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What are the health benefits of a constant water supply? Evidence from London, 1860–1910[☆]

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ABSTRACT

What are the benefits of moving from intermittent water delivery (which limits user access to less than 24 h per day) to constant service? To address this question, we study the transition from intermittent to constant water supply in London. Between 1871 and 1910, the proportion of London households with access to a constant water supply (24 h a day, 7 days a week) rose from less than 20–100 percent. Idiosyncratic delays in the negotiation process between companies and property owners generated random variation in the timing of the transition across London districts. Exploiting this variation, we find that a one percentage point increase in a local population with access to constant service decreased deaths from waterborne diseases by as much as 0.4 percent and explains approximately a fifth of the late nineteenth century decline in waterborne disease mortality. Results are robust to the inclusion of controls for population density, concerns regarding the reporting of cause-of-death, district-specific time trends, district demographics and spatial autocorrelation.

1. Introduction

The observed decline in mortality in Britain, the United States and much of Europe during the late nineteenth and early twentieth centuries is well known. While a full explanation of this mortality transition remains contested, the last couple of decades has seen strong evidence that improvements in public health, particularly investment in water and sanitation infrastructure, explain a large part of the reduction in infectious disease and infant mortality (Cutler and Miller, 2005; Ferrie and Troesken, 2008; Alsan and Goldin, 2019; Chapman, 2019; Gallardo-Albarrán, 2020). This reduction in mortality has been shown to contribute to permanent increases in life expectancy (Kesztenbaum and Rosenthal, 2017) and to increase educational attainment and earnings (Beach et al., 2016). However, recent research by Anderson, Charles and Rees ((Anderson et al., 2021)2021), using data for 25 large US cities for the period 1900–1940, has challenged the importance of public health investment. They find that most public health interventions played an insignificant role, with the exception of water filtration proving significant for explaining the reduction in infant mortality.

☆ Played a guiding role on this paper until his death in September 2018. To honor his work and his memory, we have retained him as a co-author. Any errors in the paper are attributable to the other authors.

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The existing literature focuses almost exclusively on discrete interventions.[1] For water infrastructure these include changes in water source and the introduction of filtration or chlorination. In cities with close to universal network coverage and constant high-pressure supply, most of the mortality decline from these interventions will be realized immediately, especially for diseases such as typhoid caused by distinct bacteria and predominantly transmitted through water.[2] While discrete interventions are important, most studies acknowledge that many public health interventions are rolled out more slowly and may take time to reach everyone. For example, filtering water primarily benefits those with piped supply, so subsequent network expansion will deliver longer term improvements in water quality and public health. Even with universal coverage, systems that supply water intermittently are susceptible to post-treatment contamination that may reduce the impact of discrete interventions. Supplying water constantly at high-pressure eliminates such contamination at the household or neighborhood level and can deliver meaningful health improvements. The increased availability of water under constant supply may improve personal hygiene, delivering additional health gains on the intensive margin. While connection to the network is crucial to benefit from improvements in water treatment, the frequency and reliability of service, along with complementary infrastructure, are also necessary. For such non-discrete interventions, the full public health impacts will be realized more slowly.

In this paper, we focus on the health benefits of a 25-year improvement in water quality as London transitioned from a system of intermittent water supply (IWS) to a constant water supply (CWS). Specifically, we assess the mortality effects of London's transition from an intermittent to a constant water supply between 1871 and 1910, as the proportion of London households with access to CWS (24 h a day, 7 days a week) rose from less than 20 to nearly 100 percent. To our knowledge, this is the first economic history paper to establish and measure the causal link between constant service and mortality, an important complementarity that has yet to gain recognition in the literature on the health effects of water infrastructure.

Intermittent water supply and subsequent in-house storage was common in British and other Western cities during the nineteenth century even for homes connected to the network.[3] However, intermittently supplied and domestically stored water creates the risk of post-treatment contamination. The development literature identifies two primary sources of such post-treatment contamination.[4] First, water sitting at low pressure in distribution pipes between supply periods allows for the intrusion of contaminants, particularly in crowded areas where water pipes lie in close proximity to sewers (Kumpel and Nelson 2014: 2770; Lee and Schwab 2005: 115).[5] Second, water stored in cisterns or other containers by consumers to ensure a constant domestic supply results in contamination, partly just from sitting, often uncovered, between supply periods and partly as a result of consumer neglect.[6]

London is a promising setting for three reasons. First, the introduction of a constant water supply (CWS) necessitated non-trivial investments on the part of both water companies and private home-owners, which could only be implemented after extensive multi-party negotiations. Idiosyncratic delays in the negotiation process generated plausibly exogenous variation in the timing of the transition from IWS to CWS across London districts. Second, while the transition from IWS to CWS was a widespread phenomenon in Western cities during the late nineteenth and early twentieth century, London's transition is well documented, particularly in relation to district level data on access and mortality. Third, one might worry that cities were adopting other technological innovations to improve water quality at the same time they introduced CWS. In London, however, the most rapid growth in the extension of constant service came decades after a series of legal and regulatory interventions designed to protect the London water supply from contamination, and by the same token, the city's constant, high pressure, distribution network was largely complete when the city municipalized the system in 1902 (Hardy, 1991: 85–92; Metropolitan Water Board, 1953).

The analysis below proceeds as follows. First, we convert data on mortality for all of London's registration districts for the period from 1860 to 1910 into mortality data for 19 composite health districts to address district boundary changes during the period. We then estimate the proportion of homes in each of these districts with access to CWS using data on connection rates across London's private water companies and the relative presence of these companies across districts. Although most companies and districts do not exhibit sharp increases in the provision of CWS until after 1875 and by 1910 there is near universal access to CWS, the data suggest meaningful differences in access to CWS across both districts and time in the intervening years. Exploiting this variation, we adopt a generalized difference-in-differences strategy to identify how access to CWS affected waterborne disease mortality.

Our estimated coefficients show that introducing CWS had large mortality effects, on par in magnitude with other, more heavily studied, interventions and explaining a fifth of the decline in waterborne disease mortality in London between 1875 and 1910. We show that these results are robust to controls for population, district-specific time trends, district demographics, and concerns regarding low quality reporting of cause-of-death during the early years of our sample. Recent work in economic history raises the possibility that improvements in health-related infrastructure might induce in-migration to treated places. If so, calculated mortality

[1] Two exceptions are Kesztenbaum and Rosenthal (2017), showing that the diffusion of sewer infrastructure in Paris reduced mortality throughout the city between 1880 and 1914, and Chapman (2019), showing that investment in water and sanitation in Britain over a 40-year period explains about 30% of the reduction in mortality between 1861 and 1900.

[2] Typhoid is caused by the *Salmonella enterica* serotype typhi bacteria and, according to Ewald (1994: 69, Table 5.1), 74% of typhoid infections result from waterborne transmission. The same table shows the frequency of waterborne transmission for other diarrheal diseases.

[3] In the United States, by contrast, most houses joining a water supply network connected directly to a high-pressure main.

[4] See Lee and Schwab (2005) for other sources of contamination. As they point out, it is often a combination of system flaws, exacerbated under IWS, that contribute to reduced water quality.

[5] A comparison of CWS and IWS in eight pairs of matched wards in India found that 99.3% of CWS water samples met standards requiring the absence of *E. coli* while only 68.3% of IWS samples met the standards (Kumpel and Nelson 2013: 5).

[6] Water stored by consumers for more than a day has tested for significantly higher levels of E. coli than water delivered continuously (Kumpel and Nelson, 2013: 11, 13). In his 1884 report to Parliament, Frank Bolton identified cisterns as a source of water contamination under IWS in London.

Table 1
London water companies, water sources and treatment.

Company	Water source	First filtration	Move upriver	Adopt Waterworks Clauses Act
Chelsea	River Lea	1829	1856	1852 & 1853
East London	River Lea	1854	1834	1852
Grand Junction	River Thames	1855	1855	1852
Kent	Deep wells	1845 (until 1861)	n/a	1864
Lambeth	River Thames	1841	1852	1848
New River	River Lea; wells	1855	Abandoned Thames 1852	1852
Southwark & Vauxhall	River Thames	1855	1855	1852
West Middlesex	River Thames	1855	1855	1852

Sources: Information in this table was drawn from (Bolton, 1884) and (Shadwell, 1899).
For each of London's eight water companies, this table shows water source, opening date of first filtration plant, the year abstraction location moved upriver, and the year the Waterworks Clauses Act 1847 (the first to mention constant service) was adopted.

rates based on interpolated population data (as ours) might be biased downward for inter-census years. Although this is less likely to be a concern for constant service than with more discrete sanitary interventions, we follow the existing literature and implement remedial tests that show our results are unaffected by such concerns. Reductions in typhoid morbidity have been shown to reduce deaths from other causes (Ferrie and Troesken, 2008) and the overall decline in mortality during our period suggests that CWS may also have delivered broader health benefits. We would not, however, expect CWS to directly cause district-level reductions in non-waterborne deaths. This is confirmed in placebo tests, using all deaths minus waterborne disease deaths, whooping cough (an airborne disease), and deaths from violence.

London's nineteenth century experience has contemporary relevance. Around 300 million people in the world today have only intermittent access to piped water supplies. In many developing world cities in Asia, Africa, and Latin America, urban residents receive piped water for only a few hours every day or have access to piped water only two or three days per week (Lee and Schwab, 2005: 114; Kumpel and Nelson, 2016; Heymans et al., 2016: 11). Yet, while there is broad consensus that disruptions in water access pose a serious public health risk and that universal constant service is desirable, systematic assessments of the health benefits of constant service, particularly in large metropolitan areas, are a nascent focus of research (Lee and Schwab, 2005; Ercumen et al., 2015; Galaitsi et al., 2016; World Bank Group, 2017). Our results are in line with contemporary evidence that improved water supplies, protected from organic and inorganic pathogens, is necessary but not sufficient for promoting health; centralized purification measures are relatively ineffective if service and access are inconsistent and vulnerable to regular interruptions or water is contaminated after treatment.

2. London's water system: a brief history

In this section, we briefly review the relevant history of the London water system. The first part of this narrative focuses on water treatment; the central message here is that by 1856, most London households had access to relatively safe piped water from one of the eight metropolitan water companies. The second part of the narrative focuses on the transition from IWS to CWS and shows that this transition was concentrated in the twenty-five year interval between 1875 and 1900, and occurred during a period where other water related interventions were infrequent and less significant than those that occurred before 1860.

Table 1 provides a compact summary of the water treatment and protection strategies adopted by London's eight water companies. As can be seen from the table, four of the eight companies withdrew their water from the River Thames and another three withdrew their water from the River Lee, a major tributary of the Thames. Only one company (Kent) relied on deep wells for its supply. The Thames supplied approximately half of London's water, with the River Lea and groundwater sources providing another quarter each. The two most common strategies to guarantee the purity and safety of river water were to either install filtration systems or move water intakes upstream to prevent sewage from contaminating the supply. Some of London's water companies began investing in water treatment and protection during the early 1800s, before the advent of regulatory mandates. For example, the Chelsea Water Works Company started to filter its water in 1829 and the Lambeth Water Works built a filtration plant in 1841. In 1852, the Lambeth Water Works also moved its water intake upriver and opened a new waterworks at Seething Wells. The Kent Company introduced sand filtration in 1845 but abandoned filtration when it began supplying only groundwater from local wells in 1861.

Although some companies were investing in water treatment on their own, the Metropolis Water Act of 1852 provided further impetus. The Act required all London water companies to follow industry best practice by moving surface water intakes upstream and constructing filtration plants. The Act also stipulated that by 1856 all reservoirs within a five-mile radius of St. Paul's Cathedral had to be covered unless stored water was subsequently filtered and, by December 1855, all surface water had to be filtered and supplied to customers only in covered pipes or aqueducts. All water companies met the targets established by the Metropolis Water Act[7] and, by 1856, customers supplied from the rivers Thames and Lea were receiving filtered water. The next major step in water

[7] For example, in the wake of the Metropolis Act, the Lambeth Company added larger filter beds when it moved its intake upriver, as did the Chelsea Company in 1856. The other three companies supplying water from the river Thames built new filter beds when they moved their intakes upriver in 1855. The East London Company, supplying water from the river Lea, added filter beds in 1854, while the New River Company delivering

purification measures (as opposed to distribution measures such as constant service) did not occur until 1916 with the introduction of chlorination (Jones, 2012: 105–121; Metropolitan Water Board, 1953).

In 1866, cholera broke out in parts of a district served by the East London Company. This outbreak resulted from an illegal decision to connect the company's supply lines to an uncovered reservoir and spurred two investigations into metropolitan water supply. The first investigation, in 1866, focused on assessing the impact of the Metropolis Water Act, 1852. The second, made by a Royal Commission appointed in 1867, assessed higher grounds in England and Wales as potential sources of water in addition to the overall state of water supply in the metropolis. The subsequent report found existing supplies satisfactory in terms of quantity and quality. However, it found that the one area where the companies failed to meet the expectations of the 1852 Act was in regards to frequency of supply (i.e., it was concerned that IWS remained the norm in London) and here it recommended new legislation to compel the introduction and extension of constant service across all London districts.

London officials were promoting CWS as early as the 1840s. This was reflected in both the writings of Chadwick (1842:48) and non-binding legislation passed in 1847, which, in turn, helped prompt the East London Water Company to begin providing CWS to some customers in its district. The Company required the removal of domestic water storage cisterns for those receiving CWS to prevent in-house contamination of water.[8] The goal of constant high-pressure service was restated in the Metropolis Water Act, 1852, but with sufficient caveats that it proved ineffective. Parliament continued to investigate and debate the need for a constant supply of water at high-pressure, culminating in passage of the Metropolis Water Act of 1871. Giving clear legislative mandates, the 1871 Act fostered a commitment to introduce and extend CWS among all eight water companies. As a result, the proportion of houses in London receiving water 24 h a day, 7 days a week, increased from less than 20% in 1871 to almost 100% in 1910.

Genuinely constant service – 24 h, seven days a week – required direct connection to a main or service pipe constantly charged with water at high pressure. Maintaining a constantly high pressure in water pipes prevented the intrusion of contaminated groundwater or water from leaking sewers. However, it increased the risk of waste – in today's language "unaccounted for water" – either in transit or due to inappropriate in-house plumbing. Water providers had legal control over leaks in the network, but almost no control of domestic waste; they could not require homeowners to fix leaks or assure that their plumbing could withstand the high pressure that came with CWS. In this setting, IWS was a second-best solution that gave water providers control over water availability and system pressure, particularly during emergencies such as fires or drought (Hardy, 1991; Hillier, 2014). This was one reason the 1871 Metropolis Water Act was so important: it gave companies greater control to enact and enforce the regulations on household plumbing necessary for CWS to work at a system wide level.

Hence, before committing themselves to CWS and making the requisite investments (which could be sizeable), water companies wanted homeowners to coordinate and make their own investments in improving their household plumbing systems. As early as 1851, Thomas Wicksteed (an engineer for the East London Company) argued that the main barriers to CWS were the companies' lack of power to check houses had appropriate fittings to prevent waste and landlords' unwillingness to pay for necessary plumbing. Reluctance on the part of homeowners and landlords to make these investments persisted well into the 1880s. For example, the 11th annual report of the Local Government Board noted that resistance to the extension of the constant service system came from owners and occupiers reluctant to incur the additional expense (Local Government Board, 1882: cxxiv). In the wake of the 1871 Act, water companies could overcome such reluctance through litigation, though that could be a costly and time-consuming path.[9]

The Grand Junction Company's process for introducing CWS serves to illustrate the underlying coordination problems. For all new houses, the company's inspector determined that pipes and fittings met the regulations and passed approval to the surveyor who connected the house to the company's main. For older houses, changing from intermittent to constant service, owners or occupiers had to remove waste pipes from cisterns, substituting warning pipes and adding cisterns to the lead communication pipes before connecting to the main (Bolton 1881:15). The difficulties facing the Grand Junction Company (as well as other London water companies) increased with the arrival of new housing developments at higher elevations outside the city. Providing CWS to these areas required water delivered at higher pressure. An 1881 Parliamentary investigation led by Frank Bolton, Water Examiner appointed under the 1871 Metropolis Water Act, concluded that the only way to assure such pressure was to give companies greater authority to regulate and enforce rules governing household plumbing and preventing waste of water.[10]

After the Metropolis Water Act of 1871, the two most important legislative measures affecting the provision of public service were the creation of the London County Council (LCC) in 1889 and the Metropolitan Water Board (MWB) in 1902. The LCC had the power to compel water companies to introduce CWS in the older areas of London, where there was greater reluctance to adopt constant

water from the river Lea, and from springs and wells via the New River, added filtration in 1855. The East London Company had abandoned its intake at Old Ford, within tidal reach, in 1834. The New River Company already withdrew water from the river Lea above the tidal reach and stopped withdrawals from the river Thames in 1852. (See Bolton, 1884)

[8] Removing cisterns was thought to provide an additional guarantee against on-site water contamination after the move to CWS. The downside of removing cisterns was that it left customers without water during any interruption of service. After 1876, most companies recommended the retention of cisterns to protect against unforeseen disruption of supply during periods of drought or frost.

[9] In November 1883, the Southwark & Vauxhall Company summoned J. McDonald, landlord and owner of several houses on Orb Street, Newington, to appear before a magistrate for failing to install appropriate plumbing and wasting between 5,000 and 6,000 gallons per day from one house. The judge fined him a surprisingly large sum of £10 on the grounds that "it was highly necessary the work of introducing the constant supply should be carried out." "At LAMBETH, Mr. J. M'DONALD, owner of several houses." *Times* [London, England] 6 Nov. 1883: 3. The Times Digital Archive. Web. 24 Apr. 2018.

[10] The use of Deacon's Waste-Water Meter after 1875 allowed companies switching from IWS to CWS to identify system leaks and replace or repair pipes.

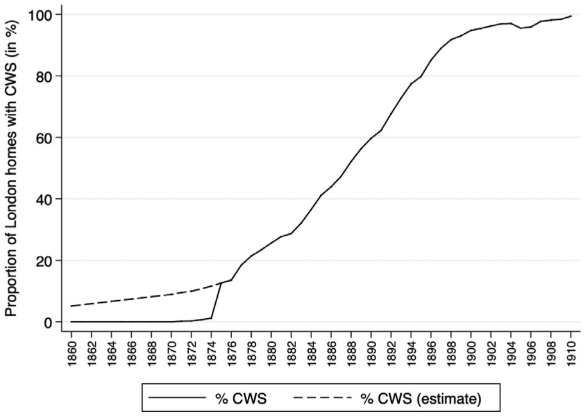

Fig. 1. Proportion of London homes with CWS, 1860–1910.
The dashed line provides an estimate for CWS, calculated using linear interpolation between 1847 and 1875. Only the East London Water Company rolled out CWS during this period.
Sources: *Annual Reports of the Local Government Board, 1876–1910.*

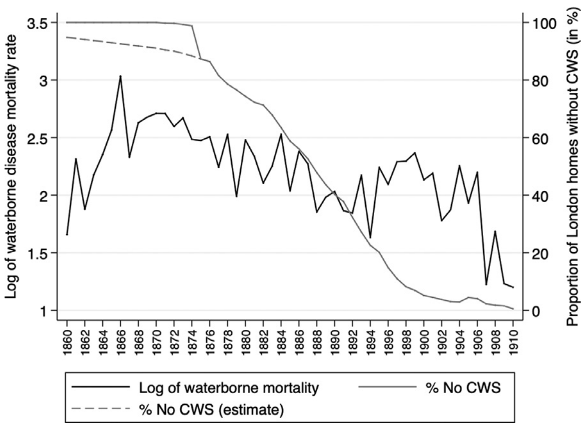

Fig. 2. Proportion of homes without CWS and waterborne disease mortality.
Sources: *Registrar General's Annual Reports for 1860–1910* (23rd-73rd; 1862–1912) corrected by Graham Mooney, The Johns Hopkins University; *Census of England and Wales* for 1861–1911; *Annual Reports of the Local Government Board*, 1876–1910.

service. This measure, however, appears to have done little more than nudge companies to continue a trend that began after the 1871 measure. This can be seen in Fig. 1, which plots the proportion of London homes on CWS from 1860 to 1910.[11] In 1904, the MWB took over management of London's eight water companies. The MWB completed the transition from IWS to CWS, particularly for houses in South London districts supplied by the Lambeth Company - the one company with less than 95% of houses on constant service in 1904.[12] By 1910, fewer than one percent of houses did not receive their water directly from the mains with constant service.

3. Constant service and waterborne diseases

The central question we ask here is if the extension of CWS between 1860 and 1910 reduced waterborne disease rates. Motivating our analysis, Fig. 2 plots the natural log of the death rate from all waterborne diseases (typhoid, cholera, diarrhea, and dysentery) in London against the proportion of all homes in the metropolis without CWS, so still receiving water intermittently. The graph reveals three patterns. First, CWS expands rapidly in the wake of the 1871 Metropolis Water Act and slows after 1898 as near universal service is reached. Second, waterborne disease rates are rising in the years before the Metropolis Water Act and the onset of more

[11] Data on the number and percentage of houses supplied with CWS by each water company are taken from the *Annual Reports of the Local Government Board* starting in 1876.

[12] The percentage of houses on constant service for the New River Company experiences a small drop in 1905 after MWB acquisition but returns to more than 98% within two years. This is a result of the expansion of 'water London' to include Tottenham and Enfield under the MWB and to our method of calculating CWS coverage using company totals (Metropolitan Water Board, 1953: 356).

Fig. 3. Composite London health districts.
Sources: Graham Mooney, The Johns Hopkins University; Great Britain Historical GIS Project.

rapid growth in CWS. Third, aside from the sudden dip in mortality after 1905, waterborne disease rates stop falling after 1895 and the slowdown in the expansion of constant service once near universal access is reached. Between 1871 and 1894, waterborne disease mortality was halved as the proportion of London households with CWS increased from less than 20% to 80%.[13]

London refers to the Registration County of London as defined by the census administration for the censuses of 1851–1911, comprising those parts of Middlesex, Kent, and Surrey that became the County of London in 1889 (Schürer and Day, 2019). While the boundaries of the Registration County of London remained the same between 1851 and 1911, the internal district boundaries did not. London had 36 registration districts in 1861, 28 in 1871, and 29 in 1881 and 1891. After the creation of the County of London, this was reduced to 29 administrative districts for the 1901 and 1911 censuses. To address this boundary change issue, we have followed Mooney et al. (1999) and created 19 composite health districts with time consistent borders.[14] These health districts are depicted in the map in Fig. 3.

In the analysis that follows, we use district-level data for these 19 health districts to explore the possibility that the correlations between IWS and mortality observed in Fig. 2 reflect a causal relationship. Each health district was served by one or more of London's eight water companies and varied both in terms of the evolution of their waterborne disease rates over time and the pace at which they introduced constant service. We exploit this variation in disease and access to CWS across both districts and time to estimate the causal impact of extending CWS on mortality.[15]

Our full analysis focuses on the years from 1860 to 1910. Ideally, we would have direct counts of the number of households with CWS (i.e., receiving water 24 h a day, 7 days a week) across districts and over time. Unfortunately, those data do not exist. Instead, we estimate the proportion of homes in every district with CWS by building up from company level data on the following: (1) the number of households served by each company with CWS; and (2) market penetration for each company at the district level. As briefly alluded to above, before 1904, eight private companies supplied water through their own networks, and this division of water infrastructure continued after 1904, during the first few years of management by the Metropolitan Water Board. These eight

[13] The increase in water-related deaths between 1895 and 1900 may be attributable to drought years and temporary reversion to IWS by the East London Company from 15 July-18 October 1895, 17 July-19 September 1896, and 23 August-7 December 1898 (London Metropolitan Archives, ACC/2558/MW/C/15/25). The heatwave itself may have altered the disease environment and contributed to this increase in mortality (Hanlon, et al. 2021: 44). There is evidence of food-borne typhoid from oysters and other shellfish during the late 1800s and shellfish regulation explains some of the steep drop in mortality after 1905 (Hardy, 2014).

[14] Mortality data kindly provided by Graham Mooney included codes for the creation of these composite health districts. Eight composite districts correspond with census districts through our period (Bethnal Green, Camberwell, Hampstead, Islington, Marylebone, Poplar and Shoreditch). For a full list showing how census districts map to our composite health districts, see Appendix A.

[15] Appendix Fig. B1 reproduces Fig. 2 for each health district.

Table 2
Percent of London's 19 composite health districts supplied by each water company.

Health District \ Company	Chelsea	East London	Grand Junction	Kent	Lambeth	New River	Southwark & Vauxhall	West Middlesex
Bermondsey				4	1		95	
Bethnal Green		100						
Camberwell				12	21		67	
Greenwich		1		86	11		2	
Hackney			60			40		
Hampstead						19		81
Holborn						100		
Islington						100		
Kensington	30		29.5					40.5
Lambeth					63		37	
London City		1.5				98.5		
Marylebone			9					91
Pancras						85		15
Poplar		100						
Shoreditch		25				75		
Southwark					52		48	
Stepney		97				3		
Wandsworth					34		66	
Westminster	58		24			18		

Source: *First Annual Report of the Metropolitan Water Board, 1905*.
Each row represents a composite health district and the numbers in each cell represent the percent of that district supplied by the water company named in the column heading. All rows sum to 100.

companies had statutory approval to supply certain parishes, often with more than one company supplying parts of the same district. Of our 19 health districts, four received water from one company, ten from two companies, four from three companies, and only Greenwich received water through four distinct networks.[16]

We know the population supplied by each water company within each registration district in 1904. These data are from Appendix A of the *First Annual Report of the Metropolitan Water Board* (Metropolitan Water Board, 1905: 17–29). We use these data to estimate the population share connected to each water company's network in those districts supplied by more than one company. The estimates are reported in Table 2. We treat these proportions as fixed over time, in part because the statutory boundaries of the water companies did not change. Concerns about our fixed share assumption may arise for two reasons: 1) demolition of houses within central districts reducing population supplied by one company more than another, and 2) construction of new houses in peripheral districts increasing one company's population share. Most housing demolition during our period was related to railway construction, with a relatively small proportion due to slum removal (Yelling, 1986). Both reduced overall district population, with five composite districts seeing some population decline between 1860 and 1910 (see Appendix Fig. A1 for graphs of composite district population). Two districts experiencing the largest population decline, London City and Holborn, were supplied by only one company. For the other three – Westminster, Marylebone, and Shoreditch – there is no evidence that housing demolition was concentrated so heavily in one company's part of a district to have introduced changes in population shares.[17] In rapidly expanding districts on the periphery all companies continued to expand their networks and there is little evidence that one company expanded more than proportionately in response to new customer demand. Kensington is the one possible exception. This rapidly growing district was served by three companies, the Chelsea, Grand Junction and West Middlesex, so may have seen a change in the share served by each company between 1860 and 1904. Customer data for 1866 (Farr, 1868): 273) and 1904 (First Annual Report of the Metropolitan Water Board, 1905), shows that all three companies expanded their network, but the Chelsea Company grew by only 50% while the other two more than doubled their number of customers. This means our value of 30% may understate the share of the Kensington district supplied by the Chelsea Company early in our period. However, the Chelsea Company did not introduce CWS until late and was the last to exceed 20% CWS coverage so any understatement of the company's population share should not cause us to underestimate CWS coverage in the district.

To determine the annual variation in CWS, we gathered data on constant service for each company from the *Annual Reports of the Local Government Board* (LGB). The LGB annual reports give the number and percentage of houses on CWS and the total number of houses supplied by each company for every year between 1876 and 1906. After 1906, the reports provide updates for those companies not yet providing CWS throughout their network. Only the East London Company provided CWS to a significant number of households before 1875. The company had introduced constant service early, connecting 1.3% of its customers to the main in 1847, and had over 50% of customers on the mains in 1875. Unfortunately, we do not know the rate at which the East London Company expanded

[16] In some cases, the statutory boundaries overlapped and either two companies supplied the same parish or they reached boundary agreements (Local Government Board, 1891: 325). For a full list of parishes each company was authorized to supply, see Metropolitan Water Board, 1908: 92-111.

[17] Following slum removal schemes in the last quarter of the nineteenth century, most tenants of demolished homes moved only short distances remaining within the same district (Yelling 1986).

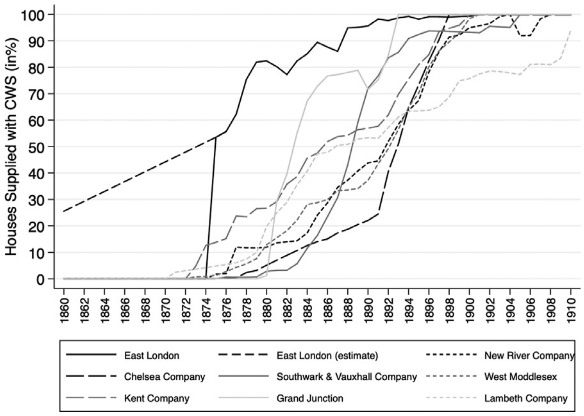

Fig. 4. Percent of houses supplied by each company on CWS, 1860–1910.
The dashed line provides an estimate for CWS for the East London Company, calculated using linear interpolation between 1847 and 1875.
Sources: *Annual Reports of the Local Government Board*, 1876–1910.

CWS across its network between 1847 and 1875, so we produce two CWS measures. The first assumes a constant annual growth rate between 1847 and 1875. The other ignores the 1847 data and assumes a more discrete introduction of CWS in 1875. The correct measure probably lies between the two. By 1904, all except the Lambeth Company had over 95% of customers receiving CWS. By 1910, every Metropolitan Water Board customer, except a few at high elevation in the district previously supplied by the Lambeth Company, received water 24 h a day. Fig. 4 plots the proportion of households served by each company with CWS over time.

We combine the data on water company penetration at the district level (Table 2) and the company level data on CWS (Fig. 4) to estimate district-level measures of the proportion of homes with access to CWS. To do this, we multiply the share of a composite health district supplied by each company by the percentage of the population supplied by that company on CWS. Generally, our measures of CWS for any district i in year t can be written as,

$$DistrictCWS_{it} = \sum_{k=1}^{n} \theta_{ik} \cdot \left(CompanyCWS_{kt}\right)$$

where, n is the number of companies providing water to district i, θ_{ik} is the proportion of the population in district i that is consuming water supplied by company k, and $CompanyCWS_{kt}$ is the proportion of water company k's customers who enjoy CWS in year t.[18] By this measure, all time-series variation in district level CWS is derived from company level changes in the number of customers with CWS.

Fig. 5 shows the variation in CWS across districts over time (5–1 assumes discrete intervention by the East London Company in 1875; 5–2 uses linear interpolation from 1847 to 1875). While all districts exhibit increases in access to CWS after the Metropolis Water Act of 1871, there is meaningful cross-district variation in both rate of increase and the magnitude of the increase. Some districts (e.g., Bermondsey and London City) concentrate the roll out of CWS over a short window of only a few years, while other districts spread out the introduction of CWS over many years (e.g., Greenwich, Islington, and Southwark) or even decades (Hackney, Shoreditch, and Stepney). Districts also vary in terms of the magnitude of the increase in access to CWS because districts supplied by the East London Company (e.g., Bethnal Green and Poplar) either see a large increase in CWS in 1875 or begin the study period with relatively high levels of initial access to CWS. By 1910, all districts, except a few with customers on the old Lambeth Company network, have made the transition to CWS.

In our formal empirical analysis, we identify the impact of CWS after controlling for district and year fixed effects, district-specific time trends, and other potential confounding factors. There are two keys to the analysis. First, the extent to which districts differ in the pace, timing, and magnitude at which they introduce CWS, as demonstrated in Fig. 5. Second is the extent to which we can treat these differences as randomly assigned.

As explained above, the rate at which companies moved towards CWS was determined partly by the willingness of customers to install appropriate plumbing and partly by a company's installing pipes able to withstand the pressure. The inter-district variation observed in Fig. 5 was therefore driven by idiosyncratic delays in the negotiation process between companies and property owners. Requests to convert to CWS were made at the parish, vestry or neighborhood level so not every part of a district, or even a parish, made the transition simultaneously. Following the 1871 Metropolis Water Act, companies initiating a conversion to CWS were required

[18] Consider, for example, our measure of district CWS (*DistrictCWS*) for the district of Camberwell. Camberwell was served by three companies: Kent, Lambeth, and Southwark & Vauxhall. Given the levels of market penetration for each of these companies, we calculate the level of CWS in the Camberwell district as follows: $DistrictCWS\text{-}Camberwell = 0.13\,(Kent)_t + 0.2\,(Lambeth)_t + 0.67\,(Southwark\&Vauxhall)_t$. *Kent* is the percentage of Kent water company customers on CWS in year t, and 0.13 is the percentage of the population of Camberwell supplied by the Kent Company; *Lambeth* is the percentage of Lambeth water company customers on CWS and 0.2 is the percentage of the population of Camberwell supplied by the Lambeth Company; and so on for the Southwark & Vauxhall company.

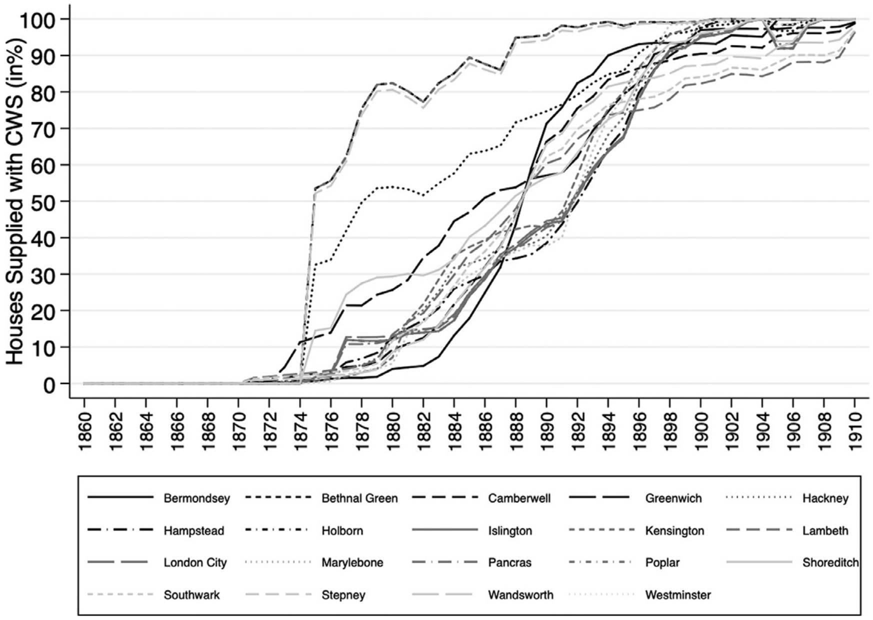

Fig. 5. (1): Percent of houses in each composite health district with CWS, 1860–1910.
(2): Percent of houses in each composite health district , 1860–1910, with estimated CWS before 1875.
Sources: *Annual Reports of the Local Government Board, 1876–1910;* Appendix A of the *First Annual Report of the Metropolitan Water Board* (Board, 1905).

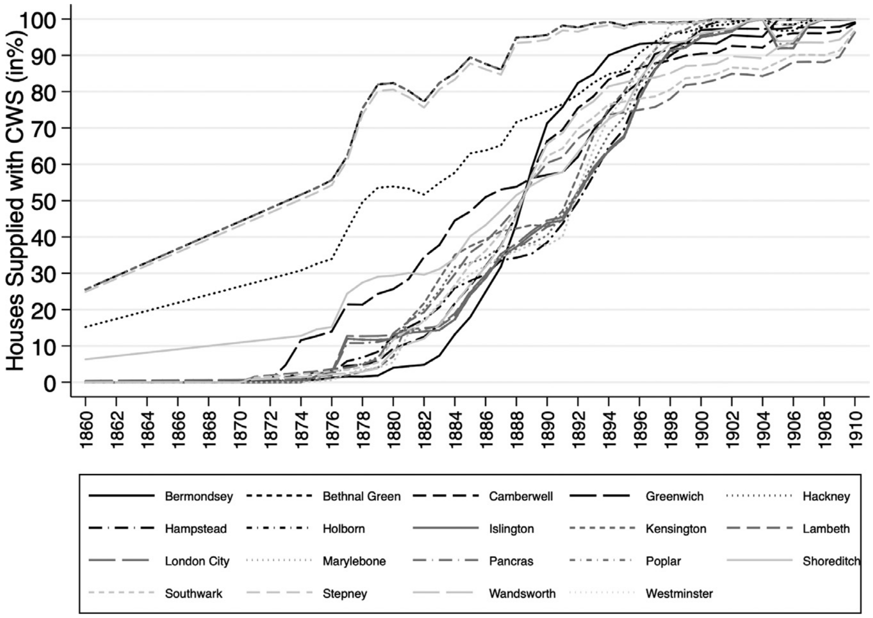

Fig. 5. Continued

to publish their intention at least three months in advance to give all customers affected time to install appropriate plumbing. Advertisements in *The London Gazette* show that company-initiated transitions to CWS within the same district took place over multiple years. For example, the New River Company announced its intention to transition parts of St. Pancras to CWS in 1883, 1884, 1885, 1886 and 1887, though even by 1887 only parts of St. Pancras had made the transition (Hardy 1991: 87).[19] For customer initiated

[19] These announcements appeared in *The London Gazette* on 16 November 1883 (issue 25288, page 5444); 11 July 1884 (issue 25375, page 3183); 7 October 1884 (issue 25402, page 4375); 3 April 1885 (issue 25457, page 1541); 16 April 1886 (issue 25578, page 1845); and 11 March 1887 (issue 25682, page 1462).

Table 3
CWS, poverty, and district demographics.

Dependent Variable: CWS	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Poverty index	0.684***									
	(0.0629)									
Time trend * Poverty index	−0.716***									
	(0.0672)									
Log(population)		−0.0340*								
		(0.0192)								
Female ratio			−1.024							
			(1.383)							
Female ratio (ages 15–30)				−2.761***						
				(0.647)						
Foreign-born ratio					−3.618***					
					(0.252)					
Age: under 5						−17.28***				
						(1.348)				
Age: 5–14							−6.564***			
							(0.628)			
Age: 15–24								−9.257***		
								(1.179)		
Age: 25–44									6.455***	
									(0.608)	
Age: 45–64										12.80***
										(0.891)
Observations	665	665	665	665	665	665	665	665	665	665
R-squared	0.819	0.907	0.907	0.910	0.922	0.925	0.920	0.919	0.923	0.928
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
District FE		Y	Y	Y	Y	Y	Y	Y	Y	Y

Sources: Constant service data comes from the *Annual Reports of the Local Government Board* and Appendix A of the *First Annual Report of the Metropolitan Water Board*. Poverty data was provided by Scott Orford and is described in Orford et al. (2002). Demographic data comes from the censuses for 1861–1911.
Robust standard errors in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$).

requests, Hillier (2014: 232–3) argues that homeowners varied in their enthusiasm for modernization and some parish councils resisted constant service due to cost, disruption, or its perception as an imposition of central power on local governments.[20,21]

Willingness to convert to CWS might be expected to correlate with customer wealth, either because wealthier customers were more likely to own their own home so avoid any principal-agent problem or because companies supplying wealthier districts would have expected customers to pay the cost of installing appropriate plumbing. This raises a concern that customer wealth will confound with CWS' effect on mortality because wealthier people would have had better access to health services so be less likely to die from digestive diseases. As a result of stronger support for CWS by the East London Company, however, some poor East London districts were the first to convert and this resulted in a negative metropolis-wide relationship between the expansion of CWS and wealth. To confirm this relationship between CWS and district wealth, we calculate a poverty index measure for 18 of our 19 composite health districts (all except Woolwich) using a version of Charles Booth's geographic, household-level, measure of social class in London in 1896, digitized and georeferenced by Orford et al. (2002).[22] Using OLS, we regress our measure of district level CWS on this poverty index, the interaction between the poverty index and a time trend, plus year fixed effects. Column 1 of Table 3 reports the results.

Early expansion of CWS in the East London districts of Stepney and Poplar, as shown in Fig. 5, meant poorer neighborhoods were first to receive a constant supply of water.[23] Table 3 reinforces this, showing that districts with a less wealthy population on average were more likely to have converted from IWS to CWS.[24] The negative coefficient on the time-trend and poverty index interaction term shows that the relationship between poverty and CWS diminished over time as all districts moved towards universal CWS. Therefore,

[20] Fittings for constant service cost approximately £8 in the 1860s (Hillier 2011: 47), although they had fallen to £5 by the late 1880s (Hardy, 1991: 78). Using the measuringworth.com purchasing power calculator, that translates to approximately £500 today.

[21] In Appendix C, we calculate a counter-factual measure of CWS that assumes each company systematically extends constant service starting with its largest district. The results are much weaker with a smaller coefficient and lower significance.

[22] We used the same methodology as employed in Orford at al. (2002). This approach converts Booth's seven classes into five classes that correspond with the Registrar General's five social classes; a higher index number represents greater poverty. The coverage of Booth's poverty map is less extensive than the geography of London so some districts have poverty data only for the edge of the district closest to central London.

[23] William Booth Bryan, engineer to the East London Company confirmed this in his testimony before the 1892 Royal Commission on Metropolitan Water Supply stating that the approximately 2,000 houses not on constant service were in the wealthiest part of the company's district in Buckhurst Hill and Woodford.

[24] In his 1884 report, Frank Bolton was quite critical of some wealthier residents with IWS who placed cisterns on the top floors of their house to increase water pressure, putting them out of sight and making them more difficult to clean (Bolton 1884).

we believe that district wealth does not challenge the impact of CWS on mortality even though we cannot use our time-invariant measure of poverty in our empirical analysis because it will be absorbed by our district fixed effects.

Willingness to connect to CWS might be influenced by other demographic characteristics of a district. Districts with a larger share of females may see greater support for CWS as women were more likely to use water within the home for cooking and laundry, although districts with more live-in servants (typically females age 15–30) may place less value on a constant high-pressure supply. Because local agreement on upgrading plumbing was necessary for the transition to CWS, districts with more foreign-born residents might be less likely to install CWS. Columns 2–10 of Table 3 show the relationship between CWS and district demographics and we use these as control variables in our subsequent analysis.

4. Empirical strategy

We use a generalized difference-in-differences (DD) approach to study the extent to which exogenous improvements in water quality, due to a neighborhood switch from IWS to CWS, impacts waterborne disease mortality within a district. Our baseline model is:

$$mort_{it} = \alpha + \beta DistrictCWS_{it} + \boldsymbol{X'}_{it}\delta + \lambda_t + \eta_i + \gamma_{it} + \varepsilon_{it}$$

where $mort_{it}$ is the natural log of deaths per 10,000 from all waterborne diseases (cholera, typhoid, diarrhea, and dysentery) for district *i* in year *t*. $DistrictCWS_{it}$ is the estimated proportion of homes in district *i* in year *t* that receive CWS; $\boldsymbol{X}_{it}$ represents a vector of control variables; λ_t, η_i, and γ_{it} represent year fixed-effects, district fixed-effects, and linear district-year trends; and ε is a random error term. We estimate this model using ordinary least squares (OLS) with district-level mortality data for the period 1860–1910. Graham Mooney provided the mortality data from the *Registrar General's Annual Reports for 1860–1910* (23rd-73rd; 1862–1912) but corrected for hospital deaths.[25] For nineteenth-century London, official mortality statistics are often distorted by a failure to return hospital and workhouse deaths to a person's home district (Mooney et al., 1999; Hardy 1993). Such misallocation of deaths in institutions could be high depending on the institution, district, and cause of death (Mooney et al., 1999: 239–241). Mooney's corrected data allows us to improve upon other studies using raw data for London during the nineteenth century. The control variables in $\boldsymbol{X}_{it}$ include measures of population and district demographics (female ratio, foreign-born ratio, and age categories: under 5, 5–14, 15–24, 25–44, 45–64 and over 65). Summary statistics for all variables are available in Appendix Table A2.[26]

The key identifying assumption for any DD approach is the parallel counterfactual trend assumption. The usual approach to test the validity of this assumption is to plot the outcome by treatment and control groups for the pre-treatment period. One difficulty we face in conducting such test is that our treatment (CWS) is a continuous measure with staggered timing, so we cannot easily define a control group or pre-treatment period. However, using our measure of CWS without estimated values for the East London Company, no district receives any CWS from 1860 to 1870 so we can use this as the pre-treatment period.[27] In an ideal case, we would also have a group of untreated districts with 0% CWS for our entire study period, but because all districts implement CWS, we do not. To solve this issue, we divide the districts into two groups - early adopters and late adopters - based on treatment timing,[28] and then compare the pre-treatment trends for waterborne disease mortality between these two groups.[29] Fig. 6 shows the average waterborne disease mortality rate among early adopters and late adopters from 1860 to 1870. The two groups generally follow a parallel trend and have similar waterborne disease mortality rates, which reduces our concern that confounding effects drive the reduction in waterborne disease mortality during our period of CWS expansion.

In addition to Fig. 6, we conducted a balance check on available mortality measures for the pre-treatment period (see Appendix Table A3). None of our mortality variables have a significant difference between early adopters and late adopters, which further supports our identifying assumption of parallel trends prior to CWS expansion.

5. Results

Regression results for our core model are presented in Table 4. Panel 1 reports results using our measure of CWS with a discrete jump in 1875 and panel 2 reports results using our estimated CWS coverage. All regressions include year and district fixed effects. We report robust standard errors and wild bootstrap *p*-values. We have too few districts to use clustered standard errors without correction

[25] The Registrar General reports have data on total and infant mortality by sub-district and by age and cause of death for some years. However, consistent time series data by cause of death is not available at a lower geographic level than district.

[26] Data and do-files to replicate all analysis in this paper are available at Open-ICPSR (Tynan and Yang, 2021).

[27] Since we do not have data for waterborne disease mortality before 1860, we are only able to use the 11 years from 1860 to 1870 for our pre-treatment period.

[28] We use 50% of CWS as the cutoff point, so districts who reach 50% of CWS in earlier years will be considered as early adopters. As shown in Fig. 5, there are clusters of districts above and below 50% CWS between 1888 and 1890, so we define early adopters as districts with 50% CWS coverage before 1888 and late adopters as districts achieving 50% CWS after 1888. This makes 11 districts early adopters and 8 districts late adopters.

[29] The idea of early vs. late adopters is borrowed from Goodman-Bacon (2018). This paper suggests a balancing test for DD studies with staggered treatment timing. Since our treatment variable is not binary, we cannot directly conduct the recommended test.

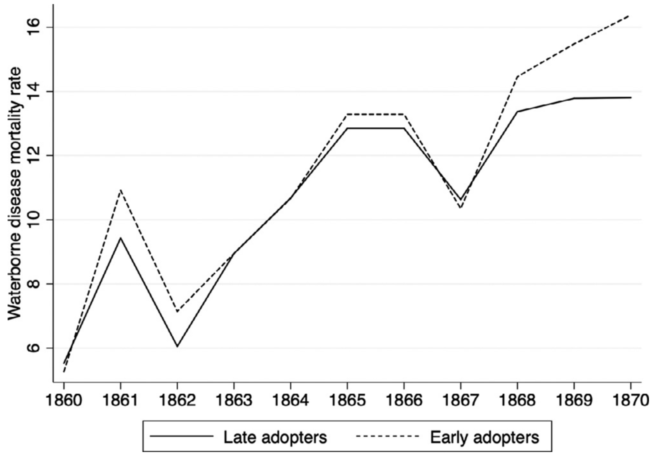

Fig. 6. Average waterborne disease mortality trends during pre-treatment period.
Note: Values for the year 1866 are replaced with values from year 1865 due to the cholera outbreak in 1866.

Table 4
CWS and waterborne disease mortality.

	Log of waterborne mortality						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel 1							
CWS	−0.336***	−0.324***	−0.338***	−0.245***	−0.401***	−0.168**	−0.149***
	(0.0708)	(0.0652)	(0.0707)	(0.0718)	(0.103)	(0.0721)	(0.0544)
	[0]	[0]	[0]	[0.0008]	[0.0003]	[0.0257]	[0.0046]
R-squared	0.809	0.880	0.814	0.867	0.900	0.819	0.885
Panel 2							
CWS (with estimate)	−0.634***	−0.455***	−0.633***	−0.373***	−0.401***	−0.242***	−0.334***
	(0.0714)	(0.0876)	(0.0702)	(0.0897)	(0.103)	(0.0857)	(0.0851)
	[0]	[0]	[0]	[0]	[0]	[0.0049]	[0.0002]
R-squared	0.817	0.881	0.821	0.867	0.900	0.819	0.887
Observations	969	969	969	969	665	836	950
Year FE	Y	Y	Y	Y	Y	Y	Y
District FE	Y	Y	Y	Y	Y	Y	Y
District time trend	N	Y	N	N	N	N	N
Controls	N	N	Log population only	All	All	All	All
Time period	1860–1910	1860–1910	1860–1910	1860–1910	1876–1910	1860–1903	1860–1910 without 1866

Robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1); Wild bootstrap p-values in brackets. Control variables include log of population, female ratio, foreign born population ratio, and age groups.

so, to account for within cluster (district) correlation, we correct the inference with a wild bootstrap method (Cameron et al., 2008) and report wild bootstrap p-values obtained from the *boottest* command in Stata described by Roodman (2015).[30]

Column 1 shows the impact of the move away from IWS on our measure of waterborne disease mortality. The coefficient on CWS is statistically significant at the 1% level and shows that a one percentage point increase in the population of a district receiving water 24 h a day, 7 days a week, reduced waterborne disease mortality in the district by 0.3–0.6%.[31]

Column 2 adds a district specific time trend. This slightly lowers the impact of a one percentage point increase in CWS on waterborne disease mortality, but it remains highly significant. Column 3 adds log population to the baseline regression while column 4 adds all our demographic variables, addressing concerns that in-migration to districts with CWS by a healthier population changed the underlying health status of a district at the same time companies expanded CWS. CWS remains significant, with only a small decline in the coefficient when we add all controls, addressing concerns that the decline in waterborne disease mortality might be due to demographic changes. The results in column 4 imply that an expansion of CWS from less than 20% to 100% of the population explains between 20% and 30% of the reduction in waterborne disease mortality between 1875 and 1910. During this

[30] We also computed standard errors that correct for spatial correlation, serial correlation and heteroskedasticity using code developed by Solomon Hsiang (Hsiang, 2010). The spatial correlation used weights of 1.6 km and 3.5 km to capture the proximity of small, central London districts but a greater distance between the centroids of larger districts on the periphery. The results are very similar to those reported here.

[31] Using typhoid alone gives similar results but with a smaller coefficient and lower significance. This makes sense given our transmission mechanism through pipe infiltration and water contamination during storage, compared to studies focusing on large-scale transmission of the typhoid bacteria throughout a city. Results are available upon request.

Table 5
CWS and waterborne disease mortality.

	Log of waterborne mortality								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
CWS (with estimate)	−0.306***	−0.234***	−0.226**	−0.197*	−0.185*	−0.258**	−0.395**	−0.222**	−0.199
	(0.0833)	(0.0904)	(0.0877)	(0.108)	(0.0975)	(0.104)	(0.157)	(0.0903)	(0.123)
	[0.0007]	[0.011]	[0.011]	[0.0675]	[0.0647]	[0.0141]	[0.0108]	[0.016]	[0.1132]
R-squared	0.816	0.875	0.860	0.887	0.863	0.871	0.886	0.856	0.868
Observations	570	570	570	570	513	361	247	475	361
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
District FE	Y	Y	Y	Y	Y	Y	Y	Y	Y
District time trend	N	Y	N	Y	N	N	N	N	N
Controls	N	N	All	All	All	All	All	All	All
Time period	1871–1900	1871–1900	1871–1900	1871–1900	1871–1900	1882–1900	1882–1894	1876–1900	1876–1894
Missing years					1895/1896/1898				

Robust standard errors in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$); Wild bootstrap p-values in brackets. Control variables include log of population, female ratio, foreign born population ratio, and age groups.

period waterborne deaths fell from 12 to less than 4 deaths per 10,000, meaning the transition from IWS to CWS saved over 1000 lives a year by 1910.

As robustness checks, we add columns 5 and 6, which repeat the regression in column 4 for two different time periods. To remove concerns about inaccurate data on CWS coverage, column 4 starts in 1876, the year when all companies start to report the share of their customers on constant service. Removing the early years also addresses concerns about lower quality reporting of cause of death prior to the distinction between typhoid and typhus in 1869.[32] To avoid any unobserved effect of the introduction of the Metropolitan Water Board on mortality, we add column 6, which ends in 1903, just before the transfer of water supply to the Metropolitan Water Board. Finally, column 7 repeats column 4 but excludes the cholera epidemic year of 1866. When we restrict our time period to 1860–1903 or exclude 1866, the impact of a one percentage point increase in CWS on waterborne disease mortality falls to around 0.2%. Otherwise, the results are similar to our preferred regression in column 4.

6. Sensitivity analysis

6.1. Narrowing the window

Our baseline analysis covered the whole period 1860–1910 to fully capture the impact of the long transition from intermittent to constant water supply. Table 4, columns 5 and 6, narrowed the window to begin with the publication of CWS data in the annual reports of the Local Government Board and to end with the transfer of London's water infrastructure to the Metropolitan Water Board. In Table 5 we report results for different time periods during which most expansion of CWS took place and that account for other possible concerns relating to our choice of years.[33]

Columns 1–4 report results starting in 1871, the year the Metropolis Water Act was passed into law and two years after separate reporting of typhoid and typhus deaths. Because the transition to CWS was nearly complete by the end of the nineteenth century, and slum clearance takes off in the 20th century, we end the period in 1900. The results in columns 1–4 confirm that CWS played an important role in reducing waterborne disease mortality in London. While the coefficients are smaller than those in Table 4, with the impact of a one percentage point increase in CWS on waterborne disease mortality falling to closer to 0.2%, CWS remains significant.

As noted above, the East London Company temporarily reverted to IWS in some neighborhoods during the summer of 1895, 1896 and 1898. This means our measure of CWS for districts supplied by the company may be overstated for these years; results in column 5 exclude them. The droughts that diminished the East London Company's water supply were a result of heatwaves in London during the late 1890s. Recent research has shown that these heatwaves may have changed London's disease environment in ways that increased digestive disease mortality (Hanlon et al., 2021).[34] Columns 7 and 9 show results for a period ending in 1894, before the drought years and temporary reversion to IWS. Columns 6–9 also narrow the window to focus on the period after 1876, when the Local Government Board started reporting annual CWS data, and after 1882, during which most expansion of CWS took place.

[32] In addition to this explicit reporting change, typhoid was often mistaken for other diseases, but diagnosis became more accurate over time (Ferrie and Troesken, 2008: 6).

[33] We use only our measure of CWS with estimated coverage by the East London Company because both measures are the same after 1875. Including a short period of four years without CWS coverage and then a large jump, forces those districts to get more weight due to their higher treatment variance (Goodman-Bacon 2019: 9). This resulted in slightly lower coefficients and significance for regressions starting in 1871. Results available upon request.

[34] Hanlonet al., (2020) argue that hot summers after 1894 likely slowed the reduction in infant mortality by five years. Although diarrhea is an important cause of infant death and a number of studies have shown that improvements in water quality and sanitation have reduced infant mortality (e.g., Knutsen 2015; Alsan and Goldin, 2019), the climate impacts present a challenge for our analysis. Nevertheless, we show results using infant mortality as our dependent variable in Appendix B.

Table 6
CWS and waterborne disease deaths.

	Waterborne Deaths						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel 1							
CWS	−83.51**	−81.60**	−85.04**	−108.7**	−102.2***	−89.61*	−35.71***
	(39.66)	(38.82)	(39.10)	(48.73)	(18.49)	(49.74)	(12.19)
	[0.01]	[0.0166]	[0.0077]	[0.0021]	[0]	[0.0397]	[0.0034]
R-squared	0.629	0.699	0.671	0.687	0.897	0.671	0.879
Panel 2							
CWS (with estimate)	−34.92*	−105.3**	−34.51**	−128.7***	−102.2***	−90.40	−80.46***
	(19.28)	(49.43)	(17.49)	(49.67)	(18.49)	(56.93)	(17.99)
	[0.0518]	[0.0216]	[0.0365]	[0.0002]	[0]	[0.0779]	[0]
R-squared	0.626	0.699	0.668	0.686	0.897	0.669	0.881
Observations	969	969	969	969	665	836	950
Year FE	Y	Y	Y	Y	Y	Y	Y
District FE	Y	Y	Y	Y	Y	Y	Y
District time trend	N	Y	N	N	N	N	N
Controls	N	N	Log population only	All	All	All	All
Time period	1860–1910	1860–1910	1860–1910	1860–1910	1876–1910	1860–1903	1860–1910 without 1866

Robust standard errors in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$); Wild bootstrap p-values in brackets. Control variables include log of population, female ratio, foreign born population ratio, and age groups.

Although the shorter time periods result in less variation and reduce the ability of later adopters to act as controls, constant service remains significant in most specifications, providing strong support for our thesis that CWS played in important role in reducing deaths from waterborne disease.

6.2. Addressing concerns about population

Any study using a log mortality rate measure and interpolated population data faces concerns that migration undermines the implicit assumption that mortality and population scale at the same rate (Arthi et al., 2020). This could result from migration to treated districts, particularly if migrants differ from the underlying population or if migration creates congestion that impacts other determinants of health. We have reason to believe that such concerns about migration between London districts during late nineteenth century are unlikely to impact our results. District level wealth is highly persistent, changing little between the late 1800s and 1991, and there is no evidence to suggest shifts in the geography of poverty during our time period (Orford et al., 2002). Slum clearance was limited until the early 20th century, resulting mostly from rail or road construction, and accelerated only slowly after the Housing of the Working Classes Act of 1890. Most people who moved as a result of housing destruction before 1900 remained within the same district, often increasing crowding in remaining buildings (Yelling, 1986; Hobhouse, 1994). Most population increase in peripheral districts was in-migration to London from outside the metropolis and our demographic control variables address the possibility that new residents were healthier adults more resilient to waterborne disease.

Nevertheless, our mortality measures are rates that rely on census population data and interpolation between census years. There might be concerns that this hides annual population changes. To address this, we repeat our regressions from Table 4 using waterborne disease deaths as our dependent variable. The results are presented in Table 6. Using disease deaths rather than mortality rates does not change the results. CWS remains highly significant in all specifications. London districts with more people receiving reliable, high-pressure, water delivery 24 h a day, 7 days a week, reported lower deaths from waterborne diseases than those with lower rates of CWS.[35,36]

6.3. Thresholds in the transition to CWS

Intermittent water supply allowed for local contamination of previously treated water through pipe infiltration or water sitting in uncovered cisterns. Transitioning a neighborhood to constant service removed these sources of local contamination, reducing the spread of waterborne disease. In testing this connection, we use a continuous measure of CWS coverage; our CWS coefficient shows the impact of a one percentage point increase in CWS whether that takes a district from zero to 1% or from 99% to 100%. If transitions to CWS generated positive neighborhood spillovers or there were negative spillovers from neighborhoods remaining on IWS, there may be threshold levels of CWS coverage that were required to reduce mortality. To test this, we divide our continuous measure into bins for each 10% increase in CWS coverage, with a baseline of 0–10% of the population in a district receiving water constantly under pressure.

[35] To check that our log transformation is not overly influencing the results, Appendix Table B2 gives results using the waterborne disease mortality rate as our dependent variable. CWS remains negative and significant in all specifications.

[36] To address concerns that measurement error may be systematically related to district size, we weighted regressions by population. The results were not substantially different.

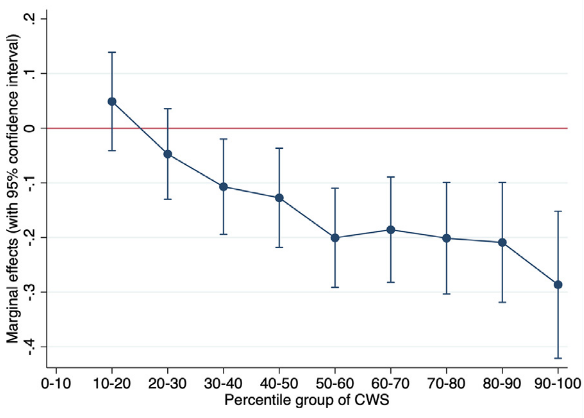

Fig. 7. Marginal effects of each 10% increase in CWS coverage.
The figure shows the marginal effects of percentile increases in CWS coverage with 95% confidence intervals.
Sources: *Registrar General's Annual Reports for 1860–1910* (23rd–73rd; 1862–1912) corrected by Graham Mooney, The Johns Hopkins University; *Annual Reports of the Local Government Board*, 1876–1910.

Fig. 7 plots the resulting coefficients and standard errors using our baseline model with year and district fixed effects and controls for population density and district demographics. It shows the marginal effect of moving another 10% of a district from intermittent to constant service. The results suggest that our baseline continuous model is reasonable, although most impact is achieved by the time 60% of a district has transitioned to CWS, with an additional gain from universal coverage.[37] The non-linearity between 60% and 90% suggests there may be some positive spillovers from CWS either within or between districts.

6.4. Broader health effects and placebo tests

Between 1875 and 1910, the overall mortality rate in London fell approximately 40% - from 240 to 140 deaths per 10,000 people. The expansion of CWS likely contributed to this decline not just through the reduction in waterborne disease deaths, but also through health spillovers including a possible reduction in deaths from sequella to typhoid fever (Ferrie and Troesken 2008: 7–8). Contemporary literature on water-washed or water-related diseases focuses on roundworm, hookworm, conjunctivitis, scabies and other infections found in developing country or refugee settings but recent evidence suggests that handwashing also reduces the risk of acute respiratory infections (Cairncross 2003).[38] For late 19th century London, the increased availability and reliability of water likely resulted in more frequent handwashing and improvements in the broader sanitary environment, contributing to a reduced transmission of a number of non-waterborne diseases. This is one reason that identifying a good disease as a placebo test of the impact of CWS on mortality is not easy.

Despite these co-benefits of CWS expansion, an overall reduction in district-level deaths is unlikely to have occurred contemporaneously with CWS roll-out. To check that we are not missing another cause of broader mortality decline that correlates with the district-level roll-out of CWS, we re-run our baseline regressions using three alternative measures of mortality as our dependent variable. The first is a measure of non-waterborne disease mortality, calculated simply using all deaths minus waterborne disease deaths. The second is deaths from violence, a cause that has no obvious relationship with water quality. The third is whooping cough, an air-borne disease that had a particularly high mortality rate in London and declined rapidly during the second half of the nineteenth century (Hardy, 1993: 10–11).[39]

An additional challenge to finding good placebo tests for late nineteenth century London is the increasing frequency of admission to hospitals in one district of infectious disease patients who lived in another district. These deaths were reported in the district housing the hospital rather than the patient's own residential district. This concern is particularly problematic for smallpox, scarlet fever, and diphtheria. As Anne Hardy (1993: 300) notes, "with the arrival of the MAB hospitals from the 1870s, and especially with the dramatic rise in hospitalization of cases of scarlet fever, diphtheria, and typhoid after 1891, district mortality figures for these diseases become increasingly doubtful; by the 1890s they are often meaningless. The clearest example of this fallacy in the registration data comes with smallpox." Whooping cough does not suffer from this challenge because London hospitals did not accept whooping cough patients (Hardy, 1993: 23).[40]

[37] The regression results for this and other specifications parallel to those in Table 5 are available upon request.

[38] Cairncross (2003) argues that handwashing may provide an additional explanation for the Mills-Reincke phenomenon observed during the late nineteenth century in addition to the three discussed by Ferrie and Troesken (2008).

[39] Mortality data comes from the *Registrar General's Annual Reports* for 1860–1910 (23rd–73rd; 1862–1912). Transcribed registration district mortality data by cause was kindly shared with us by Brian Beach. We mapped registration district data to our 19 composite health districts.

[40] Even though raw typhoid data suffers from the hospitalization fallacy, our measure of waterborne disease mortality does not because we use corrected data provided by Graham Mooney.

Table 7
CWS and non-waterborne disease, violence, and whooping cough mortality.

	Log of Nonwaterborne Mortality				Log of Violence Mortality				Log of Whooping Cough Mortality			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
CWS	0.00038	0.00166	0.0246	0.0629***	−0.0459	0.0207	−0.133***	−0.0967	−0.0308	−0.00187	−0.0741	−0.101
	(0.0143)	(0.0136)	(0.0154)	(0.0234)	(0.0461)	(0.0383)	(0.0500)	(0.0842)	(0.0822)	(0.0792)	(0.0868)	(0.176)
	[0.9787]	[0.901]	[0.119]	[0.0082]	[0.3083]	[0.576]	[0.0071]	[0.2755]	[0.7084]	[0.9803]	[0.3834]	[0.5691]
R-squared	0.941	0.962	0.959	0.958	0.84	0.911	0.884	0.944	0.776	0.807	0.798	0.773
Observations	969	969	969	475	969	969	969	475	969	969	969	475
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
District FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
District time trend	N	Y	N	N	N	Y	N	N	N	Y	N	N
Controls	N	N	All	All	N	N	All	All	N	N	All	All
Time period	1860–1910	1860–1910	1860–1910	1876–1900	1860–1910	1860–1910	1860–1910	1876–1900	1860–1910	1860–1910	1860–1910	1876–1900

Robust standard errors in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$); Wild bootstrap p-values in brackets. Control variables include log of population, female ratio, foreign born population ratio, and age groups.

Table 7 reports the results. Overall, they provide no evidence that we are missing a confounding variable; the expansion of CWS did not have immediate causal effect on deaths from non-waterborne diseases, violence or whooping cough. Despite the challenges noted above, we show results for smallpox, scarlet fever, diphtheria, typhus, and measles in Appendix Table B3. The results are mixed, suggesting only a causal impact of CWS on diphtheria mortality and these results are unreliable due to the hospitalization fallacy.

7. Final observations

Recent research on the complementarity of water and sewers in reducing mortality suggests sewer expansion as a possible confounding factor for our analysis ((Alsan and Goldin, 2019); Kesztenbaum and Rosenthal 2017). With access to piped water, more houses installed flush toilets, increasing the quantity of wastewater and sewage being flushed into the Thames. The heat of 1858 prompted Parliament to approve the public funding for Bazalgette's intercepting sewers to transport London's sewage downstream. Construction started in 1860, the primary northern and southern sewers were complete by 1865, and the full system was complete by 1874 ((Humphreys, 1930): 13). London already had an extensive network of secondary sewers and drains that did not undergo systematic expansion or improvement; they continued to be replaced, repaired or extended based on local needs and resources.[41] We do not have a district level measure of sewerage but see no indication that the intercepting sewers or broader sewer network expanded at the same time as London transitioned from IWS to CWS and our results in Table 4, column 4, starting in 1876 address concerns of a connection prior to 1874. If anything, sewers may have contributed to an increase in local outbreaks of typhoid as the popularity of oysters in the metropolis coincided with the sewage contamination of oyster beds during the late 19th century (Hardy 2014).

Compensating behavior by households with an intermittent supply may have involved the use of water gathered from shallow wells or delivered by water carrier. Such compensating behavior does not directly challenge our argument that the move to CWS reduced waterborne disease mortality because only customers with IWS would have engaged in this compensating behavior. If other sources of water became less available during our time period, however, it may weaken our argument that disease transmission under IWS resulted from pipe infiltration and in-house contamination. Common sources of water before the 1870s were shallow wells and water carrier delivery; neither were relied upon during our time period. Construction of London's intercepting sewer network resulted in the closure of almost all shallow wells before 1876 and London's last water carrier died in 1868 (Foord 1910: 151).

8. Conclusion

For the period 1876–1910, the biggest change in London's water infrastructure was the move from intermittent water delivery to constant, high pressure, service. Idiosyncratic delays as a result of parish and neighborhood level negotiations regarding fittings and costs meant that each London district experienced the transition at a different pace. Using this difference across districts, we find that a one percentage point increase in the population with access to constant service reduced waterborne disease mortality between 0.2% and 0.4%. The move away from IWS explains between 20% and 30% of the reduction in waterborne disease mortality in London during the last quarter of the nineteenth century, saving approximately 3 lives per 10,000 people. Our results are robust to demographic factors and environmental conditions measured using population density and district demographics. The replacement of London's system of intermittent supply by a modern system with water constantly available at high pressure prevented contamination from pipe intrusion during delivery or during domestic storage in cisterns and likely facilitated more frequent handwashing.

The reliance on mostly intermittent service in the 1860s despite the investment in filtration make it possible to emphasize the early improvement of London's water supply and innovative investment in filtration compared to other cities in England and Europe while simultaneously recognizing system imperfections (Tynan 2013). Similarly, the United Nations acknowledges progress made towards meeting the Millennium Development Goal targets for improved water while setting new targets for frequency of delivery needed to achieve a sustainable water supply for everyone. Just as recent development research shows that frequency of water delivery matters for water quality at the point of consumption, the evidence in this paper shows that a constant water supply contributed to London's mortality decline. Our finding highlights the need to look beyond discrete interventions in water treatment when evaluating the impact of water quality on public health.

Uncited references

(Hsiang, 2010; Knutsson, 2017).

Declaration of Competing Interest

None

Acknowledgments

The authors are particularly grateful to Graham Mooney, Scott Orford, and Brian Beach for sharing data, to Jim Ciarrocca for ArcGIS assistance, and to two anonymous referees for valuable feedback. Graham Mooney provided corrected Registrar General

[41] "For many years after 1874, few additions were made to the numbers of the sewers though the population likewise the discharge of sewage and rainwater into the sewers were continually increasing." (Humphreys 1930: 13)

mortality data funded by Wellcome Trust Grant number 044175, 'Mortality in the Metropolis, 1860–1920′. Benjamin Spock provided fast, accurate data transcription. Feedback on earlier drafts from Marcela Alsan, Vellore Arthi, Brian Beach, Walker Hanlon, Joshua Lewis, Diana Ngo, Martin Saavedra, Jim Siodla, Tony Underwood, and Tianyi Wang improved the paper, as did comments from participants at the King's College Political Economy Seminar, 2017 Social Science History Association Conference, 2018 Liberal Arts Economic History Workshop, 2018 Paris Workshop for WEHC session on Health Inequalities, 2018 Economic History Society Conference, XVIII World Economic History Congress, and 2019 LAC Dev/History Conference.

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Appendix A

Our annual district-level waterborne disease mortality data, corrected for hospital deaths, was created by Bill Luckin, Graham Mooney and Andrea Tanner as part of the Wellcome Trust *Mortality in the Metropolis, 1860–1920* project (1999). In addition to deaths from waterborne diseases, the dataset provided by Graham Mooney included population data taken from the 1861–1911 censuses. Because London had 36 registration districts in 1861, 28 in 1871, 29 in 1881 and 1891, and 29 administrative districts for the 1901 and 1911 censuses, the dataset included pathways to address these registration district boundary changes and create the time-consistent composite health districts that we use in our analysis (Luckin et al., 1999). In anticipation of district boundary changes, sanitary area population data was used for 11 districts in 1891 to prevent double counting. Table A1 shows the registration districts, sanitary areas and administrative districts that fall within our composite health districts for each census year.

Our composite district population values for census years are the sum of the registration, sanitary or administrative district populations listed in Table A1. Population values in non-census years are estimates constructed using the Das Gupta interpolation method. For districts that changed between census years, the dataset provided by Graham Mooney calculated composite district population in these years by extrapolating from registration or administrative district population and then aggregating (Luckin et al., 1999). We used interpolation from census year composite district values which means a few of our non-census year population values differ slightly from those in the Luckin, Mooney, and Tanner dataset. Fig. A1 shows the results. The advantage of our method is that it ensures interpolated gender and age variables correspond to the composite district population totals. The one possible concern is that our method does not account for differences in rates of population change between registration districts so might disguise the impacts of migration on CWS expansion, on the denominator in our calculation of waterborne mortality, or on the difference between more and less treated districts as healthier people move to treated districts, as discussed by Arthi, Beach and Hanlon ((Arthi et al., 2020)). Because most migration within London during this time period was to neighboring registration districts (Schürer and Day 2019), these potential confounders due to estimated population values are less of a concern for our composite districts than they would be at lower levels of administration.

Table A2 provides summary descriptive statistics for all variables used our analysis. All variables have 1020 observations, covering each composite health district for all years between 1860 and 1910. Waterborne, non-waterborne, whooping cough, violence, measles,

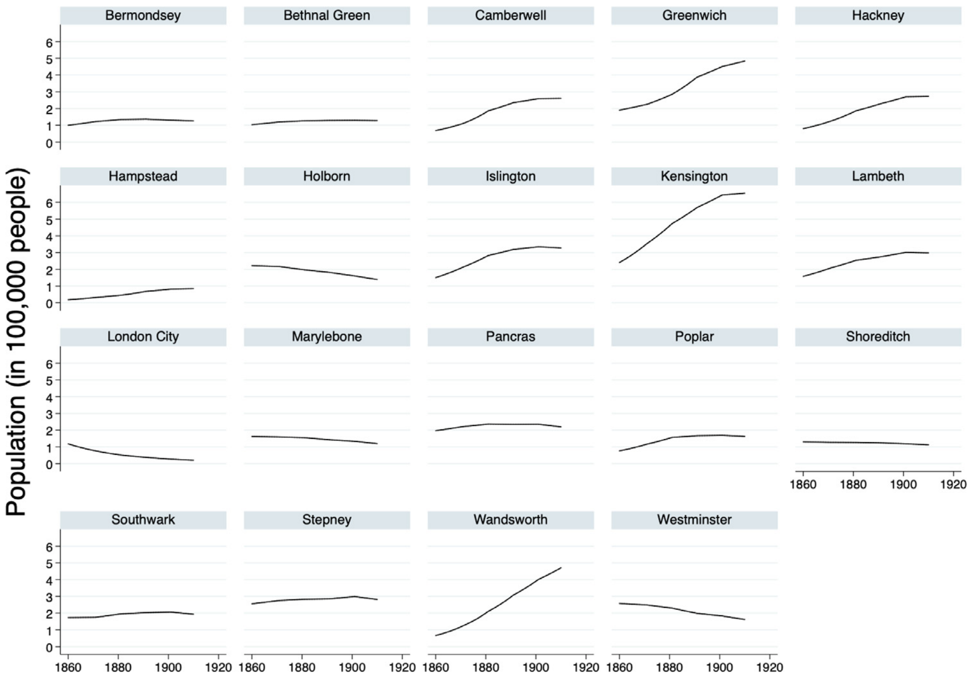

Fig. A1. Population in each composite health district, 1860–1910.

Table A1
Composite health district places.

Composite health district	Registration district (1861, 1871, 1881, 1891)	Sanitary area (1891)	Administrative district (1901, 1911)
Bermondsey	Bermondsey		Bermondsey
	Rotherhithe (1861)		
	St. Olave Southwark	St. Olave	
Bethnal Green	Bethnal Green		Bethnal Green
Camberwell	Camberwell		Camberwell
Greenwich			Deptford
	Greenwich		Greenwich
	Lewisham	Lewisham	Lewisham
	Woolwich (1871, 1881)	Woolwich	Woolwich
Hackney	Hackney		Hackney
			Stoke Newington
Hampstead	Hampstead		Hampstead
Holborn	Clerkenwell (1861)		
			Finsbury
	Holborn	Holborn	Holborn
	St. Giles		St. Giles
	St. Luke (1861)		
Islington	Islington		Islington
Kensington	Chelsea		Chelsea
	Fulham (1881)	Fulham	Fulham
		Hammersmith	Hammersmith
	Kensington		Kensington
	Paddington (1891)		Paddington
Lambeth	Lambeth		Lambeth
London City			City Of London
	East London (1861)		
	London City	London City	
	West London (1861)		West London
Marylebone	Marylebone		St. Marylebone
Pancras	Pancras		St. Pancras
Poplar	Poplar		Poplar
Shoreditch	Shoreditch		Shoreditch
Southwark	Newington (1861)		
			Southwark
	St. George Southwark (1861)		
	St. Saviour Southwark	St. Saviour	
Stepney	Mile End Old Town		
	St. George In The East		
	Stepney		Stepney
	Whitechapel		
Wandsworth			Battersea
	Wandsworth	Wandsworth	Wandsworth
Westminster			City Of Westminster
	St. George Hanover Square	St. George Hanover Square	
	St. James Westminster (1861)		
	St. Martin In The Fields (1861)		
	Westminster	Westminster	
	Strand	Strand	

smallpox, scarlet fever, typhus and diphtheria mortality rates are measured in deaths per 10,000 population. Infant mortality is measured as deaths per 1000 live births. Constant service is the percentage of a district's population with water supplied 24 h, 7-days per week. Female ratio is the number of males divided by number of females using data from the census aggregated and interpolated as described for population. Foreign ratio is the number of foreign born divided by the total population in a district. The age categories are share of a district population in each category.

Table A3 provides the results of a covariates balance test comparing early and late adopters of CWS for the pre-treatment period 1860–1870. We define early adopters as districts with 50% CWS coverage before 1888 and late adopters as districts achieving 50% CWS after 1888, giving us 11 early adopters and 8 late adopters.

Table A2
Summary statistics ($N = 969$ for all variables).

	Mean	Standard deviation	Minimum	Maximum
CWS	0.456	0.412	0	1
Waterborne mortality rate	10.041	6.289	0.926	112.707
Non-waterborne mortality rate	196.585	37.752	92.640	304.921
Violence mortality rate	8.752	6.861	2.690	55.550
Whooping cough mortality rate	6.447	3.403	0.358	23.999
Infant mortality rate	154.205	33.050	65.121	471.429
Smallpox mortality rate	2.232	12.934	0	357.796
Scarlet fever mortality rate	4.753	5.424	0	36.942
Diphtheria mortality rate	2.689	3.580	0	49.063
Typhus mortality rate	1.745	3.991	0	33.400
Measles mortality rate	5.532	2.842	0.371	19.181
Population	202,681.1	114,364.5	18,129.8	654,839.5
Female ratio	0.529	0.030	0.486	0.616
Foreign ratio	0.022	0.026	0.002	0.189
Age: under 5	0.120	0.021	0.050	0.153
Age: 5–14	0.200	0.027	0.110	0.239
Age: 15–24	0.200	0.020	0.167	0.285
Age: 25–44	0.297	0.022	0.263	0.380
Age: 45–64	0.144	0.012	0.119	0.191
Age: above 65	0.039	0.005	0.029	0.054

Sources: Waterborne disease mortality from the *Registrar General's Annual Reports for 1860–1910* (23rd-73rd; 1862–1912) corrected for hospital deaths by Graham Mooney, The Johns Hopkins University; constant service data from *Annual Reports of the Local Government Board* and Appendix A of the *First Annual Report of the Metropolitan Water Board*, as described in the text; infant mortality data from the *Registrar-General's Annual Reports for* 1860–1884 and *Quarterly Reports* for 1885–1910; deaths from other diseases from the *Registrar General's Decennial Supplements* (25th-65th; 1860–1910). Demographic data comes from the censuses for England and Wales for 1861–1911.

Table A3
Pre-treatment period (1860–1870) balance in mortality measures.

	(1) Early adopters	(2) Late adopters	(3) Overall	(1) vs. (2) Difference
Water mortality rate	13.813	10.944	12.605	−2.869
	(1.276)	(0.418)	(0.764)	(1.539)
Non-water mortality rate	227.941	223.318	225.995	−4.624
	(2.063)	(3.652)	(1.948)	(3.942)
Violence mortality rate	8.428	8.241	8.350	−0.187
	(0.393)	(0.412)	(0.286)	(0.580)
Whooping cough mortality rate	8.903	8.095	8.563	−0.807
	(0.298)	(0.326)	(0.222)	(0.447)
Infant mortality rate	156.747	162.914	159.344	6.167
	(2.044)	(1.854)	(1.430)	(2.872)
Smallpox mortality	2.791	2.797	2.794	0.006
	(0.242)	(0.408)	(0.221)	(0.449)
Scarlet fever mortality rate	11.345	10.233	10.877	−1.111
	(0.651)	(0.606)	(0.456)	(0.922)
Diphtheria mortality rate	1.745	1.925	1.821	0.179
	(0.079)	(0.101)	(0.062)	(0.126)
Typhus mortality rate	7.489	7.508	7.497	0.019
	(0.403)	(0.734)	(0.386)	(0.784)
Measles mortality rate	5.906	5.552	5.757	−0.354
	(0.339)	(0.259)	(0.224)	(0.455)
Observations	121	88	209	209

Appendix B

Fig. B1 reproduces Fig. 2 across all nineteen of London's composite health districts. The natural log of the mortality rate from waterborne diseases is on the y-axis; the estimated proportion of homes in each district with no access to CWS is plotted on the secondary y-axis. As with Fig. 2, extensions in CWS at the district level appear to be associated with reductions in the death rate from waterborne mortality and, except for the period after 1905, when districts exhibit slow or stagnant growth in extensions of CWS disease rates do not decline.

Table B1
CWS and infant mortality.

	All Districts							Without London City
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel 1								
CWS	−0.0373	−0.0247	−0.0355	−0.0938***	−0.297***	0.00528	−0.0857***	−0.0623**
	(0.0305)	(0.0254)	(0.0300)	(0.0321)	(0.0501)	(0.0260)	(0.0315)	(0.0252)
	[0.3369]	[0.2335]	[0.2278]	[0.043]	[0]	[0.8451]	[0.009]	[0.0136]
R-squared	0.589	0.805	0.625	0.733	0.832	0.681	0.742	0.786
Panel 2								
CWS (with estimate)	−0.0780*	−0.00831	−0.0785**	−0.220***	−0.297***	0.0204	−0.224***	−0.105***
	(0.0404)	(0.0340)	(0.0390)	(0.0474)	(0.0501)	(0.0321)	(0.0475)	(0.0319)
	[0.0542]	[0.8158]	[0.0439]	[0]	[0]	[0.5245]	[0]	[0.0009]
R-squared	0.590	0.805	0.626	0.733	0.822	0.680	0.742	0.780
Observations	969	969	969	969	665	836	950	918
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
District FE	Y	Y	Y	Y	Y	Y	Y	Y
District time trend	N	Y	N	N	N	N	N	N
Controls	N	N	Log population only	All	All	All	All	All
Time period	1860–1910	1860–1910	1860–1910	1860–1910	1876–1910	1860–1903	1860–1910 without 1866	1860–1910

Robust standard errors in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$); Wild bootstrap p-values in brackets. Control variables include log of population, female ratio, foreign born population ratio, and age groups.

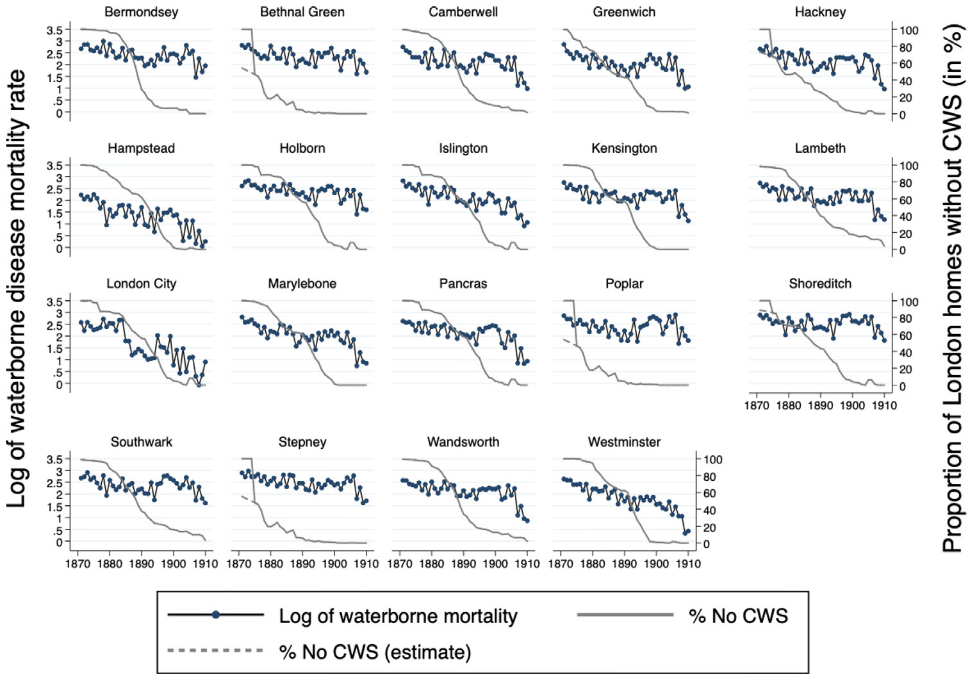

Fig. B1. Waterborne disease mortality and proportion of homes in each composite health district without CWS, 1860–1910
Sources: *Registrar General's Annual Reports for 1860–1910* (23rd–73rd; 1862–1912) corrected by Graham Mooney, The Johns Hopkins University; *Annual Reports of the Local Government Board,* Appendix A of the *First Annual Report of the Metropolitan Water Board.*

Table B1 repeats the regressions in Table 4 using infant mortality as the dependent variable. Our infant mortality variable is calculated as infant deaths/births in each district each year using infant death and birth data from the *Annual Reports of the Registrar-General of births, deaths, and marriages in England*, for 1860–1884, and *Quarterly Reports* for 1885–1910. Once we control for population and demographic variables (column 4), a one percentage point increase in CWS reduces infant mortality between 0.094% and 0.22%.

These results are weaker than those for waterborne disease mortality and more sensitive to our chosen specification for at least three reasons. First, while diarrhea is a leading causing of infant deaths, our measure of infant mortality is much broader and includes infant deaths from all causes. Second, infant deaths in London declined only slowly during the late 19th century compared to the more rapid decline in the early 20th century. Recent research by Hanlon, Hansen and Kasper (Hanlon et al., 2021)() suggests that the hot summers during the late 1890s delayed the decline in infant deaths by approximately five years. This may explain the loss of significance and positive coefficient for CWS in column 6 which ends in 1903. Third, unlike our measure of waterborne disease deaths, our measure of infant mortality is not adjusted to account for deaths in institutions located in other districts. One of our districts - London City - housed the City of London Maternity Hospital that served mothers from surrounding districts. It established an outpatient maternity department in 1872 making it increasingly likely that mothers from surrounding districts would give birth in the hospital in situations when an infant's life was most at risk. The hospital had a high mortality rate.[42] Column 8 excludes the London City district. Overall, the results suggest that CWS contributed to the slow decline in infant mortality during the late 1800s, but our measures of CWS and infant mortality are not precise enough to say more.

Table B2 repeats Table 4 using waterborne disease mortality rate as the dependent variable to check that our log transformation is not overly influencing the results. The coefficient on CWS remains negative and significant in all specifications.

Table B3 shows the results for smallpox, scarlet fever, diphtheria, typhus, and measles as the dependent variable for the period 1876–1900 during which most of the expansion of CWS took place. Overall, the results do not raise concerns that we are missing a confounding factor reducing disease mortality in London. Only columns 7–9 for diphtheria suggest a significant causal effect of CWS expansion on mortality. However, as noted in the text, the results for diphtheria, smallpox and scarlet fever are not reliable due to concerns about the hospitalization fallacy. Data for smallpox and typhus are also missing a number of observations due to zero deaths reported in some district-years.

[42] For an overview of the history of the City of London Maternity Hospital see London Metropolitan Archives, Reference code H10/CLM. Our infant mortality measure for this district increases throughout the period due to a nearly constant annual number of infant deaths but a falling infant birth rate.

Table B2
CWS and waterborne mortality rate.

	Waterborne Mortality (1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel 1							
CWS	−5.826***	−5.779***	−5.837***	−6.224***	−4.734***	−5.867**	−1.790***
	(2.114)	(2.137)	(2.115)	(2.272)	(0.780)	(2.476)	(0.494)
	[0.0006]	[0.0028]	[0.0008]	[0.0019]	[0]	[0.0209]	[0.0003]
R-squared	0.533	0.550	0.534	0.542	0.856	0.498	0.856
Panel 2							
CWS (with estimate)	−3.367***	−7.393***	−3.364***	−5.518***	−4.734***	−5.333**	−3.598***
	(0.704)	(2.669)	(0.698)	(1.758)	(0.780)	(2.177)	(0.694)
	[0]	[0.0026]	[0]	[0]	[0]	[0.0046]	[0]
R-squared	0.526	0.549	0.527	0.537	0.856	0.493	0.859
Observations	969	969	969	969	665	836	950
Year FE	Y	Y	Y	Y	Y	Y	Y
District FE	Y	Y	Y	Y	Y	Y	Y
District time trend	N	Y	N	N	N	N	N
Controls	N	N	Log population only	All	All	All	All
Time period	1860–1910	1860–1910	1860–1910	1860–1910	1876–1910	1860–1903	1860–1910 without 1866

Robust standard errors in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$); Wild bootstrap p-values in brackets. Control variables include log of population, female ratio, foreign born population ratio, and age groups.

Appendix C

Our main analysis assumes that companies do not roll-out CWS across their supply district in a systematic manner; the introduction of CWS within a neighborhood is idiosyncratic and largely based on neighborhood demand. This underlies our assumption that the percentage of a company's customers receiving CWS is distributed across districts in proportion to the district's share of a company's customers. Therefore, we multiplied the share of a district supplied by each company by the percentage of the population supplied by that company on CWS.

However, if a company fully controlled the roll-out of CWS, it is likely it would transition from intermittent supply in a more systematic manner, possibly starting with its largest market. Therefore, we introduce a counterfactual analysis using an alternative measure of district-level CWS based on the assumption that every company converts the districts it serves from IWS to CWS sequentially based on the population served in each district. In other words, we assume that a company starts by supplying CWS in its largest market only, then moves onto its second largest market after CWS reaches a penetration rate of 100% in its largest market, and so on.

To create a district-level measure of the percentage of the population supplied by each company on CWS, we multiply the district-company measure of CWS by the share of the district supplied by each company and aggregate to create the percentage of the population within a district on CWS. As above, our measures of CWS for any district i in year t can be written as,

$$District\,CWS_{it} = \sum_{k=1}^{n} \theta_{ik} \cdot \left(CWS_{kit}\right)$$

where, n is the total number of companies providing water to district i, θ_{ik} is the proportion of the population in district i that is consuming water supplied by company k, and CWS_{kit} is the proportion of water company k's customers within district i who enjoy CWS in year t.[43]

We used the following rule to calculate CWS_{kit}: Let t be some specific year, k be some water company and $P_k(i)$ be the population of district i served by company k. Suppose k serves m districts $i_1, i_2 \ldots i_m$, where $P_k(i_1) > P_k(i_2) > \ldots > P_k(i_m)$. Then we use $S(P_k(i))$ to indicate district i's share of the population served by company k in all m districts it serves , $S(P_k(i)) = \frac{P(i)}{\sum_{i=1}^{m} P_k(i)}$. Then, for each company,we have $CWS_{ki_1t} = \frac{CompanyCWS_{kt}}{S(P_k(i_1))}$. To account for some large increases in CWS from year to year, we use the following rule: for all $j \in [2, m]$, once $CWS_{ki_{j-1}t}$ hits 100%, if $\sum_{i=1}^{j} S(P_k(i_{j-1})) < CompanyCWS_{kt}$, then we have $CWS_{ki_jt} = \frac{CompanyCWS_{kt} - CompanyCWS_{k,t-1}}{S(P_k(i_j))}$. If $\sum_{i=1}^{j} S(P_k(i_{j-1})) \geq CompanyCWS_{kt}$, then we have $CWS_{ki_jt+1} = \frac{CompanyCWS_{k,t+1} - CompanyCWS_{k,t}}{S(P_k(i_j))}$.

[43] As in note 15 above, consider our counter-factual measure of district CWS (*District CWS*) for the district of Camberwell. Bold text highlights the difference. Camberwell was served by three companies: Kent, Lambeth, and Southwark & Vauxhall. Given the levels of market penetration for each of these companies, we calculate the level of CWS in the Camberwell district as follows: *DistrictCWS-Camberwell* = 0.13 $(Kent)_{it}$ + 0.2 $(Lambeth)_{it}$ + 0.67 $(Southwark\&Vauxhall)_{it}$. *Kent* is the percentage of Kent water company customers **in the Camberwell district** on CWS in year t, and 0.13 is the percentage of the population of Camberwell supplied by the Kent Company; *Lambeth* is the percentage of Lambeth water company customers **in the Camberwell district** on CWS and 0.2 is the percentage of the population of Camberwell supplied by the Lambeth Company; and so on for the Southwark & Vauxhall company.

Table B3
Additional placebo results.

	Log of Smallpox Mortality			Log of Scarlet Fever Mortality			Log of Diphtheria Mortality			Log of Typhus Fever Mortality			Log of Measles Mortality		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
CWS	0.450	−2.520	−1.475	0.606*	−0.864*	0.410	−1.092***	−1.857***	−1.097***	−0.277	−0.845	−1.155*	−0.219	0.589	−0.123
	(1.018)	(1.869)	(1.308)	(0.342)	(0.509)	(0.339)	(0.189)	(0.282)	(0.215)	(0.605)	(0.925)	(0.633)	(0.167)	(0.374)	(0.241)
	[0.6591]	[0.1717]	[0.2606]	[0.0866]	[0.0933]	[0.2234]	[0]	[0]	[0]	[0.6472]	[0.3444]	[0.0679]	[0.188]	[0.1183]	[0.6005]
R-squared	0.786	0.866	0.840	0.733	0.882	0.846	0.727	0.853	0.806	0.685	0.759	0.729	0.500	0.536	0.508
Observations	223	223	223	473	473	473	475	475	475	240	240	240	475	475	475
Year FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
District FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
District time trend	N	Y	N	N	Y	N	N	Y	N	N	Y	N	N	Y	N
Controls	N	All	All	N	All	All	N	All	All	N	All	All	N	All	All
Time period	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900	1876–1900

Robust standard errors in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$); Wild bootstrap p-values in brackets. Control variables include log of population, female ratio, foreign born population ratio, and age groups.

Table C1
Reduction in mortality from CWS assuming largest supply districts treated first.

	Log of Waterborne Mortality (with counterfactual CWS)				
	(1)	(2)	(3)	(4)	(5)
Counterfactual CWS	−0.0579	−0.108**	−0.0376	−0.115**	−0.00699
	(0.0462)	(0.0438)	(0.0453)	(0.0545)	(0.0461)
	[0.2212]	[0.0142]	[0.4208]	[0.0454]	[0.8901]
Observations	969	969	969	665	836
R-squared	0.805	0.878	0.865	0.897	0.818
Year FE	Y	Y	Y	Y	Y
District FE	Y	Y	Y	Y	Y
District time trend	N	Y	N	N	N
Controls	N	N	All	All	All
Time period	1860–1910	1860–1910	1860–1910	1876–1910	1860–1903

Robust standard errors in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$); Wild bootstrap p-values in brackets. Control variables include log of population, female ratio, foreign born population ratio, and age groups.

Table C1 provides results comparable to those in Table 4 (columns 1, 2, 4, 5 and 6) using our new, counterfactual, measure of constant service. Overall, the results support our assumption that the introduction of CWS was not systematic across districts. With only 19 composite districts, some district-year measures of CWS did not change a lot with this new approach. Nevertheless, even when CWS remains significant, the coefficient is much smaller than reported in Table 4.

References

Anderson, D.M, Charles, K.K., Rees, DI., 2021. "*Re*-Examining the contribution of public health efforts to the decline in urban mortality. Am. Econ. J. Appl. Econ.. Available as NBER Working Paper 25027 http://www.nber.org/papers/w25027 .
Alsan, M., Goldin, C., 2019. Watersheds in child mortality: the role of effective water and sewerage infrastructure, 1880–1920. J. Polit. Econ. 127 (2), 586–638.
Arthi, Vellore, Beach, Brian, Hanlon, W. Walker, 2020. Recessions, Mortality, and Migration Bias: Evidence from the Lancashire Cotton Famine. Working Paper 1–73. https://brianbbeach.github.io/Materials/WP/Arthi_Beach_Hanlon_Recessions.pdf(Accessed 24 May 2021).
Beach, B., Ferry, J., Saavedra, M., Troesken, W., 2016. Typhoid fever, water quality, and human capital formation. J. Econ. Hist. 76 (1), 41–75.
Bolton, F., 1881. "Report to Local Government Board on General Condition of Works of Grand Junction Waterworks Company, and alleged Short Supply of Water, July 1881, and Correspondence" by Lieutenant Colonel Frank Bolton, C.E., Water Examiner. Accessed 13 January 2020 at http://parlipapers.proquest.com:80/parlipapers/docview/t70.d75.1881-057638?accountid=10506.
Bolton, F., 1884. London water supply, including a history and description of the London waterworks, statistical tables, and maps. New edition, revised and expanded, (eds.) Philip A., Scratchley, M.A., 1888, London: William Clowes and Sons. Accessed 13 January 2020 at https://play.google.com/books/reader?id=ZFFKAAAAYAAJ&pg=GBS.PA11.
Cairncross, S., 2003. Editorial: handwashing with soap – a new way to prevent ARIs? Trop. Med. Int. Health 8 (8), 677–679.
Cameron, A.C, Gelbach, JB., Miller, DL., 2008. Bootstrap-based improvements for inference with clustered errors. Rev. Econ. Stat. 90 (3), 414–427.
Chadwick, E., 1842. 1997. *Report On the Sanitary Condition of the Labouring Population of Great Britain*. Routledge/Thoemmes Press, London Reprint.
Chapman, J., 2019. The contribution of infrastructure investment to Britain's urban mortality decline, 1861-1900. Econ. Hist. Rev. 72 (1), 233–259.
Cutler, D., Miller, G., 2005. The role of public health improvements in health advances: the twentieth-century United States. Demography 42 (1), 1–22.
Ercumen, A., Arnold, B.F., Kumpel, E., Burt, Z., Ray, I., Nelson, K., Colford, J.M., 2015. Upgrading a piped water supply from intermittent to continuous delivery and association with waterborne illness: a matched cohort study in urban India. PLoS Med. doi:10.1371/journal.pmed.1001892.
Ewald, P. W., 1994. Evolution of Infectious Disease. Oxford University Press, Oxford.
Farr, W., 1868. Report on the Cholera Epidemic of 1866 in England. Supplement to the Twenty-Ninth Annual Report of the Registrar-General of Births, Deaths, and Marriages in England. George E. Eyre and William Spottiswoode, London.
Ferrie, J. P., Troesken, W., 2008. Water and Chicago's mortality transition, 1850-1925. Explor. Econ. Hist. 45, 1–16.
Foord, A.S., 1910. Springs, Streams and Spas of London: History and Associations. T. Fisher Unwin, London.
Galaitsi, S.E., Russell, R., Bishara, A., Durant, JL., Bogle, J., Huber-Lee, A., 2016. Intermittent domestic water supply: a critical review and analysis of causal-consequential pathways. Water 8 (7), 274. doi:10.3390/w8070274. Accessed 9/30/2017 at http://www.mdpi.com/2073-4441/8/7/274/htm .
Gallardo-Albarrán, D., 2020. Sanitary infrastructures and the decline of mortality in Germany, 1877–1913. Econ. Hist. Rev. 1–28 (Early View 26 February 2020).
Goodman-Bacon, A., 2018. "Difference-in-differences with variation in treatment timing." NBER Working Paper 25018, http://www.nber.org/papers/w25018.
Hanlon, W.W, Hansen, C.W., Kantor, JW., 2021. Temperature, disease, and death in London: analyzing weekly data for the century from 1886 to 1965. J. Econ. Hist. 81 (1), 40–80.
Hardy, A., 1991. Parish pump to private pipes: London's water supply in the nineteenth century. Med. Hist. 76–93 Supplement No. 11.
Hardy, A., 1993. The Epidemic Streets: Infectious Disease and the Rise of Preventive Medicine 1856-1900. Clarendon Press, Oxford.
Hardy, A., 2014. The Hygiene of the Sea." Chapter 3 in *Salmonella Infections, Networks of Knowledge, and Public Health in Britain, 1880-1975*. Oxford University Press, Oxford.
Heymans, C., Eberhard, R., Ehrhardt, D., Riley, S., 2016. Providing Water to Poor People in African Cities Effectively: Lessons from Utility Reforms World Bank Water and Sanitation Group Report. Available at http://documents.worldbank.org/curated/en/316751472482999236/pdf/108074-WP-P147350-PUBLIC-add-series.pdf.
Hillier, J., 2014. Implementation without control: the role of the private water companies in establishing constant water in nineteenth-century London. Urban Hist. 41 (2), 228–246.
Hobhouse, H. (ed.), 1994. "Public housing in poplar: the years to 1919", in Survey of London: Volumes 43 and 44, Poplar, Blackwall and Isle of Dogs. (London). Accessed 12 July 2019 at British History Online http://www.british-history.ac.uk/survey-london/vols43-4/pp21-23.
Hsiang, S.M., 2010. Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. Proc. Nat. Acad. Sci. USA 107 (35), 15367–15372.
Humphreys, George W., George, W., 1930. Main Drainage of London. London County Council Accessed 15 July 2019 at https://www.sewerhistory.org/articles/whregion/1930_abm1/article.pdf .
Jones, EM., 2012. Parched City – A History of London's Private and Public Drinking Water. Winchester: Zero Books.
Kesztenbaum, L., Rosenthal, J.-L., 2017. Sewers' diffusion and the decline of mortality: the case of Paris, 1880–1914. J. Urban Econ. 98C, 174–186.
Knutsson, D., 2017. Water improvement and health: historical evidence on the effect of filtering water on urban mortality. Res. Pap. Econ. 2017 (2) Stockholm University, Department of Economics.

Kumpel, E., Nelson, KL., 2013. Comparing microbial water quality in an intermittent and continuous piped water supply. Water Res. 47 (13), 5176–5188. doi:10.1016/j.watres.2013.05.058, http://dx.doi.org/.
Kumpel, E., Nelson, KL., 2014. Mechanisms affecting water quality in an intermittent piped water supply. Environ. Sci. Technol. 48, 2766–2775.
Kumpel, E., Nelson, KL., 2016. Intermittent water supply: prevalence, practice, and microbial water quality. Environ. Sci. Technol. 50, 542–553.
Lee, EJ., Schwab, KJ., 2005. Deficiencies in drinking water distribution systems in developing countries. J. Water Health 3 (2), 109–127.
Local Government Board. 1882. Annual Report, 1881-82. Volume 11. London: H.M. Stationary Office.
Local Government Board. 1891. Annual Report, 1890-91. Volume 20. London: H.M. Stationary Office.
Metropolitan Water Board. 1905. *Annual Report of the Proceedings of the Metropolitan Water Board, and abstract of their accounts for the year ended March 31st, 1905*.
Metropolitan Water Board. 1908. Metropolis Water Act, 1902: Annual Report, Volumes 4-5. London: H.M. Stationary Office.
Luckin, W., Mooney, G., Tanner, A., 1999. Mortality in the metropolis, 1860-1920.. Funded by The Wellcome Trust. Center for Metropolitan History https://archives.history.ac.uk/cmh/projects.html#1920.
Metropolitan Water Board, 1953. London's Water Supply, 1903-1953 – A Review of the Work of the Metropolitan Water Board. Staples Press, London.
Mooney, G., Luckin, B., Tanner, A., 1999. Patient pathways: solving the problem of institutional mortality in London during the later nineteenth century. Soc. Hist. Med. 12 (2), 227–269.
Orford, S., Dorling, D., Mitchell, R., Shaw, M., Smith, G.D., 2002. Life and death of the people of London: a historical GIS of Charles Booth's inquiry. Health Place 8, 25–35.
Roodman, D., 2015. "BOOTTEST: Stata module to provide fast execution of the wild bootstrap with null imposed." Statistical Software Components S458121, Boston College Department of Economics, revised 26 Aug 2018.
Schürer, K., Day, J., 2019. Migration to London and the development of the north-south divide, 1851-1911. Soc. Hist. 44 (1), 26–56.
Shadwell, A., 1899. The London Water Supply. Longmans, Green, and Co, London.
Tynan, N., 2013. Nineteenth century London water supply: processes of innovation and improvement. Rev. Aust. Econ. 26 (1), 73–91.
N. Tynan, and Y. Yang. 2021. *What are the health benefits of a constant water supply?* Evidence from London, 1860-1910. Ann Arbor, MI: Inter-University Consortium for Political and Social Research [distributor], 2021-05-13. https://doi.org/10.3886/E140401V1
Yelling, J.A., 1986. Slums and Slum Clearance in Victorian London. Allen & Unwin, London.
World Bank Group, 2017. Reducing Inequalities in Water Supply, Sanitation, and Hygiene in the Era of the Sustainable Development Goals: Synthesis Report of the Water Supply, Sanitation, and Hygiene (WASH) Poverty Diagnostic Initiative. World Bank, Washington, DC https://openknowledge.worldbank.org/handle/10986/27831.