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Abstract

Did cholera function as a potent catalyst for the reform of urban water infrastructure in 19th century Europe's disease-ridden cities, serving as "our old ally" in the struggle for urban sanitation (Robert Koch)? Based on a detailed case study of Berlin's hydrological reconfiguration, this paper challenges popular narratives that paint the emergence of safe tap water supplies and sanitary sewers as an efficient, scientifically motivated reaction to Europe's recurrent cholera epidemics since 1831. While historians have long stressed the dominance of aesthetical and industrial over sanitary concerns, the study of Berlin's contemporary discourse suggest that the causal link between cholera and water infrastructure reform was not only weak, but ambiguous. Far from motivating the right actions for the wrong reasons, cholera's conception through the dominant miasmatist frameworks and limited proto-epidemiological tools of the prebacteriological era inspired inefficient, at times even counterproductive approaches that potentially deepened the urban mortality penalty. Berlin's role as a political and scientific center of 19th century Europe suggests that her experience was the norm rather than the exception. A nuanced understanding of Western Europe's sanitary past has important implications for the continuing struggle for urban sanitation in today's developing world.

JEL Codes: N33, N53, N93

Keywords: Cholera, Water-Borne Disease, Epidemic, Sanitation, Berlin, Germany, Tap Water, Sewers, 19th Century, Miasma, Mortality, Urban Penalty

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1 Introduction

Wherever people cohabit in a high-density environment, clean water supply and wastewater disposal technologies are crucial to the prevention and containment of infectious water-borne diseases. Today, the immense public health benefits of adequate urban water infrastructure are well recognized and, consequently, universal access to safe water sources and sanitation facilities features among the most pressing development goals (McGranahan, 2015). While most water-related diseases constitute a constant, endemic health risk, large-scale epidemics are considered powerful reminders of the need for reform. Cholera, in particular, has often been depicted as a potent catalyst of urban water infrastructure reform, up to the point where the simple bidirectional mechanism of "cholera forcing" (Hamlin, 2009a) came to dominate popular perception. According to this notion, recurrent cholera epidemics enforce the reform of urban water infrastructure, and such reforms gradually eliminate the threat of cholera. Supposedly, this was the experience of the 19th and early 20th century Western world, and thus will be the experience of the contemporary developing world.[1]

In light of fundamental technical, political and financial obstacles impeding the adoption of adequate urban water infrastructure in the developing world, the idea that cholera epidemics contain their own antidote may seem overly simplistic (McGranahan, 2015), perhaps even dangerous and counterproductive (Nilsson, 2016). However, as an approach to understanding the hydrological reconfiguration of urban space and the emergence of the "bacteriological city" (Gandy, 2006) in 19th and early 20th century Western societies, the notion of "cholera forcing" continues to attract popular and scholarly attention. Thus, a common synopsis of Western urban public health history invokes versions of the following three interrelated claims:

1. Frequent cholera epidemics motivated the reform of urban water supply and discharge systems.

2. Such reforms were largely effective in the sense that they significantly reduced the incidence of cholera.

3. While medical science could not yet provide the correct justifications for such reforms, other means such as observation, correlation, and induction allowed contemporaries to derive which shape efficient reforms should take.

Such narratives can be traced back to late 19th and early 20th century reflections on urban public health reforms and the big etiological debates of the pre-bacteriological era.[2] For instance, German microbiologist Robert Koch (1843–1910) famously called cholera "our old ally" in the struggle for urban water

[1] While having disappeared from the industrialized West, cholera continues to afflict large parts of the developing world. Current large-scale epidemics include the Haiti outbreak with approximately 800,000 cases since October 2010 (WHO, 2018), and the Yemen outbreak with approximately 1.6 million cases since October 2016 (WHO, 2019).

[2] In medicine, etiology is the study of causal origins of a disease. See Carter (2003) and Susser and Stein (2009) for historical overviews of the concept.

hygiene (see a private letter quoted in Ackerknecht (1965, 23)). Present-day historiography certainly takes cautions against the uncritical adoption of biased historical accounts. Yet, the triumphs of modern medicine, epidemiology, and urban public health reform exert strong incentives to extrapolate our current understanding of the causal nexus between water-borne diseases and the urban water infrastructure back to the past. Perhaps the most visible manifestation of this tendency is the popular depiction of English physician John Snow (1813–1858) as the father of modern epidemiology and the public health movement. A common myth states that Snow demystified cholera by means of inductive logic and visual analysis of data he gathered during the 1854 London Broad Street outbreak (McLeod, 2000, Hamlin, 2009b, 179–195).[3]

This paper revaluates the "cholera forcing" narrative on the basis of Berlin's hydrological transformation over the 19th century. As one of Europe's largest and most influential metropoles at the time, Berlin provides a natural case study. Her experience suggests a highly complicated relationship between repeated cholera outbreaks, their statistical, proto-epidemiological examination, and the reform of urban water management infrastructure. Rather than presenting an efficient reaction to a well-understood problem, Berlin's road to safe water supply and wastewater disposal conditions was long, bumpy and full of blind alleys. In particular, the emergence of centralized tap water provision by the 1850s bears no connection to the regular cholera outbreaks that plagued the city since 1831. Moreover, prominent etiological doctrines probably exacerbated the urban health crisis as failure to understand cholera's fecal-oral transmission route helped to establish contractual obligations that delayed the construction of an accompanying wastewater disposal infrastructure for more than two decades. When construction of the latter became an option in the 1870s, predominant miasmatist theories of cholera's behavior were exploited to motivate various alternatives, such as a manual waste removal system or direct sewage disposal into urban water bodies. Far from yielding the right conclusion for the wrong reasons, the fear of miasma fueled popular resistance to sanitary sewers until the early 1880s. Furthermore, despite extensive statistical coverage of the cholera epidemics, Berlin's local health officers were unable to deduce the central importance of clean drinking water from their tables, correlations, and maps. Without the tools of multiple regression and statistical modeling, and lacking a convenient natural experiment à la John Snow, ample data turned out to cause more confusion than clarity.

The remainder of the paper is structured as follows: Section 2 summarizes the 19th century etiological debate on cholera. Section 3 provides an overview of Berlin's cholera history. Sections 4, 5 and 6 discuss the emergence of Berlin's tap

[3] The continuing relevance of "cholera forcing" to our understanding of Western urban water history is also illustrated by the careful discussion of reverse causality as the central threat to identification in recent quantitative studies on the historical impact of water infrastructure on mortality. For instance, in their study on the mortality effects of public health spending in England and Wales, Bell and Millward (1998, 225) state that "[to] contemporaries, the nineteenth-century decline in mortality was quite definitely causally linked to the burgeoning programmes of sanitary reform and the concentrated sanitary efforts of local government."

water supply, its sanitary sewers, and the proto-epidemiological analyses conducted by municipal health officers, respectively. Section 7 discusses the wider implications of Berlin's experience regarding both the 19th century Western world and the struggles of today's developing world.

2 Solving the Cholera Mystery

Cholera is an infectious diarrheal disease caused by strains of *vibrio cholerae*, a bacterium mainly proliferating via the fecal-oral route, i.e. the ingestion of water and food contaminated with human feces that contain the pathogen. Cholera's symptoms include watery diarrhea and vomiting, leading to severe dehydration and reduced electrolytes concentration. If untreated, cholera may cause death within a few days with a mortality rate of 50 to 60%. While ingestion of *vibrio cholerae* does not necessarily lead to a full-blown clinical picture and lethal danger, the disease also spreads via the feces of mildly affected cases. Although risk factors and appropriate treatment methods are well understood, cholera continues to claim up to 100,000 lives worldwide each year due to inadequate sanitation, contaminated water supplies and deficient domestic hygiene. In the industrialized countries, however, the disease has become rare and mainly contracts via seafood (GTFCC, 2017).

The road to understanding cholera's origin, spread, and appropriate methods of prevention has been long and bumpy and is not yet completed. A dominant interpretation states that cholera, while having been endemic to the Indian subcontinent for centuries, was introduced to the rest of the world via the 19th century's routes of commerce and colonial exchange, subsequently becoming a global phenomenon. The narrative of an essentially "Asiatic cholera", however, has been questioned and recent biomedical evidence suggests that *vibrio cholerae* may be a much more universal vector (Hamlin, 2009b, 19–51). In any case, periodic pandemics since the 1820s sparked European physicians', medical scientists' and public health advocates' interest throughout the 19th century. When cholera first reached Western Europe in the 1830s, it quickly replaced the plague and smallpox as the most dangerous and unpredictable disease in popular imagination (Evans, 1987, 228–230).[4]

Cholera's periodic outbreaks gave rise to controversial debates and a wide spectrum of theories of the disease's nature and spread. While many contemporaries held eclectic views, some distinct lines of reasoning can be identified, allowing us to structure the contemporary debate. Broadly speaking, the *autochtonists* speculated that cholera could occur at every place and at every time, being triggered by unfavorable local characteristics, such as a certain atmospheric pressure, weather conditions or the humoral changes of the population. In contrast, the *ephodists* proposed that the disease originates at specific points in space and subsequently spreads along routes that, in principle, can be understood and manipulated. Among the ephodists, the *contagionists* believed

[4] See Hamlin (2009b) for a recent social history of cholera. Classical historical accounts of cholera include Pollitzer (1959, 1–50) and Ackerknecht (1965, 22–32).

that cholera transmits through direct or indirect contact between an infected host and another potential host, possibly through an unobservable germ. The *localists* postulated that cholera spreads whenever an infected host successfully contaminates properties of the local area, causing cholera's unknown transmission agent to develop in that locality and subsequently affect others in the same area.[5] While certain autochtonist and contagionist explanations remained popular until the 1850s, their repeated failure to explain observed incidence patterns led to the successive development of more complex, localist theories. For instance, by the 1860s, the German scientific community increasingly converged on Bavarian hygienist Max von Pettenkofer's (1818–1901) soil theory (*Bodentheorie*), that proposed that cholera's agent transmitted through the inhalation of miasma, i.e. foul air arising from moist, porous soil contaminated with decaying matter.[6]

Given cholera's mysterious observable properties, this wide spectrum of conflicting theories is hardly surprising. The disease was epidemical, usually occurring in warm, humid weather. Typically, it raged on for several months until the weather got colder and dryer. Yet it did not appear every year, leading some observers to suspect an influence of meteorological fundamentals. In some instances, cholera would hit the same place in several consecutive epidemics. In others, it would spare an area for some time while affecting other places. From a bird's eye perspective, it clearly followed a spatial contagion process, migrating along trade and sea routes from Asia to Western Europe and North America via Russia and Eastern Europe. Yet on the local level, contagionist explanations often failed as neighboring streets and even houses would exhibit very different incidence patterns despite regular contact between their inhabitants. Furthermore, family and nursing personnel that was in frequent direct contact with the infected or their clothes would only sometimes show symptoms of the disease. Localist explanations, however, also had their weaknesses as the same house, street or city could experience many cholera cases in one year while being spared in other years despite unchanged local properties such as moisture, vicinity to open water bodies, soil quality, ventilation or even its population's social status. Cholera, while not the deadliest disease of the 19th century, was arguably the most mysterious, unpredictable, and terrifying one, an impression reinforced by the swift death and dramatic changes to the victim's outer appearance it brought about.

Even after evidence for the fecal-oral transmission mechanism mounted, an immediate policy change was not likely. This was both due to the plethora of

[5] The distinction between autochtonists and ephodists originates in medieval pestilence theories (Winslow, 1944, 322). It was applied to the German cholera debate in von Pettenkofer (1887)'s classic treatment on the state of cholera research. An alternative classification by Hamlin (2009b, 152–162) aims at capturing commonalities across national scientific communities and stresses differences in scientific reasoning between positivist anticontagionists, miasmatist anticontagionists and contagionists.

[6] See Winslow (1944, 311-336) and Raschke (2007) for a detailed depiction of von Pettenkofer's soil theory. For an overview of the 19th century discussion on cholera's etiology, see Hamlin (2009b, 331–335) and Otto et al. (1990, 293–297). Briese (2003a, 92–162) provides a detailed account of the 1830s transition from pre-miasmatist to miasmatist views.

competing etiological views and both policymakers' and researchers' inability to discriminate among them. In a quasi-experimental study of the London outbreak of 1854, John Snow had provided convincing evidence for the fecal-oral transmission. He suggested that the disease spread via the ingestion of water contaminated with germs and motivated a proto-epidemiological approach to illustrate his findings (Snow, 1855).[7] However, while Snow's findings were initially taken seriously by his English peers, their policy impact was limited (Smith, 2002). For instance, London's Board of Health deemed Snow's evidence inconclusive and declared that the 1854 cholera epidemic originated in miasma. If hardly translated to policy in Britain, Snow's findings were ignored elsewhere. In Germany, for instance, Drasche (1860, 146–176)'s voluminous survey of cholera research dedicated far more space to von Pettenkofer's refutation of the "drinking water theory" (*Trinkwassertheorie*) than to the discussion of Snow's findings. Similarly, Berlin-based physician and medical historian August Hirsch's (1817–1984) survey published in the same year states that "moisture penetration" (*Durchfeuchtung*) of the soil is the "primary causal moment of cholera's genesis" while drinking water plays no role (Hirsch, 1860, 141). By the 1880s, when the relatively isolated national medical research communities slowly began their convergence to the germ theory of disease, increasingly complex miasmatist approaches still dominated much of the discussion (Briese, 2003a, 311–316). Despite Snow's evidence, the confusion about the causes of cholera thus carried on for another quarter, if not half, of a century.

It was only since the 1880s that researchers, in particular Robert Koch, were able to demystify cholera. Koch isolated cholera's "comma bacillus" in 1883 and slowly convinced the German community of cholera's water-based transmission.[8] However, when Koch pushed his findings at the 1885 Second Cholera Conference in Berlin, he met with hostility not only from his German adversary von Pettenkofer but also from French and British delegates, who blocked any discussion of cholera's etiology (Ogawa, 2002; Raschke, 2007). The "modern triumph of natural science over infectious disease and epidemics" (Otto et al., 1990, 286) and with it the universal acceptance of cholera's fecal-oral transmission route emerged only towards the end of the 19th century. In the meantime, cholera made a last deadly visit to Hamburg in 1893, killing more than 8,600 inhabitants and allowing Koch to demonstrate the proliferation of the cholera germ via contaminated drinking water through his own difference-

[7] Snow is often considered the father of both difference-in-differences designs (Lechner, 2011) and spatial epidemiology (Johnson, 2005). However, contrary to popular notions, his belief in the water-borne nature of cholera originated neither from his famous dot-density maps, nor from his comparative study of London wards. Snow had already argued against dominant miasmatist theories and speculated on the germ-based transmission of cholera via drinking water in the first edition of his treatise (Snow, 1849), adding maps and comparative quantitative evidence to support his point in the later edition (Snow, 1855). See Vinten-Johansen et al. (2003) for a recent biography of Snow.

[8] Italian anatomist Filippo Pacini (1812–1883) already identified the cholera bacillus in 1854, but his findings remained unnoticed and inconsequential. French biologist Louis Pasteur's (1822–1895) 1860s work on the germ theory of disease was highly instrumental to Koch's findings (Winslow, 1944, 291–310). See Brock (1988) for an English language biography of Koch.

in-differences analysis (Evans, 1987, 285–402).

3 "The Great World Pestilence" in Berlin

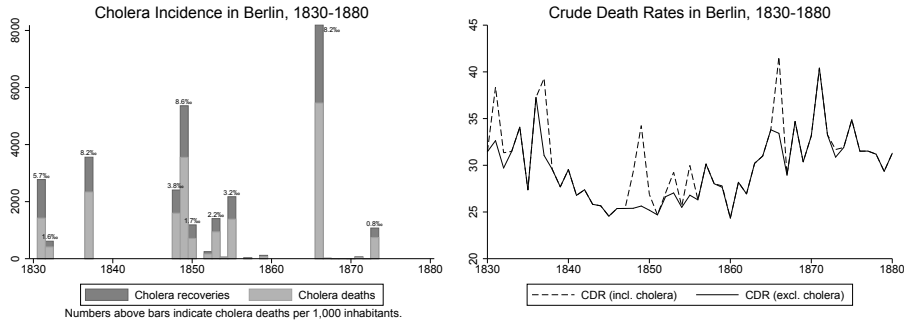
Like many other Western European cities, 19th century Berlin had a long experience with various gastrointestinal diseases, including bundles of mild cholera-like diarrheal symptoms that would later be termed *cholera nostra*, "our cholera". While "European cholera" was considered mild and tameable, the "Asiatic cholera" approaching Western Europe during the second pandemic of the 1830s was perceived as a highly dangerous intruder alien to the classical European disease panorama and to be stopped at all costs. Despite the Prussian authorities' *cordon sanitaire* to the East, the "real cholera" eventually made its way to the West, claiming its first officially documented victim in Berlin on August 30th, 1831, when Johann Christian Mater, a boatman from Magdeburg, died on his barge on the river Spree near the Schiffbauerdamm (Wagner, 1832, 192–193).[9] Two days later, the civil defense commission officially stated the outbreak of cholera in Berlin. By June, Prussian king Frederick William III had already established a health committee (*Gesundheits-Comité*) for Berlin whose foremost task was to enforce a quarantine on any affected person, household or building in order to contain the spread of cholera. Isolation of the affected proved largely ineffective and cholera raged through the city until mid-January 1832, causing 2,274 sick cases (11.2‰ of the population) of which 1,423 died (5.7‰ of the population). A prominent victim was philosopher Georg Wilhelm Friedrich Hegel, who died on November 14th, 1831. On February 9th, 1832, Berlin's health committee declared the official end of the epidemic, and festivities followed to celebrate the defeat of the invisible enemy.

These victory celebrations, however, did not last long. Cholera made a quick comeback only months later and the 1832 summer epidemic claimed another 412 lives in Berlin. While cholera spared Berlin over the following years, the pestilence returned in August 1837, somewhat unexpected since the nearest infected city at the time was distant Breslau. While it only lasted until early December, the 1837 epidemic had an even more devastating impact than Berlin's first epidemic six years earlier, affecting 12.6‰ and killing 8.3‰ of the population. Cholera, it seemed, had become a regular guest in Berlin. As quarantine-based prevention measures proved largely ineffective, official provisions increasingly turned to disinfection (Dettke, 1995, 304–308). After a decade without cholera, the "enemy advancing from the East" (Schütz, 1849, 10) made its comeback in August 1848. Only a few weeks after the violent clashes of the March Revolution abated, Berlin was among the first German cities hit during the third worldwide pandemic. The next three years saw a combined cholera death toll of 5,858 inhabitants with the 1849 epidemic killing 8,6‰ of the population. While no

[9] One day earlier, shipman Johann Wegener died of cholera in the neighboring city of Charlottenburg, today a part of Berlin. See Hartmann (2015, 36–53) and Dettke (1995) for Berlin-specific cholera histories and the *cordon sanitaire* in particular. Briese (2003b) documents contemporary reactions to the 1831/1832 epidemic in Berlin.

cases of cholera were recorded in 1851, the following years saw continuous minor outbreaks, fueling the fear that "the Great World Pestilence" (Müller, 1851, 125) had finally become endemic to Berlin and the German lands. However, this fear was quickly disproved as cholera once again disappeared, sparing Berlin between 1860 and 1865. In sum, while there were periods of relative tranquility, cholera repeatedly caused significant losses of life in Berlin the twenty years following the first outbreak.

The final major outbreak came in 1866, claiming 5,451 deaths, that is 8,2‰ of Berlin's population. When the 1866 outbreak faded by mid-November, contemporaries were not so quick to proclaim that the worst was overcome. As August Hirsch (1867, 300) wrote, "one does not need the power of divination to predict, based on our past experience, that a grim future awaits us. [...] [It seems that the people] have not yet paid their tribute to this sinister Asiatic guest and many more tears will flow and hearts will break." However, apart from a minor outbreak in 1873, the tribute was actually paid. Over the 19th century, it amounted to 18,925 documented deaths (see figure 1).[10]



(a) Absolute and relative cholera incidence.

(b) Crude Death rate with and without cholera deaths.

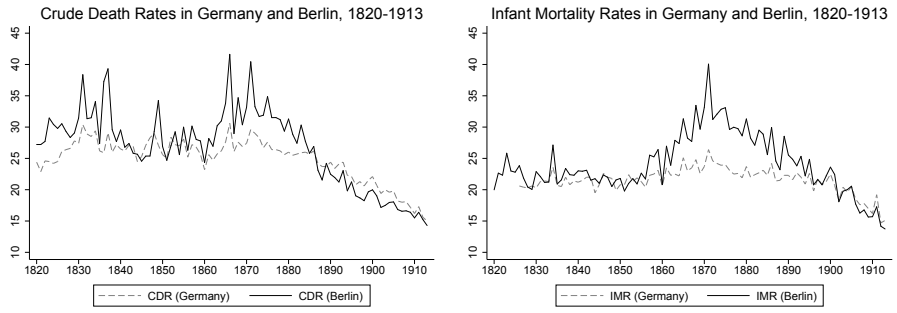
Figure 1: Cholera incidence in Berlin, 1830–1880

While cholera made a horrifying lasting impression on contemporaries, it was by no means the deadliest element of the urban disease panorama. Over the second half of the 19th century, Berlin experienced elevated death rates due to various other infectious diseases, such as typhoid fever, diphtheria, and tuberculosis. In line with the experience of other growing cities, Berlin's crude and

[10] Hartmann (2015, 36) counts 28,657 deaths, but this is approximately the total number of documented sick cases, thus including recoveries. While misspecification of causes of death is a serious problem for historical mortality research, this is less of an issue regarding cholera. While cholera's symptoms partly overlap with those of other gastrointestinal diseases, fatalities were clustered during epidemics and cholera had already been studied by Prussian physicians during their visits in St. Petersburg and Moscow in the late 1820s and early 1830s (Hartmann, 2015, 39, Vögele, 1998, 25). Accordingly, contemporary sources on cholera incidence in Berlin only differ by small amounts. All numbers presented here are taken from Müller (1874, 20), Müller (1867, 5, 7) (for 1854, 1857, and 1859), SJB, 1878, 61 (for 1867 and 1868) and Böckh (1884, 57) (for 1869, 1870, 1872, and 1874–1878).

infant mortality rates increased over the second half of the 19th century, both in absolute terms and relative to rural areas (see figure 2).[11] Air-borne and water-borne infectious diseases were the main drivers of the "urban penalty" characteristic of the 19th century urbanization process (Vögele, 1998, Gehrmann, 2011, Witzler, 1995, 33–38).

In hindsight, Berlin's "urban penalty" and her "cholera experience" were neither unique nor particularly dramatic compared to other urban centers of the 19th century (Vögele, 1998, 229–260, Dettke, 1995, 208–251). This makes Berlin a particularly well-suited case study, at least for the northern European hemisphere. With today's knowledge, it is not hard to understand why cholera raged in a repeated, yet seemingly erratic fashion. Berlin had experienced rapid population growth since the 1850s, bringing about the typical problems of increasing density, pollution, congestion and the consequent spread of infectious diseases. Commercial travelers repeatedly carried *vibro cholerae* from the East and introduced the bacillus to the local cesspools, which in turn contaminated the water of the nearby wells, spreading the disease among the population. Berlin's international connections made it an ideal candidate for initial transmission, and dense living conditions and inadequate sanitary conditions rendered the city an ideal transitional habitat for *vibrio cholerae*. As the bacillus does not survive in temperatures below roughly 10 degrees Celsius, Berlin's cold winters guaranteed that cholera did not become endemic.



(a) Deaths per 1,000 inhabitants (b) Infant deaths per 1,000 live births

Figure 2: Mortality rates in Germany and Berlin, 1820–1913

[11] The crude death rate (CDR) is defined as total deaths per 1,000 inhabitants. See SJB, 1913, 109–110 for CDRs in Berlin and Mitchell (1976, 106–116) for CDRs in Germany. The infant mortality rate (IMR) is defined as infant deaths (excluding still births) per 1,000 live births. See SJB, 1913, 172* for IMRs in Berlin and Gehrmann (2011, 849) for IMR in Germany.

4 Tap Water: A Matter of Cleanliness and Comfort

Until the late 19th century, Berlin was not exactly among the aesthetically and olfactorily most pleasing European cities. As a popular proverb stated, "Berlin's gutters stink". Increasingly, the traditional water infrastructure based on pump wells and the river Spree's natural absorption capabilities failed to cope with the liquid and solid waste produced by a rapidly growing population and expanding industry. However, despite Berlin's emerging importance as a political, cultural, and thus representative center, the Prussian capital was late in adopting a modern tap water supply system. Paris had a tap water supply since 1802, London since 1808. Only by the 1850s, Berlin introduced its own supply that would allow cleaning the streets, gutters and yards and flushing filth into the Spree, where it then could dilute and drain out of sight. The origins of Berlin's tap water network are complex and reflect a wide array of motives and interests, such as aesthetic concerns, economic incentives, and political conflicts. The prevention of cholera, however, was not among them.[12]

Delayed reform and lack of demand. The decisive impetus toward modernizing Berlin's water supply came from the police department, at the time subordinated to the Prussian state rather than the municipal administration. Berlin's old stone-line gutters and inadequately paved streets could be trusted less and less to drain rain and dispose of liquid waste into the flowing rivers and canals. Solid waste increasingly blocked gutters, piled up and disseminated stench. As gutters were not sealed, waste also trickled into the soil, potentially contaminating the groundwater sources. While urban filth and stench were not a new phenomenon, the increasing mismatch between the traditional water supply's limited flushing capacities and growing waste production resulted in an environmental, aesthetic and sanitary crisis of novel intensity. Charged with cleaning streets, gutters and public spaces, the police and its firefighting and street sprinkling divisions yearned for a tap water supply that would put an end to the cumbersome practice of manually pumping water into tank vehicles. Backed by the Prussian king and aesthetician Frederick William IV (1795–1861), police superintendent Karl Ludwig Friedrich von Hinckeldey (1805–1856) addressed a series of appeals to Berlin's magistrate, seeking the commission of a central tap water supply network.

However, throughout the 1840s, the city council and magistrate remained reluctant and rejected several approaches to the construction of a new supply network. Influential property owners feared bearing high construction and operation costs, especially after the costly municipalization of Berlin's gasworks in 1847. The larger public did not exert much pressure, being mostly satisfied with Berlin's ample well water sources and remaining unaware of the comforts and potential health benefits, that tap water could supply.[13] While acknowl-

[12] For a detailed German language account of Berlin's water supply history, see Mohajeri (2005). Grahn (1898, 20-40) provides a concise, contemporary overview. Unfortunately, no detailed English language accounts are available.

[13] Situated in a water-rich glacial valley and blessed with more than 100 days of annual rain-

edging that the accumulation of urban filth and stench presented a nuisance, the city administration pointed out the state's responsibility for the problem and saw no pressing economic or sanitary needs that would justify a financial commitment. By the end of 1852, Berlin mayor Heinrich Wilhelm Krausnick (1797–1882) stated that a tap water supply would arguably be convenient, yet not essential for sanitary reasons as the numerous cholera epidemics of the past had been more benign on Berlin than on other cities and there was no proof that the lack of a central water supply facility had any connection to the appearance and spread of cholera (Rutz, 1969, 231). As Mohajeri (2005, 44) notes, both the absence of cholera-related arguments in contemporary discussions and the lack of involvement of medial or sanitary officials cast doubt on the idea that cholera played a motivational role in the emergence of Berlin's tap water network.

A contract with far-reaching consequences. In 1852, a royal edict allowed von Hinckeldey to bypass the reluctant city administration and push the reform process forward. Impressed by the modern waterworks that operated in some English cities, he entered negotiations with London-based businessmen-engineers Charles Fox (1810–1874) and Russel Crampton (1816–1888). While maintaining formal correspondence with the magistrate and promising to consider municipal interest, the police superintendent managed to effectively pass over the city's civil representatives. Crucially, the city magistrate insisted that any contract should include provisions for the commissioned party to accumulate funds to finance the construction of a sewage disposal system that could handle the expected increase in wastewater. Von Hinckeldey, however, preferred a cheap and timely solution, discounting the importance of accompanying sewers.

The final contract, signed by the police department and the English businessmen on December 14th, 1852, clearly reflects the relative dominance of the royally empowered police department and its narrow focus on street cleaning. The "Berlin Waterworks Company" would provide tap water for cleaning, sprinkling, firefighting and five public fountains free of charge. In return, the company obtained a 25 years monopoly and the right to charge private customers in order to finance regular dividends and a net profit rate of up to 15%. Provisions for handling wastewater turned out minimal: Once the dividend reached ten percent, one percent of the annual profits were to be saved for the eventual construction of sewers, a stipulation that in hindsight proved completely inadequate.[14] Apart from not being able to ensure a proper wastewater disposal

fall and easily accessible groundwater, Berlin's private water demand was easily covered by countless public and private pump wells. Well into the first third of the 19th century, contemporaries rated the well water quality as satisfactory. For instance, in his "Medical Topography and Statistic of Berlin" of 1844, physician Hermann Wollheim (1817–1855) counted 600 public wells and "a backyard well for almost every bigger dwelling", yielding ample drinking, cooking and cleaning water for 330,000 inhabitants in varying, but generally satisfying quality that was guaranteed by the sandy soil's natural filtering capacities (Wollheim, 1844, 89).

[14] With acrid irony, the magistrate's administrative report of 1861-1876 states: "If Mr. von Hinckeldey had really believed that this contract would ensure the provision of sewers for Berlin, clearly his sanguine character had deceived him, just as it deceived him regarding the anticipated beneficial effects that the water supply would have on the state of the streets and gutters" (BüGVdSB, 1880, 119).

infrastructure, the magistrate failed to secure a formal saying in the company's business policy, only getting the option to serve as a minor silent partner to the enterprise. Collectively, the magistrate's initial unwillingness and lack of initiative, the private company's profit motives, and von Hinckeldey's narrow focus on cleaning the streets of the Prussian capital ensured that it would take another 25 years until the construction of sewers would complement the tap water supply. There has been no systematic analysis of the health consequences of Berlin's early tap water supply so far, but cholera's deadly return in 1866 and the continuing incidence of other infectious diseases suggest an ambiguous role at best.

Delayed expansion and lack of supply. With the conflict between the police department and the city administration dissolved by *fait accompli*, the following two decades were characterized by tensions between a magistrate that discovered the benefits of private tap water consumption and a commercial company that slowly turned "from an innovative motor to an inhibiting factor" (Mohajeri, 2005, 63), holding back further extensions of the supply network. Construction of the first waterworks at the Eastern Stralauer Tor began in 1853, commencing operation on July 1st, 1856.[15] The initially low expectations of private water demand are illustrated by a contractual stipulation that committed the company to lay out only 60.3 kilometers of pipes, far less than would be needed to supply all of Berlin. Both the spatial extension of the network and the connection of individual houses within the network's extent were a matter of private supply and demand. However, while residents and property owners seemed quite uninterested in the new technology at first, soon private demand increased markedly and a tap water connection became a well-sought feature on Berlin's rental market (see figure 3).[16]

Further expansion of the water supply network and its supplementation by sewers was impeded as the city magistrate and the "Berlin Waterworks Company" were incapable of solving a central incentive problem. The private company claimed that it could not amortize the fixed costs of further investments unless its monopoly privilege was extended for another 25 years. However, such an extension of the contract conflicted with the magistrate's goal to eventually municipalize the company. Observing the company's unwillingness to extend the network, city representatives increasingly discussed the option of buying the company even before the original contract ran out, in turn further lowering private investment incentives. As a result, the network ceased to expand after 1865. Most streets in the growing Northern and Eastern outskirts did not yet feature water pipes and even the cleaning and sprinkling services were increas-

[15] The water was drawn upstream from the river Spree, filtered by sand, and stored in overground reservoirs that were covered since 1858. The water quality, while probably hazardous by modern standards, seemed acceptable to contemporaries, both compared to other cities and Berlin's well water (Mohajeri, 2005, 47–48).

[16] One has to be careful in interpreting annual connection rates as a measure of demand, as sources indicate that the company experienced severe technical difficulties and actual provision was thus lagging behind private demand (Mohajeri, 2005, 61). The annual number of connected lots is given in Grahn (1898, 36). The annual number of lots in Berlin was transcribed from various editions of the statistical yearbook.

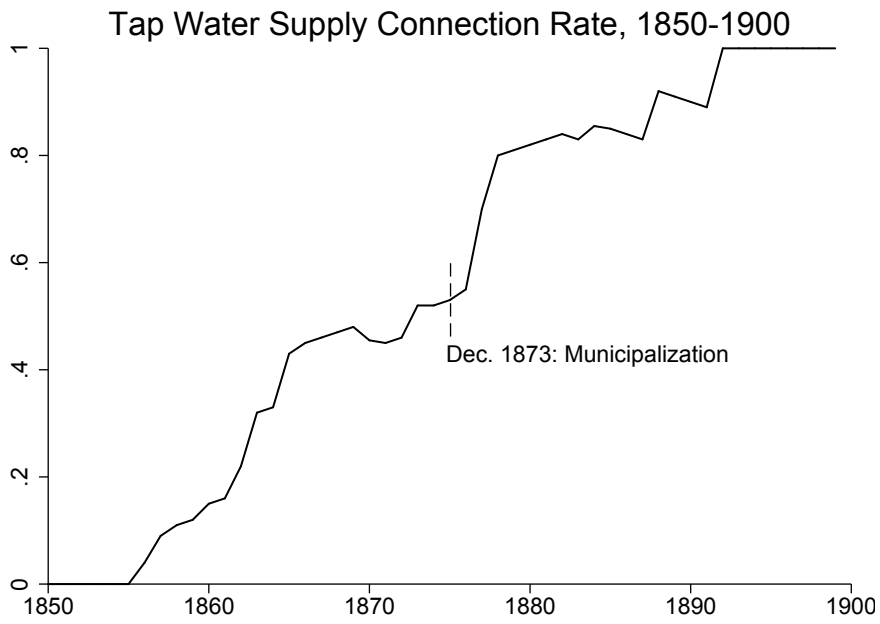


Figure 3: Share of Berlin's lots connected to the tap water supply, 1850–1900.

ingly hampered by water shortages. Despite von Hinckeldey's hopes, Berlin's streets and yards remained filthy. Although being equipped with free-of-charge tap water, the street cleaning services could not compensate for the wave of waste that a rapidly increasing population, now aided by comfortable water flush, emitted to the gutters. Furthermore, there was no hope that the construction of sewers could begin under the present contractual setup. Backed by popular opinion and the police department, and increasingly realizing the hygienic benefits of tap water provision, the city bought the company in December 1873, seven years before the original contract expired.[17]

Tap water and cholera: A complicated relationship. Municipalization largely solved the problems of the initial arrangement, albeit at great cost to the city treasury. After 1873, the capacity of the waterworks and the network's spatial extent continuously expanded and, aided by compulsory connection requirements, 100% of Berlin's lots were provided with tap water by 1892. The operation of sewers that could safely handle the increasing volume of wastewater

[17] Many subsequent treatments tend to paint this episode as a struggle between a well-meaning, far-sighted magistrate and private company interested only in short-term profits. However, the company was probably right in expecting not to be able to amortize further investments over the remaining contract duration as it was only able to realize stable profits by the 1860s and had to compete with approximately 9,900 free-of-charge pump wells across the city (Mohajeri, 2005, 28). The refusal to further extend the network was thus a rational reaction that could have been predicted at the time of the contract's commission.

began by 1878 and cholera only made a last mild appearance in 1873.

With hindsight, Berlin's delayed and ineffective transition from an essentially medieval, increasingly hazardous well-based water supply to a modern, relatively safe tap water supply can be attributed to the magistrate's initial indifference, low demand on part of residents, a complicated separation of authority and tasks among the narrowly focused Prussian state and the city administration, and a mismatch between the profit motives of the private contractor and the changing interests of the magistrate. However, contrary to what increasing cholera incidence since 1848 might suggest, water-borne diseases neither "forced", nor marginally motivated the emergence of Berlin's tap water network.[18] Moreover, contemporary failure to understand the adverse repercussions that an ample tap water supply would have on an urban water cycle that still lacked safe sewage disposal mechanisms may well have contributed to the urban health crises and cholera's incidence in particular. Thus, at least until the advent of centralized sewers in the late 1870s, the causal nexus between Berlin's tap water supply expansion and cholera is far from straightforward.

5 Sewers: Miasmatic Plague Tubes or Sanitary Solution?

While centralized wastewater disposal systems and tap water supply networks are characterized by important complementarities, most European cities introduced the former with a considerable lag relative to the latter (Vögele, 1998, 152, 262, Büschenfeld, 1997, 24, Gallardo-Albarràn, 2018, 7–10). Berlin was no exception to this rule, opening sewers in some parts of the city in 1878, i.e. more than two decades after the opening of its tap water supply. Clearly, the fact that the construction of wastewater disposal systems is both technically more challenging and financially more demanding partly accounts for this timing of events. Furthermore, sewers rely on a steady supply of large volumes of water flush provided by piped systems. In contrast, early tap water systems did not technically depend on accompanying sewers, although once in operation they incentivized waste disposal reform due to increasing water use and wastewater production (Büschenfeld, 1997, 24, 34–41). However, while the order of events in Berlin's water infrastructure transition is no mystery, the large gap between tap water provision and the construction of centralized sewers calls for an explanation. Insufficient financial provisions in the private-public tap water contract provide an idiosyncratic proximate cause, but the underlying question remains why sewers were seen as essentially expendable until the 1870s. By then, comparable European cities had already experimented with various forms of sewers, albeit often with a focus on surface drainage rather than sanitation (Gandy, 1999). London built sewers from the late 1850s on, Paris even in the early 1850s. Hamburg (1842), Leipzig (1860), Chemnitz (1864), Frankfurt (1867),

[18] Many popular accounts nonetheless ascribe a leading role to cholera prevention in Berlin's water supply history. See Mohajeri (2005, 44) for an overview.

Zurich (1867) and Prague (1868) also beat Berlin to the construction of sewers. An important reason for the long lag are ambiguous contemporary expectations regarding the effect that sewers would have on cholera. While infectious diseases motivated sanitary reform, Berlin's experience suggests that a solution based on sanitary sewers was far from inevitable.[19]

Traditional waste disposal under pressure. Before the introduction of sewers, Berlin's primary mode of waste disposal was to channel liquid waste into the river Spree via open or provisorily covered street gutters, while solid waste was stored in backyard cesspools and tons, occasionally collected by haulers who sold organic waste to the agricultural hinterland. As the poet Friedrich Rückert (1788–1866) observed, the river Spree "enters Berlin as a swan and exits it as a pig", serving as the city's ultimate waste disposal system (quoted in Hartmann (2015, 37)).[20] Contemporaries had discussed the prospect of proper sewers since the 1840s. For instance, Hermann Wollheim (1844, 129–130) argued that "the construction of underground drainage pipes, as they exist in many big cities, would be a great boon to Berlin [...] [and] in order to put an end to the pollution of water bodies, [...] sewers should be preferred to all other solutions". However, while omnipresent filth and stench presented a nuisance, polluted water bodies were primarily considered an aesthetical problem that, in the eyes of the city administration, did not obviously justify the financial and technical efforts linked to the construction of sewers.

Pressure to reform the city's outdated waste disposal infrastructure mounted by the 1860s as population growth and the increasing availability of tap water and water closets exacerbated the urban waste problem. While von Hinckeldey's police department had hoped to clean the streets with water flush, households increasingly took up the opportunity to comfortably dispose of their solid waste directly into the gutters.[21] As high volumes of semiliquid waste flew into the river Spree, it lost its capacity as natural disinfector and diluter, turning itself into a "large cesspool" (Hartmann, 2015, 149). Aside from the aesthetic challenge, hygienic concerns now motivated reform as popular miasma theories suggested a connection to the deteriorating urban health conditions and cholera in particular.

"Kanalisation oder Abfuhr?" A growing consensus of the need for reform, however, did not obviously suggest that Berlin needed sanitary sewers. Rather, the 1860s saw lengthy debates centered on the question whether all waste should

[19] For a detailed German language treatment of Berlin's wastewater disposal history, see Mohajeri (2005). Gray (2014) provides a concise English language overview.

[20] Waste disposal was regulated by the 1660 "well and alley ordinance", formally prohibiting the pollution of public and private wells. In 1814, direct disposal of solid waste into the river was limited to night hours. By 1842, it was explicitly forbidden to dispose of solid waste into the city's gutters or open water bodies. Yet, the comfortable practice of throwing excrements and solid kitchen waste into the river Spree was continued, often conducted by the infamous "night soil women". Property owners were responsible for the cleanup of cesspools and pavements, a task which the often neglected (Wollheim, 1844, 130).

[21] Furthermore, agricultural demand for manure could not absorb the growing masses of excrements and the hauling business became unprofitable, amplifying incentives to flush waste into the gutters (Gray, 2014, 281).

be handled by a mixed sewer system (*Mischkanalisation*) or solid waste should be stored in sealed and manually dischargeable tons (*Abfuhrsystem*) in order to isolate excrements and other solid foul smelling, suspicious substances from the water cycle. The Prussian government favored mixed sewers and installed an expert committee composed of urban planner James Hobrecht (1825–1902), public works director Eduard Wiebe (1804–1892) and civil engineer Ludwig Alexander Veitmeyer (1820–1899), charged with developing a plan to "canalize" Berlin. The resulting *Wiebe-Plan* proposed to discharge both liquid and solid waste into the river Spree, just downstream of the neighboring community of Charlottenburg (Wiebe, 1861). While the city magistrate largely supported the plan, a broad opposition composed of city council members, landlords, agricultural producers and haulers pushed for the discharge system, proposing to replace the cesspools by sealed and transportable containers, ban water closets and burden the Spree only with excrement-free liquid waste and rainwater (Gray, 2014, 284).

A decade-long conflict was fought out in a top-level "mixed deputation" composed of city council and magistrate representatives, involving various issues such as financial costs, agricultural needs, technological feasibility, geological conditions, and aesthetic consequences. The sanitary and hygienic effects of both approaches, however, seemed unclear as prevailing miasma-based theories could be levied to lend support to both mixed sewers and the discharge system. In particular, Wiebe argued that sewers would efficiently dilute solid waste, thereby depriving it of its miasmatic agents. Furthermore, underground sewers would drain the soil of moisture, thus further mitigating its miasma-generating properties, while even the most careful handling of discharge containers could not guarantee the isolation of miasma-producing waste. Another stated advantage of the Wiebe's plan was that the continued use of water closets would increase household hygiene. Supporters of the discharge system argued that Wiebe's sewers were nothing more than the old gutters writ large. Friedrich Behrend (1866, 3–4), responsible for the mixed deputation's sanitary assessment, called the projected sewers "the biggest sanitary disaster that Berlin could ever experience". He pointed to English cities like London that stank of rotten organic material and supposedly saw their rivers and soils polluted and their wells rendered unusable by leaking, congested sewers. Special attention was given to the problem of "sewer gases" that supposedly bred in the closed, stagnant and unaired underground pipes and would search their way into private homes, exploding in a violent manner and endangering the health of everyone in their vicinity (Behrend, 1866, 17).[22] While both sides agreed that "to the extent that our understanding of the harmful influences of decay products as the main cause of the most dangerous and deadly epidemics (typhoid fever, cholera, dysentery, diphtheria, etc.) grows, it becomes exceedingly imperative

[22] Behrend also stated that the English prince consort was killed by exposition to sewer gases, "as is well-known" (RuE, 1870–1879, 17). Supporters of the mixed sewers approach took the problem of sewer gases very serious, as can be seen by the fact that Wiebe's plan featured ventilation shafts at every connected home in order to channel fumes into the air (Gray, 2014, 288–289). Yet, as a summer visitor to 21st century Berlin will quickly notice, the problem of sewer gases was never solved.

to thoroughly and swiftly withdraw these products from the densely populated areas" (Behrend, 1866, 5), prevailing miasma theories were rather complicating the choice between sanitary sewers and the discharge system.[23]

How to neutralize contaminated sewage? Eventually, the decision in favor of mixed sewers was not induced by the forces of argument and consensus, but rather because the Prussian government saw a chance to push its preferred solution by introducing physicians and public health experts to the debate. A "Royal Scientific Deputation for the Medical System" (*Königliche wissenschaftliche Deputation für das Medicinalwesen*) was formed in 1865. Headed by the *Charité* hospital's head of the pathology department and liberal city councilor Rudolf Virchow (1821–1902), the deputation published a sanitary report in favor of sanitary sewers (Virchow, 1868). Virchow had always been critical of contagionist arguments, but his views on cholera's etiology and the role of drinking water changed throughout his life and remained rather eclectic. While being sympathetic to Max von Pettenkofer's soil-based theory and his statistical approach to epidemiology, Virchow nonetheless put less emphasis on miasma and suspected that water hygiene played a key role.[24] The deputation's report found that "groundwater has thus a twofold role [in the spread of fecal contamination]. It transports contaminating agents into both the well water and the atmosphere. The more the groundwater table rises, the more such agents trickle into the wells; the more the groundwater table falls, the more miasma the drying soil releases into the air" (Virchow, 1868, 21). Virchow's deputation claimed that sewers were the only viable answer to the mounting urban health crisis.

Virchow's deputation finally buried the ton-based discharge option, but it also questioned Wiebe's sewers plan. The deputation strongly objected to the use of the river Spree as ultimate waste disposal site, arguing that the planned direct feed-in of sewage would only proliferate pathogenic agents downstream as water-based dilution alone was not an adequate method of neutralization. Preferably, sewage should be channeled to rural seepage farms (*Rieselfelder*) where the natural filtering capabilities of the soil would decontaminate the wastewater before it rejoined the groundwater reservoir.[25] Proponents

[23] The lengthy discussions of the mixed deputation are documented in RuE, 1870–1879, albeit biased in favor of the magistrate's pro-sewers agenda (Mohajeri, 2005, 76-77).

[24] However, while coming close to singling out cholera's fecal-oral transmission mechanism, Virchow nonetheless never identified cholera as a water-borne disease and hesitated to draw definitive conclusions from what he saw as insufficient evidence. See Virchow (1879a, 128-214) and Virchow (1879b, 203–470) for his major works on cholera and Evans (1987, 273-275) for a contextualized discussion of Virchow's etiological views.

[25] See Gray (2014) for a historical overview of Berlin's seepage farms. From today's perspective, the seepage system was ecologically problematic, but certainly preferable to the direct feed-in of untreated sewage to the rivers. Two further objections to Wiebe's plan concerned the deficient inner-urban isolation of sewage. Virchow feared that Wiebe's relatively high-lying drains would actually exacerbate the problem of contaminated groundwater seeping into the city's basements, thus calling for much deeper sewers that could drain and decontaminate Berlin's moist soil. Furthermore, Wiebe's plan featured inner-urban emergency discharges into the river Spree. Suspecting that the direct communication between sewers and urban water bodies was responsible for the continuing contamination of the rivers Elbe and Thames,

of Wiebe's plan, while acknowledging the miasmatic dangers of insufficiently diluted waste, trusted the river's "self-healing capacity" (*Selbstheilungskraft*) and judged the seepage farms a greater danger that would reintroduce harmful agents to the urban water supply and spread pestilence across the urban hinterland.[26] Evidently, while the discharge system was now out of question and the debate finally centered on sanitation, health and hygiene, prevailing etiological theories of cholera and other infectious diseases could not resolve the conflict between advocates of Wiebe's direct feed-in and proponents of the seepage farm concept. Consequently, cholera's fatal return in 1866 did not trigger a swift decision and further years of tedious discussion, analysis and polemics followed. Eventually, an extended deputation headed by Virchow convinced Berlin mayor Arthur Hobrecht (1824–1912) to abandon Wiebe's plan and consider the alternative project of his brother James Hobrecht.[27]

The Hobrecht plan and popular resistance. Hobrecht's technically ambitious mixed sewer plan entered the discussion in the early 1870s and passed the relevant administrative hurdles by 1873. While the possibility of private construction and operation was briefly discussed, the municipal administration voted for a full-blown public endeavor, including compulsory connection, co-financing by fees and elimination of all cesspools. Construction of the first pumping station at the Southern Landwehrkanal began in September 1873 and on January 1st, 1878, the sewers started operation with 2,415 houses connected to 80 kilometers of pipes.[28] By 1881, large parts of the inner city linked to the sewers and by 1896, Berlin reached full coverage (see figure 4).[29] Until 1890, the city bought 11,500 hectares of former knight's estates, converted them to seepage farms that generated agricultural produce. The combined costs were astronomical, consuming about a third of the city's tax revenue until 1890. Nonetheless, Berlin's innovative sewer system found imitators worldwide, including Moscow,

Virchow warned of emergency discharges. Both adjustments made the sewers project more expensive.

[26] Virchow's own analysis suggested that the seepage farms would cause significant contamination of the soil and groundwater. However, his deputation played down this finding (Mohajeri, 2005, 90–91). The conflict over the river Spree's suitability as a waste disposal and neutralization site mirrors a contemporary national debate that only resolved by the 1880s (Witzler, 1995, 82–91). Von Pettenkofer, for instance, saw no significant danger in the disposal of raw sewage into rivers, trusting their dilution capabilities (Briese, 2003a, 156). In 1877, the direct feed-in of sewage in rivers was prohibited by the Prussian "circular provision" (*Circular-Verfügung*). However, it took several years for the new rule to take effect (Büschenfeld, 1997, 123–125).

[27] James Hobrecht, who had already constructed the sewers of Stettin, became chief engineer and oversaw the construction of Berlin's sewers for the following decades. He had already been responsible for Berlin ambitious land-use plan, the *Hobrecht-Plan*. Hobrecht, while focused on technical aspects of sewage disposal, largely followed von Pettenkofer's etiology, fearing the "Spree mud's gases" rather than contamination of the water supply (Büschenfeld, 1997, 118-119). Hobrecht (1884)'s technical documentation complements the voluminous "general report" of Virchow's extended deputation (RuE, 1870–1879).

[28] While Hobrecht's plan aimed at the eventual "canalization" of the whole city, the sewers' module structure allowed for the successive construction of 12 technically independent "radial systems" (*Radialsysteme*).

[29] The annual number of connected lots was transcribed from various editions of Berlin's statistical yearbook.

Cairo, Alexandria, and Tokyo.

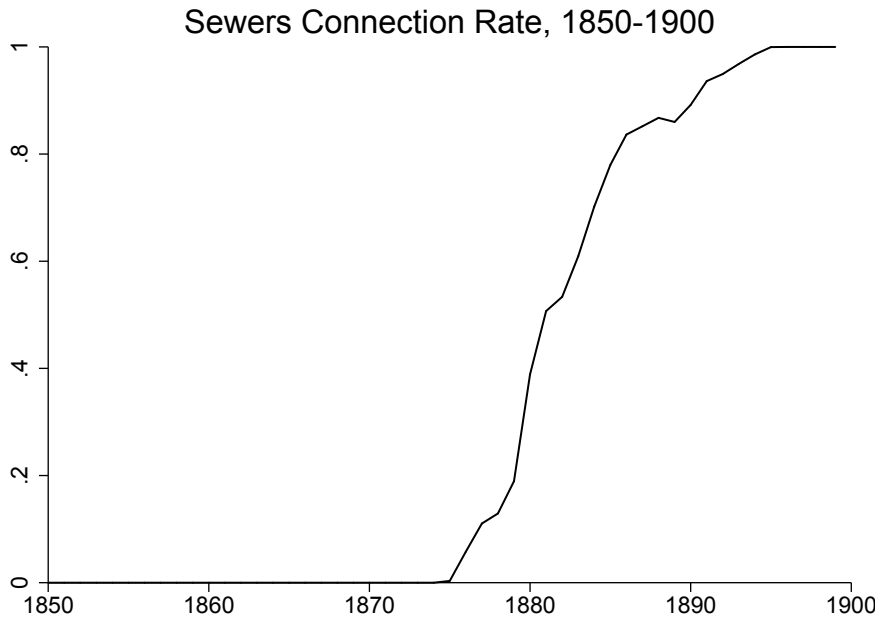


Figure 4: Share of Berlin's lots connected to the sewers, 1850–1900.

While the controversy among sanitary experts was largely resolved, Hobrecht's plan nonetheless met with heavy resistance from the public and concerned interest groups. In 1872, a widely circulated letter "to the citizens of Berlin!" warned that the sewers would soon nurture and proliferate deadly miasma to all private homes. In 1873, a repeatedly published pamphlet appealed to the rural dwellers: "Residents of Berlin's hinterlands! Countrymen! Be wary! The capital and residence city is about to be penetrated by plague tubes, whose worthless but pestilent content will be spread over your fields; 'seeping' is what the magistrate call this absurdity. They will buy up your arable lands. You will have silver in your coffers, but pestilence and disease in your homes. Be wary of Berlin's plague tube men. Do not sell!" (quoted in von Simson (1983, 125)). Hobrecht (1869, 84) had also expected that popular fear of miasma and deadly epidemics would sparkle passionate opposition to the sewers project when he stated: "It is a German peculiarity, perhaps stemming from the chronic state of being ruled [*chronisches Regiertwerden*], that we struggle to decide among alternatives, overthink all possible consequences and attach meaning even to the most improbable outcome; thus we habitually stick to oppressive and torturing evils, for a remedy could later lead to other unexpected or probable evils." While popular fears of sewer gases and "pestilence tubes" eventually faded and landlords soon would find that cesspools and discharging tons presented a sig-

nificant disadvantage on the rental market, controversy about the supposed contamination of seepage farm produce continued. Well into the 1880s, Berlin's administration was forced to perform regular tests for cholera and typhus agents and to document the healthiness of its seepage farm workers.

Sewers and cholera: A complicated relationship. Until the early 19th century, the river Spree functioned as a crude, yet satisfactory urban waste disposal, disinfection, and dilution mechanism. With the onset of massive population growth and tap-based water flush, the insufficiency of the traditional disposal system became evident and the 1840s saw the beginning three decades of erratic search for an alternative. When Hobrecht's sewers began their work in the late 1870s, "the river that previously served as a disinfection measure was now itself subject to disinfection. The biological infrastructure was simply displaced by a physical infrastructure of twelve artificial rivers (the radial sewage system)" (Hartmann, 2015, 152). In hindsight, it is tempting to interpret this lengthy transition phase as the result of technical, financial and political hurdles counteracting the inevitable triumph of a rational sanitary solution to the problems of cholera and infectious diseases. However, as Berlin's experience demonstrates, the relationship between water-borne diseases and their interpretation on the one hand, and efficient sanitary reform, on the other hand, was highly ambiguous.

While cholera's epidemic appearance motivated sanitary reform, physicians, public health advocates, urban planners, and the general public for a long time disagreed on the shape that reform should take on. Was the strict separation of liquid waste from excrement and other organic waste preferable to mixed sewers that promised dilution of the contaminated material? Should waste be left to the river's natural cleaning capabilities or were sediments and the soil's microorganisms a more reliable disinfector? Far from suggesting a straight road to sanitary sewers, prevailing etiological explanations such as von Pettenkofer's miasmatic soil theory were vague enough to levy arguments for competing solutions to the mounting urban health crises. As late 1873, the year that Berlin's sewers started operation, influential Breslau-based professor of medicine Richard Förster (1825–1902) concluded that cholera transmitted via the water supply, yet emphasized that urban tap water systems should be accompanied by a system of discharging tons, rather than sanitary sewers (Förster, 1873, 27).

6 Data: The Unsuccessful Chase for Cholera through Time and Space

Could the observational study of disease incidence pattern, i.e. epidemiology provide a way out of the ambiguity of miasma theory? Since cholera first arrived in Western Europe, health officials, physicians, and statisticians developed a keen interest in meticulously documenting various spatiotemporal aspects of the disease's incidence patterns. In the early 1830s, so-called cholera journals reported cases and their whereabouts on a daily or weekly basis, supplemented with the latest medical advice on how to protect oneself from the disease (Dettke,

1995, 197–207). The mid-19th century saw the beginnings of a more systematic approach to the statistical analysis of disease patterns, culminating in "medical topographies" and the emerging field of epidemiology (Briese, 2003a, 132–134, Susser and Stein, 2009). Popular tales credit John Snow for the successful application of spatiotemporal inference methods during the 1854 London outbreak, thereby demonstrating a promising scientific approach that would play an instrumental role in uncovering cholera's mysteries by means of systematic analysis of correlations over time and space.

While the idea that John Snow discovered cholera's transmission via observational studies and thus sparkled the urban health movement constitutes a modern myth (McLeod, 2000), contemporaries clearly believed that the study of correlations could play an instrumental role in the battle against cholera. Accordingly, many big European cities had their own committees and officials that collected, documented and analyzed cholera-related data. For instance, Poczka (2017, 250–259) documents extensive data collection and interpretation at the municipal level in Germany, where health officials and physicians tried to gain insights into cholera's behavior from the recorded information of past epidemics. Berlin features an abundance of such treatments, most importantly the early cholera journals and the reports of medical officials Wilhelm Schütz (1808–1857) and Eduard Heinrich Müller (1809–1875).

While these statistical treatments attest to impressing creativity, carefulness, and determination to defeat cholera through statistical reasoning, they also constitute a cautionary tale: Not only were observers incapable of inferring cholera's fecal-oral transmission mechanisms from observable data. Moreover, changing priors on the importance of competing explanations heavily influenced which data was collected and analyzed in the first place, often leading to the premature dismissal of correct explanations. Repeated failure to deduce general etiological laws inspired a rather superficial, eclectic approach and increasingly, Müller and his fellow health officers contended themselves with a role as mere disinterested documenters, at most being able to derive negative findings when certain explanations conflicted with their empirical data.[30] Inadequate techniques to organize large volumes of data, the lack of experimental conditions or other means of *ceteris paribus* analysis, and insufficient reflection on the role of priors in data-driven research emerged as the main limits to an empirical demystification of cholera.

Cholera journals and the politics of knowledge. When cholera first hit the German lands in 1831, so-called cholera journals were published to spread information on the disease's course and advertise commercial and medical remedies. More importantly, they served as a battlefield for the early conflict between contagionist and anticontagionist interpretations. In Berlin, the main outlet of the contagionists was the government-backed "Berlin Cholera Journal" (*Berliner Cholera-Zeitung*), edited by forensic specialist Johann Ludwig Caspar (1796–1864), while Jewish physician and anticontagionist Albert Sachs (1803–1835)

[30] Otto et al. (1990) stress that in Prussia the statistical coverage of the cholera epidemics became increasingly neutral in tone and avoided strong statements regarding cholera's etiology.

published the "Journal on the Behavior of the Malignant Cholera in Berlin" (*Tagebuch über das Verhalten der bösartigen Cholera in Berlin*) (Dettke, 1995, 197–207). Broadly speaking, conservatives and the ruling establishment favored a contagionist interpretation that implied that the government was responsible for containing the spread of cholera by implementing quarantine measures and *cordons sanitaires*. Liberal reformers, in contrast, favored anticontagionist interpretations that stressed social ills at the root of the epidemic while implying that the disruption of trade flows through quarantine was useless at best.[31]

The cholera journals provided painstaking descriptions of the course of individual incidences and summarized information such as the gender, occupation and age distribution of recent cases. While contemporaries occasionally connected their speculation about the role of contagion and local risk factors to such empirical data, the cholera journals rather served as outlets that presented alleged proof for pre-existing beliefs regarding the disease's etiology and appropriate prevention methods. The secondary role of inductive, evidence-based reasoning is illustrated by Berlin medical health officer Ernst Ludwig von Koenen's (1770–1853) reaction to the evident failure of official containment and quarantine strategies during the 1831/1832 outbreaks: "As a medical civil servant, I consider the disease contagious, [but] as a practicing physician, I have to say, no, the disease is not" (quoted in Dettke (1995, 201)). While not intended for open-ended analysis and identification of useful general laws of cholera's spatiotemporal incidence patterns, the cholera journals nonetheless served as a useful basis for later, more comprehensive approaches.

Enter Wilhelm Schütz. An early example of such comprehensive analysis of cholera's spatiotemporal behavior in Berlin is Wilhelm Schütz (1849)'s statistical treatment on the four epidemics between 1831 and 1848. Motivated by the lack of progress in cholera etiology since 1831 and the inconclusiveness of the repetitive debates between anticontagionist miasmatists and contagionists, Schütz (1849, 5) called for a renewed attempt to systematic analysis of the disease's incidence patterns along the temporal and spatial dimensions in the hope of finally identifying its mode of transmission.[32] To this end, he transcribed about 9,000 cholera cases from the health commission's official lists and cholera journals, sorted them by place and time, noted whether an incidence led to death or recovery, and identified incidence clusters.[33]

[31] See Poczka (2017, 217–357) for a detailed account of the contagionist-anticontagionist debates in Germany, France and Great Britain. Dettke (1995, 197–207, 254–311) provides an account of the political dimensions of the 1831/1832 cholera epidemics in Berlin. See Baldwin (1999) on sanitary cordons in Europe and their political implications.

[32] While not formally taking sides, Schütz (1849, 15) did not hide his anticontagionist, miasmatist sympathies. Indeed, one motivation for his treatment was the observation that during the past four epidemics conventional medical police measures inspired by contagionist interpretations, i.e. the restriction of access to infected homes, disinfection measures, the arrangement of separate graveyards for cholera victims, and the general avoidance of contact with the infected did not contain the spread of the disease. Schütz nonetheless argued that dismissal of the contagion theory might be premature as the quarantine measures could well have been too light.

[33] Schütz (1849, 6–7) regarded the information on age, occupation and gender that was collected in the cholera journals as unreliable, often misclassified and patchy, as well as in-

When Schütz compiled his work, Berlin had already experienced four distinct outbreaks. Comparing their progression over time, Schütz (1849, 11–12) noted that despite differences in detail, cholera happened "almost always at the same time of the year", i.e. from September to November, with the epidemic's apex occurring quite early during the first few weeks, followed by a long fade out. Considering that cholera was known to break out at other times of the year in other cities, "one has to conclude that a certain time of the year [...] is particularly favorable to the development of the disease in Berlin [...] [and] cholera's agent, be it a contagium or miasma, thrives primarily in summer and fall" (Schütz, 1849, 12). Which factors could account for such distinct temporal regularities? Rejecting older autochtonist theories that invoked a mysterious influence of magnetic-electrical charges and atmospheric agents (*Atmosphärilien*), Schütz (1849, 12) instead derived the natural and essentially correct explanation that cholera depended on an agent that did not survive in cold temperatures.

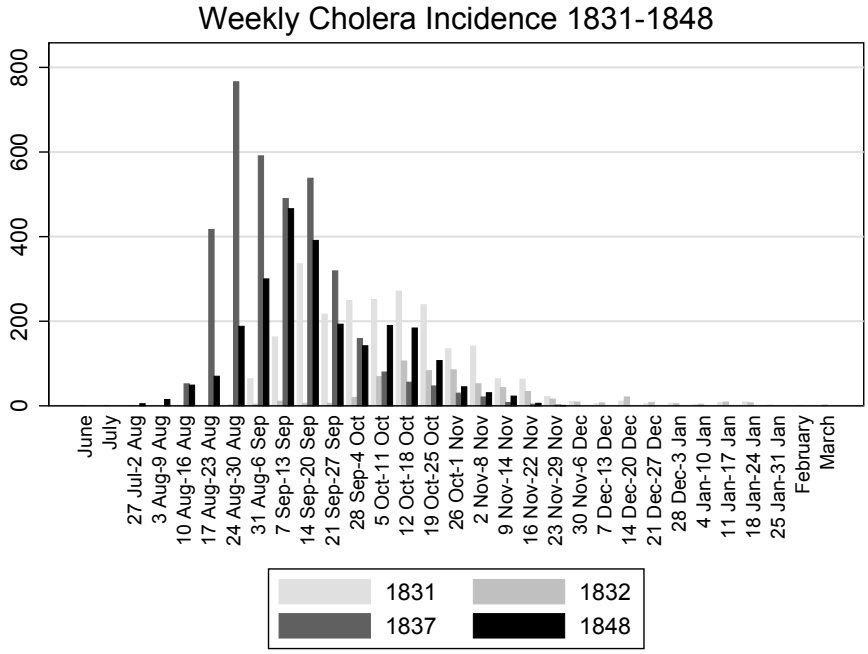


Figure 5: Weekly cholera incidence 1831–1848

Local variation suggested miasmatic causes. While temporal regularities in the incidence patterns suggested that general laws of incidence exist and older autochtonist views were misleading, they did not yield much insight into whether

consequential given the fact that cholera seemed to hit people of every gender, age and social class. He also stated that underreporting by both doctors and family members was likely; however, in his view, consequent errors would be more or less randomly distributed.

the disease spread through human contact or miasma. Schütz (1849, 16) therefore added the spatial dimension of his data to the analysis, comparing wards, streets, and even single houses, both in the cross-sections and across time. His first broad impression confirmed contemporary knowledge: Cholera tended to affect all parts of the city, though the intensity varied strongly across space. Mere differences in population density could not account for this observation, given the constant incidence rates in parts of the city that experienced significant population growth (Schütz, 1849, 21). Incidence patterns seemed fairly stable over time, where the old inner city quarters Berlin and Kölln were hit hard during every epidemic, whereas the richer Western quartiers Friedrichstadt and Dorotheenstadt were both hit less and featured more variation over time. Schütz (1849, 19) deduced that some spatially varying local conditions likely governed cholera's potential, whereas direct or indirect contagion was unlikely, given frequent cross-neighborhood contact among the city's inhabitants.[34]

Was it possible that cholera spread through "an atmosphere impregnated by foul-smelling substances" (Schütz, 1849, 22), disseminating from the rivers Spree and Panke and the canals crossing the city? The facts that cholera happened across the whole city and that houses located directly at the waterfront did not see more cases than houses farther away suggested a more complicated, locally focused explanation. To Schütz (1849, 23), stagnant water pools, overflowing cesspits, and humid soils, rather than the big flowing water bodies seemed to be the source of trouble. Such repellent conditions were most visible in the so-called family homes in the Northern Voigtland quarter, an area that was hit particularly hard during the 1831 epidemic.[35] Schütz argued that the Western quarters and Northern outskirts of the city, while not immune to such sources of miasma, profited from paved roads, closed gutters and broader streets that altogether lowered humidity and guaranteed proper ventilation (*Salubrität*).

The data does not speak. However, while the spatial correlation between dense, stinking streets, foul stagnant water and a higher cholera incidence seemed evident, Schütz struggled for an explanation why cholera was so concentrated on single houses, rather than spreading easily through neighborhoods with similar local characteristics. Furthermore, why were some houses affected during all four epidemics, while other houses with apparently equally unfavorable characteristics were spared in some epidemics? Schütz (1849, 36) had to conclude that "[if] one wants to reject contagion from individual to individual, one has to accept the assumption that the miasma concentrates in a limited space that does not differ in any way from its surroundings". Popular

[34] A further sign against the contagionist nature of cholera was that frequent demonstrations and gatherings during the 1848 uproars did not coincide with a higher incidence rate, a conjecture based on the lack of temporal correlation that Schütz (1849, 15) also invoked when noting the lack of changes in disease incidence around the beginning of October, when traditionally many Berliners would change their home and thus come into contact with each other.

[35] Dettke (1995, 180–185) describes the family homes' cholera history in detail. The family homes were a cluster of high-density buildings accommodating 1,500 lower class inhabitants, sharing two wells, forty-eight toilets, and two overflowing cesspools that swamped the narrow courtyard.

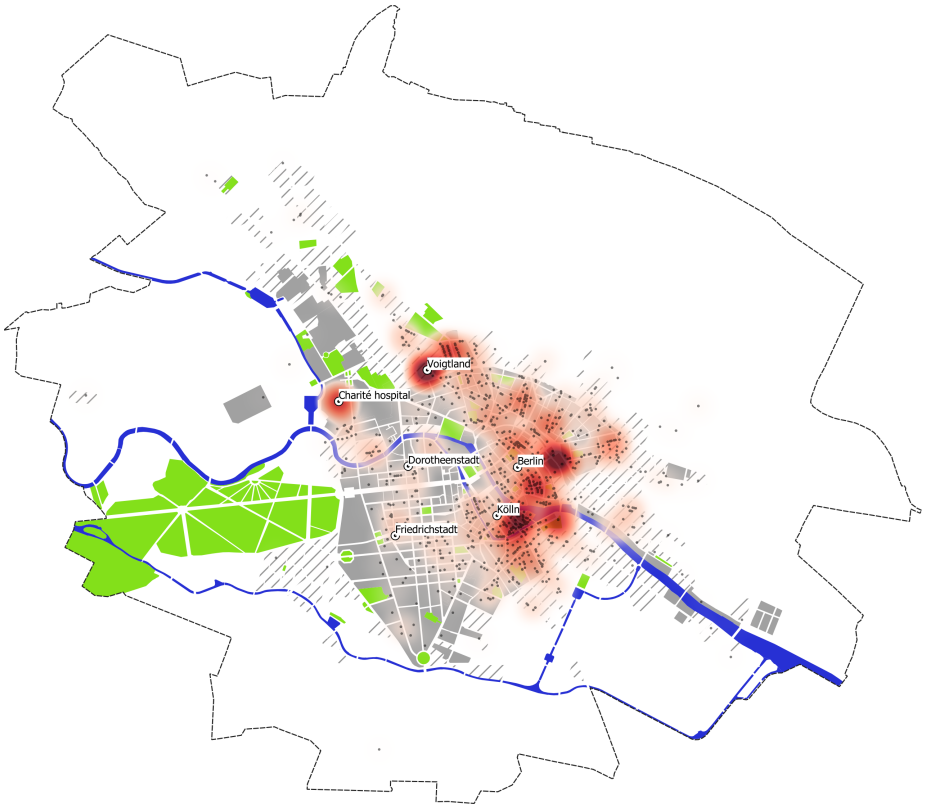


Figure 6: Cholera incidence heatmap for the 1831 epidemic. Red shades denote a local concentration of cases. Dots represent affected lots. Gray, green and blue areas represent the built-up area, green space and water bodies, respectively.

contagionist and miasmatist approaches did not yet suggest that the missing spatiotemporarily varying condition was, in fact, the contamination of drinking water. No further squeezing of Schütz's data could have produced that insight as prior beliefs prevented the examination of this factor.

Neither did Schütz (1849, 36)'s uneasiness with both contagionist and simple miasmatist explanations lead him to single out a central role for drinking water, nor did his treatment assign much importance to the presentation of data on water use and quality, despite observing "swampy, muddy" well water in cholera hotspots (Schütz, 1849, 22). His inquiry depended on prior etiological beliefs and given that these priors were sufficiently far removed from cholera's actual transmission route, empirical derivation of the central role of drinking water was unlikely. Nonetheless, Schütz managed to infer some negative findings such as the implausibility of direct contagion. His practical recommendations were inspired by liberal anticontagionist views, advising a reduction of exposure to stagnant waste and water, the paving of roads, the construction of new gutters

and sewers, and the "uplifting of the lower classes" (Schütz, 1849, 39) instead of quarantine and isolation.

Enter Eduard Heinrich Müller. With Schütz having covered Berlin's first four epidemics, Eduard Heinrich Müller took up the task of collecting and interpreting cholera-related statistics since 1849. Throughout the 1850s, his consecutive publications show both an ever-increasing volume of data on potentially relevant correlates, and growing frustration with the inability to confirm or rule out possible cholera risk factors based on that data. Consequently, Müller progressively retreated into the role of a mere documenter, collecting data that prominent theories deemed important and summarizing the various conflicting views of his local sub-officers.[36]

Containing considerably more data than his predecessor's reports, Müller (1851, 112)'s lengthy treatment on the 1849/1850 outbreaks could only conclude that "it seems that all local conditions known to us had no or at most a secondary influence on cholera." Based on his comparisons, proximity to open water bodies, humidity, altitude, density, and even the closeness of stagnant polluted water and cesspools did not play a role (Müller, 1851, 103–104). Introducing the groundwater level as a "possibly somehow connected factor", Müller (1851, 112) picked up elements that would become important in Max von Pettenkofer's soil theory, however also concluding that there is no correlation with cholera's incidence. The only "permanent local harmfulness" Müller (1851, 89, 101, 110) was able to confirm was the well-known correlation between poverty and cholera on the individual, street and building level that manifested itself in "hotspot houses", leading him to embrace disinfection as the appropriate answer (Müller, 1851, 125–126).

Ceteris non paribus. Perhaps it was disappointment with the lack of clear-cut positive findings that led Müller to dedicate a large part of his treatments to the speculative reports of local health officers (*Bezirksphysikusse*). His local subordinates presented a wild, inconsistent mix of etiological views on cholera, even invoking alcoholism, sun exposure, dietary errors, mood swings and atmospheric discharges (Müller, 1855, 398–409). While the growing influence of von Pettenkofer's miasmatic soil theory is clearly visible and local reports increasingly speculated on the role of cesspools, human excrements, and soil conditions, this did not motivate a distinct focus on drinking water quality. A local doctor Arnd's statement that, "concerning bad drinking water [...] whose adverse influence in times of cholera epidemics has been suggested, I have to remark that it seems of no importance in the case of Berlin [...] as our inhabitants can always fetch good drinking water nearby and frequently make use of such opportunities" is quite representative in this regard (Müller, 1855, 404). Eclectic approaches that invoked elements of contagion, miasma and individual disposition were popular, as exemplified by the statement of local health counselor Dr. Hammer that "following this year's outbreak, I more and more tend to

[36] While leaning towards a miasmatist interpretation and firmly believing in the value of disinfection, Müller was rather eclectic and did not rule out the possibility of contagion via direct contact. He was largely agnostic on the issue whether infection happened through an air-borne or a water-borne agent (Müller, 1867, 59).

the conclusion that cholera is an epidemic-contagious disease. Cholera incorporates a peculiar harmful agent (contagium) that plays a significant role in the disease's proliferation. However, this contagium is not only regulated by individual disposition but also encouraged and promoted, restrained and limited by atmospheric conditions" (Müller, 1856, 33-34).

Summing up the wide array of his local deputies' idiosyncratic views, Müller (1855, 423–427, 1856, 55-56) saw no concluding evidence on the role of drinking water sources and made no special reference to their contamination by excrements, cesspools and inadequate sanitation infrastructure. Why was Müller unable to establish a spatiotemporal regularity that John Snow had observed with much less data during the 1854 London outbreak? Given large amounts of data and several relevant covariates to factor in, the lack of *ceteris paribus* conditions delegitimized simple cross tables and rank correlations as methods of causal inference. How to compare two houses that vary simultaneously with regards to their inhabitants' social status, street width, altitude, proximity to open water and their well water source, with all these factors possibly interacting with each other? Snow's "difference-in-differences" approach circumvented the issue and modern multiple regression techniques can easily approximate artificial conditions of *ceteris paribus*.[37] Müller, however, retreated to caution and vagueness. Discussing the influence of atmospheric conditions on the proliferation of cholera, he intuitively grasped the insufficiency of contemporary modeling tools: "If the analysis [...] remains inconclusive to this point, it seems to me that this is due to a defect in the observational approach. The atmosphere is a whole. But if one merely measures wind conditions, air pressure, temperature, humidity, and electric charge, without re-assembling them to an entity, a whole, the analysis has to remain inconclusive, for each isolated observational element yields a conclusion for itself, but not for the whole" (Müller, 1856, 54). More data could not easily compensate for the difficulties of testing the increasingly complex, multicausal etiological theories of cholera.

Water supply enters the picture. After 1855, cholera largely disappeared from Berlin. A major outbreak in nearby Saxony in 1865 reminded the population that a comeback was always possible. When cholera eventually returned in the summer of 1866, Müller took up the opportunity to revisit the statistical approach to cholera. Motivating his yet most detailed report, Müller (1867, III) stated that "science still confronts cholera like an unsolvable mystery. [...] However, we gather new insights into its causes by precise statistical surveys of every single epidemic and through the most diligent observation of the characteristic conditions under which the disease spreads [...], whether we are yet able to grasp their harmful influence or not." In light of his earlier difficulties, the objective had become more modest: His role was merely to gather statistical evidence in the hope that someday, someone would find it useful in solving cholera's mystery.

By 1867, the medical profession treated the contamination of drinking water

[37] An additional difference between Snow's and Müller's situation was that Berlin's higher density of public and private wells rendered the use of a Voronoi diagram approach pointless.

by human excrements as a serious contender for the spread of cholera, although von Pettenkofer's miasmatist soil theory still dominated the German debate.[38] Müller's latest report strongly reflected the new focus on water-related factors. Importantly, it documented each affected house's water source and presented statistics on the use of tap water and water closets. The report prominently discussed Berlin's water infrastructure, assessed hygienic aspects of the new tap water supply, inspected the issue of well water contamination with quantitative indicators and referred to the continuing problem of inadequate urban waste disposal (Müller, 1867, 3–4, 13).[39] While the fecal-oral transmission mechanism was not yet at the center of professional attention, drinking water quality certainly was.

A modifiable areal unit problem. Analyzing the spatial spread of the 1866 cholera epidemic, Müller (1867, 47–48) observed that houses connected to the tap water supply had a much lower incidence rate than those still using well water. Furthermore, areas with a larger prevalence of water closets also suffered less. Drawing definitive conclusions was still a risky step as "those areas are usually also located at more advantageous locations, feature superior construction designs, are cleaner and more affluent, such that one cannot simply attribute the low cholera incidence to the water closets." However, "this finding refutes the theory that water closets actually promote the spread of cholera" (Müller, 1867, 47). The conclusion that access to clean drinking water and its isolation from human excrements were important mitigating factors in the transmission of cholera now seemed inescapable.

However, the limits of Müller'ss reasoning become clear when considering his final report on the 1873 epidemic. Now, Müller (1874, 7) found that houses with access to tap water actually had a higher incidence rate.[40] Why did his findings regarding the water supply differ from what he concluded in 1866? Müller speculated that tap water might exert an incentive to comfortably flush excrements into the gutters rather than bringing it to the cesspool, thus spreading contaminating soil across the neighborhood and canceling out the individual benefits. Cautiously, he concluded that "a distinct influence of soil conditions and the quality of drinking water on the cholera incidence could not be proven so far" (Müller, 1874, 14). Our modern understanding of the fecal-oral transmission route indeed suggests that measuring the correlation of tap water access and cholera incidence solely at the level of individual houses might be misleading. As *vibrio cholerae* enters the human body via the ingestion of contaminated drinking water, individual access to a safe water supply is associated with significant health benefits. In the absence of safe waste disposal mechanisms, however, enhanced flushing capabilities due to tap water access may cause neg-

[38] Despite the profession's shift to a localist etiology, however, official policy in Prussia and other German states was still largely inspired by contagionist theories (Evans, 1988, 141–142).

[39] Furthermore, a protocol of the Royal Sanitary Commission's (*Königliche Sanitäts-Commission*) meeting in June 1866 was annexed, discussing the "newest scientific findings" (Müller, 1867, 146) regarding the proliferation of cholera via excrements.

[40] In contrast, his older conclusions regarding the role of water closets were strengthened as he found that the presence of a water closet at the level of individual houses lowered the probability of cholera.

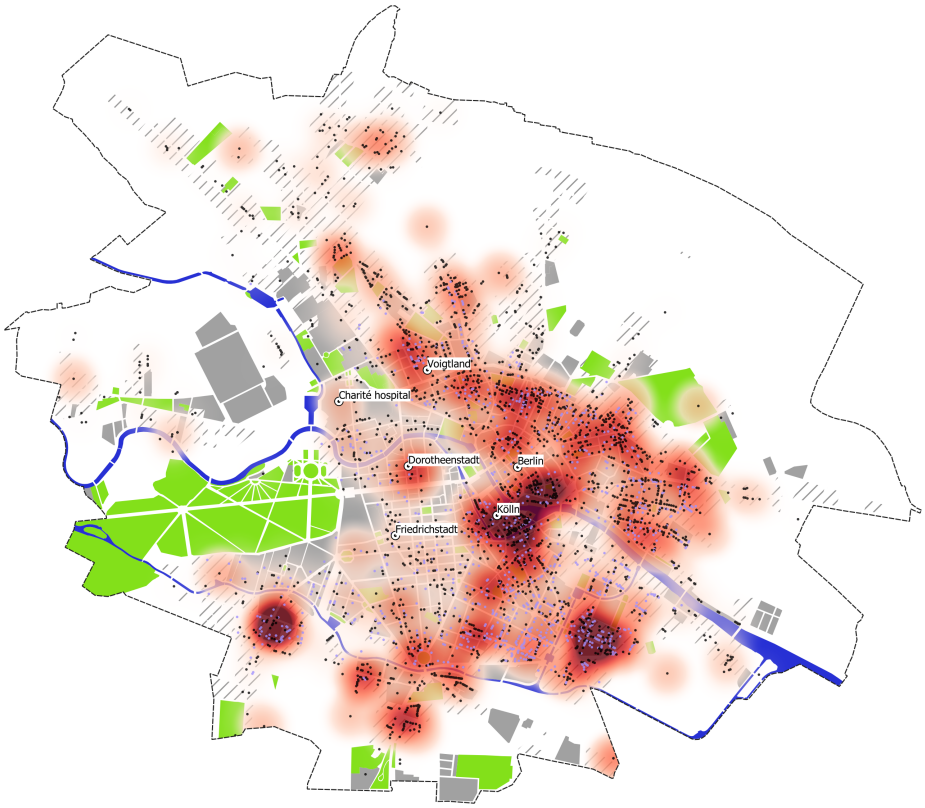


Figure 7: Cholera incidence heatmap for the 1866 epidemic. Red shades denote a local concentration of cases. Dots represent affected lots, where blue dots denote cases on lots with tap water access. Gray, green and blue areas represent the built-up area, green space and water bodies, respectively.

ative externalities on the neighborhood level.[41] If individual homes' tap water connection statuses are spatially correlated, the strength and even sign of the measured correlation between access and cholera incidence may depend on the level of aggregation. In modern parlance, Müller encountered a modifiable areal unit problem (MAUP) resulting from a violation of the stable unit treatment value assumption (SUTV).

Statistics and cholera: A complicated relationship. While John Snow's often-cited proto-epidemiological analysis of the 1854 London cholera provided strong evidence in favor of his theory of the water-borne cholera germ, von Pettenkofer's less-known analysis of the 1854 Munich outbreak led him to firmly conclude that drinking water played no significant role in the proliferation of cholera. Just like

[41] Individual connection to the sewers, in contrast, is not expected to yield significant individual health benefits. However, significant positive externalities at higher levels of aggregation should be expected.

von Pettenkofer, Schütz and Müller put massive effort into the collection and interpretation of statistical data on cholera. Yet, they were mostly in the dark, only beginning to focus on water infrastructure issues when external theoretical and practical impulses indicated their importance.[42] Suggesting that this experience was quite representative for attempts to utilize statistical inquiry in the battle against cholera, Poczka (2017, 252) concludes that "statistical analysis was not able to induce an epistemological or categorical turn in the order of knowledge production. Perhaps it can never be instrumental in generating new insights that are not already implied in the theoretical horizon that led to the formation of the respective statistic. In other words: [Statistical analysis] could refute assumptions, but it could not question the foundational paradigms on which these assumptions rested."

Schütz's and Müller's inability to uncover the central role of drinking water thus resulted from the epistemological limits of their approach. They closely traced the shifts from contagionist to miasmatist to complicated hybrid theories à la von Pettenkofer, but at all times prevailing etiologist priors defined which data was collected, how it was interpreted, and consequently, which conclusion could be drawn. Their statistical analysis was thus more a reaction to, rather than a driver of knowledge generation. The lack of adequate analysis techniques posed a further problem: Ever larger amounts of observations and volumes of covariate data did not compensate for but rather complicated the problems of causal inference when observations varied along many dimensions simultaneously and inference relied on cross tables and unconditional correlations.[43] Finally, complicated etiological working hypotheses offered little guidance to the question on which level of aggregation the analysis should be performed. With

[42] While ground water levels played an important role in later renditions of von Pettenkofer's theory, he vehemently opposed the idea of transmission via drinking water until the late 1880s (Briese, 2003a, 156, Rimpau, 1935). Reflecting on the impact of his colleague Koch's isolation of the cholera bacterium, he stated: "I certainly considered the possibility of an influence of drinking water on cholera during the 1854 epidemic in Munich with an open mind, [...] still, I had to out my wisdom into the following words: I take it for granted that one cannot assign a causal role to drinking water in cholera's etiology. However, by this statement I do not want to claim that it is without consequence whether the population has access to good or bad drinking water during an epidemic [...]. However, Munich has provided incontrovertible evidence that a cholera epidemic can break out despite the highest quality drinking water [...]" (von Pettenkofer, 1887, 181–182). Rimpau (1935, 427–450) provides a critical account of von Pettenkofer's famous study of the 1854 Munch epidemic. While arguing that von Pettenkofer's failure to identify drinking water as cholera's transmission vehicle was partly due to the 1854 Munich epidemic being a "contact epidemic" rather than an outbreak proliferated by drinking water, he documents various errors in von Pettenkofer's statistical reasoning as well as inadequate data sources. Briese (2003a, 154–162) argues that deep cultural prejudices regarding the supposed cleaning properties of water motivated von Pettenkofer to conceptualize cholera as an essentially air-borne disease. While von Pettenkofer's soil theory is often portrayed as a powerful catalyst for urban water reform, Morabia (2007) argues that his miasmatist framework was rather ambiguous in this respect.

[43] The lack of probabilistic (as opposed to deterministic) interpretations and models of causation exacerbated the problem of inference from observational data, as demonstrated by Winslow (1944, 250–255) in his discussion of the London Metropolitan Sanitary Commission's 1848 report on infectious diseases. See Hacking (1990) for a general discussion of 19th century models of causation.

hindsight, it is not at all surprising that Berlin failed to produce its own John Snow as the latter's analysis profited from unique circumstances approximating a natural experiment (Freedman, 1991).

7 "Cholera Forcing": Tales, Realities, and Implications

The Western city's 19th and early 20th century transformation from the "organic city" and its patchwork of ineffective, largely privately operated water supply and waste disposal mechanisms to the efficient, publicly managed "bacteriological city" with its centralized tap water supply and integrated sewers was a highly complex process (Gandy, 2006). The idea that epidemic cholera served as a central catalyst for this transition, motivating a "wave of sanitary reform which swept over the civilized world in the middle of the nineteenth century" (Winslow, 1944, 244) and thus bringing about its own demise remains influential in popular imagination (Hamlin, 2009a). At first glance, "cholera forcing" is indeed a convincing idea, fitting into larger attempts to explore the disease's historical role as a driver of revolution, reform and technological change in the 19th century Western world (Briggs, 1961; Evans, 1988; Rosenberg, 1966).

The origins of cholera's depiction as a "shock therapist" reach back to the late 19th and early 20th centuries' proud retrospective treatments on the transformation and civilizing of the city. For instance, in his laudatory biography of von Pettenkofer, Rimpau (1935, 376) sums up the West's (and, in particular, Germany's) successful struggle against cholera as follows: "Millions of people prematurely died from cholera; cholera brought incredible physical and spiritual misery and moreover, it heavily damaged the world economy and individual fortunes. However, from the hard lessons it taught came the advances in the fields of hygiene and sanitation; we learned to keep house, village, and city clean. Cholera inspired [von] Pettenkofer to formulate his soil theory and eventually crowned a Robert Koch with eternal fame through the discovery of 'vibrio cholerae'." In a modern rendition of the claim, Tauxe et al. (1994, 453) find reasons for optimism regarding the continuing threat of cholera in the developing world: "Just as cholera spurred the sanitary reform movement and the development of the field of public health in 19th-century Europe and North America, recurrent epidemic cholera will continue to drive constructive change in the developing world."

Partly, the popularity of "cholera forcing" can be attributed to the optimistic lessons it provides: "sometimes the right measures were adopted in advance of their eventual scientific justification" (Baldwin, 1999, 191–192). While pre-bacteriological etiological views turned out fundamentally wrong, ostensibly they converged to the right conclusions and consequently, "sanitary reforms, such as sewerage, made as much sense to Snowians, who thought the disease spread through excrement, as to those who saw general filth as its source" (Baldwin, 1999, 191–192). Of course, this convergence was not by pure chance, but

rather because proto-epidemiological analysis, empirical reasoning, and "powerful death maps" (Geels, 2006, 1073) à la John Snow progressively demystified cholera and effectively compensated for the microscope and the germ theory of disease: "[...] the theory of miasms had enough truth in it to work. When the sanitary reformers cleaned up the masses of putrefying filth through which our great-grandfathers moved, the epidemics of typhoid and cholera and typhus and dysentery actually ceased. The miasmatic theory was the first generalization of epidemiology to be actually – and on a world-wide scale – justified by its fruits" (Winslow, 1944, 249). It "[...] was based on a sound empirical recognition of the relation between filth and disease; and this relationship had sufficient validity to make possible the achievement of phenomenal results in the control of epidemic disease by practical application of the theory" (Winslow, 1944, 266).

However, good narratives are not always true. The preceding sections argued that "cholera forcing" is hardly applicable to the historical experience of Berlin. Both the timing of epidemics and reforms, and the arguments invoked by involved parties cast doubt on a strong link between both concurrent phenomena. Moreover, failure to understand cholera's water-borne nature may well have led to crucial errors in the design of water infrastructure, illustrated by the ambiguous effects of Berlin's early tap water supply that lacked accompanying sewers. In hindsight, the weak links between cholera and water reform are not surprising: Given primitive statistical, computational and methodological tools, the hope to uncover cholera's etiology through empirical reasoning and logical induction turned out to be an illusion, with respect to both Berlin's health officers and the larger German national research community.

In light of Berlin's role as a political and scientific center of 19th century Europe, there are reasons to believe that her experience was the norm rather than the exception. Indeed, qualitative work has long emphasized that the desire for comfort, aesthetic motives, and industrial needs dominated health concerns in contemporary discussions over the introduction and expansion of urban tap water and sanitation infrastructure (Vögele, 1998, 159–164, Büschenfeld, 1997, 101–108). Furthermore, it has been argued that financial, technical, and administrative obstacles severely slowed down whatever reform momentum epidemics generated (Hamlin, 1988). As Vögele (1998, 160)'s standard account of the German mortality transition concludes, "[the] absence of any clear link between the extensive cholera literature and sanitary reform in contemporary German reports places in severe doubt the general view that cholera functioned as the initial driving force for sanitary reform."[44] Of course, rhetoric and motives may

[44] Several city-level case studies find that cholera played at best a minor role in the emergence of urban tap water systems. Perhaps the most striking example is Evans (1987, 226–284)'s seminal study of mortality in 19th century Hamburg, where, despite frequent cholera outbreaks, authorities and the wider public saw no reason to reform the deficient water supply infrastructure, culminating in the 1892 epidemic. While Hamburg's stubborn resistance to reform may constitute an extreme case, city-level narrative studies do not support a strong interpretation of "cholera forcing", i.e. the notion that regular outbreaks were the single most important driver of reform. Hamlin (2009b, 325–331), Vögele et al. (1994, 12–14) and Dettke (1995, 10–13, 318–327) provide an overview of such case studies. However, as Hennock (2000) argues, sanitation certainly became a more important motivational factor over time.

differ. However, focusing on what contemporaries did rather than what they said, Brown (1998) finds no significant effect of the number of cholera epidemics on the demand for urban waterworks for a large sample of 19th century Rhenish cities.

A weaker interpretation of "cholera forcing" may simply state that cholera served as a minor motive for efficient water reform. On the conceptual level, this claim hinges on the assumption that contemporaries, while not necessarily motivated by a correct understanding of the disease's behavior, still drew approximately correct practical conclusions. Indeed, the demise of early contagionist views and the emergence of complex miasmatist etiology shifted the focus from individual responsibility and hygiene to the urban infrastructure and public hygiene. In their belief that cholera developed in filthy, contaminated localities and transmitted through poisonous miasma evaporating from polluted water bodies and moist soil, many contemporaries clearly saw the value of clean water provision and effective wastewater disposal. Germany's most prominent public health advocate von Pettenkofer, himself a miasmatist who fiercely disputed Robert Koch's ideas, was also one of the most outspoken proponents of sanitary sewers. Another influential advocate of urban water infrastructure reform was Rudolf Virchow, who mocked Koch's germ-based etiology and held on to an eclectic view that incorporated miasmatist theories.[45]

However, narratives envisioning an increasingly unchallenged consensus in favor of effective urban water reform tend to ignore that widely believed hypotheses on cholera's origin and spread actually fueled resistance to effective reforms and diverted efforts to ineffective measures. Most importantly, there is evidence that the expansion of tap water networks initially contributed to the urban health crises rather than alleviating it. One plausible interpretation is that the easy availability of water flush made relatively safe methods of waste removal such as the disposal in transportable barrels less attractive and propelled the discharging of solid waste into leaky open sewers and water bodies, which in turn further contaminated groundwater sources. While the mechanisms remain cloudy, evidence has shown that tap water systems only became an unambiguous part of a safe urban water environment when complemented by the systematic construction of impermeable underground sewers (Gallardo-Albarràn, 2018, Hassan, 1985, Bell and Millward, 1998, 226, 238).[46] While Berlin's 25 years lag

[45] Famously, von Pettenkofer deliberately consumed a solution containing *vibrio cholerae* in order to prove its harmlessness. He survived with only mild discomfort, possibly due to an immunity acquired during an earlier epidemic. Naturally, Koch and other bacteriologists did not take this attempted rebuttal of the germ theory seriously (Morabia, 2007, 1235). See Raschke (2007) on the dispute between von Pettenkofer, Koch and Virchow.

[46] Furthermore, before the advent of chemical water filtration and chlorination, tap water was not necessarily safe or even safer than well water. As (Vögele, 1998, 177) notes, "[in] the case of an epidemic, an inadequate central water supply would imply that it was serving only to distribute the disease over the whole area that was connected." Once again, Hamburg serves as a prime example. Since 1849, the city took its water out of the river Elbe and stored it in underground reservoirs before distribution. As the water was stored for increasingly shorter periods, natural filtration capabilities of the soil deteriorated over time. In 1892, cholera spread via contaminated river water proliferated through the tap water supply (Vögele, 1993, 358).

until the joint operation of both systems was certainly extreme, simultaneous construction efforts were rare in 19th century Germany, suggesting that contemporaries possessed only a limited understanding of the potentially harmful impact that incomplete infrastructure would have. A similar issue arose concerning the various alternative waste discharge systems discussed in the second half of the 19th century. Neglecting the water-borne nature of cholera, contemporaries not only underestimated the potential benefits of sanitary sewers but actually used miasma theories to develop arguments against their construction such as the view that sewers would be conducive to the development and spread of poisonous air.[47]

While the emergence of modern water infrastructure was characterized by trial and error, setbacks and counterproductive efforts, recent quantitative studies find that the introduction of centralized water supply networks and sanitary sewers caused a significant net reduction of mortality rates in 19th and early 20th century Western cities (Gallardo-Albarràn, 2018, 2).[48] The underlying mechanisms, however, are not well understood and empirical research only begins to entangle the various channels that contributed to an overall beneficial effect. At best, ongoing ambiguity over the exact role that water played in the spread of disease meant that contemporary views regarding the appropriate pace and direction of urban water infrastructure reform differed widely, contributing to lengthy planning and construction phases, and thus prolonging the "urban penalty" relative to an efficient transition as envisioned by the "cholera forcing" framework.

To an impartial observer, it might not seem surprising at all that 19th century contemporaries were unable to imagine the complex effects that their experiments with different types of urban water infrastructure approaches would have. In contrast, it seems unlikely that by application of proto-epidemiological reasoning based on observed data, contemporaries were able to derive a complex miasmatist theory that yielded approximately correct practical recommendations despite being fundamentally wrong. Yet, "cholera forcing" relies on the idea that repeated observation and the analysis of correlation patterns set the 19th century public health community "on the right track". In the words of von Pettenkofer's biographer Kisskalt (1948, 74–75): "We all know [...] examples where wrong assumptions in science and practice lead to a correct result. Often, we are aware of such errors and call them fictions. It has been stated that a wrong hypothesis is better than none".

[47] In addition, the direct feed-in of raw sewage into open urban water bodies, either intentionally or via emergency outlets, was common practice until the last third of the 19th century. While the health consequences of such intra-urban disposal sewers have not been systematically assessed, it is safe to assume that they were ambiguous at best. London's famous 1858 "Great Stink" arose from human and industrial waste that was discharged from the sewers directly into the river Thames.

[48] However, quantifying the effect of tap water provision and sanitary sewers on specific epidemic diseases such as cholera is difficult as their timing had large random elements and evidence usually comes from time series (Vögele, 1993, 347). Empirical work thus focuses on endemic diseases. In principle, however, intra-urban cross-sectional data could be used to investigate the effect of the water infrastructure environment on epidemic disease incidence.

In reality, Eduard Heinrich Müller and his fellow Berlin health officers increasingly lost track. Not only did the extensive collection of data and its careful analysis fail to yield compelling reasons to rely on clean drinking water and sanitary sewers. Moreover, their work is characterized by false negatives, for instance rejecting a significant role of contaminated drinking water based on a low unconditional correlation between a building's connection to the supply network and its cholera incidence. The failure of Germany's most prominent advocate of the proto-epidemiological approach, von Pettenkofer, to derive from empirical observation the importance of clean drinking water and the dangers of unfiltered sewage discharge into rivers suggests that Müller was no unlucky exception.

The lack of adequate mathematical and statistical tools was one important obstacle (Hamlin, 2009b, 192–203). Modern epidemiology deals with spatial and temporal autocorrelation, handles non-linear relationships as well as multiple correlates and allows for randomly distributed errors.[49] Such tools were nowhere near to the grasp of Müller, von Pettenkofer and their contemporaries, yet they would have been indispensable in order to test increasingly complex miasmatist ideas. Thus, in practice miasma theories functioned less as a framework that yielded testable hypotheses, but rather as flexible rhetorical containers that could accommodate almost any empirical correlation. As Briese (2003a, 147–148) puts it: "Miasma was an imponderability, a hollow significate to be animated with freely floating bits of arbitrary semantic. It was a universal projection surface and thus was the source of its sustained attractiveness. It was connected to the airs, winds, the atmosphere, to the sun, the moon and the stars, to volcanoes and earthquakes, to magnetism and electricity, to climate and weather, to swampy decay, to urban stenches and effluvia, etc."[50]

Given methodological deficiencies and strong priors in favor of an essentially

[49] Apart from the statistical modeling of dependencies, data collection and interpretation limited what the 19th century proto-epidemiologist could achieve. For instance, while contemporaries took note of and worried about foul smell, unusual color, bad taste or the presence of particulate matter in their traditional well water sources, such signs were neither a sufficient, nor a necessary condition for contamination with *vibrio cholerae* or other water-borne pathogens. Accordingly, a contemporary observer could interpreted the low spatiotemporal correlation between apparently polluted well water and actual disease incidence as proof that water played no or only a contingent role in cholera's proliferation. Consequently, she would underestimate the relative benefits of tap water withdrawn from distant sources, especially since pre-filtration tap water could exhibit very similar superficial properties despite being far less likely to be actually contaminated with germs.

[50] In his biography of John Snow, Johnson (2005, 134–135) comes to a similar conclusion: "Miasma turns out to be a classic case of what Freud, in another context, called 'overdetermination'. It was a theory that drew its persuasive power not from any single fact but rather from its location at the intersection of so many separate but compatible elements, like a network of isolated streams that suddenly converges to form a river. The weight of tradition, the evolutionary history of disgust, technological limitations in microscopy, social prejudice [...] The river of intellectual progress is not defined purely by the steady flow of good ideas begetting better ones; it follows the topography that has been carved out for it by external forces. Sometimes that topography throws up so many barricades that the river backs up for a while. Such was the case with miasma in the mid-nineteenth century". On the interpretational flexibility of miasma theory, see also Briese (2003a, 316–330).

untestable theory, how much could have been expected of the 19th century proto-epidemiologist? The popular myth of John Snow's proof by visual and statistical correlation inspires the optimistic view that proto-epidemiology was indeed instrumental in the emergence of urban water infrastructure reform, identifying the right correlations while assigning the wrong causations. A closer reading of the typical proto-epidemiological treatment à la Müller rather suggests otherwise: The causations were largely treated as given, while the correlations were mostly meaningless. In 1893, hygienist Carl Flügge (1847–1923) commented on the lack of progress concerning cholera's etiology: "Two generations later we still face the same divergence of opinions: One side declares cholera an eminently contagious disease on the same level as smallpox and typhus, to be treated with such rigorous quarantine and disinfection measures that it becomes questionable whether the latter or the disease itself presents the greater calamity. The other side fiercely emphasizes the non-contagious character of cholera and declares all those annoying, economically disastrous quarantines to be unnecessary. The dogmatism with which both opinions are brought forward makes it likely that both bear some truth, but also that both overshoot the mark in their respective direction" (Flügge, 1893, 124–125). In his view, only Robert Koch's and Louis Pasteur's experimental approaches could succeed where "observational epidemiology" had failed.

Cholera may not have forced the Western world's urban water infrastructure transition, but its continuing incidence in large parts of the contemporary developing world certainly forces us to reconsider the implications of historical experience. Of course, there is no immediate danger of history repeating itself, as comprehension of both cholera's etiology and the importance of safe water systems dramatically improved. Still, the absence of any automatisms in the Western cholera-sanitation-nexus at the least suggests a cautious interpretation of the disease's potential to induce change. As Hamlin (2009a, 1952) argues: "The opportunity cholera affords may be real. Crisis, however, is no adequate basis for works that are expensive, require the coordination of a wide variety of technical skills over an extended time, depend on continued public support, and need to be entrusted to well-trained and reasonably compensated experts backed by adequate budgets for supplies and tools – and that, even then, may not always work."[51] On a deeper level, however, powerful narratives of the West's past struggles are highly consequential regarding the attitudes, recommendation, and modes of assistance that today's developing world receives (Konteh, 2009). While it originates from a misleading backward extrapolation of modern technocratic approaches and scientific knowledge to the past, the real danger of the "cholera forcing" narrative arises when extrapolation of an imagined Western past serves as the basis for present policy recommendations (Nilsson, 2016). Concerns over the divergence between the historical West's and the contemporary developing world's roads to safe urban water may well reflect the idealizations of the past, rather than shortcomings of the present.

[51] An additional point raised by Hamlin (2009a, 1952) is that modern cholera vaccines and standardized means of oral rehydration therapy lower the incentives to invest into the costly reform of urban water infrastructure.

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