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Sanitary infrastructures and the decline of mortality in Germany, 1877-1913

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Abstract

Clean water provision is considered crucial towards eradicating water-borne diseases. However, the benefits of piped water are limited in the absence of efficient systems of waste disposal due to recontamination or the exposure of citizens to excrement. In this article, I analyse the historical experience of German cities and estimate the impact of water supply and sewerage systems on mortality. The results show that waterworks lowered mortality, although to a lower extent than suggested previously. I observe a much stronger effect of sanitary interventions in cities that also established sewerage systems. Together they explain 19 percent of the overall mortality decline during this period. Three pieces of evidence show that the limited effects of waterworks is related to illnesses spread via faecal-oral transmission mechanisms. First, sanitary infrastructures account for a quarter of the decline in infant mortality, which is largely affected by water-borne ailments. Second, I find a large effect for enteric-related illnesses, while deaths from etiologies with a different pathological basis are not affected. Finally, the estimated effect is related exclusively to the sanitary interventions because mortality only declines significantly after their completion, and not before.

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1 Introduction

Infectious illnesses transmitted through water such as diarrhoeal diseases are still an important cause of death in the developing world (World Health Organization, 2016). Resembling this mortality pattern, advanced economies during the late 19th century also experienced extraordinarily high death rates from water-borne diseases. Consider the case of Germany as an example. In the late 1870s, almost a third of the population died from gastrointestinal diseases. Among infants, this figure was even higher, around 50 percent (Vögele, 1998, 2000). Contrary to today's developing countries, Germany and other industrialised economies experienced a strong decrease in deaths from these diseases in the subsequent decades that would ultimately result in their complete disappearance. Examining the drivers of this unprecedented long-term mortality decline, an emerging body of literature has provided renewed support for the idea that the provision of clean water was a key factor by quantifying its positive effects (Cutler & Miller, 2005; Ferrie & Troesken, 2008; Ogasawara, Shirota, & Kobayashi, 2016; Beach, Ferrie, Saavedra, & Troesken, 2016).

However, the prevalence of water-borne ailments transmitted through faecal-oral mechanisms does not only depend on clean water provision. First, the effectiveness of piped water alone may fall short because of contamination of the source or during transport (Fewtrell et al., 2005; Kremer, Leino, Miguel, & Peterson, 2011; Kesztenbaum & Rosenthal, 2017). 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 (Alsan & Goldin, in press). And third, the use of inadequate toilets or open defecation increase the exposure of the population to diarrhoeal diseases (Brown, 2000; Alsan & Goldin, in press; UNICEF, 2017). In sum, these mechanisms cast doubt on the effectiveness of clean water provision alone and call for an integrative analysis considering both systems of water supply and waste disposal. In this paper, I take such an approach and examine the individual and joint impact of these sanitary infrastructures on mortality to gain a better understanding of the contribution of public health interventions to the long-term mortality decline.

To study the link between public health interventions and mortality, I consider the case of Germany during the period 1877-1913 and created two new datasets containing information on city-level overall and infant mortality; deaths by different types of disease; and the timing when substantial improvements were made in water provision and waste disposal. With these new data, I provide a new perspective to the literature in three different respects. First, I complement previous studies focusing on a single sanitary intervention by looking at the marginal effect of waterworks and sewerage systems on various measures of mortality. This approach yields new insights into the degree of complementarity of different sanitary infrastructures and the potential limited effects of waterworks. Second, my focus goes beyond 'traditional' analyses of very large cities (e.g. Cutler and Miller, 2005; Ferrie and Troesken, 2008) since my sample contains municipalities whose population ranged from a few thousands to almost a million. Third, the analysis of cities located in different states within the German empire complements studies that have considered a relatively homogeneous area or a single city (e.g. Ferrie and Troesken, 2008; Alsan and Goldin, in press; Ogasawara et al., 2016; Kesztenbaum and Rosenthal, 2017). Even after 1871, public health policies were the responsibility of the different states and therefore were shaped by diverse political and sanitary institutions (Hennock, 2000).

The results of this article show that improvements in water provision have a significant effect on citizens' health, although limited: water interventions account for seven percent of the decline in overall mortality between 1877 and 1913; and eleven percent for infant mortality. While waterworks usually provide clean water for drinking, cooking or hygienic purposes, the inadequate disposal of human waste or its storage next to households can severely limit their effectiveness. When including sewerage systems in the analysis, I observe a much stronger effect of public health infrastructures on mortality indicating that both of them were largely complementary. According to my results, together they account for at least 19 percent of the mortality decline during the period 1877-1913 (23 percent if we take into account learning effects).

I find three pieces of evidence pointing that the main reason explaining the limited effects of water provision and the decline in mortality is related to illnesses spread via faecal-oral transmission mechanisms. First, I show that sanitary infrastructures account for a substantial 24 percent of the decline in infant mortality, which is largely affected by water-borne diseases. Second, public health interventions have no effect on airborne illnesses such as tuberculosis or pneumonia, whereas water-borne diseases experience a large decline after their establishment. This supports the idea that these mostly influence enteric-related diseases, while deaths from etiologies with a different pathological basis are not affected. And third, I show that the observed mortality decline is related exclusively to the sanitary infrastructures, and not to other unobserved factors. Assuming that the interventions took place before the actual years yields statistically insignificant results.

This article is related to a long-standing literature looking at the factors driving the mortality decline in the early phase of the epidemiological transition. On one side, some scholars emphasize the role of increasing income and caloric intake on the nutritional status of individuals, which made people more resistant to the disease environment (McKeown, 1976; Fogel, 2004; Floud, Fogel, Harris, & Hong, 2011). Another mechanism has been explored by

Eli (2015) who analyses the effect of increasing individual income on health among Union Army soldiers who enlisted in the American Civil War. According to her findings, veterans employed as farmers increased the number of children in the household following a rise in income, who contributed positively within the household. Alternatively, higher fertility – and therefore less resources per individual in the household – is also associated with higher infant mortality (Brown & Guinnane, 2017). On the other side, studies by Preston (1975), Easterlin (1999) or Deaton (2013) highlight the role of medical knowledge and the implementation of public health infrastructures. These effects have been found for several countries such as the United States (Cutler & Miller, 2005; Ferrie & Troesken, 2008; Beach et al., 2016; Alsan & Goldin, in press; Lewis, 2018); England (Szreter, 1988; Chapman, 2018); France (Kesztenbaum & Rosenthal, 2017); or Japan (Ogasawara et al., 2016; Ogasawara & Matsushita, 2018). This research adds to this literature by analysing the case of Germany. Furthermore, I complement an earlier study Brown (2000) in three respects. First, I explicitly study the interaction between improvements in water provision and waste disposal. Second, I use a more general measure of mortality beyond infant mortality and a more comprehensive picture of the German urban context in that I do not only consider the largest German cities. And third, I analyse water-borne and airborne illnesses individually to obtain a more precise idea about the mechanisms driving the decrease in mortality.

Another related body of literature studies the effectiveness of sanitary interventions for recent time periods (Watson, 2006; Cairncross et al., 2010; Kremer et al., 2011; Bennet, 2012). The experience of Germany at the turn of the 20th century is particularly interesting because it experienced persistently-high death rates in comparison with other countries at the time. Actually, the literature has termed this excess mortality as 'German penalty' (Leonard & Ljungberg, 2010). However, the disease environment improved dramatically in the subsequent decades until the eve of the first world war as crude death rates declined by a third and infant mortality by almost a half (Vögele, 1998). This development highly contrasts the high prevalence of similar preventable diseases in developing areas nowadays more than a hundred years later (Cutler, Deaton, & Lleras-Muney, 2006; Deaton, 2013; World Health Organization, 2016).

The remaining of this article is structured as follows. First, I will discuss the historical context in Germany with a special emphasis on various public health measures undertaken to improve citizens' health. Second, I will present the two new datasets on city-level mortality and sanitary interventions for the period 1877-1913. Fourth, I will outline the empirical framework used for the analysis. Then, I will show the results and discuss the main mechanisms. And finally, I will test the robustness of my results and conclude.

2 Historical context

2.1 Public health measures and mortality

In the decades leading to the analysed period, Germany started experiencing a strong urbanisation process. From the mid-19th century to 1880 the percentage of the population living in rural areas steadily declined from 67 to 59 percent (Knodel, 1974, 4). In some areas, this process was more intense than in others as the experience of the Ruhr area shows. Whereas in 1800 the combined population of this region amounted to less than 40,000 people, a century later close to one and a half million people lived there (Leonard & Ljungberg, 2010). The rapid growth of the population in urban areas deteriorated citizens' health because overcrowding and congestion in cities provided a favourable environment for the transmission of airborne and waterborne infectious diseases (e.g. tuberculosis or typhoid fever).[1]

In the late 1870s, the excess mortality in urban areas relative to the countryside – the so-called urban penalty – was at its highest (Vögele, 1998). Putting these figures in international perspective reveals the existence of, as Leonard and Ljungberg (2010, 119) put it, a 'German penalty' since mortality rates were higher than in other countries such as England. If we consider the age dimension of this process, we can clearly see that the two penalties particularly affected urban infants who suffered predominantly from diseases affecting the digestive system. This overall pattern differed across regions within the German empire because infant mortality rates (IMR) were higher in the eastern and southern regions than in the north-western part of the nation (Haines & Kintner, 2000). Despite the bleak status of citizens' health during these years, it is precisely at this time when we can observe a sustained health improvement. 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, but also across other German states. Actually, progress was so remarkable that the urban-rural differential disappeared shortly around the turn of the 20th century, even though urbanisation accelerated in these decades (Matzerath, 1990; Vögele, 1998; Gehrmann, 2011).

One explanation put forward for this development is related to advances in medical knowledge. Although slow and somewhat rudimentary for today's standards, new medical knowledge translated into treatments for several diseases such as smallpox, rabies or diphtheria (Easterlin, 1996, 1999). In Germany, vaccination against smallpox was made universal and compulsory from 1875 to 1889 (Hennock, 1998). However, the potential of such treatments of reducing mortality significantly was rather limited since they did not provide a cure to the

[1] The early phase of industrialisation not only had negative consequences for citizens' lives because wages typically rose due to increases in productivity. See Steckel and Floud (1997) and Gallardo-Albarrán (2016) for an analysis of the evolution of broader welfare combining several dimensions of well-being such as wages, health or working time.

main killers of the time such as tuberculosis.

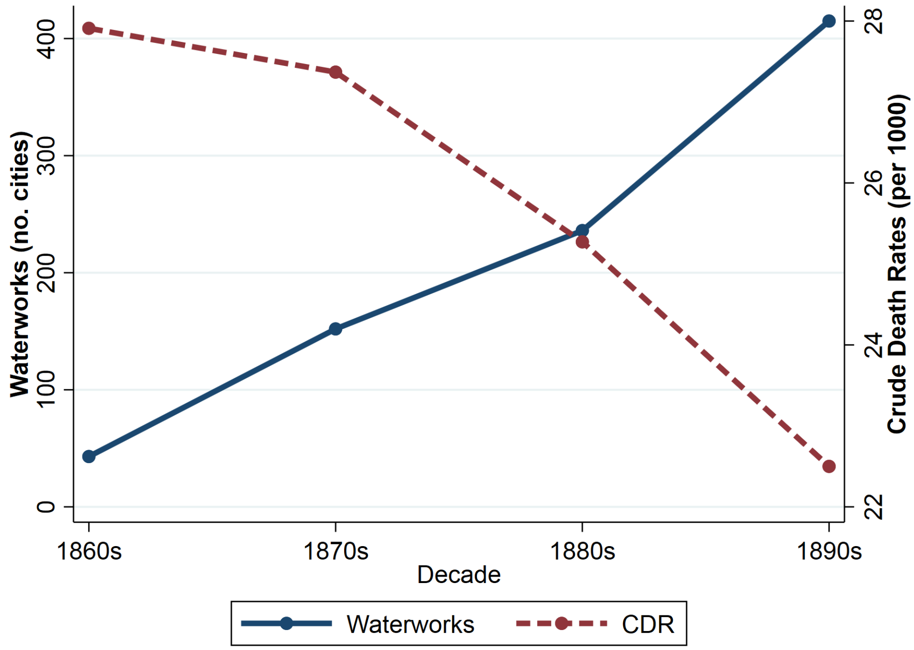
A more important role for medicine can be recognised in relation to diffusing health knowledge. By understanding the transmission mechanisms of diseases, households could adopt more hygienic habits while dealing with home cleanliness or food preparation to reduce their exposure to infectious illnesses (Mokyr & Stein, 1996; Mokyr, 2000). Public authorities contributed to food regulation by enacting a law in 1879, although its implementation took many years (Guinnane, 2003). Another way of spreading best-practices was through the provision of health care. Bauernschuster, Driva, and Hornung (2018) find that the compulsory health insurance scheme established in 1884 by Otto von Bismarck reduced mortality through the diffusion of new hygiene knowledge by physicians.[2] Despite being significant, this factor does not explain why mortality started decreasing already in the 1870s.

Another aspect that could be improved significantly with better knowledge on how diseases spread concerns infant care (Mokyr & Stein, 1996). Using individual-level data for the city of Munich, Brown and Guinnane (2017) find that infant care – especially limited breastfeeding and poor nutrition after weaning – was an important determinant of the survival chances of infants. To improve feeding practices, public health authorities tried different strategies such as providing pasteurised milk. This was not very successful because it remained rather marginal during the analysed period (Vögele, 1998). Another strategy was to encourage breastfeeding through infant welfare centres. However, their effectiveness was rather low in the German case because enforcing breastfeeding required a large number of bureaucratic, and sometimes discriminatory, procedures that discouraged working class mothers from attending them (Vögele, Rittershaus, & Halling, 2013).

Besides implementing the aforementioned public health measures, local authorities made significant efforts towards improving the disease environment by establishing systems of water supply and waste disposal. These large-scale public health investments had a significant potential to make public environments safer at that time given the high prevalence of waterborne diseases in comparison with other countries (Spree, 1988; Hennock, 2000; Brown, 2000). In the following, I discuss these in more depth.

[2]Evidence for this channel has been found for other countries. Winegarden and Murray (1998, 2005) and Bowblis (2010) find that government-sponsored health insurance schemes contributed to the mortality decline in several European countries from the 1870s until the first world war by making medical care more affordable and disseminating information concerning health awareness. For a more recent period, Strittmatter and Sunde (2013) argue that the introduction of public health care systems had a significant immediate effect on infant mortality and crude death rates.

Figure 1: CDR and waterworks during the second half of the 19th century in Germany



Note: Grahn (1904) for waterworks and Thomas (2015) for crude death rates.

2.2 The sanitary revolution

In the late 19th century, neither the technology nor the actual establishment of piped water and sewerage systems were new in Germany. The first of these large scale health infrastructures was established 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 supply and waste disposal (Evans, 1987). Similar systems were installed in other cities such as Altona, Berlin or Leipzig before the 1870s, although they were exceptions rather than the norm since only seven percent of localities with more than 2,000 inhabitants had a central water supply system by 1880. In contrast, an extraordinary 47 percent of English cities had waterworks at that time (Hennock, 2000).

This situation of relative backwardness would change rapidly in the subsequent decades until the turn of the 20th century. As shown in Figure 1 (left axis), whereas in the 1860s less than 50 cities supplied piped water to their citizens, a hundred projects were completed in the following decade and then two hundred more during the 1890s. As a result of this enormous public effort, more than four hundred cities benefited from central water provision by 1900. Sewerage systems underwent a similar development although 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 (Hennock, 2000). At the same time, Figure 1 shows that these developments were followed by a long-term decrease in crude death rates that accelerated during the period where most projects were finished.

The establishment of these infrastructures were not complete historical accidents, although their precise timing had a large random component for several reasons. The first factor to consider is the state of medical knowledge with regards to the spread of infectious diseases. Throughout most of the 19th century the predominant view among public officials, sanitarians and scientists was that that illnesses were transmitted through poisonous and bad-smelling vapors known as *miasmas*. As new knowledge gradually accumulated, this view started to change. An important step was made after the discoveries of John Snow or William Budd in the 1850s that water, and not vapors, was the main carrier of cholera and typhoid. More formal knowledge was created in the laboratories of Louis Pasteur in the 1860s and Robert Koch from the 1870s onward by discovering pathogenic organisms responsible for communicable diseases (Mokyr & Stein, 1996). Although this new knowledge seemed to better explain the terrible health conditions of the urban areas, public authorities were still divided and therefore their willingness to invest in public health infrastructures was low. Consider the case of Hamburg as an example. This city was the first in Germany in having a centralised water supply system. In contrast with its much smaller neighbouring municipality, Altona, or the big city of Berlin, Hamburg did not filter its water, although it was planned already in 1852 (Grahn, 1904). As late as the 1880s, the head engineer of the State Waterworks established that a sand-filtration plant was not really necessary for Hamburg because the water was taken from the Elbe and stored, without further treatments, in large reservoirs (Evans, 1987, 147). The disbelief in the germ theory of disease in turn automatically dismissed measures of isolation and quarantine to fight against epidemics that were not favoured by the economic elite of the city, whose interests were closely linked to the uninterrupted course of trade. Given the wealth of Hamburg and the various epidemics it suffered during the 19th century, the precise timing at which safe water was supplied did not ultimately depend on financial or health issues, but rather on the beliefs concerning disease transmission mechanisms and the economic interests of the local elite (Vögele, 1998).

Secondly, sanitarians at the time had to fight hard political battles over years and sometimes decades in order to persuade city councils of the benefits of the new sanitary technologies (Cutler & Miller, 2005). Consider the case of Frankfurt. This municipality had an active project to build a sewerage system since 1839. However, the city council cut off the funds after several years of protest by the opponents to this program led by Georg Varrentrapp. The opponents to the project wanted a more comprehensive system that could remove surface-water, household-waste water and human faeces at the same time. This system was preferred by Dr. Varrentrap, who was familiar with the English sanitary movement and their more advanced sanitary technologies (Hennock, 2000). 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 the project in 1867, which was finished decades later in 1896 (Brix, Imhoff, & Weldert, 1934, 323). This complex and arduous process was not unique of Frankfurt, but it also took place in other cities such as Hanover, Bielefeld or Münster (Hennock, 2000).

A third element that adds to the randomness of the precise timing of water infrastructures is related to the political organisation of the German empire. During the late 19th century, states had an important degree of autonomy. These translated into different public health policies and priorities concerning the establishment of sanitary infrastructures within the Empire. Hennock (2000) argues that this autonomy was often well-secured since when German sanitarians tried in the early 1870s to persuade the state authorities to set up local health boards with prescribed duties, they were refused on the grounds that this would infringe the power of individual states. Instead, an Imperial Health Authority was set up in Berlin with limited advisory power.

The last point deals with the local factors that determined the timing of sanitary infrastructures. As suggested previously, municipalities were the prime responsible authorities for the construction of these systems. After the manifold hurdles were passed and local authorities were convinced of establishing sanitary infrastructures, discussions emerged with regards to the specific technology to be used and its funding. Given the lack of precise knowledge about the mechanisms of disease transmission, local authorities had to decide whether to first implement a sewerage or a water supply system (or both). Once this decision was made, new questions emerged with respect to each specific system. For instance, to provide piped water municipalities had to consider whether it would have to be taken directly from a nearby river, reservoirs located next to them, a lake or underground water (also if the water was to be filtered). With respect to sewerage systems, some technologies involved carrying wastewater together with rain water and others in separate canals. These choices involved a process of deliberation and discussion that differed by city in that geographic conditions and political dynamics varied substantially.[3]

Another variable to take into account was whether the infrastructures were to be financed publicly or privately. During several decades after mid-19th century, both possibilities were used and choosing one over the other had consequences for their timing. For instance, the city of Mülheim decided to build waterworks and called for bids in 1873. However, the contractor

[3]For the United States, Alsan and Goldin (in press) find empirical evidence supporting that the timing of sanitary infrastructures was strongly influenced by local geographic features and not by pretreatment demographic characteristics.

commissioned in 1874 could not find any investors for the city. Therefore, the city had to build it itself, finishing the works in 1876 (Schramm, 2004). Brown (1988) has looked at this issue more formally by empirically assessing the determinants of the timing of water provision in the Rhineland. The study finds that industrial demands and median's voter tax payment are the most important factors, and not health-related variables such as cholera outbreaks or population density. This evidence suggests that emerging industries such as cloth finishing and dyeworks fostered the demand for water supply both because they needed it in their production process and because of the rising incomes they brought to a local elite that demanded this type of infrastructures. In turn, the economic elite had a large influence on local political matters since franchise was granted to a small minority of wealthy residents. After excluding the poorest section of the city inhabitants, the remaining 20 to 35 percent of adult males were assigned into three voting classes. The group paying the top third of total taxes (i.e. income, property and business taxes) chose one third of the assembly, the next third chose another third, etcetera (Brown, 1988, 310).

3 Data

I will use city-level data to investigate the role of sewerage and water supply systems on the mortality decline. For various measures of mortality, population and birth data I have used the annual reports of the Imperial Health Office between 1877 and 1913 that record such information for cities with more than 15,000 inhabitants (*Veröffentlichungen des Kaiserlichen Gesundheitsamtes* and *Medizinalstatistische Mitteilungen*). Using the data in these reports, I constructed indicators of infant mortality rates (per 1000 births);[4] overall mortality (per 1000); and deaths due to some digestive and respiratory ailments (per 1000). Analysing measures of mortality according to age and type of disease are useful to deal with some of the potential weaknesses related to the latter type such as misdiagnosis. As noted by Ferrie and Troesken (2008) for the city of Chicago, and more generally for the American context, this issue was relatively common in the late 19th century. For instance, typhoid fever was often confused with other diseases in its early stages since it resembled respiratory diseases such as pneumonia or bronchitis. Accurate diagnosis was only possible after the development of new tests.[5]

To obtain information on the year at which each city established either of the sanitary infrastructures analysed in this research, I proceeded in two steps. First, I began with

[4] Following Alsan and Goldin (in press) and Brown (2000), I have used infant mortality rates per birth instead of per person. In the robustness tests I also use a per-person measure and the results are unchanged.

[5] Vögele (1998, 25) mentions that these difficulties were also present in Germany where deaths were classified according to their symptoms rather than the actual cause in a modern sense.

water provision and used Grahn (1898-1902, 1904) to record the year in which waterworks started operating in a certain city.[6] Then, I identified those cities whose intervention date took place after 1881 due to both lack of mortality data for the pre-1877 period and to have some variation between the pre- and post-intervention periods. This feature of the data is particularly useful because it allows calculating the marginal effect of waterworks on mortality by observing death rates before and after their implementation. The second step involved finding data on the intervention years for sewerage systems drawing on Salomon (1906-1911) and Brix et al. (1934).[7] It is important to note that these often mention when canalisation was finished in a certain city, although this did not always imply that a system of waste disposal was in place. A large number of cities first started these projects to control rainwater and, in some cases, household wastewater without including human faeces. Given that the mechanism of mortality reduction explored in this article concerns the faecal-oral transmission of infectious diseases, I coded the intervention years when all waste could be disposed through canals. Matching the two datasets results in a 41-city sample, among which 27 of them had sewerage systems by the end of the period.[8]

In Table 1, I present some descriptive statistics on mortality and control variables for three selected years: 1877, 1900 and 1913 (a more comprehensive overview of the employed variables can be seen in Table A1). Comparing these figures with those for Germany as a whole by Knodel (1974, 5), we can conclude that they are relatively similar. Whereas infant mortality and crude death rates were 26.1 and 227 respectively for overall Germany in the period 1876-1880, the cities in my sample exhibit values of 25.8 and 247 in 1877 (the same applies for 1913).

Before presenting the rest of the variables used in the analysis, a careful discussion about the main variables of interest is necessary (i.e. sanitary infrastructures). In this article, I follow the literature and look at the date at which sanitary projects started operating.[9] However, this approach has several weaknesses that make difficult identifying the existence of a significant effect of sanitary improvements on mortality. First, the procedure assumes that the whole population is covered by a certain infrastructure, even though this is not realistic in some cases. For instance, although the city of Koblenz finished its canal network

[6]The interventions coded mostly involved providing piped water from various sources (e.g. lake, underground, etcetera). In the case of Hamburg, the intervention consisted on filtering water.

[7]As before, I restricted the sample to the cities that established this system before 1909 to have at least five years of variation during the post-treatment period.

[8]I also excluded localities that only had data for a few years. The resulting sample consists of: Schwerin, Stargard, Tilsit, Insterburg, Bromberg, Landsberg, Munich, Stuttgart, Nürnberg Fürth, Zwickau, Gera, Weimar, Weissenfels, Spandau, Brandenburg, Charlottenburg, Guben, Kottbus, Hamburg, Osnabrück, Bielefeld, Hildesheim, Oldenburg, Harburg, Barmen, Hagen, Trier, Rheydt, Solingen, Mainz, Mannheim, Kaiserlautern, Worms, Düren, Ludwigshafen, Giessen, Herford, Lüdenscheid, Oppeln and Neumünster.

[9]See Cutler and Miller (2005), Alsan and Goldin (in press) or Beach et al. (2016).

Table 1: Summary statistics for some selected variables

	Statistic	CDR	IMR	log_pop	Percent Industry	Share Protestant	Share Catholic	Citizens per dwelling
1877	mean	25.09	243.95	10.36	0.34	0.69	0.29	8.28
	sd	3.50	59.22	0.74	0.13	0.30	0.29	1.72
	min	16.37	135.99	9.68	0.13	0.04	0.00	6.03
	max	33.42	373.44	12.78	0.64	0.99	0.95	13.61
1900	mean	19.42	215.08	10.88	0.38	0.68	0.30	9.22
	sd	3.06	58.99	0.80	0.13	0.29	0.28	2.42
	min	14.54	93.72	10.12	0.15	0.04	0.01	5.99
	max	25.88	335.88	13.46	0.70	0.98	0.95	18.24
1913	mean	13.52	139.90	11.16	0.40	0.66	0.31	9.98
	sd	2.59	32.75	0.86	0.13	0.27	0.28	3.21
	min	9.46	61.85	10.24	0.16	0.05	0.02	6.80
	max	20.87	191.00	13.84	0.71	0.97	0.95	21.02

Note: see the text for the sources. *CDR* stands for crude death rates; *IMR* for infant mortality rates and *log_pop* for log-transformed population.

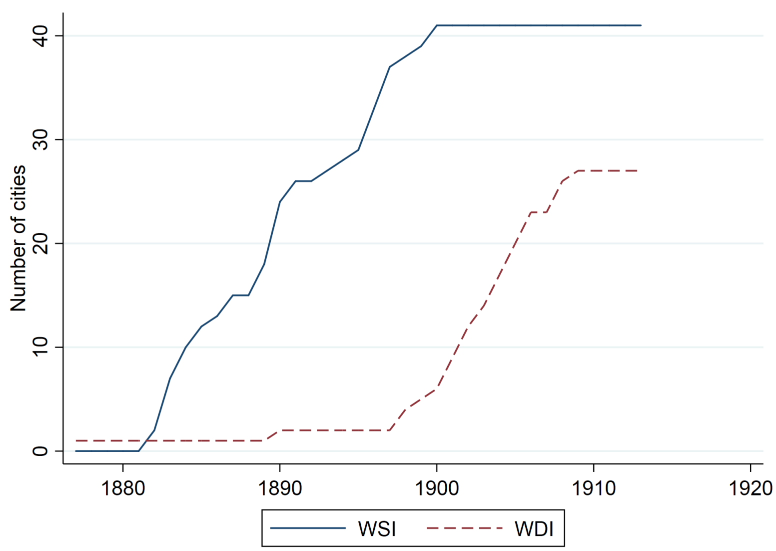
in 1899, there was no obligation to be connected to it and the poorest part of the city did not benefit from it until several years after its establishment. A similar case can be observed in Trier where the second part of the city – on the right bank of the river – was finished in 1905, although its infrastructures were set in 1903 (Salomon, 1906-1911). A further issue has been identified in the American context where some well-off neighbourhoods may have had earlier access to the sanitary infrastructures (Troesken, 2002). Second, the completion of water supply and sewerage systems did not end with their opening in a given year. Maintenance and extension works could improve their efficiency as engineers and sanitarians learned from experience and new medical knowledge became increasingly available (I will elaborate more on this later). The third issue concerns the sanitary technologies that could be used. In the case of sewerage systems, municipalities could install a *mixed system* that carried rain and waste water together or a *separate system* with different canals carrying rain water and wastewater separately. On top of this, the geographic features of each city determined two further aspects of the project. On one side, the canals could be above ground, underground or a mix of both. On the other side, the procedure to transport waste water through the canal network could rely on natural slopes, artificial elevation using steam pumps, air pressure or vacuum (Brix et al., 1934). Given that these systems may perform differently in different contexts, a simple binary variable does not account for the heterogeneous effects they may have on mortality.[10] All these considerations suggest that the effect of sanitary infrastructures

[10] Including this aspect of sewerage systems into the analysis is very problematic because I do not have enough information on this and, most importantly, some cities could have several systems in place such as

on mortality may take some time after their establishment. Therefore, the found effects can be interpreted as lower-bound estimates because using dummy variables for the sanitary interventions leads to a downward bias in the estimates.

What does the timing of the sanitary revolution look like in my sample? In Figure 2 I present the number of improvements in water supply (WSI) and waste disposal (WDI) that took place during the period 1877-1913. As we can see, starting in the early 1880s an increasing number of cities introduced centralised systems of water supply, and by 1900 all of them had established this infrastructure. Consistent with the literature, the introduction of sewerage systems came somewhat later and seemed to take off around the turn of the 20th century (Hennock, 2000).

Figure 2: Timing of improvements in water supply and waste disposal



Note: the sources are Grahn (1898-1902, 1904) and Brix et al. (1934). WSI and WDI stand for water supply and waste disposal improvements.

4 Empirical framework

The empirical analysis exploits the plausibly exogenous timing of safe water and sewerage interventions. In this framework, I will use several measures of city-level mortality annually to examine whether the introduction of public health infrastructures had an effect on their decline in the subsequent years after its introduction. More specifically, I will estimate the

Hildesheim (Salomon, 1906-1911). Also, with the growth of urban areas and the integration of municipalities that had different sewerage systems in place, categorizing the resulting city is not straightforward.

following model:

$$
\begin{aligned}
log(mortality_{i,t}) = \beta_0 + \beta_1 WSI_{i,t} + \beta_2 WDI_{i,t} + \\
\mathbf{d}'_{i,t}\boldsymbol{\gamma} + \mathbf{o}'_{i,t}\boldsymbol{\delta} + \zeta_i + \eta_t + \zeta_i \cdot t + \epsilon_{i,t},
\end{aligned}
\tag{1}
$$

where i and t index city and time respectively; $mortality_{i,t}$ can refer to per-person total mortality, infant mortality, and deaths by infectious diseases affecting the digestive and respiratory organs; $WSI_{i,t}$ and $WDI_{i,t}$ refer to water supply and waste disposal improvements (turning one in the year t in which city i implemented one of these) conditional on city-fixed effects, time effects and city-specific linear trends. The city-specific 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. The time effects (η_t) are of crucial importance to isolate the effect of public health infrastructures from factors that change over time and that are common to the whole sample (e.g. weather fluctuations). The last set of control variables ($\zeta_i \cdot t$) refer to factors that are specific to each of the cities and that may change over time such as wage increases. Following Alsan and Goldin (in press), I cluster the standard errors at the city level.[11] To account for potential autocorrelation with an alternative approach, I will also use up to 5-year lags of the dependent variable in the robustness section as done by Cutler and Miller (2005).

If we are interested in the marginal effects of improvements in water provision, β_1 is the coefficient of interest. It shows the average mortality levels following the provision of piped water. To look at the marginal effect of improvements in waste disposal, we must consider β_2. Given that all cities in my sample, except for Hamburg, introduced sewerage systems after clean water was provided, β_2 represents the marginal effect of such infrastructures once water supply has been provided. Finally, I consider β_1 and β_2 jointly to determine the extent to which changes in water provision and waste disposal reduce the number of deaths.

It is important to note that besides controlling for city, time and city-specific time varying effects, I also include a set of demographic variables (these are included in the vector $\mathbf{d}$). At the city level, I control for total population. At the district level (*Regierungsbezirk*), I control for the percentage of males in the population, the age structure (i.e. percentage of individuals below 15, between 15 and 40, 40 and 60, and above 60) to make sure that the change in, say, infant mortality is not due to a change in the proportion of these over the total population. To measure potential differences in childbearing practices or general attitude towards life, I include two variables that measure the percentage of the population with a catholic and protestant background.[12] Also, to make sure that trends in urbanisation do not drive the

[11] This procedure is also recommended by Bertrand, Duflo, and Mullainathan (2004).

[12] Imhof (1981) argues that the impoverishment of the population and the lack of cattle led to bad infant

results, I include a variable that measures the number of citizens per dwelling and the share of people in a given district living in municipalities larger than 2,000 inhabitants (see Table 1 and A1). I gathered this demographic information from the population censuses of 1880, 1900 and 1910 (Kaiserliches Statistisches Amt, 1883, 1903, 1915). Yearly data was obtained using linear interpolation and extrapolation for the first and last three years of the analysed time period. For the gender structure of the population, I took information for an additional benchmark in 1905.[13]

The regressions also include variables that capture the percentage of people working in industry and services at the district level (**o**) taken from Hohls and Kaelble (1989). I introduced these controls motivated by the idea that the introduction of waterworks was influenced by the presence of industry (mostly cloth finishing and dyeworks) in the city (Brown, 1988). Furthermore, as noted by Alsan and Goldin (in press, 9), this information may be important in the case of infant mortality rates because if mothers working in factories are less likely to breastfeed, their children may be more exposed to feeding alternatives that may make use of contaminated water. In the robustness section, I will look at more disaggregated data by sector to confirm that this potential issue is not driving the main results.

I will perform two additional exercises to further support the assumption that the introduction of sanitary infrastructures was not determined by mortality in the years prior their introduction. The first consists of adding two 5-year lead variables of each treatment in Equation 1. A positive and significant coefficient of this variable would indicate that mortality levels were relatively high five years prior the coded interventions. A negative coefficient would indicate the presence of pre-intervention negative trends that would be ascribed to other factors than the main variables of interest.

The second exercise elaborates further on this idea and tests the sizeable and highly-significant coefficients for WSI and WDI. If the mortality decline is related to sanitary interventions exclusively, then a level-shift in the number of deaths should be observed upon the introduction of sanitary infrastructures (or immediately afterwards), and not before. More specifically, I will estimate the following equation:

feeding practices and the development of a fatalistic mentality that was particularly present in catholic areas. More recently, Gehrmann (2011) has highlighted the role of customs and attitudes in determining the survival chances of infants. A further issue that this variable would capture is that of registration of infant deaths. According to Vögele (1994) and Haines and Kintner (2000), the number of registered still-births was relatively lower due to the custom of emergency baptism by Catholics. In areas where infant deaths occurred within a mandatory three-day registration period infant mortality was underrated.

[13]With controls at the district level, I account for broad trends in several demographic trends that may not be captured by the time effects and city-specific linear trends. Given the varied spatial distribution of the cities analysed, I am exploiting variation from 28 different districts: Mecklenburg-Schwerin, Danzig, Gumbinnen, Bromberg, Frankfurt an der Oder, Oberbayern, Neckarkreis, Mittelfranken, Zwickau, Reuss älterer Linie, Sachsen-Weimar, Merseburg, Potsdam, Hamburg, Osnabrück, Minden, Hildesheim, Oldenburg, Lüneburg, Düsseldorf, Trier, Rheinhessen, Mannheim, Pfalz, Aachen, Oberhessen, Oppeln and Schleswig-Holstein.

$$
\begin{aligned}
log(mortality_{i,t}) = \alpha + \sum_{k=-4}^{k=4} \beta_k WSI_{i,t+k} + \theta_k WDI_{i,t+k} + \\
\mathbf{d}'_{i,t}\boldsymbol{\gamma} + \mathbf{o}'_{i,t}\boldsymbol{\delta} + \zeta_i + \eta_t + \zeta_i \cdot t + \epsilon_{i,t},
\end{aligned}
\tag{2}
$$

where k indexes the lag (or lead) chosen for the analysis.

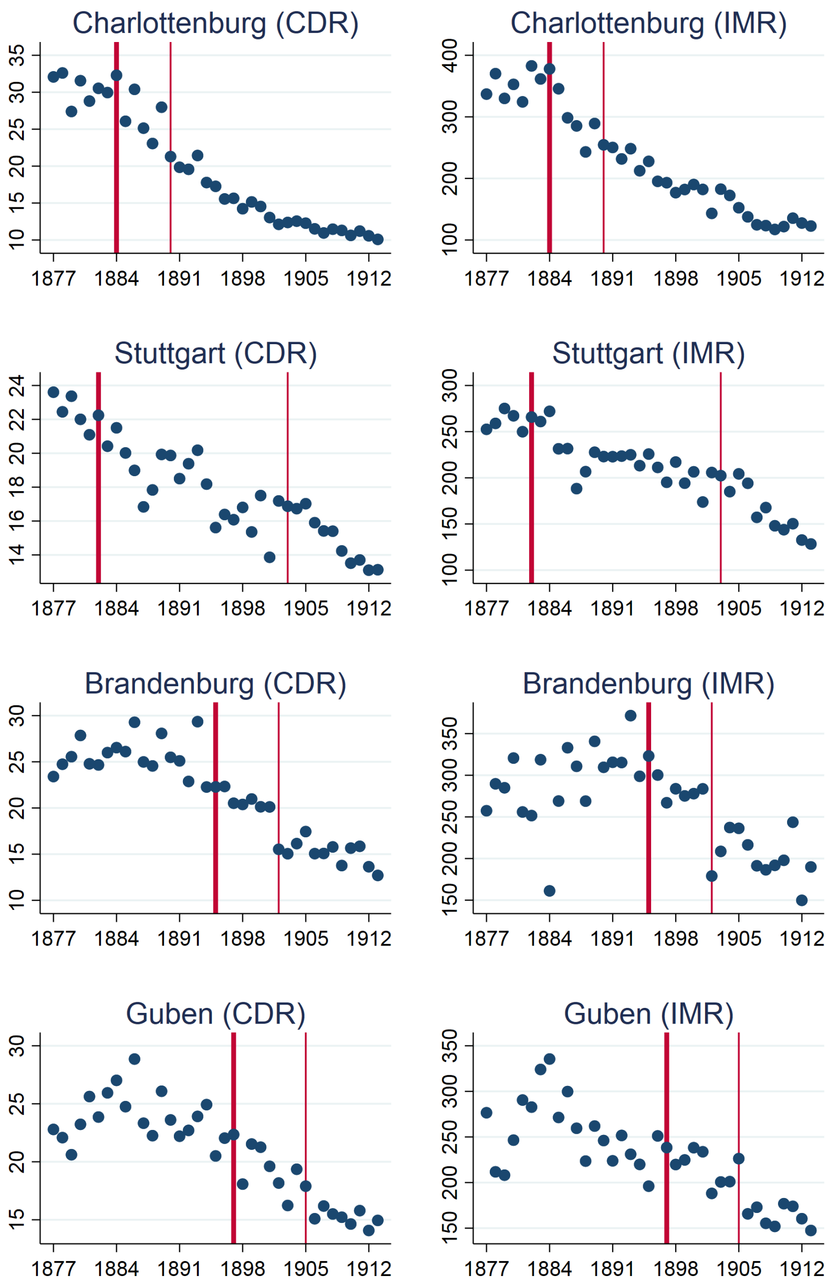
5 Results

5.1 Main Results

Before turning to the results of the model outlined in the previous section, it is instructive to look at some of the mortality data and the timing of sanitary interventions for several cities. In Figure 3, I present information on overall mortality (left side) and infant mortality (right side) for two relatively large and small cities: Charlottenburg, Stuttgart, Brandenburg and Guben. The thick vertical line marks the year when a system of piped water started operating, and the thinner line the opening of a sewerage system. Consider infant mortality rates in Charlottenburg. Before any intervention took place, the number of infant deaths hovered around 350 per 1000 births, a figure that was 54 percent higher than the national average. By the end of the period, IMR dropped to around 100 (60 percent of the national average). This decline took place gradually in the course of the almost four decades considered with substantial drops immediately after investments in water provision and waste disposal took place in 1884 and 1890, respectively. For CDR, we can observe the same pattern. It is also interesting to note the mortality decrease around 1903 happened several decades after the recorded sanitary interventions. This was probably the result of the extension of the sewerage network into areas of the city that were previously not covered (Salomon, 1906-1911, 194). This decline would not be fully captured by the dummy-variable approach I discussed previously, which reinforces the idea that my results provide a lower-bound estimate of the effect of sanitary infrastructures. The case of Stuttgart is slightly different because the coded improvement in waste disposal only came 20 years after piped water was provided. In this case, we observe an initial decline in infant mortality and a period of almost stagnation during the 1880s and 1890s. A substantial drop only happened shortly after citizens had access to a sewerage system. The last four examples of Figure 3 show a similar pattern for much smaller cities: death rates decline significantly following investments in public health infrastructures.

With this simple exercise, we can clearly see the potential influence of sanitary interventions, although we cannot rule out the influence of confounding factors. To isolate their effect, I estimate Equation 1 and present the results in Table 2. In Column 1, I look at the

Figure 3: Mortaliy and sanitary interventions in four selected cities



Note: the thick and thin vertical lines mark the year at which improvements in water supply and sewerage systems take place. The sources for water supply and sewerage systems see Figure 2; for mortality I used the publications of the Imperial Health Office (*Veröffentlichungen des Kaiserlichen Gesundheitsamtes* and *Medizinalstatistische Mitteilungen*).

individual effect of safe water provision on CDR and observe that it has a statistically significant and negative sign, indicating that mortality declined following investments in water supply. If we consider improvements in waste disposal in Column 2, we can observe the similar strong and negative relationship. To obtain an estimate of their marginal effect on overall mortality net of their potential influence on each other, I include both WSI and WDI in Column 3. We can see that the marginal effect of water supply improvements on mortality is lower than that of sewerage systems since the coefficient for WDI is larger than the one for WSI. According to the results, piped water provision reduced overall mortality by 0.035 logarithmic points. Given that the total mortality decline in my sample is 0.53 logarithmic points, water infrastructures are associated with a 7-percent reduction in overall mortality (0.035/0.53). In turn, waste disposal improvements induced a mortality decline by 0.066 logarithmic points, which accounts for 12 percent of the overall mortality decline. Together, they account for 19 percent of the overall mortality decline in the sample.

Before discussing these findings further, it is worth looking at the impact of sanitary interventions on another widely used measure of health: infant mortality. Furthermore, considering this indicator will shed some light on the potential mechanisms driving the mortality decline because infants deaths were predominantly caused by water-borne ailments (Vögele, 1998). In the first and second column of Table 3, I show the individual effect of piped water and sewerage systems on infant mortality. As one would expect, the coefficients are negative and statistically significant indicating that infant mortality was lower in cities where its inhabitants had access to these sanitary infrastructures. More importantly and supporting the previous results, Column 3 of Table 3 shows that the marginal effect of improvements in water supply is lower than that of sewerage systems. Actually, my results imply that the former account for 10 percent (0.048/0.45) of the infant mortality decline and the latter by 14 percent (0.061/0.45), thus jointly explaining almost a fifth of the overall decrease in the sample. Interestingly, this result is very close to that by Brown (2000) using a sample of large German cities.[14]

The findings for overall and infant mortality suggest that water improvements alone had limited effects. Possibly this was due to water recontamination and the exposure of citizens to diseases transmitted via faecal-oral mechanisms since illnesses transmitted through water affect infants disproportionately (more evidence on the mechanisms will be provided below). This idea is in line with the study by Kremer et al. (2011) for Kenya, which shows that investments in spring infrastructure reduced faecal contamination, but household water quality improved less due to recontamination. Furthermore, evidence for Massachusetts at the turn

[14] This comparison should be made with caution, though. The variable capturing the state of waste disposal by Brown (2000) is whether water closets were installed in the entire city.

of the 20th century suggests that piecemeal improvements in sanitary infrastructures are unlikely to significantly improve child health (Alsan & Goldin, in press). Focusing on the same time period, Kesztenbaum and Rosenthal (2017) support this idea by examining the impact of the sewerage network in Paris. They find that establishing multiple sanitary infrastructures is needed to help decrease mortality. In other words, their degree of complementarity is so significant that establishing them at the same time yields substantial benefits.

Table 2: The impact of improvements in water supply and sewerage on overall mortality

	(1)	(2)	(3)	(4)
WSI	-0.0407**		-0.0348**	-0.0340**
	(0.0161)		(0.0161)	(0.0153)
WDI		-0.0712***	-0.0662***	-0.0531**
		(0.0204)	(0.0196)	(0.0213)
WSI_lead5				0.000589
				(0.0180)
WDI_lead5				-0.00103
				(0.0164)
Joint Effect			-0.101***	-0.0871***
(statistic)			(15.1)	(11.01)
Control variables	Yes	Yes	Yes	Yes
Observations	1462	1462	1462	1257
R-squared	0.892	0.893	0.894	0.859

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Note: all regressions include time effects, city fixed effects, city-specific trends as well as the demographic and occupational controls discussed in the text.

The impact of improvements in water supply found in this article is relatively low in comparison with other benchmark estimates from the literature (Cutler & Miller, 2005; Ferrie & Troesken, 2008; Ogasawara et al., 2016; Beach et al., 2016; Ogasawara & Matsushita, 2018).[15] Several factors can explain this. First, the size of the cities in some other studies is bigger than in my sample. Consequently, the potential for improving the disease environment

[15]It is worth noting that Alsan and Goldin (in press) have an even more pessimistic view on the effectiveness of waterworks because their individual effect on infant mortality is not statistically significant.

is larger in more densely-populated areas because congestion and overcrowding caused by urbanisation were more problematic. Second, the treatments analysed by Cutler and Miller (2005) or Ogasawara et al. (2016) represent superior improvements – water filtration and chlorination – than those considered here. A third reason is the learning effect experienced by engineers and local politicians concerning building and running these sanitary infrastructures, which in turn may have increased their efficiency. Given that the time period considered in this article is earlier than in some of the aforementioned studies, the municipalities analysed here possibly faced more uncertainties than those investing in these systems during the first decades of the 20th century.

Table 3: The impact of improvements in water supply and sewerage on IMR

	(1)	(2)	(3)	(4)
WSI	-0.0529***		-0.0475**	-0.0432**
	(0.0198)		(0.0198)	(0.0198)
WDI		-0.0679***	-0.0610***	-0.0565**
		(0.0242)	(0.0234)	(0.0236)
WSI_lead5				-0.0170
				(0.0194)
WDI_lead5				0.00298
				(0.0203)
Joint Effect			-0.1085***	-0.0997**
(statistic)			(11.84)	(8.41)
Control variables	Yes	Yes	Yes	Yes
Observations	1462	1462	1462	1257
R-squared	0.878	0.878	0.880	0.860

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Note: all regressions include time effects, city fixed effects, city-specific trends as well as the demographic and occupational controls discussed in the text.

In the last column of Table 2 and 3, I add two 5-year lead variables of each treatment to the main specification in Column 3 to test whether mortality levels were relatively high in the years leading to the sanitary interventions. A positive and significant coefficient would indicate that their timing may have responded to mortality instead of other factors such as the presence of certain industries in a city (Brown, 1988). Two points are worth highlighting from this exercise. First, these variables do not have a consistent sign and, most importantly, neither of them are significant for overall and infant mortality. This also should make us confident that the intervention variables are not capturing pre-existing decreasing trends in mortality that may be ascribed to other factors (this issue will be explored in more detail below). And second, the coefficients estimated in Column 3 are not sensitive to including these variables.

5.2 Mechanisms

The previous results highlight the limited effects of waterworks alongside their complementarity with sewerage systems. Although I suggested that the mechanism explaining these was related to the recontamination of water sources or the continued exposure of citizens to faecal-oral transmission diseases, I only provided indirect evidence for supporting this idea. More specifically, I argued that the larger effect of sanitary interventions found for infant mortality seem to confirm the presence of these mechanisms because this group of the population is the most vulnerable to enteric diseases. In the following, I provide further evidence for this argumentation by taking advantage of some of the digestive diseases recorded in the sources such as diarrhoea, enteritis and catarrh of the stomach. Given that these are mainly transmitted through faecal-oral mechanisms, the sanitary interventions must have affected their development more decisively than any other type of disease.

In Table 4, I present the results of regressions using deaths affecting the digestive organs as the dependent variable. Surprisingly, the coefficient for WSI is statistically insignificant, while that for WDI is statistically significant and negative (see Column 3). Jointly, their effect is statistically significant and sizeable. Together, they account for a substantial 49 percent of the reduction in mortality from the digestive diseases recorded in this variable. These findings clearly point out that the investments in water provision should be complemented with the establishment of sewerage systems to significantly reduce diseases spread via faecal-oral transmissions mechanisms. The results so far show that the two infrastructures acted together in contributing to a cleaner and safer disease environment once city waste was carried away in an efficient manner.

Another aspect of the results in Table 4 that can be discussed is related to the lead variables for WSI and WDI. Consistent with the previous regressions where I used overall and infant mortality as the dependent variables, the coefficients for these variables do not have a consistent sign and, most importantly, are not statistically significant. Thus, they reinforce the idea that the introduction of sanitary infrastructures was not determined by pre-existing trends in mortality. This is in line with evidence for Germany and the United

States (Brown, 1988; Vögele, 2000; Cutler & Miller, 2005; Alsan & Goldin, in press).

Table 4: The impact of improvements in water supply and sewerage on digestive diseases

	(1)	(2)	(3)	(4)
WSI	-0.115		-0.102	-0.0890
	(0.0727)		(0.0728)	(0.0718)
WDI		-0.157*	-0.142*	-0.162**
		(0.0819)	(0.0815)	(0.0747)
WSI_lead5				-0.00334
				(0.0788)
WDI_lead5				0.0429
				(0.0594)
Joint Effect			-0.244**	-0.251**
(statistic)			(11.84)	(8.41)
Control variables	Yes	Yes	Yes	Yes
Observations	1462	1462	1462	1257
R-squared	0.755	0.755	0.756	0.751

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Note: all regressions include time effects, city fixed effects, city-specific trends as well as the demographic and occupational controls discussed in the text.

If sanitary interventions mostly protected the population from diseases transmitted through faecal-oral mechanisms, then one should expect a much lower (or lack of) impact on airborne diseases affecting respiratory organs such as tuberculosis or pneumonia. To test this, I use deaths by respiratory diseases (e.g. tuberculosis, measles, diphtheria, croup, etcetera) as a dependent variable in Table 5. In line with the main hypothesis of this article, the results in Column 3 imply that neither improvements in water provision nor waste disposal had a significant effect on airborne diseases. WDI has a negative sign, which yields some support for the diffused effects found for the city of Chicago by Ferrie and Troesken (2008), although it is not significant (regressions using individual diseases show the same pattern). Also, WSI and WDI are not jointly significant as opposed to the results for the previous regressions.

Table 5: The impact of improvements in water supply and sewerage on respiratory diseases

	(1)	(2)	(3)	(4)
WSI	0.0212		0.0236	0.0176
	(0.0292)		(0.0289)	(0.0294)
WDI		-0.0239	-0.0273	-0.00819
		(0.0402)	(0.0403)	(0.0458)
WSI_lead5				-0.0295
				(0.0452)
WDI_lead5				0.00416
				(0.0388)
Joint Effect			-0.0037	-0.0094
(statistic)			(1.15)	(0.38)
Control variables	Yes	Yes	Yes	Yes
Observations	1462	1462	1462	1257
R-squared	0.774	0.774	0.774	0.725

Standard errors in parentheses

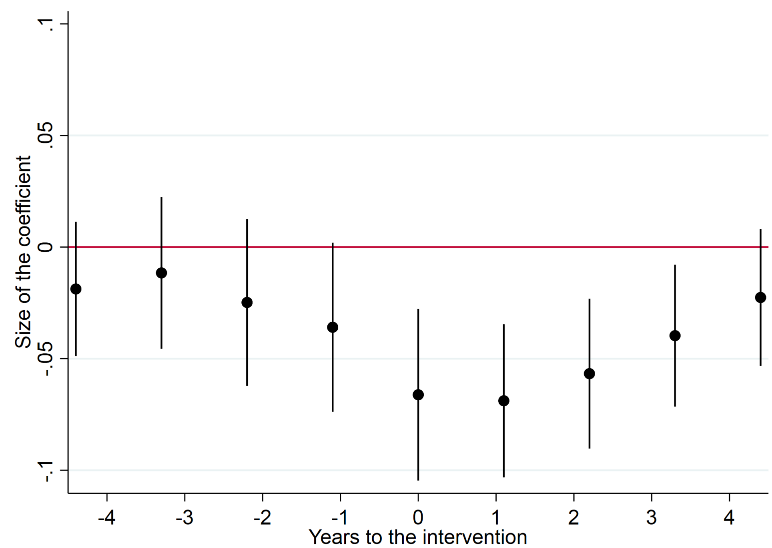
* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Note: all regressions include time effects, city fixed effects, city-specific trends as well as the demographic and occupational controls discussed in the text.

While all the evidence presented so far should give us confidence that sanitary infrastructures lowered the rate of mortality by improving the safety and cleanliness of the disease environment, one may be sceptical about the size of their effect. In other words, how can we be sure that the ascribed impact to sanitary interventions is not picking up the effect of other interventions such as pasteurized milk supply, street cleaning or food regulation? If the main variables of interest (i.e. WSI and WDI) are not capturing trends in factors related to mortality other than the public health infrastructures considered in this article, we would expect a level-shift in mortality only in the intervention year (or immediately afterwards), and not before.

In Figure 3, I argued that this was indeed the case for four cities in the sample. Shortly after the introduction of piped water and sewerage, both CDR and IMR experienced a steady decline. Then, I have shown that the five-year lead intervention variables in the fourth specification of each regression table not only do not affect the main results, but also are not significant in any of the regressions. To further complement these analyses with a more detailed and formal exercise, I have estimated different models using up to four-year lead and lag intervention variables (see Equation 2) to determine whether a level-effect can be observed when a city has both centralized water provision and a sewerage system. Figure 4 plots the size of the coefficients for each lag and lead of WDI as well as their 95 percent confidence interval in regressions where the dependent variable is CDR.[16] As we can see, the coefficients are not significantly different from zero before both interventions take place. Then in the actual intervention year it turns statistically significant and, most importantly, a substantial level effect is observed with respect to the rest of the coefficients.

Figure 4: Impact on overall mortality before and after both sanitary interventions have been implemented



5.3 Diffused effects of sanitary interventions over time

It is interesting to further explore the idea that the effect of sanitary infrastructures are not unique to the actual intervention year. Increasing effects over time can be due to the accumulation of knowledge by local authorities on how to best operate them; rising health returns as a result of complementarities in private hygienic practices (Murphy & Topel, 2003); or a decline in deaths by non-waterborne diseases as morbidity declines (Ferrie & Troesken, 2008). Alternatively, the effects may diminish over time if sanitary infrastructures induce less hygienic practices at the household level (Bennet, 2012); public health interventions crowd out costly private preventive measures (Philipson, 2000); or most of the associated benefits

[16]The same pattern can be observed for IMR (see Figure A1).

are related to the mere connection of citizens to the network.

Table 6 explores these alternative views by regressing five-year lags of WSI and WDI, their ordinary and five-year lead versions, and all the controls included previously on various measures of mortality. Thus, the lag variables capture the effect of the sanitary infrastructures five years after their implementation.

Table 6: Delayed effects of interventions on various mortality measures

	CDR	IMR	Digestive diseases	Respiratory diseases
	(1)	(2)	(3)	(4)
WSI	-0.0256	-0.0452**	-0.0915	0.0197
	(0.0174)	(0.0215)	(0.0782)	(0.0303)
WDI	-0.0635***	-0.0704***	-0.164**	-0.0340
	(0.0170)	(0.0236)	(0.0827)	(0.0379)
WSI_lag5	-0.0248**	0.00743	-0.126**	0.0190
	(0.0122)	(0.0173)	(0.0580)	(0.0282)
WDI_lag5	-0.00982	-0.0140	-0.102**	0.0206
	(0.0146)	(0.0207)	(0.0521)	(0.0233)
Joint Effect	-0.0891***	-0.1156***	-0.2555**	-0.0143
(statistic)	(15.93)	(12.80)	(6.72)	(1.06)
Joint Effect (5-year lag)	-0.0346*	-0.0065	-0.228***	0.0396
(statistic)	(4.67)	(0.64)	(10.47)	(1.42)
Control variables	Yes	Yes	Yes	Yes
Observations	1292	1292	1292	1292
R-squared	0.896	0.883	0.773	0.782

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Note: all regressions include time effects, city fixed effects, city-specific trends as well as the demographic and occupational controls discussed in the text.

If we first consider CDR in Column 1, we can see that the joint significance of the lead intervention variables point to some delayed effects, although decreasing over time. Taking these into account, sanitary interventions explain 23 percent of the overall mortality decline. In the case of infant mortality (Column 2), the joint effect of the lag variables is not significant, thus indicating that most of the associated decline in mortality took place right after the public health investments. For infectious diseases affecting the digestive system, I find large delayed effects. Actually, the joint effect of WSI and WDI as well as their 5-year lags indicate that sanitary interventions account for almost all the reduction in mortality from this category.

In sum, I find decreasing or no effects over time for overall and infant mortality, respectively. On the other hand, the evidence for digestive diseases suggests that large delayed effects for water-borne diseases were present due to learning over time and diffused effects as emphasized in other studies such as Cutler and Miller (2005) or Ferrie and Troesken (2008).

5.4 Robustness Tests

In this section, I show that the main estimates discussed previously are robust to a number of alternative tests. The first of these looks at the percentage of infant mortality decline accounted for sanitary infrastructures when using a per-capita instead of a per-birth measure. Analysing the results of this exercise in Table A2, we can see that the coefficients for WSI, WDI are always negative and highly significant. The implied reduction in IMR in Column 3 is 20 percent, almost the same as the estimate presented previously. Continuing with IMR, I test whether the substantial level effect identified after the introduction of sanitary infrastructures for CDR can be observed for infant mortality. We can clearly see in Figure A1 that both no coefficient is significantly different from zero before the sanitary intervention takes place and a large negative effect is observed when public health infrastructures started operating. This evidence together with Figure 4 strongly suggest that the effects captured by WSI and WDI are related to the interventions, and not to other confounding factors.

In Table A3, I replicate the benchmark results for overall mortality in Table 2, but using more refined measures of the occupational structure of the labour force. For instance, I consider the ratio of female over males employed in agriculture, industry and services in Column 1. In Column 2, I use industry-level measures to control for differences in employment across sectors.[17] In the last column I consider the ratio of female to male workers in the same industries as before. The different specifications show that changes in these controls barely have an impact on the size, sign or significance level of the main estimates of this article.

In the next robustness test, I repeat the main estimations for all mortality variables, but using a sample in which all cities receive both treatments. This exercise is interesting for at least two reasons. First, it tests the main findings throughout the article on a different

[17]The sub-sectors are: agriculture, mining, metal production, metal processing, machine construction, chemical industries, textile industry, cloth industry, food industry, construction, supply industries, 'other industries', producers' services, transport, trade, social services, public services, personal services, 'other services'.

sample as the number of cities that receive both sanitary infrastructures is reduced to 27 cities. And second, I check that the main results are not driven by these cities, if they had a set of characteristics that are substantially different from the rest. Three points are worth highlighting from this exercise in Table A4. First, the negative association between sanitary interventions and CDR, IMR and deaths affecting digestive organs holds strongly. Secondly, the percentage of the mortality decline in this sample accounted for improvements in water provision and sewerage are virtually the same as the ones calculated earlier. And third, respiratory diseases are not affected by any of the public health projects considered, thus reinforcing the idea that a reduced exposure to diseases transmitted via faecal-oral mechanisms is the main driver of the mortality decline.

The last robustness test concerns a potential issue with serial correlation. The main estimates of this article use clustered errors at the city level. In Table A5, I experiment with the approach by Cutler and Miller (2005) by including five lags of the dependent variable on the right hand side of Equation 1. As we can see the results are practically unchanged. Both piped water and sewerage systems had a sizeable and significant impact on CDR, IMR and deaths by digestive diseases.

6 Conclusions

The prevalence of waterborne diseases and the lack of access to sanitary infrastructures in many developing regions nowadays is a well-known feature of European countries at the turn of the 20th century such as Germany. In this country, the challenges posed by a strong process of urbanisation and industrialisation during the course of the 19th century resulted in a steady deterioration of its urban health status up to the 1870s. The situation was so dramatic in these years that around 40 percent of overall mortality was accounted for by infants deaths. Immediately after this decade, the bleak picture portrayed by contemporaries and health indicators would dramatically improve so that by 1913 CDR and IMR had declined by a third and a half respectively. By creating two new datasets on city-level mortality and intervention dates for investments in water supply and sewerage systems, I have looked into one of the key factors behind the long-term mortality decline: public health investments.

I find that improvements in water provision have a significant effect on mortality. However, these effects were limited due to water recontamination and the lack of efficient systems of waste disposal. As my results show, cities that implemented sewerage systems experienced larger mortality declines than those having only established waterworks. Jointly, these infrastructures account for (at least) 19 percent of the observed mortality decline during the period 1877-1913 (23 percent if we take into account learning effects).

The main reason explaining the limited effect of waterworks and the overall mortality decline is related to the reduced exposure of citizens to faecal-oral transmission diseases. This idea is broadly supported by three further pieces of evidence. First, sanitary interventions had a larger effect on IMR which are mostly affected by waterborne diseases. Actually, these explain a fifth of the decline in infant mortality. Secondly, I find sizeable and highly-significant results for deaths from several digestive diseases (more than 50 percent of the decline from these are accounted for the main variables of my analysis), while the same is not true for respiratory diseases which are mainly airborne. And thirdly, I showed that the infrastructure variables are not affected by pre-intervention trends since a significant and negative effect on mortality is only found after the intervention dates, and not before.

The findings in this article point to the importance of considering the complementarity effects of sanitary interventions. The inefficient disposal or storage of human waste can severely limit the effectiveness of waterworks, even though they usually provide good clean water for drinking, cooking or hygienic purposes. More broadly, the results in this article also have implications for the long-standing literature looking at the determinants of the long-term mortality decline in industrial economies. Particularly, this article supports a stream of the literature that has highlighted the role of public health policy as an important determinant of the rise of health since the late 19th and early 20th century.

The case of 19th-century Germany has also implications for present-day policy makers because the comprehensive efforts put in by German authorities in that period resemble programmes such as the 'Swachh Bharat Mission' to achieve universal sanitation in India or the Water, Sanitation and Hygiene (WASH) programme to bring basic sanitary infrastructures to everyone in over 100 countries (UNICEF, 2017). The case of Germany at the turn of the 20th century suggests that these types of initiatives have a great potential to reduce the prevalence of infectious diseases transmitted via faecal-oral mechanisms, specially through their complementarity with systems of water supply.

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Appendices

Table A1: Summary statistics

	Statistic	Overall Mortality	IMR	log_pop	Percent Agriculture	Percent Industry	Percent Services
1877	mean	25.09	243.95	10.36	0.41	0.34	0.25
	sd	3.50	59.22	0.74	0.13	0.13	0.07
	min	16.37	135.99	9.68	0.05	0.13	0.18
	max	33.42	373.44	12.78	0.64	0.64	0.60
1900	mean	19.42	215.08	10.88	0.36	0.38	0.25
	sd	3.06	58.99	0.80	0.15	0.13	0.07
	min	14.54	93.72	10.12	0.03	0.15	0.18
	max	25.88	335.88	13.46	0.66	0.70	0.59
1913	mean	13.52	139.90	11.16	0.35	0.40	0.25
	sd	2.59	32.75	0.86	0.16	0.13	0.08
	min	9.46	61.85	10.24	0.03	0.16	0.17
	max	20.87	191.00	13.84	0.66	0.71	0.60

		Share male	Share female	Share pop. below 15	Share pop. 15-40	Share pop. 40-60	Share pop. above 60
1877	mean	0.49	0.51	0.36	0.38	0.18	0.08
	sd	0.01	0.01	0.02	0.02	0.01	0.01
	min	0.48	0.49	0.30	0.36	0.15	0.05
	max	0.51	0.52	0.40	0.45	0.21	0.10
1900	mean	0.50	0.50	0.35	0.39	0.18	0.08
	sd	0.01	0.01	0.03	0.03	0.01	0.01
	min	0.48	0.48	0.31	0.34	0.15	0.05
	max	0.52	0.52	0.40	0.44	0.20	0.11
1913	mean	0.49	0.51	0.34	0.40	0.18	0.09
	sd	0.03	0.04	0.04	0.03	0.02	0.06
	min	0.30	0.48	0.22	0.26	0.13	0.05
	max	0.52	0.72	0.40	0.47	0.21	0.48

		Share Protestant	Share Catholic	Citizens per squared meter	Citizens per dwelligs	Share pop. in cities (>2000)
1877	mean	0.69	0.29	131.56	8.28	0.42
	sd	0.30	0.29	160.04	1.72	0.21
	min	0.04	0.00	33.93	6.03	0.13
	max	0.99	0.95	1024.46	13.61	0.94
1900	mean	0.68	0.30	188.91	9.22	0.55
	sd	0.29	0.28	289.17	2.42	0.19
	min	0.04	0.01	41.66	5.99	0.19
	max	0.98	0.95	1850.11	18.24	0.98
1913	mean	0.66	0.31	248.45	9.98	0.62
	sd	0.27	0.28	418.44	3.21	0.20
	min	0.05	0.02	49.51	6.80	0.22
	max	0.97	0.95	2659.61	21.02	0.98

Figure A1: Impact on IMR before and after both sanitary interventions have been implemented

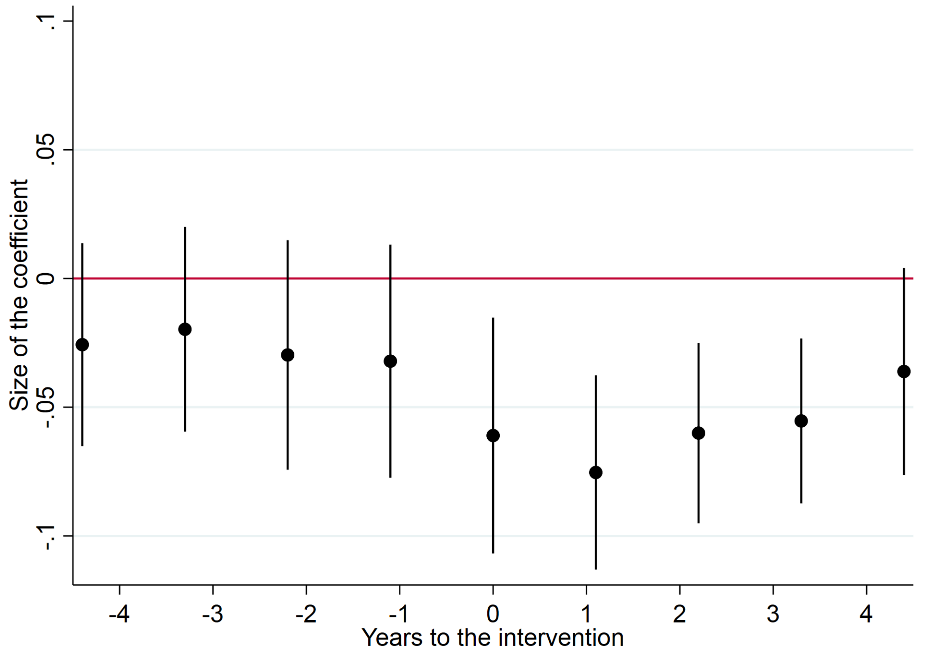

Table A2: The impact of sanitary interventions on IMR (per 1000 inhabitants)

	(1)	(2)	(3)	(4)
WSI	-0.0901***		-0.0811***	-0.0731***
	(0.0268)		(0.0268)	(0.0255)
WDI		-0.112***	-0.0999***	-0.0787**
		(0.0350)	(0.0334)	(0.0338)
WSI_lead5				-0.00583
				(0.0245)
WDI_lead5				0.00857
				(0.0240)
Joint Effect			-0.181***	-0.1518***
(statistic)			(21.35)	(14.34)
Control variables	Yes	Yes	Yes	Yes
Observations	1462	1462	1462	1257
R-squared	0.924	0.924	0.925	0.906

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Note: all regressions include time effects, city fixed effects, city-specific trends as well as the demographic and occupational controls discussed in the text.

Table A3: The impact of sanitary interventions on CDR (with varying occupational controls)

	(1)	(2)	(3)
WSI	-0.0385**	-0.0425**	-0.0377**
	(0.0171)	(0.0169)	(0.0163)
WDI	-0.0672***	-0.0637***	-0.0770***
	(0.0198)	(0.0174)	(0.0187)
Joint Effect	-0.1057***	-0.1062***	-0.1147***
(statistic)	(15.66)	(18.39)	(30.88)
Control variables	Yes	Yes	Yes
Observations	1462	1426	943
R-squared	0.895	0.901	0.930

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Note: Column 1 considers the ratio of female over males employed in agriculture, industry and services. Column 2 includes industry-level measures to control for differences in employment across these. And Column 3 uses the ratio of female to male workers in the same industries as before. All regressions include time effects, city fixed effects, city-specific trends as well as the demographic and occupational controls discussed in the text.

Table A4: The impact of sanitary interventions on several mortality measures (for cities that receive both interventions)

	(1) CDR	(2) IMR	(3) Digestive diseases	(4) Respiratory diseases
WSI	-0.0287	-0.0459*	-0.0480	0.0661
	(0.0211)	(0.0262)	(0.0978)	(0.0441)
WDI	-0.0746***	-0.0672***	-0.172**	-0.0562
	(0.0183)	(0.0206)	(0.0770)	(0.0453)
Joint Effect	-0.1033***	-0.1131***	-0.22**	0.0099
(statistic)	(19.45)	(15.21)	(7.95)	(3.09)
Control variables	Yes	Yes	Yes	Yes
Observations	968	968	968	968
R-squared	0.901	0.869	0.744	0.787

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Note: all regressions include time effects, city fixed effects, city-specific trends as well as the demographic and occupational controls discussed in the text.

Table A5: The impact of sanitary interventions on several mortality measures (adding up to 5-year mortality lags)

	(1) CDR	(2) IMR	(3) Digestive diseases	(4) Respiratory diseases
WSI	-0.0348**	-0.0489**	-0.0576	0.0183
	(0.0161)	(0.0211)	(0.0679)	(0.0228)
WDI	-0.0662***	-0.0642***	-0.135**	-0.0435
	(0.0196)	(0.0217)	(0.0641)	(0.0293)
Joint Effect	-0.101***	-0.1131***	-0.1926**	-0.0252
(statistic)	(15.10)	(14.22)	(6.49)	(2.46)
Control variables	Yes	Yes	Yes	Yes
Observations	1462	1257	1257	1257
R-squared	0.894	0.886	0.789	0.801

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01

Note: all regressions include time effects, city fixed effects, city-specific trends as well as the demographic and occupational controls discussed in the text.