive in Stockholm. Bacteriological analysis of the drinking water in Stockholm was not systematically undertaken until 1884 (Cronström, 1986).

[4] It would not be until 1875 that a large-scale system was planned and started to be constructed. Other important factors that led to water being prioritized were related to needs of pressurized water in manufacturing and fire safety concerns.

[5] The piped water was examined in 1879 in terms of fecal residue and was found to be superior to the piped water in, for example, London (Cronström, 1986). This technology is still viewed as an effective way of cleaning water of pathogens (Huisman and Wood, 1974).

[6] Online Appendix Figure A1 shows the initial network, constructed before 1861 (in blue), which is heavily concentrated in the central parts of Stockholm. In 1872, around 70 percent of the population in Stockholm had in-house access to piped water. The distribution network had already increased to 80 km in length, and to increase availability, a few public fountains were set up where water could be collected free of charge.

[7] See: http://www.drickkranvatten.se/virtuellt-vatten. Since there were no user-specific measurements, some of this water went to industry, street cleaning, and cattle. However, income statements from the Stockholm Water Company suggest that most of the water was used by households. In 1870, 70 percent of revenue from water consumption came from households. Industry and buildings owned by the city had water meters and paid per utilization (Kommunalförvaltning, 1875). This increased consumption should not have affected the intake water quality much, as few residential buildings were located close to the water cleaning plant. See Online Appendix Figure A2.

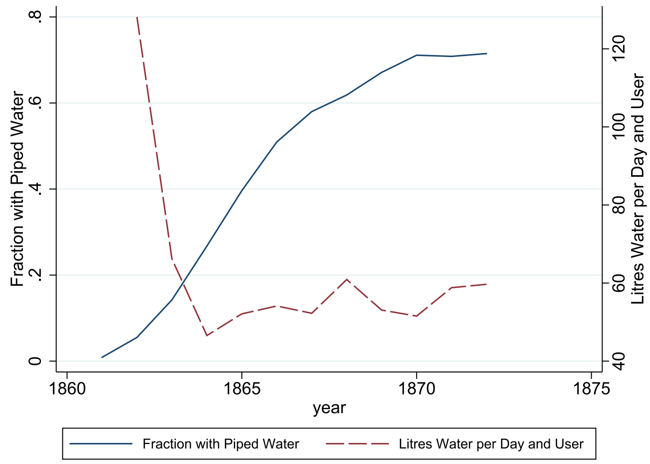

Fig. 1. Take-up of piped water and consumption.
Note: This graph shows the uptake of piped water among households and the per-user consumption of piped water. Access to piped water is calculated as the estimated number of billed users divided by the total population. At this time, there was no water metering, so the measure of water usage is total consumption divided by the number of users. This measure somewhat overestimates usage, as street cleaning and businesses also contributed to usage.
Source: Kommunalförvaltning (1875).

was often as high as 50 percent (Koch, 1894).[8] Cholera is still a feared disease due to its rapid spread and high mortality rate. At present, with access to oral and intravenous rehydration therapies, mortality is much lower and mainly affects small children who are less resilient to dehydration. Cholera mortality among children under five makes up approximately half of all deaths in endemic countries (UNICEF, 2019).

The last severe outbreak of cholera in Stockholm was in 1866. The first and last recorded deaths from cholera took place on the 28th of June and the 29th of October (Sundhets-collegii, 1869, pp.25). At almost the same time, cholera cases were discovered in both Stockholm and the second-largest city in Sweden, Gothenburg. During these four months, cholera was widespread in Stockholm. All eight geographical parishes comprising Stockholm reported cholera cases and deaths.[9]

Most of the recorded cholera deaths and cases were concentrated in adults between 20 and 50 (see the left panel of Fig. 2). Adults more often contracted cholera but died less often from the disease. Children under age 10 died in almost half of all documented infections, i.e., a CFR from cholera of approximately 0.42. Prime-aged adults (aged 20–50) had a much lower CFR of 0.26, while those over age 60, had an even higher CFR of 0.55 (Sundhets-collegii, 1869, pp.25).[10] These, extemely high, CFRs are in line with estimates from contemporary observers of cholera (Koch, 1894).

The high cholera mortality rate in Stockholm and other historical settings can be related to the medical knowledge available. Ingestion of contaminated water was not considered a way for diseases to spread. Instead, fumes from filth and waste were seen as spreading diseases, and the pressurized water was partially motivated by its ability to clean the streets. However, there are several reasons why cleaning and distributing water technology could have affected cholera mortality, even before the advent of modern medicine. Besides providing access to clean drinking water and improved street cleaning, the residents in Stockholm could also have benefited from reduced crowding around water pumps and better access to water for washing, cleaning, and drinking. Although unknown then, access to filtered, pressurized water could have been a powerful preventive technology against cholera.

The lack of modern medical knowledge becomes evident in a pamphlet distributed by the Physicians Association in Stockholm during the 1866 cholera outbreak, where one can read how to prevent cholera infections.[11] People were encouraged to eat and drink in moderation, to drink less liquor, not to go out in the morning without having eaten anything, to keep their feet warm and dry, and to bring fresh air indoors by opening windows. The pamphlet presented no consideration of water ingestion at all.

The state of knowledge implies that socioeconomic status wmay have been less critical for preventive behaviors than it is today. However, a socioeconomic gradient in cholera mortality could emerge even without reliable information to respond to Luque de Haro et al. (2021). Unfortunately, the social class of those who died of cholera in 1866 is poorly documented. However, as different social classes often lived in the same buildings, the disease could have been difficult to avoid. This argument is corroborated by documentation from an earlier cholera outbreak in Stockholm, showing that excess mortality was 2–3 times the average among the upper classes, making up some 30 percent of the population. For the lower classes, mortality was 3–4 times the average during the outbreak (Zacke, 1971, pp. 167). As with most infectious diseases, the poor are usually more susceptible to infections and subsequent death than higher social classes due to poor nutrition, residential crowding, and poor health. Nevertheless, while poverty was likely an additional risk factor for dying from cholera in a setting without access to clean water, all residents were at high risk.

3. The historical data sources

To credibly study how filtered water affects cholera mortality requires detailed historical mortality records and information on water take-up, preferably in a context without competing health technologies. Combining such data with a health shock that is credibly affected by clean water, increases the analysis's precision. Although these data are rarely available, the city of Stockholm provides one such example where this linking is possible (Knutsson, 2017). I merged data from three different sources at the address level to accomplish the investigation. The sources are the 1860 Swedish census, archival water contract information, and individual-level mortality data from parish registers.[12]

In a historical context, linking data on water access within a city to mortality data over time can be problematic for several reasons. New buildings can appear in the data, and uninhabited buildings can become habited over time. To avoid such noise in the data, I first obtained information on all residential buildings in 1860 by digitizing part of the 1860 census in Sweden concerning Stockholm. These data contain information on the existing addresses of all residential buildings in 1860, which I used to set up a population of addresses. In addition to defining residential buildings, the data contain information on the number of residents at each address, the number of households in the building, and the sex composition at the time of the census.

[8] Cholera-infected, suffering from extreme dehydration, often developed a characteristic blue skin tone (thereby called “The Blue Death”).

[9] The parishes reported between 20 and 122 deaths from cholera during the outbreak. In total, there were 655 documented deceased and 2200 infected.

[10] Historical evidence corroborate these demographic patterns. Davenport et al. (2019) found that in London, despite the high severity of the cholera outbreaks in 1849, 1854, and 1866, infant mortality was largely unaffected during these outbreaks. Evidence from Denmark shows that the cholera mortality rate during the 1850s was lowest among children under 5 (2.7 %) and highest among older adults (16.7%) (Phelps et al., 2017).

[11] This pamphlet can be found on the Swedish historical web page Stockholmskällan (SLL, 1866). Even though the British physician John Snow already had a good idea about how cholera spread among people in 1849, this was not common knowledge in Sweden or elsewhere for several decades (Snow, 1849).

[12] A replication package is available and can be downloaded, see Knutsson (2025). This paper is an updated and heavily revised version of Knutsson (2017) using the same water contract data.

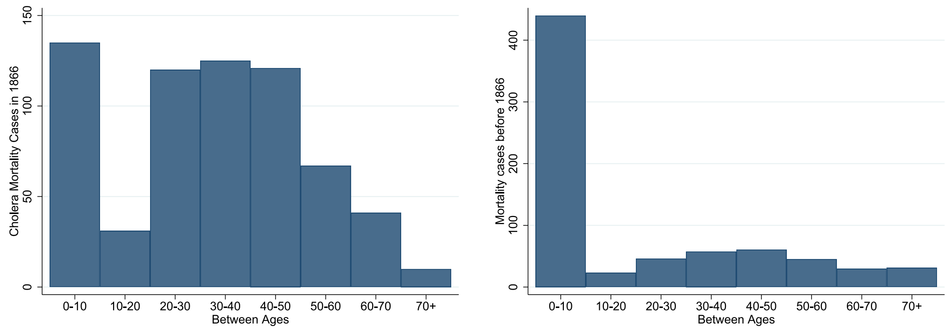

Fig. 2. Age distribution of Cholera deaths in 1866 and all-cause mortality 1860–1865.
Note: The left panel shows the age distribution for documented cholera cases in Stockholm during the outbreak according to official records (Sundhets-collegii, 1869, pp.25). The right panel describes the age distribution of all-cause mortality cases in the data averaged over the period 1860–1865 and only using deaths from July through October.

After setting up a consistent population of addresses over time, I merged information on access to in-house filtered water. This information was retrieved from water contract lists preserved at the Stockholm City Archives for the public water utility. The archive included a contract book dating from 1861 to 1872, the source of the contract data. The contract data is exact and contains information on each contract's precise day, month, year, address, parish, block, and number of rooms debited (see Online Appendix Figure A3). The water data contains 3530 contracts, of which I can match 2700 to the population of houses described above. Those that cannot be matched belong to buildings with no residential population (e.g., a factory or warehouse), buildings constructed after 1860, or buildings missing from the census for other reasons. Of these matched contracts, 1564 are unique. When houses changed owners, a new contract had to be written and counted twice or more in the data.[13]

Finally, I include information on individual deaths reported at the residence address. These mortality data were made available by the Swedish Genealogical Society (Sveriges släktforskarförbund). They have digitized all deaths in Sweden between 1860 and 2017 in their searchable database, The Swedish Death Index (SSF, 2018). This database contains information on date of birth, date of death, sex, marital status at the time of death, and address at the time of death. The primary underlying source for this database is the parish records. I merge the mortality data with the census population and water contract data using the month and address of death. I aggregate the number of deaths to this level for a balanced panel at the address-month level.

Given the historical nature of the data, some information is inevitably lost. The lost mortality data can be sorted into three sources: lost by exclusion, missing from the sample, and missing by lack of information. I deliberately exclude deaths at public and private institutions, such as poor houses, prisons, orphanages, military installations, and hospitals. These institutions are challenging because they have unstable populations, are often large, and have unclear or changing addresses.[14] Moreover, temporary residents at institutions who died were moved to the records of their parish of residence.

Additional missing information results from the requirement of observing a consistent population of residential houses over time. When excluding deaths at institutions, 9000 entries with a valid address are lost because the address is not in the sample defined by the census data. This loss is due to houses missing in the census data, newly constructed residential buildings not existing in 1860, or uninhabited buildings in 1860. A final 6500 deaths are missing by lack of information on either street address, street number, or both. The final sample contains 28,557 valid observations of diseased individuals.[15]

The three sources of missing data can have different implications for estimating the effect of filtered water on mortality. Omitting institutions means that I am taking away a part of the population that is more at risk of disease and death. Military installations, poor houses, and orphanages often housed many people living close to each other under poor conditions. Removing these from the sample means I lose many deaths, which could attenuate the estimated effects. A similar reasoning also applies to the missing data with an incomplete address in the death record. Unregistered residents and residents without a valid address would have been the poorest in Stockholm and thereby exposed to increased health disadvantages. More information on the matching procedure and missing data is provided in the Online Appendix.

While the dataset I have created has a unique level of detail in some aspects, it does not contain information on the cause of death. Although this is a limitation, using all-cause mortality allows me to capture the effect on cases where cholera is an underlying, but not the primary, cause of death and cases where the cause is misclassified. This approach allows me to consider mortality also from other causes of death as a result of cholera infections.

3.1. Descriptive statistics

Table 1 presents descriptive statistics of the data. I define the primary outcome variable as the all-cause mortality rate per 100,000 population at each address and month.[16] During the cholera outbreak in

[13] Furthermore, I cannot separate addresses with the same street name and street number but separated by letters (e.g., a, b, c, d). These addresses were part of the same building but with different entry doors and are unfortunately not well distinguished in the census data. I merge these special cases by their street name and number.

[14] To match this selection in the census data, I exclude households with more than 50 inhabitants in 1860 (the average household size is approximately 5 in the sample). Establishments housing the poor and military installations contain up to 100–300 inhabitants per household (as defined in the census data). After excluding buildings without a valid address, removing institutions reduces the sample by approximately 56 households. The census data contain 3208 valid addresses with residents in 1860. However, the available census data are likely incomplete. Summing up the total number of inhabitants in the data, without exclusions, I have 107,191 residents compared to the official number of 117,000. Unfortunately, some of the archives could have gone missing over the years.

[15] The crude mortality data, between 1860 and 1872, contain 52,172 entries. A meaningful fraction of these belong to institutions not used in the data. At least 8000 entries belong to an institution, where the largest one is an orphanage (Allmäna Barnhuset) with approximately 3000 deaths.

[16] To create this variable, I collapse the data by summing deaths at the address and month level. I divide this sum of deaths by the population in 1860 and multiply by 100,000. The same procedure is used to measure child mortality and mortality by sex. Since I have information on the number of males and females in each house in 1860, I divide by their respective populations when generating sex-specific outcomes. Using the actual number of male and female residents in 1860 will induce some measurement error due to changes in the composition of residents between 1860 and 1866. However,

Table 1
Descriptive statistics.

	Mean	SD	Min	Max	Observations
Water variables					
Water Before Cholera	0.260	0.439	0	1	500 448
Water × Cholera	0.005	0.071	0	1	500 448
Water Before 1873	0.489	0.500	0	1	500 448
Controls					
Popualtion in 1860	33	38	1	857	3208
Fraction female 1860	0.56	0.14	0.00	1.00	3208
Households per House 1860	6.31	5.42	1	62	3208
Mortality rate 1860–1865	0.141	0.183	0.000	4.000	3208
Mortality variables (monthly)					
Mortality count	0.057	0.276	0	34	500 448
Mortality count female	0.028	0.182	0	16	500 448
Mortality count male	0.029	0.184	0	19	500 448
Mortality count under 5	0.027	0.181	0	11	500 448
Mortality (100k pop)	212	1508	0	100 000	500 448
Mortality rate female (100k pop)	191	1856	0	200 000	499 200
Mortality rate male (100k pop)	262	2681	0	200 000	494 052
Child Mortality (100k pop)	96	990	0	100 000	500 448

Note: The water and mortality variables come monthly at the address level. The census provides cross-sectional data for 1860 only. Some values seem implausible, for example, the mortality rate from 1860 to 1865. The implausibly large values can be due to scaling with a constant population. If the census recorded one inhabitant at an address in 1860, four could have died over the six following years due to an increased population or just four consecutive residents at a high risk of dying. Similarly, the mortality rates for males and females are scaled by the male and female population in 1860, which could differ from the sex composition at later times.

1866, 26 percent of the houses in the data had in-house filtered water. Access had increased to 49 percent as of the end of 1872. The average house had 33 residents and slightly more females than males. These residents were divided into 6.3 households per house, meaning an average household contained 5.5 inhabitants. On average, 14 percent of house residents died over the first six years of the 1860s. The outcome variables show that an address suffered a death on average every 18th month. Males had a higher mortality rate than females, and deaths among children under five make up around half of all deaths in the data. These descriptive statistics point to the crowding and poor health environment prevailing in Stockholm at the time.

4. Descriptive results

A direct way to visualize the relationship between filtered water and cholera mortality is to plot time series of mortality for houses with and without access to water. Fig. 3 shows the monthly mortality rate per 100,000 population for houses with and without filtered water in June 1866. The water group, containing approximately 26 percent of the houses in the data, is somewhat more volatile than the larger group without water in 1866. Nevertheless, there is a clear comovement between the two series, in terms of trends and levels. If these groups differed on mortality-related characteristics, we expect to see at least a clear difference in the mortality levels.[17]

The exception to this movement is during the time of the cholera shock (marked in Grey in Fig. 3). During those months, there was a clear spike in mortality in the group of houses without filtered water, while there was no visually clear response in houses with filtered water. After the shock, the series converge again and move closely together. Consistent with other accounts of cholera, the disease spreads rapidly after entering a population and quickly decreases in intensity (Koch, 1894). According to official records, peak mortality was only four weeks after the first case was recorded (Sundhets-collegii, 1869, pp.25).

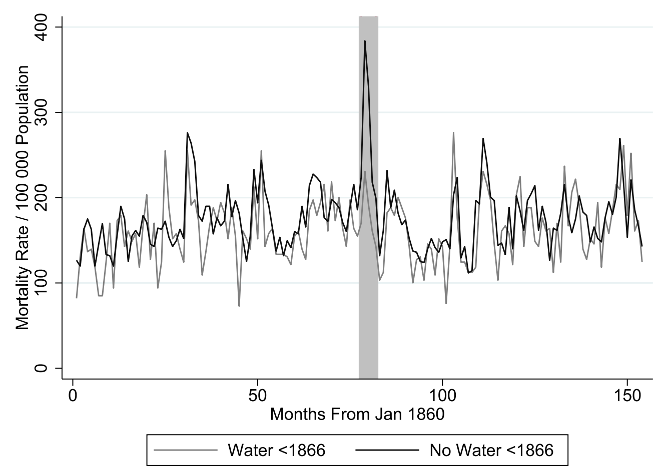

Fig. 3. All-age mortality rate between water and no water in 1866.
Note: The cholera shock is marked in gray. The two groups described in the figure are defined based on having a water contract in June 1866. The water group (black) had a water contract before July 1866, while the no-water group (gray) did not have access to water. The figure is created by summing the deaths and population over the two groups over time. I divide the mortality by the population and multiply by 100,000.

Fig. 4 presents a shorter time frame, focusing on the three years enveloping the outbreak. The Figure shows the mortality surge for non-water houses during the initial epidemic. During the first two months of the cholera outbreak, houses without water had nearly twice the mortality rate than houses with water access. Mortality before cholera followed the same trend between the two groups and returned to a common path after cholera. The filtered water group seems to have been virtually insulated from the outbreak's impact on mortality. This observation accentuates the potential efficacy of filtered water in mitigating waterborne bacterial diseases.

An additional observation from Fig. 4, is that mortality for both treated and controls decreased slightly after the cholera outbreak. Since both groups experienced a similar decrease after the shock, it

this error is not mitigated by dividing by the entire population. For children, I do not have any additional information on the number of residents in 1860, and I have to divide child mortality by the total population.

[17] I test whether the treated and control groups had similar average mortality before the cholera shock and find that the mortality rates are almost identical one month before the cholera outbreak began (263 and 262.7, respectively, p-value = 0.99), which is relevant because significant level differences in outcomes can cast doubts on the plausibility of the parallel trends assumption (see, e.g., Kahn-Lang and Lang, 2020).

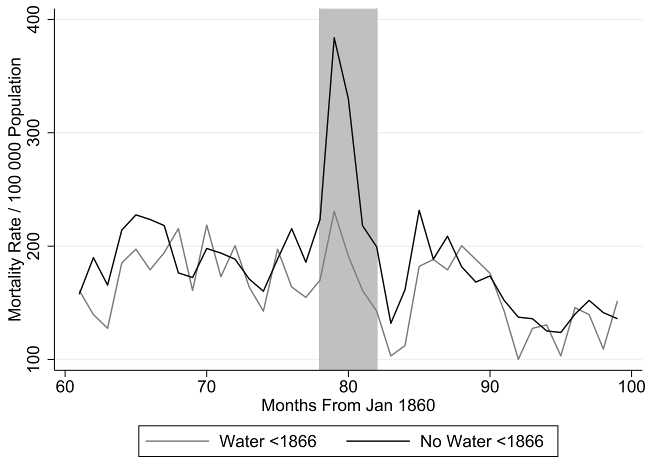

Fig. 4. All age mortality rate between water and no water in 1866.
Note: The cholera shock is marked in gray. The two groups described in the figure are defined based on having a water contract in June 1866. The water group (black) had a water contract before June 1866, while the no-water group (gray) did not have access to water. The figure is created by summing deaths and population over the two groups and by time. I divide the mortality sum by the population sum and multiply by 100,000.

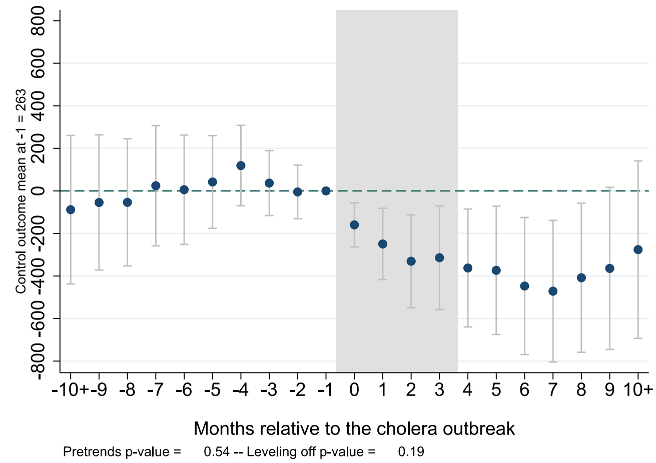

Fig. 5. Cumulative effect of filtered water on mortality rate per 100k population.
Note: The cholera shock is marked in gray. The two groups described in the figure are defined based on having a water contract in June 1866. The water group had a water contract before June 1866, while the no-water group did not. The coefficients are estimated using Eq. (1) and represent cumulative effects. The pre-trends p-value comes from a Wald test of the NULL that all pre-treatment coefficients equal to zero. The leveling-off p-value described in the figure comes from a test of the NULL that the dynamic effects do not change outside the event study window, i.e., that the dynamic effects are leveling off (Freyaldenhoven et al., 2021). Standard errors are clustered at the address level.

should not be related to the excess mortality caused by cholera in the control group. Instead, the mortality dip could have been caused by behavioral responses related to the cholera outbreak, common to all residents. For example, fear of the disease could have induced reductions in social activities that may have persisted sometime after the outbreak had ended. Importantly, if people in the treated and control houses responded similarly in preventative ways after the outbreak, they may also have responded similarly during the outbreak. The observation suggests that differences in behavioral responses may not be an important explanation of the mortality differences.[18]

5. Methodology and regression results

The graphical evidence show a clear spike in mortality during the cholera outbreak for addresses without filtered water but almost no response for houses with access to water (see Fig. 4). To quantify the magnitude of the protective effect of filtered water, I use an event study specification to estimate cumulative treatment effects for nine months before and after the cholera outbreak (Freyaldenhoven et al., 2021; Schmidheiny and Siegloch, 2023).[19] Estimating the accumulated mortality effect over time has several advantages compared to estimating monthly effects. With this methodology, I can estimate the total mortality effect of a short-lived shock. Additionally, cumulative mortality effects make the persistence, further increase, or reversion of the initial shock salient. To estimate the event study specification, I start with the following distributed lag model:

$$\text{Mortality rate}_{ht} = \sum_{k=-8}^{9} \beta^k \text{Water}_{h(t-k)}^{June1866} + \alpha_h + \lambda_t + \epsilon_{ht}. \tag{1}$$

In Eq. (1), subscripts h define unique addresses, while t describes the time in months from January 1860. α and λ are house and month-fixed effects, respectively. ϵ_{ht} captures random mortality shocks specific to each address. The parameters of interest are β^k, where k refers to the treatment's kth lag. $\text{Water}_{h(t)}^{June1866}$ is defined as an indicator variable, taking the value one at the first month of cholera for houses with water in June 1866 and zero otherwise.

Notably, the coefficients, β^k, from the distributed lag model in Eq. (1) can also be expressed as an event study design (Freyaldenhoven et al., 2021; Schmidheiny and Siegloch, 2023). Cumulative treatment effects are calculated by accumulating the coefficients from the distributed lag model starting from the reference period (Schmidheiny and Siegloch, 2023). Since I define the treatment-shock interaction as a one-period event, the cumulative effects are defined as $\delta_m = -\sum_{k=-2}^{m} \beta^k$ if $-8 \le k \le -2$, $\delta_m = 0$ if $k = -1$ and $\delta_m = \sum_{k=0}^{m} \beta^k$ if $9 \ge k \ge 0$, where m defines event time around the start of the cholera shock. The cumulative dynamic effects have a natural interpretation as the persistence in the mortality shock up to nine months after the first documented case.

In Fig. 5, I estimate Eq. (1) using OLS, calculate the cumulative effects, and investigate whether the treatment and control houses follow parallel trends in mortality before the outbreak. The results show that the estimated pre-treatment coefficients are close to zero without a clear trend. A Wald test on all pre-treatment coefficients equal to zero confirms the visual evidence (p-value = 0.54).

The dynamic treatment effects, also presented in Fig. 5, are decreasing for the first three months, consistent with the official cholera mortality reports described in Online Appendix Figure A5.[20] After three

[18] Recommendations from the physician association to avoid becoming infected by cholera included personal hygiene, opening windows, drinking alcohol in moderation, and cleaning indoors. These recommendations could promote health if adhered to. Moreover, in response to the episode, the city council also opened three temporary cholera hospitals and engaged 24 additional physicians (Sundhets-collegii, 1869). These resources might have been used sometime after the cholera outbreak ended to benefit the entire population.

[19] The treated group are houses connected to the water network which signed a contract before June 1866. The control group consist of houses that did not have water. Since the shock lasted only four months, this narrow time frame reduces the scope for installing an in-house tap in response to the shock. Online Appendix Figure A4 shows that only a small fraction of the water users connected during the cholera shock of 1866, more reflecting it being summer when the temperature allowed for construction work than a demand response.

[20] The estimated dynamic effects do not match perfectly with the recorded deaths from cholera in Sundhets-collegii (1869). This source describes cholera deaths in weeks from the first case on the 28th of June, which cannot be

months, buildings with water had accumulated 330 fewer deaths per 100,000 residents than houses without water access. Moreover, the dynamic cumulative effects over a longer time horizon than motivated by the cholera shock shows that the impact on mortality persisted after the cholera outbreak ended. This suggests that those succumbing to cholera were not at high risk of dying of competing causes over the next nine months, which is consistent with most deaths occurring among prime-age adults (see Fig. 2).

The estimated effects are significant up to 8 months after the cholera outbreak began, with a peak magnitude of around −400 deaths per 100,000 residents. This is a substantial figure, given that the average monthly mortality rate was 212. This finding suggests that water filtration during the 19th century was an effective, stand-alone technology in mitigating cholera mortality. In line with these findings, other research has found that filtered water reduced typhoid mortality by around 36 percent (Cutler and Miller, 2005; Anderson et al., 2022).[21] Together, these findings suggest that water filtration can be effective against bacterial waterborne disease mortality more generally.

5.1. Robustness

Although the event-study results are consistent with the visual evidence presented in Section 4, the estimated effects could still be sensitive to deviations from the specification described in Eq. (1) or be affected by underlying confounding. To address the concern of unobserved confounding, I estimate placebo event study figures starting in the same calendar month as the cholera outbreak in 1866 but for earlier years. I omitted 1865 from the placebo events to avoid overlapping with the cholera outbreak. Similarly, I omitted 1860 as the pre-treatment period is not long enough to match the specification of Eq. (1). In total, I have four years to define the placebo cholera shocks, namely 1861–1864.

Online Appendix Figure A6 presents the resulting event-study figures. These figures show no significant differences in cumulative mortality before or after the placebo interventions. Even though Stockholm experienced constant shocks to health during this time, they are not systematically related to whether houses had water in 1866. This finding significantly reduces the plausibility of alternative explanations, such as location-specific characteristics, socioeconomic status, or demographic differences between treated and control buildings, to be credible explanations of the estimated effects of filtered water on mortality.

The placebo tests presented so far mimic the empirical strategy from the main results. Another transparent way of showing how the treated and control groups respond to health shocks is by showing differences in monthly mortality for the entire period. If the two groups are different in how they respond to health shocks, we should be able to observe a pattern where the treated group experiences systematically less severe shocks compared to the control group. Such figure is presented in the Online Appendix (Figure A7) where I show demeaned, monthly differences in mortality between the two groups. This figure shows no clear pattern except for during the cholera months. It seems unlikely that the treated houses are unaffected by cholera but similarly affected by all other health shocks. These findings suggest that both groups were equally exposed and responsive to the health shocks that constantly affected urban residents during the mid-19th century in Stockholm. Differences only emerged when purposeful technology coincided with a specific health shock in 1866.

To further probe the appropriateness of the model and specification used, I use a count data estimator, try other levels of clustering, include control variables, and use weighted least squares. These and other additional robustness checks on specification issues and inference are presented and discussed in the Online Appendix.

5.2. Heterogeneity and spill-over effects

Heterogeneity

That water improvement efforts can have heterogeneous effects on different groups has previously been documented (Anderson et al., 2021). However, less is known about the heterogeneous impacts of water filtration on cholera mortality. Since cholera spreads mainly through contaminated drinking water, infections should be evenly distributed in the population as everyone drinks water to some extent.[22] I use information on the sex and age of the deceased in my data to study how these different groups were affected and validate the findings against reported cholera mortality demographics. Online Appendix Figures A8, A9, and A10 show separate estimations of the filtered water effect for females, males, and both sexes under the age of five.

According to official reports following the outbreak, 45 percent of the cholera infected and 43 percent of the dead were female (Sundhetscollegii, 1869). My findings align well with these reports as I find no significant difference in the estimated cumulative effects between men and women (Online Appendix Figures A8 and A9). The only notable difference is that the coefficients are more precisely estimated when investigating female mortality. The more precise estimates for females could be due to women spending more time at home and using more water daily, thereby being more exposed to contaminated water where they live. This would lead to a more precise treatment mapping to the residence address.

The estimated effects on mortality under age five are insignificant and smaller than the baseline estimates. A reduced magnitude is expected since the child mortality rate is measured by 100,000 people in the total population. Comparing the magnitude to the child population share, the estimated effects are similar to those of adults. Fig. 2 shows that children under five made up at most one fifth of all cholera deaths, which is similar to the reduced magnitude observed in Online Appendix Figure A10. The observation that cholera was not more of a threat to children, in contrast to the cholera mortality risk today, is consistent with the previous historical evidence on cholera mortality among children (Davenport et al., 2019). These findings suggest that cholera was rather indiscriminate between sexes and ages.

Spillover-effects

A prime concern in studies of mitigation efforts of infectious diseases relates to externalities. Treatments that are effective for some may reduce exposure to others. There are several ways in which a water tap, providing clean water, can benefit residents in surrounding buildings. Neighbors can have direct access to the water from the tap, improving the quality of their drinking water. Since the water was not charged per usage in Stockholm, sharing the water was low cost. Moreover, pressurized water can affect untreated nearby houses by facilitating the removal of waste from the streets, thereby reducing exposure to ground waste and contaminated pools of water. Additionally, higher water usage can reduce the likelihood of contaminants infiltrating local groundwater reservoirs and thereby contaminating the wells by

exactly translated into deaths during calendar months. Moreover, since I have missing information in the mortality data and restrict the sample of houses included in the analyses, the relative mortality between the months may not perfectly represent all cholera deaths.

[21] My descriptive evidence suggested that water cleaning and distribution technologies could have nearly eradicated bacterial waterborne diseases, such as cholera. Similar visual evidence in Cutler and Miller (2005) and Beach et al. (2016) also point to this conclusion.

[22] Minor exceptions could include brewery workers (Tulchinsky, 2018).

keeping a steady flow of water through the street ditches.[23] With any of these spillover effects, I would be underestimating the impact of water filtration on cholera mortality.

To explore the importance of spillovers, I exclude subsets of houses without water that are close to addresses with water. With spillover effects from treated to nearby control houses, both are, to some extent, treated. By removing controls likely affected by treatment, we can observe if the treatment effects become meaningfully larger in magnitude, indicating the presence of spillover effects. Although there are many ways of estimating spill-over effects, this is a straightforward way where the contaminated units are directly excluded.[24]

I consider two different geographical levels where spillovers can be analyzed: the street and the block. City blocks and streets differ in a few critical ways, which makes it relevant to study both. Streets are natural places where residents interact, and street cleaning through pressurized water will affect residents living close to each other on the same street. In contrast, as exemplified in Online Appendix Figure A11, the city block is smaller than a street, and people living in the same block live closer to each other. They would use the same water supply without piped water and share other amenities like toilets.

In Online Appendix Figure A12, I show the effects of removing control houses on streets and blocks with different intensities of water connections. I present three figures removing controls on streets or blocks with more than 30, 60, and 90 percent water uptake in 1866. The latter is very close to the baseline specification since few observations are removed when conditioning on having more than 90 percent water coverage.

The most significant effects are found in the specification when removing controls in areas with more than 30 percent water coverage. Comparing the cumulative impact of piped water between specifications removing controls on streets or blocks with more than 90 and 60 percent water coverage, the effect sizes are very similar to the baseline specification, with around 400 deaths per 100,000 population at most. However, when removing controls on streets or blocks with more than 30 percent water coverage, the effect sizes are almost twice as large.[25] These findings indicate that spill-over effects, from buildings with filtered water to nearby buildings without filtered water, may have been substantial. Furthermore, the findings imply that the protective effect of clean water was even more significant when considering spill-over effects.

There are only minor differences between specifications using city blocks or streets as the unit of spillovers. The similarity in findings between the street- and the block level suggests that the mechanisms specific to each geographical level may be less critical. Shared amenities, like toilets and wells, generally shared within house blocks but to a lesser extent within streets, may not have been crucial for the externalities to materialize. Instead, sharing drinking water, keeping wells clean, street cleaning, and fewer cholera cases in the local community may have been more critical in producing spill-over effects.

These substantial spill-over effects suggest that even partial take-up of water distribution systems may have effectively mitigated cholera and other waterborne bacterial diseases. Once a neighborhood got access to a main pipe and some houses started connecting, they were all somewhat protected. This finding implies that even with only 26 percent of buildings having access to filtered water, such infrastructure could have accounted for the milder impact of cholera in 1866 compared to earlier outbreaks.

6. Conclusions

Cholera, which plagued European cities during the 19th century, witnessed a sharp decline in mortality even before the advent of effective treatments or modern medicine. Notably, this decline aligned with the introduction of water-filtration infrastructure across many European cities. This paper explores the role of filtered tap water in Stockholm during a cholera epidemic in 1866. An important question that has received little attention since the work of Snow (1849).

To study this question, I have compiled a novel dataset with information on mortality and the availability of filtered tap water at individual addresses throughout the 1860s in Stockholm. Using an event-study design, I studied the effect of filtration and distribution during a brief cholera outbreak. The short exposure window and the absence of other competing technologies resulted in a clean, natural experiment.

During the cholera outbreak, houses with filtered water witnessed drastically lower mortality rates, indicating that water filtration was an effective countermeasure against cholera. From visual evidence, the clean water group looks almost unaffected by the cholera outbreak indicating that water filtration was a highly effective technology in mitigating bacterial waterborne diseases. Using regression models, I estimate that water filtration and distribution averted around 400 deaths per 100,000 population during the outbreak. This effect could be up to twice as large when considering spill-over effects.

The importance of water filtration on urban mortality decline has received much attention from researchers (Cutler and Miller, 2005, 2022; Anderson et al., 2022, 2021). My findings provide new results to this ongoing discussion. First, this study confirms the critical role of water filtration in mitigating waterborne bacterial disease mortality (Anderson et al., 2022; Cutler and Miller, 2005). Moreover, this study uniquely highlights the direct effect of water filtration on reducing cholera mortality, a previously underexplored aspect of mortality decline during the 19th century.

Additionally, water filtration and distribution could have contributed significantly to the demise of cholera during the second half of the 19th century. With cholera claiming millions of lives during the 19th century, water filtration may have contributed significantly to the mortality decline at this time. If cholera was stopped by waterworks preventing it from getting a hold in large, interconnected European cities, these technologies could partly explain why cholera was nearly eradicated in Europe at the turn of the 20th century.

Urban water supplies are essential for sanitation and health, especially in developing countries. This paper shows that even water filtration systems built 150 years ago effectively reduce waterborne disease mortality. These historical lessons are still relevant today. Despite modern advancements, over 2 billion people worldwide still lack access to clean drinking water (WHO, 2021). Simple and affordable solutions, like slow sand filtration, piped water, and community water points, can save many lives, particularly where large-scale infrastructure is not yet in place.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used Chat GPT-4 and Grammarly in order to improve the fluency of the writing. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

[23] A negative externality could appear if connected houses move street waste to other neighborhoods or parts of the same street. Untreated homes located downstream could experience an accumulation of waste and, thereby, a worse health environment and water quality. Although negative externalities are possible in this sense, the positive externalities likely dominate. I cannot study this feature without detailed information on geography, for example, elevation.

[24] With spill-over effects, the Stable Unit Treatment Value Assumption (SUTVA) does not hold since the treatment of one individual affects the potential outcomes of other individuals (Angrist et al., 1996). If there are violations of SUTVA, bias should decrease when removing control houses close to those with water access. In this way, the estimated effects when removing affected controls could be closer to the causal effect of water filtration and distribution on cholera mortality.

[25] Although the estimated cumulative effects are vastly different, the event study coefficients are not significantly different from each other between the various models since the standard errors are quite large.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jue.2025.103752.

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