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Sanitary infrastructures and the decline of mortality in Germany, 1877–1913[†]

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Clean water provision is considered crucial for eradicating waterborne diseases. However, the benefits of piped water can be limited in environments characterized by the inadequate storage and disposal of waste. This article studies the impact of waterworks and sewerage on mortality in German cities during the period 1877–1913. The results show that the supply of safe drinking water reduced the number of deaths, although to a lower extent than suggested previously. In the absence of efficient systems of sewage removal, contact with faeces and water contamination created a favourable environment for the spread of enteric ailments, offsetting some of the positive effects of waterworks. Moreover, the study shows that sanitary investments had important heterogeneous effects. First, their impact was markedly lower in municipalities with high levels of economic inequality and employment in the textile sector. Second, cities located in non-Prussian territories experienced lower declines in mortality following the construction of sanitary infrastructures. The results in this article highlight the importance of analysing public health measures jointly as well as their interaction with local socioeconomic and institutional factors to understand historical progress against ill health and premature death.

Access to clean water and sanitation facilities is very limited in many parts of the world. A recent report by the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) estimates that 844 million people lack basic drinking water service, and that more than two billion people do not have access to efficient systems of waste disposal.[1] At the same time, infectious illnesses transmitted through water are a significant cause of death in the developing world due to widespread open defecation and the consumption of impure surface water.[2]

Similarly, advanced economies during the late nineteenth century exhibited extraordinarily high rates of death from waterborne diseases. Consider the case of Germany as an example. In the late 1870s gastrointestinal ailments accounted for almost one-third of deaths.[3] Unlike today's developing countries, Germany and

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[1] WHO and UNICEF, *Progress on drinking water*, pp. 3–4.

[2] WHO, 'Deaths by cause'.

[3] Vögele, 'Urbanisation and the urban mortality change', p. 45.

other industrialized economies experienced a large decrease in deaths from these illnesses in the subsequent decades that would ultimately result in their complete disappearance.[4] An emerging body of empirical literature has examined the drivers of this process, providing renewed support for the idea that the provision of safe drinking water was a key factor.[5]

However, the prevalence of waterborne ailments transmitted through faecal-oral mechanisms does not just depend on centralized water provision. First, the effectiveness of waterworks may fall short because of contamination of the water source or during transport.[6] Second, in the absence of efficient systems of waste disposal the incidence of enteric ailments may still remain high due to the inadequate storage of human excrement. This can attract vectors transmitting diseases and contaminate the food or water supply when flooding occurs.[7] Third, the use of inadequate toilets or open defecation increases the exposure of the population to diarrheal ailments.[8] In sum, these mechanisms cast doubt on the effectiveness of clean water alone, and call for an integrative analysis considering both waterworks and sewerage systems. This article aims to provide such an analysis by studying the case of Germany during the period 1877–1913.

In the 1870s, German cities experienced persistently high mortality levels in comparison with other European states.[9] However, crude death rates and infant deaths rapidly declined by almost half until the eve of the First World War.[10] Coinciding with these declines in mortality, the percentage of cities with waterworks increased from 9 to 52 per cent between 1870 and 1900,[11] and more than 250 municipalities initiated a systematic plan to establish drainage systems.[12] These parallel developments in the public health and mortality domains present an interesting and relevant case study for assessing the contribution of sanitary infrastructures to long-term mortality decline.

This article examines two new datasets containing information on various measures of mortality at city level (overall deaths, infant mortality, and cause-specific deaths) and the timing of improvements in water supply and sewage disposal by municipalities. Using a sample of cities that invested in these large-scale projects during the period analysed, their effect is empirically estimated by comparing mortality trends before and after their implementation. This exercise contributes to the literature in three ways. First, it provides new insights into the impact of public health measures on mortality, and thus complements previous studies focusing on individual sanitary interventions. This approach is similar to work by Alsan and Goldin, looking at the determinants of child mortality

[4] Easterlin, 'Worldwide standard of living'.

[5] Cutler and Miller, 'Role'; Ferrie and Troesken, 'Chicago's mortality transition'; Ogasawara, Shirota, and Kobayashi, 'Public health improvements'; Beach, Ferrie, Saavedra, and Troesken, 'Typhoid fever'. These studies contrast with the conclusions of an earlier and more pessimistic literature with regard to the effects of water supply on mortality; van Poppel and van der Heijden, 'Effects of water supply'.

[6] Fewtrell, Kaufmann, Kay, Enonaria, Haller, and Colford, 'Water'; Kremer, Leino, Miguel, and Zwane, 'Spring cleaning'; Kesztenbaum and Rosenthal, 'Sewers' diffusion'.

[7] Alsan and Goldin, 'Watersheds'.

[8] UNICEF, *UNICEF field notes*; Geruso and Spears, 'Neighborhood sanitation'.

[9] Leonard and Ljungberg, 'Population and living standards'.

[10] This fall in mortality refers to the cities with more than 15,000 inhabitants between 1877 and 1913 reported in Kaiserliches Gesundheitsamt, *Veröffentlichungen des Kaiserlichen Gesundheitsamtes*.

[11] Grahn, 'Die städtischen Wasserwerke', p.309.

[12] Hennock, 'Urban sanitary movement', p. 282.

in Massachusetts, although our analyses differ in several respects.[13] This study examines crude death rates as well as mortality among the youngest to assess whether the mechanisms of disease protection provided by sanitary infrastructures differed due to age.[14] The sample used here exhibits a large degree of variation that allows an analysis of the interaction between sanitary infrastructures and a number of local economic, cultural, and institutional factors. The study of Germany sheds new light on the interplay of improvements in water supply and waste disposal because, unlike the case of Massachusetts, the establishment of sewerage systems experienced a delay of one or two decades relative to the construction of waterworks.[15] Moreover, some mechanisms of disease spread, such as water recontamination, may have been less important in Germany than in the US, since most German water supply systems relied on underground sources.[16]

The second contribution of this article is related to the varied range of cities considered. Its focus goes beyond 'traditional' analyses of very large cities[17] or homogeneous areas in political and cultural terms,[18] because it uses a dataset that contains municipalities located across nine different German states with populations ranging from a few thousand to more than half a million. This wide variation makes it possible to explore the universality (or the lack thereof) of the impact of public health investments, as well as supporting the external validity of the findings.

The third contribution is the provision of insight into the heterogeneous effects of sanitary infrastructures that remain unobserved in the usual estimation of average effects. By using information on cities' socioeconomic and cultural characteristics, context-specific factors that impacted on their effectiveness are uncovered, such as female employment and economic inequality. These analyses highlight that the interplay of public health measures and the local context is important for understanding some of the mechanisms that reduced mortality.

The results show that piped water reduced mortality, although its effects were limited in the absence of efficient systems of waste removal. Jointly, the two sanitary measures account for at least 21 per cent of the decrease in crude death rates between 1877 and 1913. The mere provision of clean water does not sufficiently explain the downward trend in infant deaths either, because sewers were equally important in providing effective protection against waterborne illnesses. Together, they explain 25 per cent of the fall in infant mortality. These findings are interpreted causally because both interventions had a persistent short-term impact on mortality right after their implementation, and not before. When cause-specific deaths are examined, evidence shows that sanitary infrastructures mainly reduced mortality in two ways. First, they protected urban citizens from digestive diseases that are

[13] Alsan and Goldin, 'Watersheds'.

[14] During the analysed period, the share of infant mortality (deaths before reaching one year of age) in total deaths fell from 32% to 24% in Prussian cities. For child mortality (deaths before reaching five years of age), this figure dropped from 49% to 32%; Königliches Statistisches Bureau in Berlin, *Preussische Statistik*, vols. 55 and 238. Thus, crude death rates increasingly reflect developments affecting adults.

[15] Hennock, 'Urban sanitary movement', pp. 281–2. The sample used by Alsan and Goldin, 'Watersheds', shows the opposite pattern since most cities with both sanitary interventions installed sewers earlier than waterworks.

[16] Grahn, *Die städtische Wasserversorgung*, p. 14.

[17] For instance, see Cutler and Miller, 'Role'; Ferrie and Troesken, 'Chicago's mortality transition'; Kesztenbaum and Rosenthal, 'Sewers' diffusion'.

[18] Ogasawara et al., 'Public health improvements'; Alsan and Goldin, 'Watersheds'.

transmitted through water and via faecal-oral mechanisms. The construction of waterworks and sewerage systems explain more than 50 per cent of the decline in deaths from this category. Second, airborne ailments became less lethal following the fall in morbidity from enteric diseases (such as typhoid fever) that weakened the immune systems of their sufferers.

The second part of the analysis examines the heterogeneous effects of sanitary interventions along different dimensions. The first finding is that their effectiveness does not vary significantly by city size. Second, a high presence of the textile sector in the local economy was associated with larger declines in infant deaths. Third, municipalities with high levels of economic inequality experienced lower health improvements from the construction of waterworks than more egalitarian cities. Fourth, the effects of sanitary infrastructures were not universal. Their most significant effect was on Prussian localities, which suggests that the relative importance of factors explaining the decline in mortality may have been very different across regions.

This article is related to a well-established literature on the factors driving the mortality decline in the early phase of the epidemiological transition. On the one hand, some scholars emphasize the role of increasing income and caloric intake in the nutritional status of individuals, which made people more resistant to the disease environment.[19] On the other hand, a number of studies highlight the role of medical knowledge and the implementation of public health infrastructures.[20] The effects of the latter have been found for several countries, including the US, England, France, and Japan.[21] This research adds to this literature by putting the case of Germany in an international comparative perspective and by taking an encompassing approach that jointly considers systems of water supply and sewage disposal.

Furthermore, this article contributes to the body of literature that looks at the determinants of mortality in Germany by empirically quantifying the relative importance of public health infrastructures.[22] In this respect, it complements earlier work by Brown in several ways.[23] This study explicitly examines the interaction between improvements in water provision and waste disposal. It explores their heterogeneous effects along various dimensions such as population size, culture, local economic factors, and institutions. Consideration is given to crude death rates as well as infant mortality, and the period of analysis is extended back to 1877.[24]

The remainder of this article is structured as follows. Section I discusses the historical context in Germany, with a special emphasis on various public health measures undertaken to improve citizens' health. Section II presents two new datasets on city-level mortality and sanitary interventions for the period

[19] McKeown, *Modern rise of population*; Fogel, *Escape from hunger*; Floud, Fogel, Harris, and Hong, *Changing body*.

[20] Preston, 'Changing relation'; Easterlin, 'How beneficent is the market?'; Deaton, *Great escape*.

[21] Cutler and Miller, 'Role'; Chapman, 'Contribution of infrastructure'; Kesztenbaum and Rosenthal, 'Sewers' diffusion'; Ogasawara et al., 'Public health improvements'.

[22] Spree, *Health and social class*; Vögele, *Urban mortality change*; Gehrmann, 'Infant mortality in Germany'; Brown and Guinnane, 'Infant mortality decline'.

[23] Brown, 'Economics and infant mortality'.

[24] Brown's analyses of infant mortality and some causes of death in start in 1889 and 1903, respectively.

1877–1913, and outlines the empirical framework used for the analysis. Section III presents the results, and section IV offers some conclusions.

I. Historical context

Germany began to undergo a rapid urbanization process from the mid-nineteenth century to 1880, as the percentage of the population living in rural areas steadily declined from 67 to 59 per cent.[25] This process was very intense in some regions, such as the Ruhr area, where the population increased from less than 40,000 in 1800 to around one-and-a-half million a century later.[26] During this period of rapid demographic growth citizens' health deteriorated because overcrowding and congestion provided a favourable environment for the transmission of airborne and waterborne infectious diseases.

In the late 1870s, excess mortality in urban areas relative to the countryside—the so-called urban penalty—was at its highest.[27] Putting these figures in international perspective reveals the existence of a 'German penalty' since death rates were higher than in other industrialized countries such as England.[28] These two 'penalties' particularly affected urban infants who suffered predominantly from digestive diseases. This overall pattern differed across regions within the German Empire because infant mortality rates varied significantly across regions, in part due to breastfeeding practices.[29] Despite the bleak condition of citizens' health during these years, it is precisely at this time when a sustained mortality decline becomes visible. As illustrated by the case of Prussia, overall and infant mortality not only converged between urban and rural regions in the three decades prior to 1900 (see figure 1), but also across other German states. Actually, progress was so remarkable that the urban–rural difference disappeared around the turn of the twentieth century, even though urbanization accelerated in these decades.[30]

One explanation put forward for this development is related to advances in medical knowledge. Although somewhat rudimentary by today's standards, medical innovations translated into treatments for several diseases such as smallpox, rabies, and diphtheria.[31] In Germany, vaccination against smallpox was made universal and compulsory from 1875 to 1889.[32] However, the potential of such treatments for significantly reducing mortality was rather limited, since they did not provide a cure for the main killers of the time, such as tuberculosis.

A more important role for medicine can be recognized in relation to the diffusion of health-enhancing knowledge. By understanding the transmission mechanisms of diseases, households could adopt more hygienic habits in relation to home cleanliness and food preparation, in order to reduce their exposure to communicable illnesses.[33] Public authorities approved food regulations in

[25] Knodel, *Decline of fertility*, p. 4.
[26] Leonard and Ljungberg, 'Population and living standards', p. 114.
[27] Vögele, 'Urbanization and the urban mortality change', p. 44.
[28] Leonard and Ljungberg, 'Population and living standards', p. 119.
[29] Haines and Kintner, 'Mortality transition'; Kintner, 'Trends and regional differences'.
[30] Matzerath, 'Prussia's urbanization'; Vögele, *Urban mortality change*; Gehrmann, 'Infant mortality in Germany'.
[31] Easterlin, *Growth triumphant*; idem, 'How beneficent is the market?'.
[32] Hennock, 'Vaccination policy'.
[33] Mokyr, 'Why "more work for mother"?'; Mokyr and Stein, 'Science'.

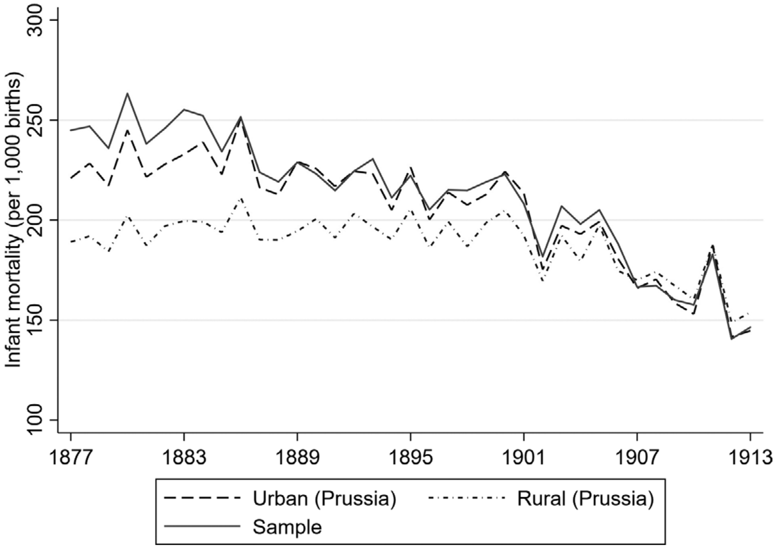

Figure 1. *Evolution of infant mortality, 1877–1913*

Notes: WSI = water supply improvements; WDI = waste disposal improvements.
Sources: For the series 'Urban (Prussia)' and 'Rural (Prussia)': Königliches Statistisches Bureau in Berlin, *Preussische Statistik*, vols. 50–245; for 'Sample': annual reports of the Imperial Health Office (Kaiserliches Gesundheitsamt, *Veröffentlichungen Des Kaiserlichen Gesundheitsamtes*; idem, *Medizinal-Statistische Mittheilungen*). See app. tab. S1 for the composition of the sample.

1879, but their implementation took many years.[34] Another way of spreading best practices was through the provision of health care. The compulsory health insurance scheme established in 1884 by Otto von Bismarck may have reduced mortality through the diffusion of new hygiene knowledge by physicians.[35] However, this factor does not explain why mortality already started decreasing in the 1870s in some areas.

The diffusion of improved knowledge of disease transmission is an important determinant of infant deaths because it influences feeding practices. Public health authorities in Germany recognized this and promoted a pasteurized milk supply, although this measure was not very successful during the analysed period.[36] Another strategy was to encourage breastfeeding and better infant care through infant welfare centres, which rapidly diffused across large German cities in the decade preceding the First World War.[37] However, these welfare centres had limited success in enforcing breastfeeding because they established a large number of bureaucratic, and sometimes discriminatory, procedures that discouraged working-class mothers from attending them.[38]

Local authorities also made significant efforts towards improving overall hygienic conditions in cities by paving streets, cleaning public spaces, and improving the building standards of dwellings, especially in large cities.[39] One of the main

[34] Guinnane, 'Population and the economy'.
[35] Bauernschuster, Driva, and Hornung, 'Bismarck's health insurance'.
[36] Vögele, *Urban mortality change*, p. 189.
[37] Brown, 'Economics and infant mortality', p. 182.
[38] Vögele, Rittershaus, and Halling, '"Breast is best"'.
[39] Neefe, *Statistisches Jahrbuch Deutscher Städte*.

spending areas was related to the provision of centralized water and waste disposal. These large-scale public health investments had considerable potential to make public environments in urban areas safer at a time marked by the high prevalence of diseases transmitted through water and faecal-oral mechanisms.[40]

In the late nineteenth century, neither the technology nor the actual establishment of waterworks and sewerage systems was new in Germany. The first of these health infrastructures was constructed in Hamburg after a serious fire in 1842. Fearing future similar events, rather than the high level of disease in the city, the local authorities commissioned a British engineer to build a public system of water provision and waste disposal.[41] Analogous infrastructures were installed in other cities such as Altona, Berlin, and Leipzig before the 1870s, although they were exceptions rather than the norm, since only 12 per cent of localities with more than 2,000 inhabitants provided piped water by 1880.[42] In contrast, an extraordinary 47 per cent of English cities had waterworks at that time.[43]

This relative backwardness would change rapidly in the subsequent decades. In the 1860s, fewer than 50 cities supplied clean water to their citizens. However, 100 projects were completed in the following decade, with 200 more during the 1890s.[44] These systems gradually replaced traditional well-water economies, consisting of public and private wells, with a complex pipe network and water pumps that distributed efficiently water to the whole city. Evidence for 1900 shows that most waterworks drew water from underground sources,[45] which possibly had a larger benefit for the population (in the absence of filtration systems) in comparison with surface water, since source contamination was less likely. Sewerage systems underwent a similar development, albeit with a delay of several decades. In towns with more than 1,000 inhabitants, systematic plans to establish main drainage schemes grew from 17 in the 1870s to 186 in the 1890s.[46] Besides carrying urine and faeces out of the city efficiently, this infrastructure significantly altered how households dealt with waste, as privies and ditches used for storing faeces were increasingly replaced by water closets connected to the sewerage network.[47] These developments were followed by a strong convergence in infant mortality between urban and rural areas (see figure 1) and increases in life expectancy throughout the age distribution.[48]

The construction of sanitary infrastructures was not a series of complete historical accidents, although their precise timing was largely random for several reasons. The first factor to consider is the state of medical knowledge with regard to the spread of infectious diseases. Throughout most of the nineteenth century

[40] For comprehensive reviews of the literature on various countries, see van Poppel and van der Heijden, 'Effects of water supply'; Costa, 'Health and the economy'; Harris and Helgertz, 'Urban sanitation'; Floud et al., *Changing body*.

[41] Evans, *Death in Hamburg*.

[42] Grahn, 'Die städtischen Wasserwerke', p. 309.

[43] Hennock, 'Urban sanitary movement', p. 281.

[44] Grahn, 'Die städtischen Wasserwerke', p. 309.

[45] Grahn, *Die städtische Wasserversorgung*.

[46] Hennock, 'Urban sanitary movement', p. 282.

[47] Schramm, 'Privatisation'. During the early stage of this process, sharing water toilet facilities may have increased the risk of the spread of diarrheal disease; Brown, 'Economics and infant mortality', p. 176.

[48] Vögele, 'Urbanization and the urban mortality change', p. 47. The literature has also considered other factors driving mortality such as declining fertility (I will further elaborate on this below) and economic development; Brown and Guinnane, 'Infant mortality decline'; Vögele, *Urban mortality change*, pp. 131–5.

the predominant view among public officials, sanitarians, and scientists was that illnesses were transmitted through poisonous and bad-smelling vapours known as miasmas. As new knowledge gradually accumulated, this view started to change. John Snow and William Budd contributed to the debate in the 1850s when they discovered that water, rather than vapours, was the main carrier of cholera and typhoid. More scientific knowledge was created in the laboratories of Louis Pasteur in the 1860s and Robert Koch from the 1870s onward with the discovery of various pathogenic organisms responsible for communicable diseases.[49]

Although the germ theory of disease offered a compelling explanation for the causes of the terrible urban health conditions, public authorities were divided between the two theories, and therefore their willingness to invest in costly large-scale infrastructures was sometimes low. Consider the case of Hamburg as an example. This city was the first in Germany to have a centralized water supply system. In contrast with its much smaller neighbouring municipality, Altona, or the large city of Berlin, Hamburg did not filter its water, although this had been planned in 1852.[50] Disbelief in the germ theory of disease meant that measures of isolation and quarantine against epidemics—which furthermore were not favoured by the economic elite of the city, whose interests were closely linked to the uninterrupted course of trade—were automatically dismissed. Given the wealth of Hamburg and the various epidemics it suffered during the nineteenth century, the precise timing of the supply of safe water did not therefore ultimately depend on financial or health issues, but rather on beliefs concerning disease transmission mechanisms and the economic interests of the local elite.[51]

Second, sanitarians fought long political battles in order to persuade city councils of the benefits of the new sanitary technologies.[52] Consider the case of Frankfurt. This municipality started on an active project to build a sewerage system in 1839. However, the city council cut off the funds after several years of protest by opponents of this programme, led by Dr Georg Varrentrapp. Varrentrap, who was familiar with the English sanitary movement and their more advanced sanitary technologies,[53] wanted a more comprehensive system that could remove surface water, household-waste water, and human faeces at the same time. In 1863, a commission consisting of the director of town planning, two engineers, Varrentrapp, and a government building officer revised the drainage system issue and paved the way for the beginning of this new project in 1867, which was finished decades later in 1896.[54] This complex and arduous process was not unique to Frankfurt; it occurred in other cities including Hanover, Bielefeld, and Münster.[55]

A third element that adds to the randomness of the precise timing of water infrastructures relates to the political organization of the German Empire. During the late nineteenth century, states had a high degree of autonomy that influenced sanitary efforts within their boundaries. An example of this is the prohibition that Prussia introduced in 1874 on pouring untreated urban sewage into rivers. The

[49] Mokyr and Stein, 'Science'.
[50] Grahn, 'Die städtischen Wasserwerke', p. 303.
[51] Vögele, *Urban mortality change*.
[52] Troesken, *Water, race and disease*; Cutler and Miller, 'Role'.
[53] Hennock, 'Urban sanitary movement', p. 273.
[54] Brix, Imhoff, and Weldert, *Stadtentwässerung in Deutschland*, p. 323.
[55] Hennock, 'Urban sanitary movement'.

ban lasted until 1888, which partly explains why the implementation of sewers experienced some delay.[56] Therefore, state regulation in the field of public health could affect the implementation of sanitary infrastructures in some cities of the German Empire regardless of their level of mortality.

The last point is related to local idiosyncratic factors that determined the timing of sanitary infrastructures. Once sanitarians convinced local authorities to establish them, discussions emerged with regard to the specific technology that would be used. In the case of waterworks, municipalities had to consider whether water would be taken directly from a nearby river, nearby reservoirs, a lake, underground water, or a combination of these (and also whether the water was to be filtered). With respect to sewerage systems, some technologies involved carrying waste water together with rain water, and other technologies used separate sewers. These choices involved a process of deliberation and discussion that differed among cities with varying geographic conditions and political dynamics.

Another variable was whether the infrastructures were to be financed publicly or privately. Cities used both strategies during several decades from the mid-nineteenth century onwards, and choosing one over the other had consequences. For instance, the city of Mülheim decided to build waterworks and called for bids in 1873. However, the contractor commissioned in 1874 could not find any investors for the city project. Therefore, the city had to finance the project itself, finishing the works in 1876.[57] Brown has looked at this issue by empirically assessing the determinants of the timing of water provision in the Rhineland. He finds that industrial demands and median voter tax payment are the most important factors, rather than health-related variables such as cholera outbreaks or population density. Emerging industries such as cloth finishing and dyeworks fostered the demand for the water supply that was necessary for their production process. Moreover, the rising incomes this sector brought to the local elite increased the demand for this type of infrastructure.[58] Overall, while the reasons behind the precise timing of when sanitary infrastructures started operating are hard to pinpoint and were the result of a varied set of factors, the evidence presented in this section suggests that mortality levels did not play an important role.[59] In other words, the year in which waterworks started operating and city waste was disposed of via sewers was independent of mortality, and this is an important point for the econometric exercise performed below.

II. Data and method

The growing importance of urban areas in terms of the German population, along with the disappearance of the urban penalty around 1900, provides strong motivation for analysing the determinants of health in cities. To obtain data on various measures of mortality, this study uses the annual reports of the Imperial

[56] Ibid., pp. 281–2.

[57] Schramm, 'Privatisation', p. 8. Besides city-specific economic factors, Hennock mentions that the economic crisis of the late 1870s and subsequent years of stagnation delayed investments in sanitation.

[58] Brown, 'Coping with crisis?', p. 310.

[59] Further supporting the array of qualitative and quantitative evidence presented in this section, I perform quantitative exercise in online app. S2 showing that the level of mortality in the cities in my sample was not higher than that of a set of almost 250 other German cities five years prior to the construction of waterworks and sewerage systems.

Table 1. *Summary statistics for some selected variables*

	Mean	*Std. dev.*	*Min.*	*Max.*
CDR (per 1,000 inhabitants)	20.60	4.81	10.12	35.71
IMR (per 1,000 births)	213.11	60.50	78.93	463.45
WSI	0.66	0.47	0.00	1.00
WDI	0.22	0.42	0.00	1.00
Population	66,837.28	82,900.40	16,154.00	63,4867.00
Employment in industry (%)	46.07	14.26	17.23	76.98
Employment in services (%)	36.54	14.09	11.67	68.73
Male population (%)	49.45	0.86	47.55	51.48
Population younger than 15 years (%)	34.96	2.61	27.26	40.30
Population aged between 15 and 39 (%)	39.15	2.19	34.20	46.02
Population aged between 40 and 59 (%)	18.02	1.29	15.35	21.41
Protestants (%)	69.99	28.86	4.23	99.13
Citizens per square metre	4.71	0.68	3.52	6.52
Population living in cities with more than 2,000 inhabitants	50.45	18.98	12.77	95.13

Sources: For CDR and IMR: annual reports of the Imperial Health Office (Kaiserliches Gesundheitsamt, *Veröffentlichungen des Kaiserlichen Gesundheitsamtes*). For water supply and waste disposal improvements: Grahn, 'Die städtischen Wasserwerke'; idem, *Die städtische Wasserversorgung*; Salomon, *Die städtische Abwässerbeseitigung*; Brix et al., *Stadtentwässerung in Deutschland.* For the economic structure of the labour force: Kaiserliches Statistisches Amt, *Statistik des Deutschen Reichs: Die Volkszählung im Deutschen Reich am 1. Dezember 1880*; idem, *Statistik des Deutschen Reichs: die Volkszählung im Deutschen Reich am 1. Dezember 1900*; idem, *Statistik des Deutschen Reichs: die Volkszählung im Deutschen Reich am 1. Dezember 1910*. For the rest of the variables: idem, *Statistik des Deutschen Reiches (Neue Folge, Bd. 2)*; idem, *Statistik des Deutschen Reichs, Neue Folge, Band 117*; idem, *Statistik des Deutschen Reichs, Neue Folge, Band 118*; idem, *Statistik des Deutschen Reichs, Neue Folge, Band 209.*

Health Office between 1877 and 1913 that record such information for cities with more than 15,000 inhabitants (*Veröffentlichungen des Kaiserlichen Gesundheitsamtes* and *Medizinalstatistische Mittheilungen*).[60] In addition, data on population and number of births have been gathered to construct indicators of infant mortality rates (IMR), crude death rates (CDR), and causes of death. Table 1 shows the descriptive statistics.

Analysing both age- and cause-specific deaths is a useful way to deal with some of the potential weaknesses of the latter related to misdiagnosis, as medical knowledge was sometimes insufficient for an accurate identification of diseases. In this period, deaths were classified according to their symptoms rather than the actual cause in a modern sense.[61] An example of this was typhoid fever, which was often confused with other diseases in its early stages, since it resembled respiratory diseases such as pneumonia or bronchitis.[62] An accurate diagnosis only became possible after the development of new tests.

This analysis draws on work by Grahn in order to understand the state of municipal water supply.[63] In particular, data were gathered on the year in which cities started operating waterworks, which represented major water supply improvements (WSI), in order to observe when municipalities shifted from a well- or fountain-based system to a network system of pipes providing water from underground sources or lakes. To obtain information on waste disposal

[60] Kaiserliches Gesundheitsamt, *Medizinal-Statistische Mittheilungen*; idem, *Veröffentlichungen Des Kaiserlichen Gesundheitsamtes*.
[61] Vögele, *Urban mortality change*, p. 25.
[62] Ferrie and Troesken, 'Chicago's mortality transition'.
[63] Grahn, *Die städtische Wasserversorgung*; idem, 'Die städtischen Wasserwerke'.

improvements (WDI), local sanitary and technical reports were used.[64] These reports describe the sanitation facilities operating in a city and their subsequent changes. Before major investments took place in this domain, households stored their waste in ditches, barrels, or buckets that were emptied once or twice a week. With the construction of sewers, this system gave way to a more centralized and efficient method of waste disposal. However, this transition was sometimes gradual because some municipalities first built sewers to control rainwater and did not allow them to be used for carrying human faeces (in some cases, liquids were exempt from this prohibition). To ensure comparability across investments in sanitation, the intervention years when fecal matter could be disposed through sewers was coded. This approach has the advantage of measuring a very specific intervention that can be easily identified, and that was, epidemiologically speaking, the most relevant against diseases transmitted by oral-faecal mechanisms.

A dataset was created, consisting of 34 cities that established water supply and sewerage systems between 1882 and 1908, of which 24 had sewerage systems by the late 1910s.[65] Therefore, the sample consists of municipalities that built either a single water supply system or both infrastructures during the analysed period (10 cities implemented water supply systems only). The cut-off years ensure that it is possible to observe mortality levels for at least five years prior to and after the coded interventions. Having enough variation between pre- and post-treatment periods is important because the empirical framework draws on within-city variation. Figure 2 presents the timing of improvements in WSI and WDI in the sample during the period 1877–1913. Consistent with the literature, the introduction of sewerage systems came somewhat later and seemed to take off around the turn of the twentieth century.[66]

If we return to figure 1 briefly, we can assess whether the sample is representative of the general urban experience, using infant mortality in the large state of Prussia as a benchmark for comparison. Reassuringly, the series 'Urban (Prussia)' and 'Sample' show similar trends and levels throughout the period, especially after 1885.

The empirical analysis exploits the plausibly exogenous timing of safe water and sewerage interventions by estimating the following model:

$$\log\left(mortality_{i,t}\right) = \alpha + \beta\, WSI_{i,t} + \gamma\, WDI_{i,t} + \boldsymbol{X'}_{i,t}\boldsymbol{\delta} + \zeta_i + \eta_t + \zeta_i t + \epsilon_{i,t}, \quad (1)$$

where i and t index city and time respectively; $mortality_{i,t}$ refers to a mortality indicator; $WSI_{i,t}$ and $WDI_{i,t}$ refer to water supply and waste disposal improvements, turning one in the year t in which city i started operating either one of these. City fixed effects (ζ_i) are useful for controlling for municipality-level factors that may have an impact on mortality and that remain constant through time, such as climate, geographic features, or certain institutional aspects. Year fixed effects (η_t) control for factors that change over time and that are common to the whole sample (such as weather fluctuations). City-specific trends ($\zeta_i \cdot t$) refer

[64] Salomon, *Die städtische Abwässerbeseitigung*; Brix et al., *Stadtentwässerung in Deutschland*. I also draw on the sanitation section in selected volumes of the *Statistisches Jahrbuch Deutscher Städte* when information was lacking or unclear for some cities.

[65] Online app. tab. S1 presents the full sample.

[66] Hennock, 'Urban sanitary movement'.

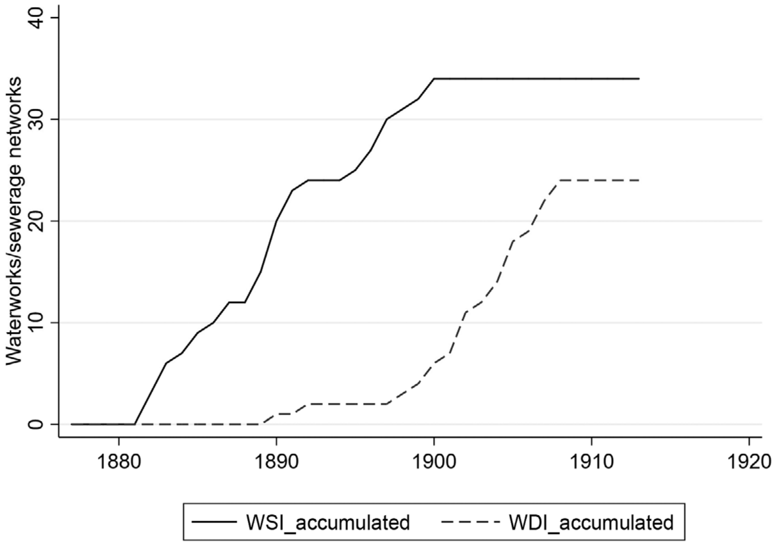

Figure 2. *Timing of improvements in water supply and waste disposal*
Notes: WSI = water supply improvements; WDI = waste disposal improvements. The lines refer to the accumulated number of waterworks and sewerage systems constructed in the sample cities during the period 1877–1913.
Sources: Grahn, 'Die städtischen Wasserwerke'; idem, *Die städtische Wasserversorgung*; Salomon, *Die städtische Abwässerbeseitigung*; Brix et al., *Stadtentwässerung in Deutschland*.

to factors that are specific to each municipality and that may change over time. Standard errors are clustered at the city level.[67]

The coefficient on water improvements (β) shows whether mortality changed after waterworks started operating. Therefore, the marginal effect captures the shift from a well-based water regime to a centralized system using pipes. The coefficient on sewage disposal improvements (γ) shows the mortality difference before and after citizens could dispose of their waste through sewers, once piped water had been provided. Therefore, γ represents the additional effect of sewerage networks over clean water. This interpretation follows from the aforementioned delay in the construction of sewers (see figure 2 and online appendix table S1). Finally, the sum of the coefficients for *WSI* and *WDI* represents the total effect of public health infrastructures.[68]

Before proceeding further, a careful discussion of the main variables of interest would be useful. In the empirical framework, this article follows the main approach in the existing literature by considering the year when sanitary projects started operating, in order to measure their effect on mortality.[69] However, this strategy has several weaknesses that bias the coefficients towards zero. First, using a simple dummy variable to measure whether, for instance, a municipality had a sewerage

[67] Bertrand, Duflo, and Mullainathan, 'Estimates'. This type of clustering allows for dealing with serial correlation. The results are also robust to using wild bootstrap standard errors.

[68] Unlike Alsan and Goldin, I do not include an interaction term between water supply and sewerage because the municipalities that implemented the latter infrastructure during the analysed period already provided piped water to their citizens. Consequently, an interaction term between *WSI* and *WDI* would be exactly equal to *WDI*.

[69] Troesken, *Water, race and disease*; Cutler and Miller, 'Role'; Ferrie and Troesken, 'Chicago's mortality transition'; Beach et al., 'Typhoid fever'; Alsan and Goldin, 'Watersheds'. A different approach involves using outstanding loan stocks in urban infrastructures; Chapman, 'Contribution of infrastructure'.

network assumes that everyone had access to sewers, even though this may not be realistic in some cases. For instance, the city of Koblenz finished its sewer network in 1899, but there was no obligation to be connected to it. Consequently, the poorest part of the city did not benefit from improved sewerage until several years after its construction.[70] Second, investments in public health infrastructures did not end with their completion in a given year. Maintenance and extension works could improve their efficiency as engineers and sanitarians learned from experience and as new medical knowledge became available. The third issue concerns the sanitary technologies that could be used. In the case of sewerage systems, municipalities could install a mixed system (*Mischverfahren*) that carried rain and waste water together, or a system with different sewers carrying rain water and waste water separately (*Trennverfahren*). On top of this, the geographic features of each city determined two further aspects of the project. In some cases, the sewers could be above ground, underground, or a mix of both; in others the procedure used to transport waste water through the network could rely on natural slopes, artificial elevation using steam pumps, air pressure, or vacuum.[71] A simple binary variable does not account for the heterogeneous effects that different systems may have on mortality.[72] All these considerations suggest that the effect of sanitary infrastructures on mortality may be gradual after their establishment, and that β and γ can be interpreted as lower-bound estimates.

Equation 1 includes a set of controls (**X**) that can be divided into three groups. The first measures the economic structure of the labour force using information on the percentage of people working in industry and services. Controlling for industrial employment is important since the introduction of waterworks may have been influenced by the scale of this sector in the city.[73] Furthermore, if mothers working in factories were less likely to breastfeed, their children could have been exposed to dangerous feeding alternatives using contaminated water. These data come from the economic censuses carried out in 1882, 1895, and 1907.[74] Linear interpolation and extrapolation were used to obtain information per year.[75]

The second group of controls comes from the population censuses of 1880, 1900, and 1910.[76] Yearly data were obtained using linear interpolation and extrapolation.

[70] Salomon, *Die städtische Abwässerbeseitigung*, pp. 81–2.

[71] Brix et al., *Stadtentwässerung in Deutschland*.

[72] Including this aspect in the analysis is very problematic because the sources do not have enough information and, most importantly, cities could have several systems in place. Also, categorizing types of sewerage networks is not straightforward in a context in which the rapid growth of some urban areas resulted from the integration of neighbouring municipalities that may have been operating different systems.

[73] Brown, 'Coping with crisis?'.

[74] Kaiserliches Statistisches Amt, *Statistik des Deutschen Reiches (Neue Folge, Bd. 2)*; idem, *Statistik des Deutschen Reichs, Neue Folge, Band 117: Berufsstatistik nach der allgemeinen Berufszählung von 1895. Erster Teil*; idem, *Statistik des Deutschen Reichs, Neue Folge, Band 118*; idem, *Statistik des Deutschen Reichs, Neue Folge, Band 209*. I gratefully acknowledge the kindness of Alexander Donges in providing me with these and some of the data I use in the second part of my analysis. See also Donges, Meier, and Silva, 'Impact of institutions'. In particular, I refer to employment in the textile sector, the percentage of Protestants, and land access inequality (as measured by the Gini coefficient). I matched these county-level data with the cities in my sample that are considered in the censuses as a separate county (except for Neumünster, Rheydt, and Wandsbeck).

[75] It would be better to use higher frequency data instead of relying on linear interpolation to fill the gaps in those years for which no censuses were carried out; however, such data are not available.

[76] Kaiserliches Statistisches Amt, *Die Volkszählung im Deutschen Reich am 1. Dezember 1880*; idem, *Die Volkszählung im Deutschen Reich am 1. Dezember 1900*; idem, *Die Volkszählung im Deutschen Reich am 1. Dezember 1910*.

These controls include demographic variables at district level (*Regierungsbezirk*): percentage of males, and percentage of individuals below the age of 15 years, between 15 and 39, between 40 and 59, and 60 and above. It is useful to keep these factors constant, to make sure that the change in, say, infant deaths is not due to a change in the proportion of children in the total population. Finally, the percentage of the population with a Protestant background is controlled for, to account for potential differences in childbearing practices or other activities influencing health outcomes.[77] Furthermore, variables are included that capture trends in urbanization using the share of people in a given district living in municipalities larger than 2,000 inhabitants and the number of citizens per square metre (see table 1).[78]

III. Results

Before discussing the results from the econometric exercise, it is instructive to look at mortality patterns and the timing of sanitary interventions. Figure 3 presents information on crude death rates and infant mortality for a large city and a small one: Charlottenburg and Guben.[79] The thick and thin vertical lines mark the year when waterworks and sewerage systems started operating, respectively. Consider infant mortality rates in Charlottenburg. Before any sanitary interventions took place, the number of infant deaths was around 350 per 1,000 births (54 per cent higher than the national average). By the end of the period, after the city had provided safe water and efficient waste disposal in 1884 and 1890, this figure had dropped to around 100 (60 per cent of the national average).[80] Guben also exhibits persistently high levels of CDR until the construction of waterworks in 1897 and the sewerage system in 1905. The decline in infant mortality in Guben was even steeper, falling from 230 deaths per 1,000 births to 160 between 1905 and 1906.

This discussion of figure 3, although suggestive, does not take into account the other factors that may be driving health improvements, such as the provision

[77] The impoverishment of the population and the lack of cattle may have led to unhealthy infant feeding practices that were particularly present in Catholic areas; Imhof, 'Unterschiedliche Säuglingssterblichkeit', Gehrmann, 'Infant mortality in Germany'. A further issue that this variable would capture is that of registration of infant deaths. These tended to be higher in Catholic areas, as the custom of emergency baptism led to under-reporting of still-births. In areas where infant deaths occurred within a mandatory three-day registration period, infant mortality was under-reported; Vögele, 'Urban infant mortality'; Haines and Kintner, 'Mortality transition in Germany'.

[78] With controls at the district level, I account for broad trends in several demographic trends that may not be captured by the year fixed effects and city-specific linear trends. In total, I exploit variation from 24 different districts (see online app. tab. S1). There may be some year-to-year fluctuations in urbanization due to strong migration flows that these controls could fail to capture; however, this issue is not very problematic in my sample. As Guinnane, 'Population and the economy', p. 51, shows, the percentage of the German population living in municipalities with more than 100,000 inhabitants grew from 5% to 21% during the period 1871–1910. In contrast, the share of citizens living in cities with between 2,000 and 100,000 inhabitants only rose from 31% to 38%. Given that my sample contains a large number of middle-sized cities (see online app. tab. S1), it is reasonable to argue that the effect migration flows and urbanization can have on mortality—after using district-level urbanization controls and city-specific linear trends—does not represent a significant problem in my setting.

[79] In 1900, Charlottenburg and Guben had around 180,000 and 30,000 inhabitants, respectively.

[80] Notice the further decrease in infant deaths around 1903 when the city extended the sewerage network into areas that were previously not covered; Salomon, *Die städtische Abwässerbeseitigung*, p. 194. The effect of this extension of sewers would not be fully captured by the dummy-variable approach, which reinforces the idea that my results provide a lower-bound estimate of their effect.

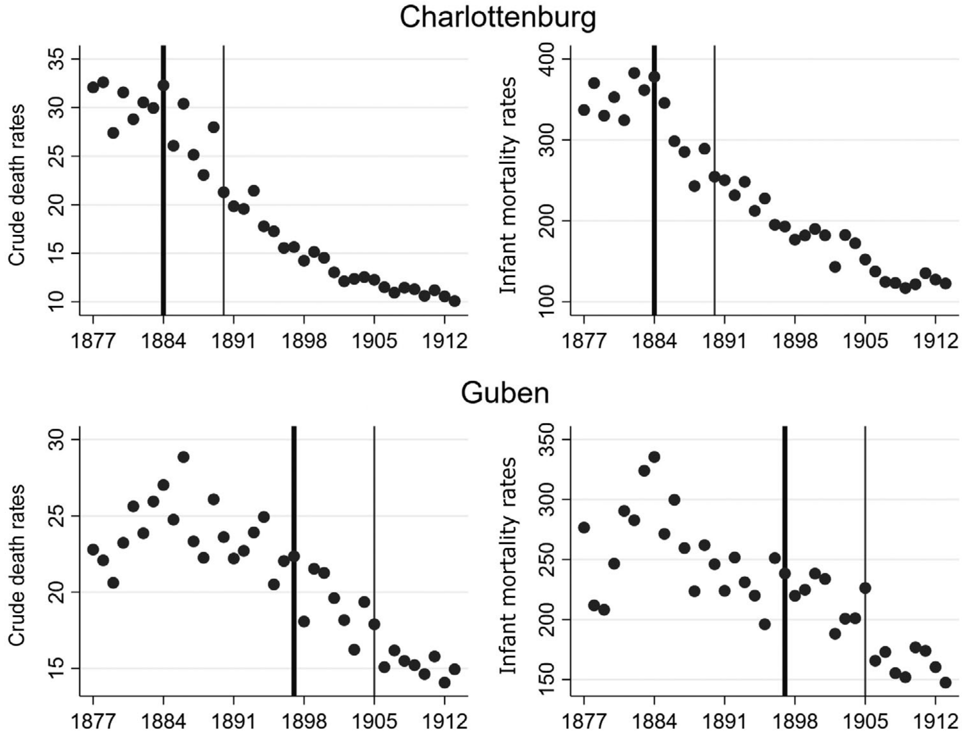

Figure 3. *Mortality and sanitary interventions in two selected cities*

Note: The thick and thin vertical lines mark the initial year when cities had piped water and sewers, respectively.
Sources: See tab. 1.

of pasteurized milk, street cleaning, and so on. For this reason, an estimation of equation 1 is used, and the decrease in mortality that can be attributed to the investments in clean water and sewerage is quantified by considering the coefficients for *WSI* and *WDI* (β and γ). Table 2 displays the results for the CDR with standard errors clustered at the city level.[81] The first specification only includes city fixed effects and shows that the coefficients of interest have the expected negative sign and are statistically significant, both individually and jointly. Including year fixed effects in column 2 does not change their sign, but it does reduce their size considerably, which highlights the importance of controlling for time-varying unobserved factors.[82] The third column in table 2 includes city-specific linear trends that can capture changes in, for instance, local death registration systems or different reactions to local weather conditions. Their inclusion improves the estimation since the coefficient on water supply (β) increases, as does the joint effect of both sanitary interventions ($\beta+\gamma$). The subsequent specifications control for cities' characteristics related to the labour force (that is, the percentage of workers employed in the secondary and tertiary sector); districts' demographics

[81] The full regression table is reported in online app. tab. S2.
[82] This size change is substantially lower (around 10%) in a regression specification that includes the whole set of controls as in tab. 2, col. 6.

Table 2. *Impact of improvements in water supply and sewerage on CDR*

	(1)	(2)	(3)	(4)	(5)	(6)
WSI	−0.1924***	0.0007	−0.0199	−0.0214	−0.0248	−0.0223
	(0.0171)	(0.0251)	(0.0183)	(0.0187)	(0.0168)	(0.0169)
WDI	−0.2429***	−0.0717**	−0.0662***	−0.0670***	−0.0855***	−0.0888***
	(0.0322)	(0.0337)	(0.0241)	(0.0234)	(0.0202)	(0.0200)
WSI+WDI	−0.4353***	−0.0710**	−0.0861***	−0.0885***	−0.1102***	−0.1111***
(statistic)	155.8652	4.7104	8.5081	9.1112	17.3224	16.6485
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	No	Yes	Yes	Yes	Yes	Yes
City trends	No	No	Yes	Yes	Yes	Yes
Occupational controls	No	No	No	Yes	Yes	Yes
Demographic controls	No	No	No	No	Yes	Yes
Other controls	No	No	No	No	No	Yes
Observations	1,222	1,222	1,222	1,222	1,222	1,222
R^2	0.6606	0.8278	0.8903	0.8905	0.8954	0.8977

Notes: The results were obtained by estimating equation 1 using CDR as the dependent variable and clustering the standard errors at city level. Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Sources: See tab. 1.

(that is, the percentage of male citizens and the age structure of the population); and others (that is, the number of citizens per square metres, the share of the population living in cities with more than 2,000 inhabitants, and the percentage of Protestants). As we can see, the coefficients are consistently negative and their joint effect is statistically significant throughout all specifications, which shows that access to clean water and sewerage networks is strongly associated with reductions in mortality.

The estimates in table 2 (column 6) indicate that the CDR was 0.109 logarithmic points lower once a city had installed both a water supply and a sewerage system. Given that the overall mortality decline in the sample is 0.54 logarithmic points, they account for 21 per cent of the reduction in the CDR between 1877 and 1913 (0.111/0.54).[83] Furthermore, improvements in sewage disposal seem to have played a more important role than safe water since the coefficient on the former is higher. However, this should not be taken as evidence that clean water had no effect on mortality since the sum of the coefficients for *WSI* and *WDI* is highly statistically significant.

Before interpreting these results, it is useful to consider the analyses for infant mortality. Besides being an interesting indicator because infants are affected by a different set of diseases than adults, the study of infant mortality is often used as an indication of health and economic success;[84] it has been an important driver of improvements in life expectancy since 1870;[85] and some studies in the literature have looked into its determinants, which makes it possible to compare the results given here to those presented in other works.[86] Table 3 displays the results of

[83] I calculated the decline in CDR using three-year averages at the beginning and end of the period to avoid the potential effect of outliers.
[84] Huck, 'Infant mortality and living standards'; Sen, 'Mortality'; UN, *Sustainable development goals*.
[85] Easterlin, 'Worldwide standard of living'; Deaton, *Great escape*.
[86] Brown, 'Economics and infant mortality'; Brown and Guinnane, 'Infant mortality decline'; Alsan and Goldin, 'Watersheds'.

Table 3. *Impact of improvements in water supply and sewerage on IMR*

	(1)	(2)	(3)	(4)	(5)	(6)
WSI	−0.1104***	0.0146	−0.0352*	−0.0361*	−0.0410**	−0.0405**
	(0.0211)	(0.0277)	(0.0189)	(0.0186)	(0.0190)	(0.0194)
WDI	−0.2302***	−0.0563*	−0.0502*	−0.0481*	−0.0670***	−0.0675***
	(0.0286)	(0.0326)	(0.0273)	(0.0264)	(0.0223)	(0.0231)
WSI+WDI	−0.3407***	−0.0417	−0.0854**	−0.0841**	−0.1081***	−0.1080***
(statistic)	124.4578	1.7005	6.1435	6.3119	11.7781	11.3719
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	No	Yes	Yes	Yes	Yes	Yes
City trends	No	No	Yes	Yes	Yes	Yes
Occupational controls	No	No	No	Yes	Yes	Yes
Demographic controls	No	No	No	No	Yes	Yes
Other controls	No	No	No	No	No	Yes
Observations	1,222	1,222	1,222	1,222	1,222	1,222
R^2	0.7002	0.8146	0.8636	0.8639	0.8678	0.8680

Notes: The results were obtained by estimating equation 1 using IMR as the dependent variable and clustering the standard errors at the city level. Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Sources: See tab. 1.

estimating equation 1 using infant mortality as the dependent variable.[87] The first two specifications show that the coefficients on both sanitary interventions have the expected negative sign when only fixed effects are included, and that their size sharply declines with the introduction of year fixed effects.[88] The coefficients of interest are sizeable and statistically significant across subsequent regression specifications (see columns 3, 4, 5, and 6). The joint effect of β and γ in column 6 implies that cities experienced a 0.108 logarithmic-point lower IMR after they improved their water supply and sewage removal. Together, they explain 25 per cent of the fall in infant mortality during the analysed period (0.108/0.439).[89]

To assess the causal interpretation of the previous findings, let us examine the short-term patterns of mortality decline after cities improved their water quality and sewage removal. If significant decreases in deaths happened before their construction, then other factors unrelated to sanitation would have been driving the results. For this purpose, the following equation is estimated:

$$\log\left(mortality_{i,t}\right) = \alpha + \sum \beta_k WSI_{i,k} + \sum \gamma_k WDI_{i,k} + \boldsymbol{X'}_{i,t}\boldsymbol{\delta} + \zeta_i + \eta_t + \zeta_i t + \epsilon_{i,t}, \tag{2}$$

where k refers to event time (grouped into two-year periods) and it spans eight years prior to and after the coded interventions. Considering the year preceding

[87] The full regression table is reported in online app. tab. S3.
[88] The coefficients are virtually the same if year fixed effects are included or excluded from a regression specification with all control variables.
[89] Given the large share of infant deaths over total mortality, I checked whether the results for IMR drive those for CDR by using deaths above the age of one year as the dependent variable. As we can see in online app. tab. S7, the statistical significance of the sum of *WDI* and *WSI* suggests they played an important role in the decline in mortality after the first year of life, although the effect of waterworks seems to be close to zero. Overall, the sum of *WDI* and *WSI* accounts for 15% of the fall in non-infant mortality. The effect of sanitary infrastructures may have differed across cities with different levels of illegitimate infant mortality, since Brown, 'Economics and infant mortality', found that the effect of clean water and better waste disposal was larger for this group than for legitimate children.

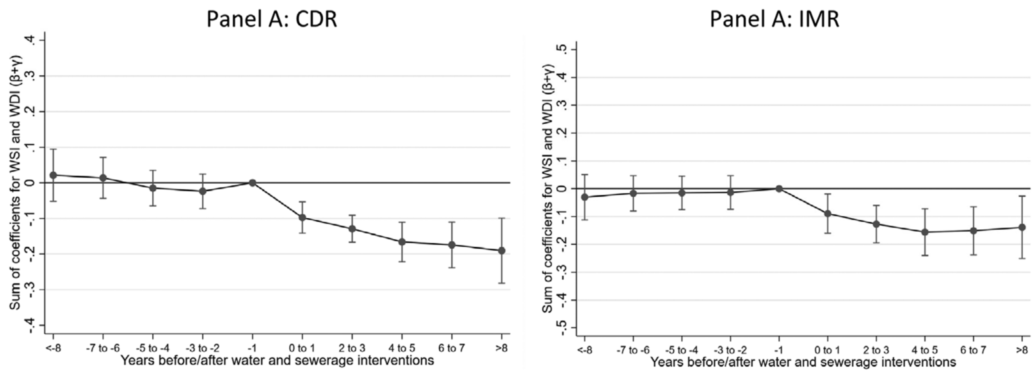

Figure 4. *Joint effect of water supply and sewerage over time*

Notes: The figure shows the joint effect of β and γ over time for CDR and IMR ($\beta_k+\gamma_k$ from equation 2). The vertical bars are 90% confidence intervals.
Sources: See tab. 1.

the construction of sanitary infrastructures as the reference group, the dummy variables for *WSI* and *WDI* measure their effect on mortality after they have been operating for two years, four years, and so on. Prior to the coded interventions, the dummy variables show the level of mortality (relative to the reference group) during the years leading up to the public health investments.

Figure 4 displays the results of estimating equation 2 and plotting the sum of the coefficients for *WSI* and *WDI* ($\beta_k+\gamma_k$) to analyse whether mortality declined right after the implementation of both water supply and sewerage systems. Panels A and B plot the sum of the coefficients using CDR and IMR as dependent variables, respectively. Three observations stand out in both panels. First, the number of deaths sharply declined immediately after the investments in safe water and sewage disposal. Second, mortality levels were not trending downwards before the interventions. Third, the improvement in the disease environment persisted over time.[90] This is also true for the individual coefficients (see online appendix figure S1).[91] The first two observations indicate that the potential effect of other public health measures that are not directly controlled for in the regressions (such as a pasteurized milk supply, street cleaning, or food regulation) are not (at least not significantly) influencing the coefficients of interest. Therefore, β and γ are mostly capturing improvements in water supply and sewage removal because a statistically significant decrease in mortality happens after the coded interventions, and not before. The third observation lines up well with the steady pattern of gradual reductions in CDR and IMR shown in figure 3. In some cities, this was the result of a piecemeal roll-out of infrastructures that would gradually cover the whole population only a few years after the construction works started (as was the case, for instance, in Charlottenburg). In other cases, subsequent public health investments were aimed at increasing the amount of water reaching households or at properly disinfecting urban waste in treatment plants.

[90] The standard errors become larger after the sixth and seventh year of operation because the variation in the samples falls.

[91] Online app. fig. S1 shows that the short-term decline in mortality is sharper upon the construction of a sewerage network than waterworks.

The results for the CDR and IMR indicate that the mere provision of piped water was not enough to explain the substantial share of the fall in CDR at the turn of the twentieth century. Possibly, waterworks had limited effects in the absence of efficient methods to remove urban waste, which could contaminate sources of water or attract vectors transmitting diseases. Therefore, the introduction of sewers and, in particular, the permission to dispose of faeces through them was crucial for improving the disease environment. This idea has recently received empirical support from Alsan and Goldin for the case of Massachusetts.[92] However, the mechanism they highlight, that most of the impact of clean water and sewerage systems on child survival was due to their interaction, rather than their individual effect, is less likely to have been valid for Germany. First, the individual effect of clean water on infant mortality is not negligible. The point estimates in table 3 imply that the mere provision of piped water reduced infant mortality by almost 10 per cent (the same applies to the CDR, although the effect is lower). This may be partly explained by the prevalence of underground sources for supplying German waterworks, especially in middle-sized cities, which reduced the risk of water recontamination.[93] Furthermore, the statistical significance of the coefficient on water improvements indicates that even though public wells may have drawn water from underground sources before the construction of waterworks, water quality improved with the arrival of the new sanitary technology. Second, online appendix figure S1 shows that the coefficients on waterworks become negative and statistically significant after several years of operation.[94] Third, the historical experience of Germany is different from that of Massachusetts in that sewers were implemented with some delay relative to piped water.[95] Therefore, the individual effect of sewerage (γ in equation 1) cannot be calculated without taking into account that sewers functioned in cities where piped water was being provided.

There are two mechanisms through which clean water and sanitation can reduce mortality. The first works directly through reduced exposure of citizens to pathogenic micro-organisms, as faecal-oral transmission of some diseases become less likely. The second is an indirect mechanism and is related to the scarring effect of some waterborne ailments such as typhoid fever. This affliction as such has a low death rate, but its severe symptoms weaken the immune system of its victims, which makes them more likely to die from other diseases. Therefore, mortality from non-waterborne illnesses such as tuberculosis may decline when the prevalence of typhoid decreases.[96]

If the influence of sanitary infrastructures on diseases characterized by faecal-oral transmission mechanisms was indeed considerable, we would expect a substantial reduction of deaths caused by enteric pathogens upon their establishment. The results in table 3 indicate that this was indeed the case because infants are disproportionately affected by these types of illnesses. However, this may be

[92] Alsan and Goldin, 'Watersheds'.

[93] Grahn, *Die städtische Wasserversorgung*. In American cities, ground sources may have been more common; Ferrie and Troesken, 'Chicago's mortality transition'; Alsan and Goldin, 'Watersheds'.

[94] This pattern is not present in figs. 5 and B6 in Alsan and Goldin, 'Watersheds'.

[95] Alsan and Goldin, 'Watersheds', tab. A1, shows that most cities with both sanitary interventions installed sewers a few years earlier than waterworks. As we can see in online app. tab. S1, municipalities in my sample experienced the opposite situation.

[96] Ferrie and Troesken, 'Chicago's mortality transition'.

Table 4. *The impact of sanitation on various measures of mortality*

	Waterborne diseases (1)	*Airborne diseases* (2)	*Violent deaths* (3)
WSI	−0.0652	0.0603	0.0354
	(0.0792)	(0.0400)	(0.0520)
WDI	−0.2274***	−0.0759***	−0.0053
	(0.0740)	(0.0259)	(0.0583)
WSI+WDI	−0.2927***	−0.0156	0.0300
(statistic)	12.0016	0.1043	0.2296
Fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
City trends	Yes	Yes	Yes
Occupational controls	Yes	Yes	Yes
Demographic controls	Yes	Yes	Yes
Other controls	Yes	Yes	Yes
Mortality decline explained (in %)	59.18	9.3	–
Observations	1,222	1,222	1,220
R^2	0.7423	0.7869	0.6137

Notes: The results were obtained by estimating equation 1 using the dependent variables: death due to waterborne diseases, airborne illnesses, and violence. Standard errors are clustered at the city level. I used the coefficients for *WSI* and *WDI* to calculate the explained mortality decline from waterborne diseases. For airborne illnesses, I used the coefficient for *WDI*. Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Sources: See tab. 1.

considered indirect evidence because infants did not only die due to enteric ailments. A more direct approach involves analysing diseases with different pathological bases that make it possible to study the presence of different mechanisms. Table 4 presents a set of regressions using waterborne and non-waterborne diseases as dependent variables that are analogous to column 6 in table 2.[97] Regressing deaths from some diseases transmitted through water (diarrhea, typhoid fever, and catarrh of the stomach) on the sanitary interventions reinforces the patterns discussed earlier. The coefficients for *WSI* and *WDI* in column 1 are negative, their sum is statistically significant, and the effect of sewerage is larger than that of water supply. Taken together, improvements in water quality and sewage disposal account for more than half of the decline in deaths from this category.

If sanitary infrastructures mostly protected the population from bacteria transmitted through water, we would not expect any impact on airborne illnesses. On the other hand, a lower morbidity environment can influence mortality from respiratory afflictions, by reducing the scarring effect of waterborne diseases on immune systems. This mechanism may have been particularly relevant in Germany which, at that time, experienced persistently high death rates in comparison with other countries.[98] To test this, the second column of table 4 displays the results of using deaths from respiratory diseases as the dependent variable (tuberculosis, measles, diphtheria, croup, and so on). The joint effect of β and γ is not statistically significant, although the findings show that improvements in sewage removal are associated with lower deaths due to respiratory conditions. Actually, they explain about 9 per cent of the decrease in deaths from this category, thus indicating

[97] The full regression table is reported in online app. tabs. S4, S5, and S6.
[98] Leonard and Ljungberg, 'Population and living standards'; Gehrmann, 'Infant mortality in Germany'.

that the protection provided by clean water and sewerage networks goes beyond waterborne ailments.

The last column in table 4 uses violent deaths as an outcome variable (accidents, homicides, and suicides). This regression can be considered a placebo test because investments in public health infrastructures are not expected to affect mortality from this category, and hence support the causal interpretation of the previous findings.[99] Consistent with this intuition, there does not seem to be any evidence that either the individual or the joint effect of sanitary interventions is associated with changes in violent deaths.

The results presented so far are robust to excluding city-specific trends (online appendix table S8),[100] using a balanced panel (online appendix table S9), and excluding cities that did not construct sewerage systems (online appendix table S10).

So far, no consideration has been given to the fact that the effects of sanitary infrastructures may have differed across cities. The richness of the sample used here, which includes municipalities with inhabitants ranging from a few thousand to more than half a million, allows us to explore the heterogeneous effects—or the lack thereof—of public health investments along an important dimension: population size. For this purpose, *WSI* and *WDI* are interacted with three dummy variables that classify municipalities as small, medium, or large cities.[101] The first two columns in table 5 show that none of the interactions is statistically significant, which implies that the decline in mortality across municipalities of different size was similar. This evidence lines up well with results presented by Brown, who ascribes around 30 per cent of the decrease in IMR to improved water quality and access to toilets in cities with more than 50,000 inhabitants between 1889 and 1912.[102] This estimate is very close to the 24 per cent reported earlier using a sample with smaller cities.

The second dimension that may affect the effectiveness of public health infrastructures concerns the habits and strategies of households for dealing with home cleanliness and infant care. In this respect, women played a central role, since their employment opportunities influenced the proportion of mothers who breastfed, as well as their fertility and food consumption.[103] To examine the interplay of these (and related) aspects with *WSI* and *WDI*, they are interacted with two variables that convey information about the economic structure of a city: the percentage of workers employed in the primary and the textile sectors, respectively. Column 3 shows that none of these interactions is statistically significant using the CDR as outcome variable. If we turn to the results in column 4, however, there is a negative and statistically significant coefficient for the interaction term

[99] Chapman, 'Contribution of infrastructure'.

[100] My preferred specification includes city linear trends because they can capture time-varying and local-specific factors that are unobserved by the control variables. The year fixed effects only account for factors common across municipalities and, while useful, they miss the specificities of each municipality, especially in a sample that varies substantially in terms of geography, institutions, and culture. Excluding city trends results in a somewhat lower impact of sanitary interventions, as we can see in online app. tab. S8 (except for CDR), but the remaining results remain qualitatively similar. The results are also robust to using quadratic instead of linear trends.

[101] The population ranges of small, medium, and large cities are less than 40,000 inhabitants, between 40,000 and 80,000, and more than 80,000 respectively, in 1900. The resulting sub-groups contain 12, 15, and 7 cities, respectively.

[102] Brown, 'Economics and infant mortality', p. 191.

[103] Millward and Bell, 'Infant mortality in Victorian Britain'.

Table 5. *Heterogeneous effects of sanitary interventions across different dimensions*

	CDR (1)	*IMR* (2)	*CDR* (3)	*IMR* (4)
WSI	0.0014	−0.0125	−0.1236**	−0.1762**
	(0.0275)	(0.0316)	(0.0527)	(0.0653)
WDI	−0.0912**	−0.0726*	−0.1296**	−0.1455*
	(0.0335)	(0.0402)	(0.0568)	(0.0798)
WSI x med. size	−0.0359	−0.0637		
	(0.0356)	(0.0421)		
WSI x large size	−0.0516	−0.0055		
	(0.0365)	(0.0493)		
WDI x med. size	0.0226	0.0202		
	(0.0419)	(0.0575)		
WDI x large size	−0.0301	−0.0174		
	(0.0506)	(0.0569)		
WSI x % employment in agriculture			−0.0001	−0.0014
			(0.0008)	(0.0010)
WDI x % employment in agriculture			0.0012	−0.0002
			(0.0011)	(0.0017)
WSI x % employment in textile sector			−0.0009	0.0001
			(0.0014)	(0.0021)
WDI x % employment in textile sector			−0.0005	−0.0027**
			(0.0010)	(0.0011)
WSI x % of Protestants			0.0001	0.0004
			(0.0005)	(0.0006)
WDI x % of Protestants			−0.0005	0.0004
			(0.0004)	(0.0007)
WSI x gini			0.0019*	0.0023**
			(0.0010)	(0.0010)
WDI x gini			0.0011	0.0012
			(0.0011)	(0.0010)
Fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
City trends	Yes	Yes	Yes	Yes
Occupational controls	Yes	Yes	Yes	Yes
Demographic controls	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes
Observations	1,222	1,222	1,222	1,222
R^2	0.8984	0.8690	0.8997	0.8701

Notes: The results were obtained by estimating equation 1 and interacting *WSI* and *WDI* with several variables. The standard errors are clustered at the city level. Cols. 3 and 4 do not include the control variable for industrial employment. Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Sources: See tab. 1 and n. 14.

between *WDI* and the percentage in textile employment. Consistent with the idea that women's workload was a determining factor in infant mortality, a negative interaction may reflect that female employment diverted time away from infant care or breastfeeding. Alternatively, a large textile sector may have contributed to problems related to water contamination because industries such as dyeworks and textile finishing increased the demand for this resource.[104] Either way, the estimates imply that a difference of 10 percentage points in textile employment was associated with a further reduction in mortality of 0.027 logarithmic points (0.0027*10).[105]

[104] Brown, 'Coping with crisis?'.
[105] Online app. tab. S11 shows that the sign, size, and statistical significance of this interaction are robust.

Another variable that can proxy for cultural attitudes affecting infant deaths is the religious background of the population. This can influence mortality via differences in fertility or breastfeeding practices.[106] For this reason, the percentage of Protestants in a city is interacted with *WSI* and *WDI*. Columns 3 and 4 show that the interactions have a positive sign, although they are statistically insignificant. Certainly, this finding does not refute the idea that Catholics experienced higher infant mortality,[107] but rather that differences in religious attitudes did not create a regional mortality gap that sanitary infrastructures could bridge.

The next dimension examined in conjunction with sanitary interventions is the level of local economic inequality. For this purpose, the variables on clean water and sewage removal are interacted with land access inequality as measured by the Gini coefficient.[108] Columns 3 and 4 show that all interactions are positive, and in the case of *WSI* statistically significant.[109] In a context of chronic and widespread deprivation, in terms of material living standards, an unequal economic environment pushes citizens close to subsistence levels and may discourage them from paying for a connection to local sanitary infrastructures.[110] If this mechanism were operating, cities with high levels of inequality would tend to experience a smaller decrease in CDR and IMR upon the establishment of centralized water supply systems.

The heterogeneous effects of sanitary infrastructures presented in table 5 suggest that these investments may have had a different impact across German states, since they exhibited a large degree of geographic, institutional, and cultural variation. To see whether this was the case, municipalities are grouped into three sub-samples: 'Prussia', 'Bavaria', and 'Other states'—containing 22, 4, and 8 cities, respectively—and the analyses are repeated.[111] Table 6 displays the results using CDR and IMR as dependent variables.[112] Beginning with crude death rates (panel A), we can see that the effect of waterworks and sewerage systems was not homogeneous across German states. Whereas the sum of *WSI* and *WDI* is sizeable and statistically significant in the 'Prussia' and 'Other states' samples, it is, although negative, statistically insignificant for 'Bavaria'. For IMR (panel B), the pattern is similar, and even stronger, because statistically significant results are only found for Prussia.

The results in table 5 provide an indication of the factors behind the different impact of sanitary infrastructures across states, since municipalities with high levels of employment in the textile sector and equality benefited from investments in water supply and sewage disposal. Indeed, Prussian municipalities in the sample present lower Gini coefficients and higher levels of textile employment. Contrarily,

[106] Kintner, 'Determinants'; Millward and Bell, 'Infant mortality in Victorian Britain'. Religious attitudes can also operate at the neighbourhood level, creating negative externalities; Geruso and Spears, 'Neighborhood sanitation'.

[107] Brown and Guinnane, 'Infant mortality decline'.

[108] Given that I control for the economic structure of the city in the regressions, the variable on land inequality captures the aspect of economic inequality that is not directly affected by the structure of employment in the city.

[109] Online app. tab. S12 shows that the sign, size, and statistical significance of this interaction are robust.

[110] Ashraf, Glaeser, and Ponzetto, 'Infrastructure'.

[111] The motivation for this sample split is that most cities are located in Prussia and Bavaria. For the remaining German states I only observe one or, at most, two localities (see online app. tab. S1).

[112] I did not include year fixed effects in the non-Prussian samples due to lack of observations. If I use the same specification for the Prussian samples (that is, excluding year fixed effects), the results remain unaltered.

Table 6. *Heterogeneous effects of sanitary interventions across German states*

	Panel A: CDR			*Panel B: IMR*		
	Prussia (1)	*Bavaria* (2)	*Others* (3)	*Prussia* (4)	*Bavaria* (5)	*Others* (6)
WSI	−0.0135	0.0050	−0.0403	−0.0255	−0.0781	−0.0505
	(0.0196)	(0.0063)	(0.0323)	(0.0218)	(0.0711)	(0.0430)
WDI	−0.1029***	−0.0181	−0.0107	−0.0970***	0.0199	0.0885
	(0.0236)	(0.0207)	(0.0220)	(0.0215)	(0.0263)	(0.0728)
WSI+WDI	−0.1165***	−0.0132	−0.0510*	−0.1225***	−0.0582	0.0381
(statistic)	14.3798	0.3104	3.8750	12.6225	0.5523	0.2323
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
City trends	Yes	Yes	Yes	Yes	Yes	Yes
Occupational controls	Yes	Yes	Yes	Yes	Yes	Yes
Demographic controls	Yes	Yes	Yes	Yes	Yes	Yes
Other controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	778	148	296	778	148	296
R^2	0.8971	0.9277	0.8862	0.8601	0.8908	0.8552

Notes: The results were obtained by estimating equation 1 using CDR and IMR as dependent variables for three sub-samples consisting of Prussian, Bavarian, and other municipalities. The standard errors are clustered at the city level. Standard errors in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.
Sources: See tab. 1.

the Bavarian region exhibited higher inequality and low textile employment.[113] In addition, there may be other factors that can explain the results in table 6, such as fertility changes. Brown and Guinnane studied the decline in infant mortality in Munich and showed that it started decreasing in the early 1870s, well before the construction of the water supply and sewerage systems.[114] Furthermore, their analysis, drawing on individual-level data, showed that the high-pressure fertility regime characterized by short inter-birth intervals lowered infant survival probabilities substantially.[115] This evidence suggests that the relative importance of the transition to a demographic environment with fertility control could have been higher in some places than others, thus affecting the overall impact of sanitary investments on mortality.[116] In sum, the results in table 6 show that

[113] The average Gini coefficient and employment share in textiles in the sample are 52.4 and 6.9 for Prussia; 60.4 and 2.7 for Bavaria; and 54.7 and 4.7 for the remaining regions.

[114] Brown and Guinnane, 'Infant mortality decline', p. 854.

[115] Cities with higher levels of fertility may have experienced more population growth than those with lower fertility, thus contributing to overcrowding and less sanitary and economic resources per citizen. I test whether the impact of sanitary investments differed across cities with high and low population growth rates in online app. tab. S13 and find no statistically significant differences of waterworks and sewerage systems between the two groups of municipalities. This is not to say that the theoretical link between sanitation and fertility does not exist, but rather that the specific population growth channel related to fertility does not seem to influence the effect of waterworks and sewerage systems.

[116] Thinking about the relationship between sanitary interventions, fertility, and mortality changes in a complementary manner may be more fruitful than assuming they were substitutes, because the evidence presented in this article indicates that the *WSI* and *WDI* are not capturing the potential effect of fertility. First, changes in fertility mostly affect IMR, and online app. tab. S7 shows that the results for this variable do not carry over for crude death rates. Moreover, tab. 4 provides evidence that the mechanisms of disease reduction are related to the reduced exposure of citizens to diseases transmitted through impure water or contact with human faeces. Second, fig. 4 and online app. fig. S1 show that statistically significant decreases in mortality only happen after cities established waterworks and sewerage systems, and not before. For developments in fertility to explain these

the determinants of the long-term mortality decline are multiple and that the relative importance of certain factors may have varied across regions. For this reason, extrapolating on the basis of analyses focusing on specific regions should be handled with caution.

IV. Conclusions

This article has studied the causes of the first sustained decline in mortality in Germany by looking at the role of public health infrastructures. For this purpose, two new databases were created, containing information on various indicators of city-level mortality and investments in water supply and sewage disposal.

The analyses show that safe drinking water contributed to the improvement of the disease environment. However, its effects were limited in the absence of sewerage networks, since mortality decreased more in municipalities that implemented both sanitary infrastructures and waterworks than in those with only waterworks. Jointly, they explain (at least) 21 per cent of the observed fall in the CDR during the period 1877–1913. The results for the IMR are similar in that both public health interventions were needed to provide effective protection against illnesses spreading via faecal-oral transmission mechanisms; they explain 25 per cent of the fall in infant deaths. Their short-term effect was examined, and this showed that they had a persistent impact right after their implementation, not before, which supports the causal interpretation of these findings.

Two mechanisms explain the impact of sanitary infrastructures on mortality. First, they reduced the exposure of citizens to diseases, such as diarrhea or typhoid fever, transmitted through impure water or contact with human faeces. Consistent with this idea, this study found that more than half of the decrease in digestive diseases can be ascribed to improvements in water quality and sewage disposal. Second, the lower incidence of ailments that damage the immune system of their victims (such as typhoid fever) increases the chances of surviving non-waterborne diseases such as tuberculosis. The results suggest that a small percentage of the fall in airborne ailments (8 per cent) can be explained by the construction of public health infrastructures. Moreover, the study has shown that this relationship is causal because it found no effect on deaths from a very different set of causes, such as homicides, suicides, and accidents.

The second part of the analysis examined the heterogeneous effects of sanitary interventions across different dimensions. First, citizens in small and large cities profited equally from their protection because their effectiveness did not vary significantly by city size. Second, improvements in sanitation are associated with larger declines in infant deaths where the presence of the textile sector was greater. This could be due to worse infant care in municipalities where female employment may have diverted time away from breastfeeding, or due to the contamination of water resources by the textile industry. Third, waterworks reduced mortality to a

results, sudden changes in these variables should have coincided with the coded interventions across all (or, at least, most) cities in the sample. Even though such a coincidence is very unlikely, assuming this was indeed the case would be problematic, since both *WSI* and *WDI* are significantly associated with declines in mortality. Therefore, sudden fertility changes across cities would have to coincide in time with both coded interventions, that were established with different delays among cities. Finally, accounting for the possibility that these factors followed non-linear trends does not change the results of the analysis (the results are available upon request).

lower extent in localities with high levels of land access inequality. In a context of widespread economic misery, a skewed income distribution may have delayed the access of the poorest to the pipe network. Fourth, the effects of sanitary infrastructures are not universal. Repeating the analysis for several sub-samples showed that their effect was lower (and sometimes statistically insignificant) in non-Prussian municipalities.

The results of this article have two implications for the existing literature on the determinants of the long-term mortality decline in industrial economies. First, these findings support other studies that have highlighted the role of public health infrastructures, although it has been shown that the mere provision of clean water had limited effects. In the absence of efficient methods to remove urban waste, water recontamination and vectors transmitting diseases offset some of the benefits of piped water. Second, the substantial heterogeneous effects of water supply and sewerage systems call for a deeper understanding of how local socioeconomic conditions determined the effectiveness of sanitary technologies. In sum, considering how these sanitary investments affected mortality jointly and their interaction with local socioeconomic conditions is crucial for understanding the drivers of the epidemiological transition.

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Footnote references

Alsan, M. and Goldin, C., 'Watersheds in child mortality: the role of effective water and sewerage infrastructure, 1880–1920', *Journal of Political Economy*, 127 (2019), pp. 586–638.

Ashraf, N., Glaeser, E. L., and Ponzetto, G. A. M., 'Infrastructure, incentives, and institutions', *American Economic Review: Papers & Proceedings*, 106, 5 (2016), pp. 77–82.

Bauernschuster, S., Driva, A., and Hornung, E., 'Bismarck's health insurance and the mortality decline', *Journal of the European Economic Association* (2019), advance article, https://doi.org/10.1093/jeea/jvz052.

Beach, B., Ferrie, J., Saavedra, M., and Troesken, W., 'Typhoid fever, water quality, and human capital formation', *Journal of Economic History*, 76 (2016), pp. 41–75.

Bertrand, M., Duflo, E., and Mullainathan, S., 'How much should we trust differences-in-differences estimates?', *Quarterly Journal of Economics*, 119 (2004), pp. 249–75.

Brix, J., Imhoff, K., and Weldert, R., *Die Stadtentwässerung in Deutschland* (Jena, 1934).

Brown, J. C., 'Coping with crisis? The diffusion of waterworks in late nineteenth-century German towns', *Journal of Economic History*, 48 (1988), pp. 307–18.

Brown, J. C., 'Economics and infant mortality decline in German towns, 1889–1912: household behaviour and public intervention', in S. Sheard and H. Power eds., *Body and city: histories of urban public health* (Aldershot, 2000), pp. 166–93.

Brown, J. C. and Guinnane, T. W., 'Infant mortality decline in rural and urban Bavaria: fertility, economic transformation, infant care, and inequality in Bavaria and Munich, 1825–1910', *Economic History Review*, 71 (2018), pp. 853–86.

Chapman, J., 'The contribution of infrastructure investment to Britain's urban mortality decline, 1861–1900', *Economic History Review*, 72 (2019), pp. 233–59.

Costa, D. L., 'Health and the economy in the United States from 1750 to the present', *Journal of Economic Literature*, 53 (2015), pp. 503–70.

Cutler, D. and Miller, G., 'The role of public health improvements in health advances: the twentieth-century United States', *Demography*, 42 (2005), pp. 1–22.

Deaton, A., *The great escape: health, wealth, and the origins of inequality* (Princeton, NJ, 2013).

Donges, A., Meier, J.-M. A., and Silva, R. C., 'The impact of institutions on innovations' (2019), https://ssrn.com/abstract=2815541 (accessed on 14 July 2019).

Easterlin, R. A., *Growth triumphant: the twenty-first century in historical perspective* (Ann Arbor, Mich., 1996).

Easterlin, R. A., 'How beneficent is the market? A look at the modern history of mortality', *European Review of Economic History*, 3 (1999), pp. 257–94.

Easterlin, R. A., 'The worldwide standard of living since 1800', *Journal of Economic Perspectives*, 14, 1 (2000), pp. 7–26.

Evans, R. J., *Death in Hamburg: society and politics in the cholera years, 1830–1910* (New York, 1987).

Ferrie, J. P. and Troesken, W., 'Water and Chicago's mortality transition, 1850–1925', *Explorations in Economic History*, 45 (2008), pp. 1–16.
Fewtrell, L., Kaufmann, R. B., Kay, D., Enanoria, W., Haller, L., and Colford. Jr., J. M., 'Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis', *Lancet Infectious Diseases*, 5 (2005), pp. 42–52.
Floud, R., Fogel, R. W., Harris, B., and Hong, S. C., *The changing body: health, nutrition, and human development in the western world since 1700* (Cambridge and New York, 2011).
Fogel, R. W., *The escape from hunger and premature death, 1700–2100. Europe, America, and the Third World* (Cambridge, 2004).
Gehrmann, R., 'Infant mortality in Germany in the 19th century', *Comparative Population Studies—Zeitschrift für Bevölkerungswissenschaft*, 36 (2011), pp. 839–68.
Geruso, M. and Spears, D., 'Neighborhood sanitation and infant mortality', *American Economic Journal: Applied Economics*, 10, 2 (2018), pp. 125–62.
Grahn, E., *Die städtische Wasserversorgung im Deutschen Reiche sowie in einigen Nachbarländern*, 2 vols. (Munich and Leipzig, 1898).
Grahn, E., 'Die städtischen Wasserwerke', in R. Wuttke, ed., *Die deutschen Städte. Geschildert nach dem Ergebnissen der ersten deutschen Städteausstellung zu Dresden 1903*, vol. 1 (Leipzig, 1904), pp. 301–44.
Guinnane, T. W., 'Population and the economy in Germany, 1800–1990', in S. Ogilvie and R. Overy, eds., *Germany: a new social and economic history*, 3: *Since 1800* (2003), pp. 35–70.
Haines, M. R. and Kintner, H. J., 'The mortality transition in Germany, 1860–1935; evidence by region', *Historical Methods: A Journal of Quantitative and Interdisciplinary History*, 33 (2000), pp. 83–104.
Harris, B. and Helgertz, J., 'Urban sanitation and the decline of mortality', *History of the Family*, 24 (2019), pp. 207–26.
Hennock, E. P., 'Vaccination policy against smallpox, 1835–1914: a comparison of England with Prussia and Imperial Germany', *Social History of Medicine*, 11 (1998), pp. 49–71.
Hennock, E. P., 'The urban sanitary movement in England and Germany, 1838–1914: a comparison', *Continuity and Change*, 15 (2000), pp. 269–96.
Huck, P., 'Infant mortality and living standards of English workers during the industrial revolution', *Journal of Economic History*, 55 (1995), pp. 528–50.
Imhof, A. E., 'Unterschiedliche Säuglingssterblichkeit in Deutschland, 18 bis 20 Jahrhundert —warum?', *Zeitschrift für Bevölkerungswissenschaft*, 7 (1981), pp. 343–82.
Kesztenbaum, L. and Rosenthal, J.-L., 'Sewers' diffusion and the decline of mortality: the case of Paris, 1880–1914', *Journal of Urban Economics*, 98 (2017), pp. 174–86.
Kintner, H. J., 'Trends and regional differences in breastfeeding in Germany from 1871 to 1937', *Journal of Family History*, 10 (1985), pp. 163–82.
Kintner, H. J., 'Determinants of temporal and areal variation in infant mortality in Germany, 1871–1933', *Demography*, 25 (1988), pp. 597–609.
Knodel, J. E., *The decline of fertility in Germany, 1871–1939* (Princeton, NJ, 1974).
Kremer, M., Leino, J., Miguel, E., and Zwane, A. P., 'Spring cleaning: rural water impacts, valuation, and property rights institutions', *Quarterly Journal of Economics*, 126 (2011), pp. 145–205.
Leonard, C. and Ljungberg, J., 'Population and living standards, 1870–1914', in S. Broadberry and K. H. O'Rourke, eds., *The Cambridge economic history of modern Europe*, 2: *1870 to the present* (Cambridge, 2010), pp. 108–29.
McKeown, T., *The modern rise of population* (New York, 1976).
Matzerath, H., 'Prussia's urbanization, 1815 to 1939. GESIS Data Archive, Cologne. ZA8050 Data file', Version 1.0.0 (1990), https://doi/org/10.4232/1.8050.
Millward, R. and Bell, F., 'Infant mortality in Victorian Britain: the mother as medium', *Economic History Review*, LIV (2001), pp. 699–733.
Mokyr, J., 'Why "more work for mother"? Knowledge and household behavior, 1870–1945', *Journal of Economic History*, 60 (2000), pp. 1–41.
Mokyr, J. and Stein, R., 'Science, health, and household technology: the effect of the Pasteur revolution on consumer demand', in T. F. Bresnahan and R. J. Gordon, eds., *The economics of new goods* (Chicago, Ill., 1996), pp. 143–205.
Neefe, M., *Statistisches Jahrbuch deutscher Städte* (Breslau, 1892).
Ogasawara, K., Shirota, S., and Kobayashi, G., 'Public health improvements and mortality in interwar Tokyo: a Bayesian disease mapping approach', *Cliometrica* (2016), pp. 1–31.
van Poppel, F. and van der Heijden, C., 'The effects of water supply on infant and childhood mortality: a review of historical evidence', *Health Transition Review*, 7 (1997), pp. 113–48.
Preston, S. H., 'The changing relation between mortality and level of economic development', *Population Studies*, 29 (1975), pp. 231–48.
Salomon, H., *Die städtische Abwässerbeseitigung in Deutschland. Wörterbuchartig angeordnete Nachrichten und Beschreibungen städtischer Kanalisations- und Kläranlagen in deutschen Wohnplätzen* (Jena, 1906).

Schramm, E., 'Privatisation of German urban water infrastructure in the 19th and 21st centuries', in P. Wilding ed., Urban infrastructure in transition: what can we learn from history? 6th International Summer Academy on Technology Studies, 11–17 July 2004 (2004), pp. 339–51.
Sen, A., 'Mortality as an indicator of economic success and failure', *Economic Journal*, 108, 446 (1998), pp. 1–25.
Spree, R., *Health and social class in Imperial Germany. A social history of mortality, morbidity and inequality*, S. McKinnon-Evans and J. Halliday, trans. (Oxford, 1988).
Troesken, W., *Water, race and disease* (Cambridge, 2004).
UN (United Nations), *The sustainable development goals report* (New York, 2017).
UNICEF (United Nations Children's Fund), *UNICEF field notes on community approaches to total sanitation. Learning from five country programmes* (Geneva, 2017).
Vögele, J., 'Urban infant mortality in Imperial Germany', *Social History of Medicine*, 7 (1994), pp. 401–25.
Vögele, J., *Urban mortality change in England and Germany, 1870–1913* (Liverpool, 1998).
Vögele, J., 'Urbanization and the urban mortality change in Imperial Germany', *Health & Place*, 6 (2000), pp. 41–55.
Vögele, J., Rittershaus, L., and Halling, T., '"Breast is best": infant-feeding, infant mortality and infant welfare in Germany during the late nineteenth and twentieth centuries', *Health*, 5, 2 (2013), pp. 2190–203.
WHO (World Health Organization), 'Global health estimates 2016: disease burden by cause, age, sex, by country and by region, 2000–2016' (Geneva, 2016), https://www.who.int/healthinfo/global_burden_disease/estimates/en/index1.html (accessed on 1 June 2019).
WHO (World Health Organization) and UNICEF (United Nations Children's Fund), *Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines* (Geneva, 2017).

Official publications
Kaiserliches Gesundheitsamt, *Veröffentlichungen des Kaiserlichen Gesundheitsamtes* (Berlin, 1878–1914).
Kaiserliches Gesundheitsamt, Medizinal-Statistische Mittheilungen aus dem Kaiserlichen Gesundheitsamte*, vols. 1 and 2* (Berlin, 1893, 1895).
Kaiserliches Statistisches Amt, *Statistik des Deutschen Reichs: Die Volkszählung im Deutschen Reich am 1. Dezember 1880. Vol. Band 57 (Alte Folge)* (Berlin, 1883).
Kaiserliches Statistisches Amt, *Statistik des Deutschen Reiches (Neue Folge, Bd. 2): Berufsstatistik des Reiches und der kleinen Verwaltungsbezirke nach der allgemeinen Berufszählung Vom 5. Juni 1882* (Berlin, 1884).
Kaiserliches Statistisches Amt, *Statistik des Deutschen Reichs, Neue Folge, Band 117: Berufsstatistik nach der allgemeinen Berufszählung von 1895. Erster Teil* (Berlin, 1898).
Kaiserliches Statistisches Amt, *Statistik des Deutschen Reichs, Neue Folge, Band 118: Berufsstatistik nach der allgemeinen Berufszählung von 1895. Zweiter Teil* (Berlin, 1898).
Kaiserliches Statistisches Amt, *Statistik des Deutschen Reichs: die Volkszählung im Deutschen Reich am 1. Dezember 1900. Vol. Band 150* (Berlin, 1903).
Kaiserliches Statistisches Amt, *Statistik des Deutschen Reichs, Neue Folge, Band 209: Berufs- und Betriebszählung vom 12. Juni 1907* (Berlin, 1910).
Kaiserliches Statistisches Amt, *Statistik des Deutschen Reichs: die Volkszählung im Deutschen Reich am 1. Dezember 1910. Vol. Band 240* (Berlin, 1915).
Königliches Statistisches Bureau in Berlin, *Preussische Statistik* (Berlin, 1878–1914).

Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

S1. Complementary tables and figure
S2. Additional information on sources and mortality before the establishment of sanitary infrastructures