Essential, Illustrative, or … Just Propaganda? Rethinking John Snow's Broad Street Map

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Abstract

For more than a century John Snow's iconic map of an 1854 cholera outbreak in the Broad Street area of Soho, London, has been the very definition of how to discover the source of a disease. Some now argue, however, that the map was merely an illustrative and not very imaginative graphic. Here we argue that this position is incorrect. Snow's mapping of the Broad Street outbreak produced a spatial argument that was a critical evidentiary statement. This position requires us to ask, If that is true, is the map in part responsible for Snow's inability to convince contemporaries of his argument that cholera was water-borne and not airborne? In doing so, we use mid-nineteenth-century methodologies to demonstrate that the problem was not in the map but in Snow's handling of the data. This review of a seminal study in the history of disease studies not only informs historical perspective but, in its conclusions, speaks to the utility of medical mapping in contemporary disease studies, where spatialization of a disease event remains a critical method of investigation.

Keywords: cholera, disease studies, epidemiology, history of cartography, John Snow, medical cartography, public health

Résumé

Pendant plus d'un siècle, la carte iconique de John Snow portant sur une flambée de choléra en 1854 dans le secteur de la rue Broad du quartier Soho, à Londres, a défini la manière de découvrir la source d'une maladie. Toutefois, certains affirment maintenant que la carte n'a servi que d'illustration, sans vraiment être imaginative. Selon nous, cette prise de position est incorrecte. La carte de Snow représentant l'épidémie de la rue Broad a été au cœur des observations : la carte a fourni un argument spatial, un énoncé de preuve essentiel. Cette position nous oblige à nous demander : « Si cela était vrai, la carte est-elle en partie responsable de l'incapacité de Snow à convaincre ses contemporains de son observation selon laquelle le choléra se propageait par l'eau et non par l'air? » On utilise des méthodologies du milieu du XIX^e siècle pour démontrer que le problème n'était pas la carte, mais la manière dont Snow a utilisé les données. Cette revue d'une évaluation séminale de l'histoire de l'étude des maladies ne sert pas seulement à donner une perspective historique, mais, dans sa conclusion, explique l'utilité du mappage médical lors de l'étude des maladies contemporaines, dans lesquelles la spatialisation d'une maladie demeure une méthode essentielle d'investigation.

Mots clés : choléra, étude de maladie, épidémiologie, histoire de la cartographie, John Snow, cartographie médicale, santé publique

For more than 100 years John Snow's iconic maps of an 1854 cholera outbreak in the Broad Street area of Soho, London, have been the very definition of how to discover the source of a disease outbreak (Snow 1855a, 1855b). A standard image in public-health texts since W.T. Sedgwick's landmark publication in 1901 (Koch 2005a, 132–

40; Sedgwick 1901), Snow's Broad Street map has been a foundational example advanced at varying times by cartographers (Robinson 1982), graphic experts (Tufte 1983, 1997), geographers (Koch and Denike 2004; Monmonier 1996), public-health officials (Sedgwick 1901), and historians of science, medicine and technology (Shapin 2006). Nor is interest in Snow's mapping limited to professional communities; the story of John Snow and his maps is also the subject of popular books (S. Johnson 2006; Hempel 2006) and Web sites (Frerichs 2008).

Yet some modern commentators dismiss Snow's mapping as merely illustrative (Brody and others 2000), at best "merely preparation" for Snow's real analysis (Vinten-Johansen and others 2003, 336). At worst, the maps are denigrated as mere propaganda, and not very good propaganda at that (Monmonier 2002, 155). This is also the perspective of some Snow biographers who, in devaluing Snow's Broad Street mapping, dismiss medical cartography and geography in general as fields for those "those who won't do the hard work of building a careful and decisive argument about the nature and origin of a disease outbreak" (Vinten-Johansen and others, 397–98).

Here we consider this curious division, one in which the Broad Street map is either incidental and irrelevant or, as we insist, central to Snow's fundamentally spatial argument correlating mortality in the Broad Street cholera outbreak with proximity to the Broad Street pump and well. We argue that in denying the importance of Snow's maps, the modern critics ignore the essentially spatial nature of his argument and, by extension, of disease mapping in general. Asserting the evidentiary importance of Snow's maps raises an interesting question: If the map was central to Snow's argument, was his inability to convince contemporaries of his argument a failure of the maps themselves? At the least, it is useful to ask whether Snow's maps, the traces of his argument, give some insight into the nature of Snow's argument and its popular failure in mid-nineteenth-century medicine and public health. Asking these questions raises the more general question of the nature and role of mapping in disease studies.

Snow's Cholera

Snow published a short monograph, *On the Mode of Communication of Cholera* (1849a [MCC1]), that argued the then radical thesis that cholera was not, as most believed, a miasmatic disease borne on the foul airs of the city but instead a water-borne disease that was ingested, not inhaled. Most agreed with an anonymous reviewer, probably E.A. Parkes, who wrote in the *London Medical Gazette* that while Snow's theory of water-borne disease was intriguing, the data he presented were inconclusive ([Parkes] 1849). Almost immediately, Snow attempted to bolster his argument, publishing two supporting papers within months (Snow 1849b, 1849c) to reinforce his thesis with new data.

Snow was not alone in his search to unravel the nature of cholera. Scores of researchers across Europe and North America were simultaneously advancing different theories of cholera, most advocating an airborne disease agent within the then current miasmatic disease theory (Koch 2005a). Some researchers saw water as a potential cholera source, either alone or as part of a theory of air- and water-borne cholera. This was the argument advanced by William Farr, compiler of abstracts for Britain's General Register Office (GRO), who in 1852 published an encyclopaedic 400-page study of the cholera epidemic of 1848–1849 in Great Britain. In 100 pages of text supported by 300 pages of maps, graphs, and tables, Farr argued a complex, multi-factorial theory of cholera that included air and water as elements contributing to its generation and dissemination (Farr 1852).

As the medical historian P.E. Brown put it in 1961, albeit without conscious irony, "All the elements of his [Snow's] theory were already in the air" by 1849. In 1848, for example, R.D. Thomson and William Farr expressed their concerns about the wells of Glasgow in *The Lancet* (Brown 1961, 30); the next year William Budd argued that sewer-contaminated well water was a source of typhoid and likely of cholera as well. "The frightful fatality of the disease in particular parts of infected towns," Budd concluded, was caused by the sewer-contaminated drinking water found in that single well (1849, 9). Elsewhere, a researcher in Cincinnati, Ohio, argued that well water was the likely source of a local cholera outbreak and promoted drinking rainwater as a prophylaxis (Lea 1850). He believed, however, that the mineral content of the water, and not contamination, was the cause of cholera.

A reviewer in *The Lancet* argued that conclusive proof of the nature of cholera was almost impossible without definite proof of its invisible agent (*Lancet* 1853). That proof would have to wait until Robert Koch's identification of the bacterium in 1883. Snow, however, believed that he could craft a conclusive argument, even without that evidence, on the basis of three studies he carried out simultaneously during the 1854 cholera epidemic, investigating cholera in South London's registration districts, a localized outbreak in the town of Deptford, and, finally, a ferocious outbreak in the Broad Street area of St. James, Westminster, in central London (Snow 1854). In 1855 these separate investigations were published together in a greatly expanded second edition of Snow's 1849 monograph (Snow 1855a [MCC2]).

In it pride of place was devoted to the ambitious South London cholera study. This was, Snow asserted, work "on the grandest scale," a natural experiment involving "no fewer than three hundred thousand people, of both sexes, of every age and station" in which cholera mortality would be correlated with water provided by one or another local water supplier (Snow 1855a, 75). Snow sought to make his case at three distinct scales: that of the local water-supply companies (first categorized by Farr in 1852), that of registration districts, and the very fine scale of registration sub-districts within them.

"All that was required," wrote Snow, "was to learn the supply of water to each individual house where a fatal attack of cholera might occur" (Snow 1855a, 75). Alas, those data were unavailable until well after MCC2 went to press. As Snow admitted later, "I was unable at the time to show the relation between the supply of houses in which fatal attacks took place, and the entire supply of each district and sub-district, on account of the latter circumstance not being known" (1856, 7). Without those data, Snow's 1855 study could only argue cholera at the coarse scale of local water suppliers, one that did not rule out either the geographic or the socio-economic variables that Farr and others had argued might be determinants of the disease. The result was, as one reviewer correctly noted, at best suggestive but certainly not definitive (Parkes 1855). Nor, when the necessary data became available (Simon 1856), was Snow able to successfully calculate a conclusive argument based on these new data (Koch and Denike 2006).

The Deptford study was similarly suggestive but inconclusive. The Broad Street outbreak, therefore, was the only study in which Snow could rigorously construct a precise and fine-grained argument, one based on street-by-street mortality, that cholera could only be a water-borne disease. In addition to the version published in MCC2, Snow prepared a second report for a local parish investigation into the outbreak centred on Broad Street (Snow 1855b).

Broad Street: Case Evidence

For his study Snow collected two separate types of evidence. The first employed short case histories of cholera victims in an attempt to demonstrate that all drank water from the Broad Street pump. Most of these cases were not collected by Snow but reported to him by other physicians practising in the stricken area, most notably Dr Marshall of Greet Street (Snow 1855a, 43) and Dr Fraser of Oakley Square (44). In addition, Snow could draw upon the case histories collected by the local curate, Rev. Henry Whitehead, who in 1854 published a detailed analysis of cholera in his parish.

While certainly suggestive, the circumstantial evidence presented by these histories was less than conclusive to Snow's contemporaries. Dr John Simon, for example, questioned the scale of the neighbourhood study as a basis for a general theory of cholera (Simon 1856). Rev. Whitehead's cases pointed to the possibility of divine providence, and, as E.A. Parkes would later point out in a review of MCC2, many of the cases could be explained in other ways (Parkes 1855, 456–57). The problem was not specific to Snow but a general problem of arguing on the basis of anecdotal case histories: they could be used to prove anything. In 1855, for example, Dr George Johnson, an assistant physician at King's College Hospital in London, published a 294-page treatise with 54 case histories (including autopsy reports) to insist that cholera must be pulmonary, and therefore inhaled (G. Johnson 1855). An anonymous reviewer praised the study for the thoroughness of its case presentation, if not for its treatment protocols promoting the "eliminative plan of treatment": castor oil ("Bibliographical Record" 1855).

Broad Street Evidence: The Maps

The second class of data presented by Snow was cartographic. In his maps Snow used mortality records collected by the GRO to create a class of cholera incidence related in the map by proximity to public water sources. The purpose of the map was not "hypothesis generating" (Monmonier 2002) but "hypothesis testing." By creating a mapped class of all cholera deaths located in relation to the Broad Street well and pump (see Figure 1), Snow crafted a spatial argument in which one class of events, cholera deaths, was positively correlated on the map with one member of a class of suspected contagion sites.

In the MCC2 map, a dotted line defines a principal study area, based on registration sub-district boundaries, within which cholera deaths reported to the GRO were located by address. The overwhelming centrality of the Broad Street pump in relation to the majority of GRO-reported deaths was the fine-grained, spatially precise argument Snow had promised but had been unable to deliver in previous studies, including the South London study. The combination of case histories and the map that made of them a single analytic field is what in 1855 distinguished Snow's argument from those of others, such as Johnson of King's College Hospital.

Antecedents

There was nothing exceptional about Snow's construction of a spatial argument lodged in maps of a specific disease event. In nineteenth-century disease studies generally (Koch 2005a, 2005b) and in the cholera literature specifically (Koch 2008), disease mapping was an accepted medium of analysis. The use of maps as a medium in which spatial arguments related disease incidence to suspected origin sites was an eighteenth-century innovation that by the mid-nineteenth century was generally accepted, even expected. Among the earliest surviving studies of this type are Valentine Seaman's 1796 maps correlating the incidence of yellow fever with sites of "furry miasmata," odiferous human and animal waste, in New York City. These "hypothesis-testing" maps attempted to prove the

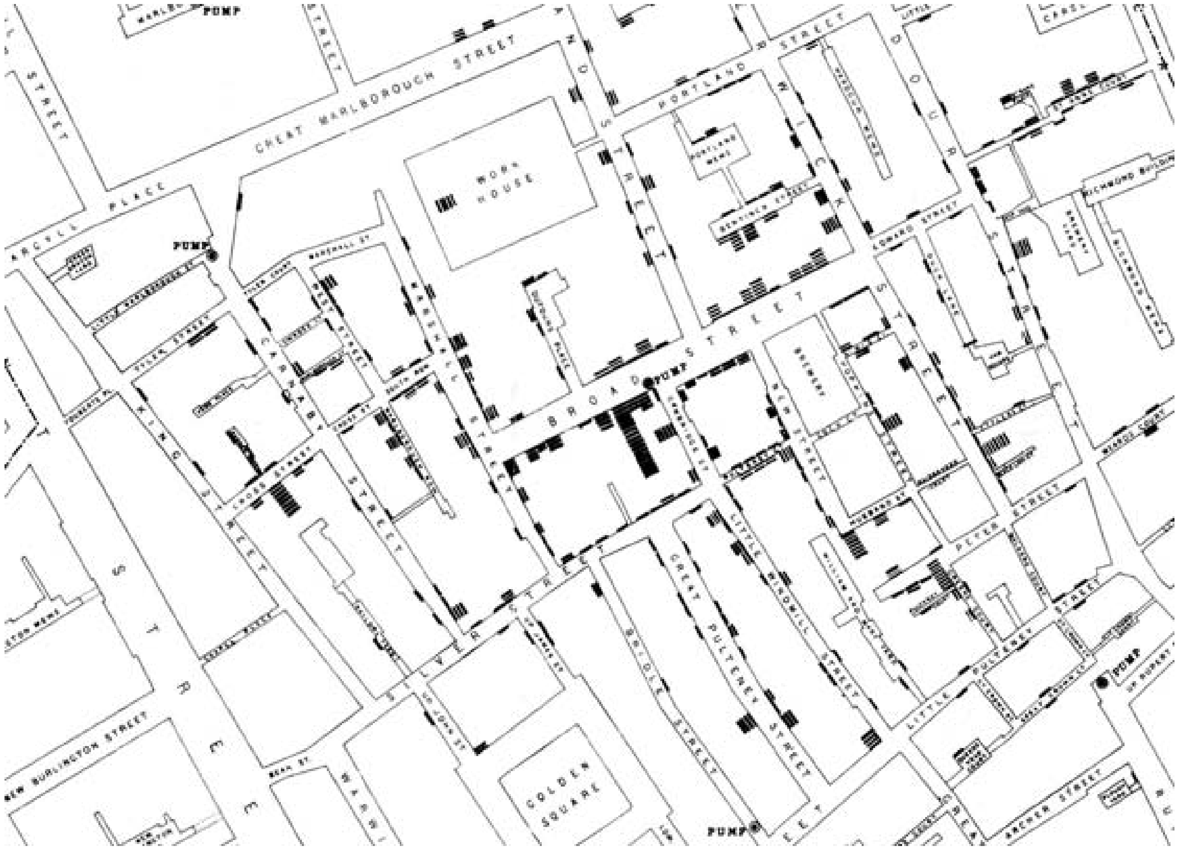

Figure 1. John Snow's famous map of the 1854 Broad Street epidemic attempted to positively correlate disease intensity with proximity to a single water source, the Broad Street well and pump.

airborne nature of yellow fever through the demonstrable proximity of yellow-fever deaths to sites of odiferous waste (Koch 2005a, 28–33).

In the first decades of the nineteenth century, the use of such maps in disease studies grew rapidly (Koch 2010). Certainly, from the first report of cholera's incidence in India in 1819 (Jameson 1819), cholera was continually mapped at the scale of the neighbourhood (Lea 1850), the city (Hammett 1832; Reese 1833; Hellis 1833), the nation (Farr 1852), and the world ("History of the Rise" 1831). Scores, perhaps hundreds, of books, papers, pamphlets, and reports published in England, Europe, and North America used maps to explore various theories of cholera through the analysis of patterns of disease incidence in relation to potentially causal environmental elements.

Even those whose reports did not include maps recognized the importance of the medium in disease research. For example, Dr John Simon, medical officer of health for the City of London, wrote in a report on cholera mortality in 1854 that "when the 211 deaths are mapped upon a house-plan of the City (as may conveniently be done by stamping a black ink mark at each place where one of them has occurred) the broad features of the epidemic are rendered visible at a glance" (10–11). While Simon included no maps in this report, the map "thinking" (Brody and others 2000, 68), and its importance as a methodology, was clearly stated in his work. Absent a robust microscopy, the spatial analytic of the map was perhaps the central medium in disease studies in this era.

Within this tradition, Snow's maps were neither incidental nor merely illustrative. They were the workbenches on which Snow constructed a fundamentally spatial argument relating clusters of disease mortality in relation to a suspected environmental disease source. Other researchers simultaneously investigating the Broad Street outbreak – including the London Sewer Commission engineer Edmund Cooper (1854) and parish curate Rev. Henry Whitehead (1855) – similarly mapped GRO mortality records in separate investigations of what Snow called "the most terrible outbreak of cholera which ever occurred in this kingdom" (1855a, 38).

Snow's Maps

Snow hired C.F. Cheffins, a prominent London engraver best known for his transportation maps, to modify an existing street map of Snow's study area to create the

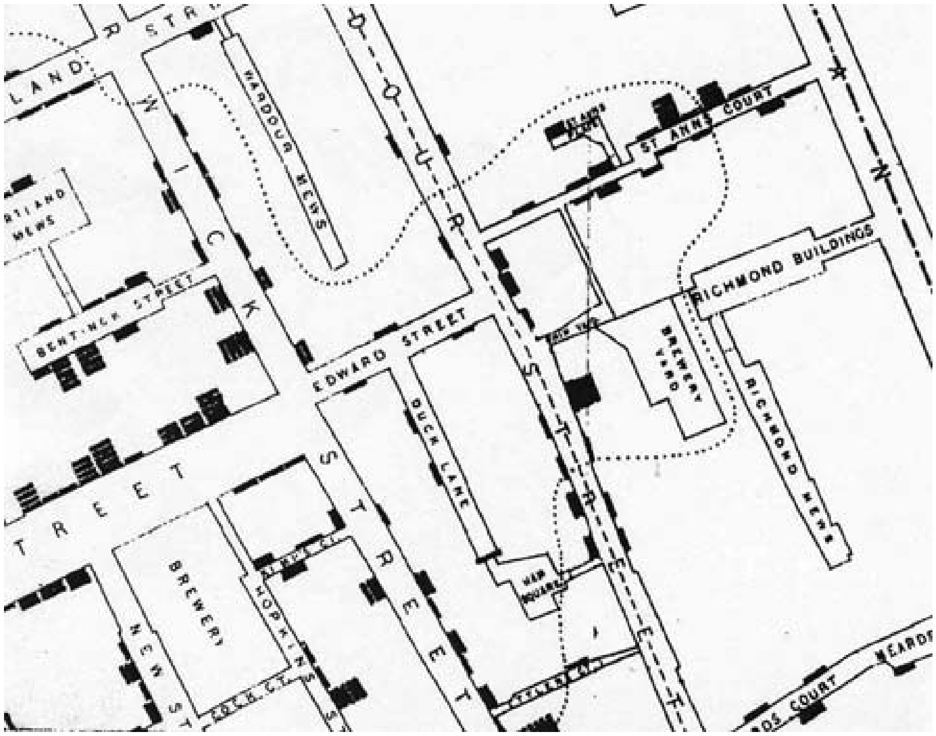

Figure 2. In a second map prepared for a local parish inquiry committee, Snow created an irregular polygon based on walking distance to identify a subset of cholera deaths located nearest the Broad Street pump.

cartographic arena in which Snow might make his case. Measuring 415 × 384 mm, the foldout map included a dotted line that created out of official registration sub-district boundaries a single study area in which Snow's argument could be inscribed. To this Snow had added the location of 14 public wells, as well as those of 596 deaths reported to the GRO. Each death was symbolized by a black rectangular mark, signifying the home of each decedent. In Snow's second map, for the parish inquiry, he included additional deaths for which he had earlier had no home address.

These postings, as Denis Wood and John Fels (2008) would call them, permitted Snow to demonstrate a positive correlation between increasing mortality and decreasing distance from the Broad Street well and pump at the epicentre of the outbreak. Snow's evidentiary use of the map, which he described as "a diagram of the topography of the outbreak" (1855a, 45), was limited to the observation that deaths appeared to be clustered in the area of the Broad Street pump: "It may also be noticed," he wrote, "that the deaths are most numerous near to the pump where the water could be more readily obtained" (1855a, 47). To a second map prepared for the St. James Parish inquiry committee Snow added an irregular polygon based on walking distance from the Broad Street pump (Snow 1855b; see Figure 2). In the first map Snow therefore created a class of mapped cholera deaths across the study area; the second map's polygon identified a subset, "Broad Street pump deaths," defined by their relative proximity to that water source. The apparent density of that cluster, which was not analysed in any other fashion, was the centrepiece of Snow's spatial argument.

In the main, Snow's contemporaries found his conclusions suggestive but certainly not definitive. One problem was that the Broad Street pump at the epicentre of the outbreak was well known for the quality of its water and therefore seemed an unlikely source for the cholera outbreak. England's best-known microscopist, Arthur Hill Hassall, examined a sample of the well water and declared it "relatively bereft of [contaminated] microscopic animal life" (Vinten-Johansen and others 2003, 247). Snow admitted that the absence of observable contaminates forced him to "hesitate to come to a conclusion" on the pump water's complicity in the outbreak (1855a, 39). He could demonstrate the centrality of the well and pump but could only assert deductively its pollution: "Whether the impurities of the water were derived from the sewers, the drains, or the cesspools, of which latter there are a number in the neighborhood, I cannot tell" (1855a, 53).

Another problem was that some researchers were reluctant to accept as definitive the results of a single large-scale neighbourhood study. Simon (1856), for example, argued that because most London neighbourhoods were served by a plethora of local wells, there would always be a water source near the centre of a neighbourhood outbreak. Other researchers similarly mapped other local

Table 1. Three researchers created three different maps for simultaneously studies of the Broad Street outbreak. In addition to Snow's maps (given here as one) were another by Rev. Henry Whitehead and a third produced for the London Sewer Commission by engineer Edmund Cooper.

	Total Map Area m^2	Study Map Area m^2	Total Streets *n*	Total Deaths *n*	Total Pumps *n*
Snow (MCC2)	867,849	538,077	304	596	14
Whitehead	588,096	442,903	190	684	11
Cooper	673,654	494,473	190	351	9

outbreaks and their water sources, only to arrive at conclusions very different from Snow's – for example, John Lea (1850) in Cincinnati, and Thomas Shapter (1849) in Exeter.

A third problem was Snow's wholly non-quantitative treatment of his data in a period when mortality ratios were the common mechanism for describing disease mortality. In his 1849 monograph Snow had insisted that "the subject is capable of being decided by exact numerical investigation" (1849a, 16; Paneth 2004). Elsewhere – in MCC2 and in other papers – Snow made frequent use of mortality ratios. Yet in the Broad Street study, the only study in which precise mortality data could easily have been crafted, Snow made no effort to quantify his visual argument. But the mapped cluster of cholera deaths meant little without data on the population of the streets in which the cholera victims lived. If the population of Broad Street was 10 times that of, say, Rupert Street, then 10 times as many deaths might be expected in the former as in the latter.

Finally, many objected to Snow's declarative style, his strident insistence that his data and its treatment were sufficient to prove his theory (see, e.g., Parkes 1855). In the same vein, many objected to Snow's often dismissive rejection of other theories of cholera and the arguments that supported them: "Snow's colleagues did not so much oppose his theory as they objected to his dismissing other explanations for cholera's occurrence" (Eyler 2001, 26). It was not that Snow was wrong but that he had not proved his thesis that water, and *only* water, was the source of the outbreak. The problem was not in the maps, we argue, but in Snow's handling of mapped data that were cartographic and spatial.

Quantifying Broad Street

To satisfy his contemporaries Snow would have needed three things. First he would have needed to transform his visual argument into "exact numerical investigation" based on his mapped data (Snow 1849, 16; Paneth 2004). Second, he would have needed a mechanism permitting him to compare the Broad Street water-service area with others in the affected registration sub-districts. Third, Snow would have needed to demonstrate, within the limits of the science of his day, that his solution was more likely than those advanced by other researchers as suspected sources of cholera. Below we demonstrate that with very little extra effort Snow could, within those limits, have completed these tasks using data that, like his, were cartographic and spatial.

Snow could not count the number of deaths in the observed cluster in the famous MCC2 map (Figure 1) because its boundaries were unclear. Did Carnaby, King, or Marshall Street define its western boundary? Where did the cluster begin and end to the south? Without some form of geographic boundary, Snow could only speak generally about cholera incidence in his study area. This problem was solved in Snow's parish inquiry map, with its irregular polygon based on walking distance. Within Snow's Broad Street service area, a total of 381 deaths were mapped in 223 houses; in other words, approximately two-thirds of Snow's 596 mapped deaths were located in the Broad Street pump's service area. Calculated another way, more than half of all houses in which cholera occurred in the general study area ($N = 403$) were situated in the Broad Street water-service polygon (see Table 1). Even this level of quantification of the mapped data would have transformed Snow's argument based on a visual impression into a forceful, numerically-based conclusion.

The data required for a rigorous consideration of Broad Street mortality were available to Snow. We can see this in the map produced for the Sewer Commission by Edmund Cooper (1854; see Figure 3) and in another submitted by Rev. Henry Whitehead (1855) as part of his report to the St. James Parish Cholera Inquiry Committee. Whitehead's map, in turn, modified one produced for the Board of Health's report on cholera and the Broad Street outbreak (Board of Health 1855). Cooper's map posted only 351 deaths, those occurring in the first two weeks of the outbreak, while Whitehead's map and that of the Board of Health included a total of 684 deaths occurring across the outbreak. Snow's maps used a data set of the outbreak that included only deaths through September 1854. In Snow's mapping, cholera deaths were assigned to streets that included no address. In Cooper's and

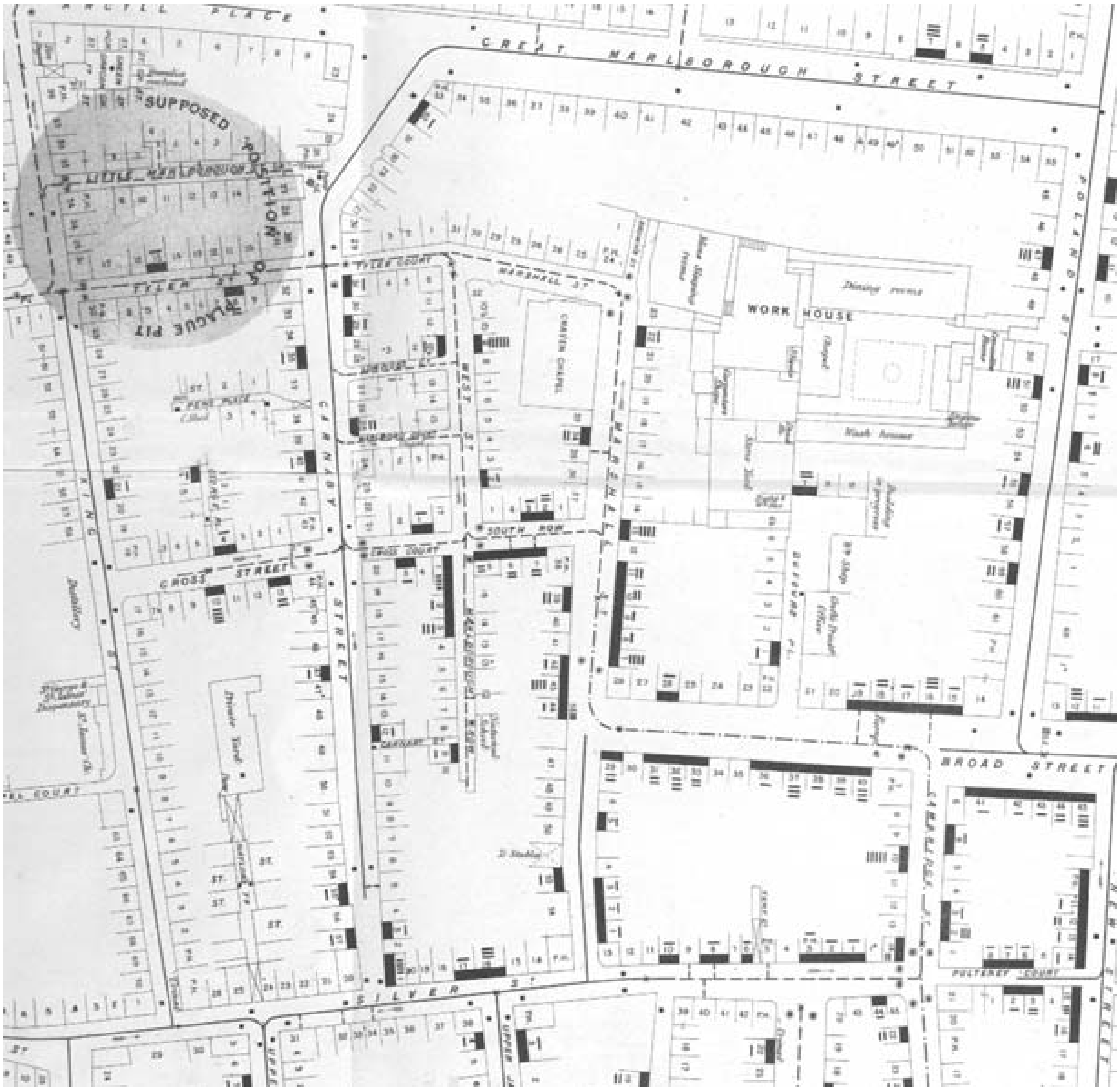

Figure 3. Edmund Cooper located cholera by house number. Thick black lines indicate homes in which cholera deaths occurred; shorter black bars stacked under the black lines signify multiple deaths at a single location. Evident in the map is the erroneous location of the 1665 plague burial site.

Whitehead's maps of the outbreak, each street in their respective study areas included the number of houses on each street and located mortal cholera cases by house address.

Like Snow's, the study areas of Cooper's and Whitehead's maps were bounded to the west by Regent Street and to the north by Oxford Street. Snow, however, included several deaths and water sources outside that boundary in his maps, whereas Cooper and Whitehead confined their street-address and mortality-incidence data to the study area. The data included in these other maps provided the platform Snow could have used to make his case more forcefully within the parameters of the science of the day. To demonstrate this, we transferred data from Whitehead's map to a photocopy of Snow's second map and, in the nineteenth-century manner, did the necessary calculations by hand.

The numbers of houses per street recorded in Whitehead's and Cooper's maps were manually counted (they were the same) and then added to the copy of Snow's map. Taking the total number of deaths in Snow's irregular polygon as numerator and the total number of houses in the area as denominator, we fashioned a crude mortality ratio of deaths per house. Given a reported average occupancy of 10 persons per house, based on 1851 census data (Farr 1852), the population (10 persons/house) of all

Table 2. Calculating mortality in Broad Street water-service areas*

Pump Locations	Snow Cholera Deaths	Snow Cholera Houses	Intensity per House (Deaths/Houses)	Total Houses in Service Area	Population for Service Area	Mortality per 1000 persons
Broad Street	381	223	1.71	255	2550	149.41
Rupert St.	38	60	0.63	209	2090	18.18
Little Marlborough St.	59	43	1.37	228	2280	25.88
Briddle St.	30	28	1.07	135	1350	22.22
Warwick St.	19	16	1.19	154	1540	12.34
Marlborough Mews	7	5	1.4	48	480	14.58
Berniers St.	13	14	0.93	115	1150	11.3
Newman St.	21	14	1.5	N/A	N/A	

* A *mortality ratio* is defined as the total number of deaths divided by the total population of a pump's service area. *Population* was defined as the number of houses per service area multiplied by an average of 10 persons per house.

255 houses in the irregular polygon as the denominator represented a better divisor (2550), being a mortality ratio of 149.41 deaths per 1000 persons.

To be convincing, however, Snow would have required comparative mortality ratios for adjacent pump catchments. He could have created catchments similar to his single polygon based on walking distance for other pumps in his study area; however, he did not. Here we faced a methodological problem. The difference between the London of the mid-1850s and the modern, automobile-dominated city makes it impossible to create equivalent service catchment areas based on pedestrian walking distance today. Street traffic and access have changed too much.

To demonstrate the potential for a nineteenth-century districting analysis, therefore, we drew a set of Thiessen polygons centred on other mapped water pumps in the study area. The lines joining all these individual service areas created a Voronoi network, a continuous set of polygons each centred on a single public well and pump. Formally, the result is called a Dirichlet tessellation, after Snow's contemporary, the nineteenth-century mathematician P. Lejeune Dirichlet, who first described the procedure (Bailey and Gattrell 1995). The procedure requires that points be located midway between all subject locations, in this case water wells and pumps. These points are then connected to create polygons whose edges are each equidistant between two and only two centroids (wells). All subjects (deaths) in each of the resulting polygons (catchments) are nearer to its centroid than to any other in the set (of wells and pumps).

The polygons created by hand in this manner served as water-service catchments for all pumps in the study area. Polygons were not created for pumps whose areas extended beyond Oxford and Regent Streets and thus beyond Cooper's or Whitehead's mapped data set of house locations and numbers. Together, however, the eight water-service areas for which polygons were constructed contained slightly more than 93% of all deaths mapped by Snow. For this study, deaths were counted to create numerators for each polygon, and the number of houses in each polygon was used to construct a mortality denominator.

The results, summarized in Table 2, would have strongly supported Snow's thesis, with 28.71 deaths per 1000 in the Rupert Street pump-service area, 25.88 deaths per 1000 in the Little Marlborough Street pump-service area, and 12.34 deaths per 1000 person in the Warwick Street pump-service area. Importantly, the number of deaths per house, a simple nineteenth-century measure of intensity, diminishes as one moves outward from the Broad Street service area.

Using this very nineteenth-century methodology, Snow also could have discounted the likelihood that other, frequently mentioned sites of potential contagion were the source of the outbreak. Consider, for example, the 1665 plague burial site. Inexplicably, Cooper located it in the northwest quadrant of the study area, and Snow accepted that assignment based on Cooper's assessment and the word of Cooper's London Sewer Commission boss. "Non-medical people" thought the old "pest-field" was more central, Snow wrote; "the situation of the supposed pit is, however, said to be Little Marlborough Street, just out of the area in which the chief mortality occurred" (1855a, 54).

Unfortunately, Cooper was wrong, and the "non-medical" people were right. Whitehead correctly described the location of the former plague burial site as both larger and nearer the epicentre of the outbreak, its southwest boundary a block's distance from the Broad Street well and pump (see Figure 4). To confirm this, we checked historical maps of the district by engraver Richard Blome

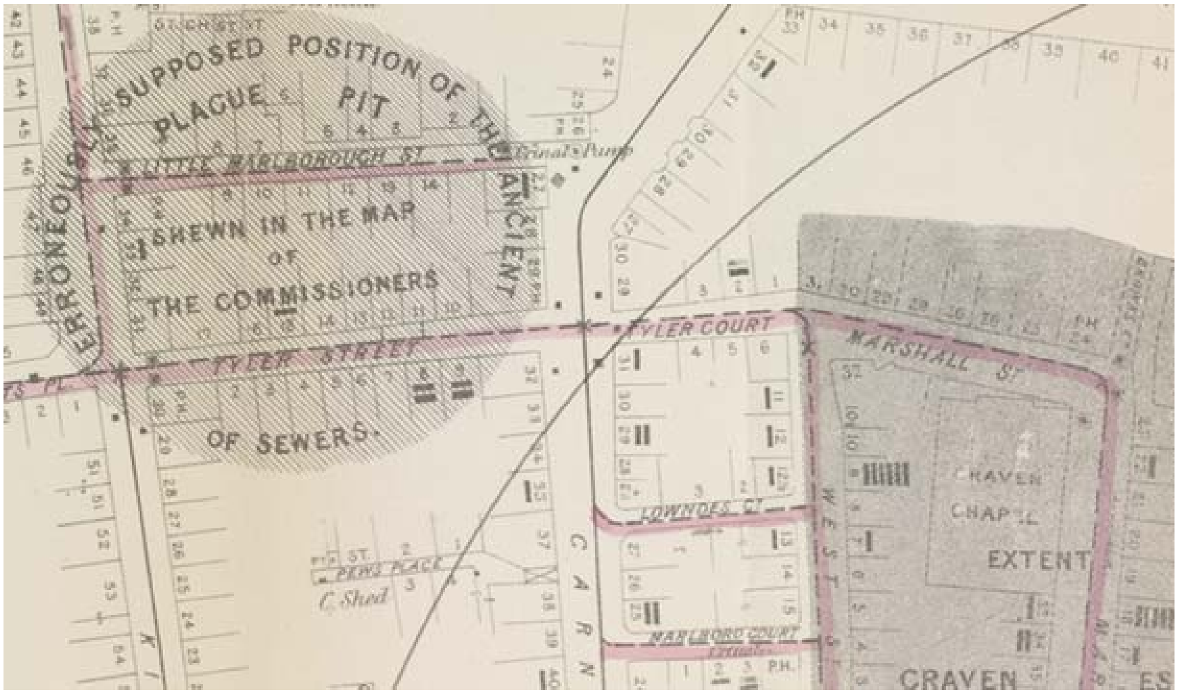

Figure 4. Rev. Henry Whitehead included in his map both Cooper's incorrect location of the 1665 plague burial site and a correctly sited area whose southwest corner is a block from the Broad Street pump.

(1720). Snow certainly knew that others believed the old "pest-field" to be proximate to the outbreak's centre. We know, too, that during this period Snow worked in close association with Whitehead, the parish curate, and thus would presumably have had access to his materials (W. Whitehead 1865).

Using Whitehead's map as a guide, we drew the boundaries of the old plague burial site on a photocopy of Snow's MCC2 map. To this we added an approximately 10-m buffer to allow for the winds that some believed carried miasmatic odours, mentioned in popular reports, into neighbouring streets. We then counted all deaths that occurred within the heavily settled buffered area, as well as the number of houses on all street segments within it. There were 113 cholera deaths in 57 affected houses (of a total 209 houses), a mortality ratio of 104.63 deaths per 1000 persons – sufficiently high to explain the concern of Snow's contemporaries, but far lower than the mortality ratio centred on the Broad Street well and pump. Within the parameters of mid-nineteenth-century science, we believe this would have been very convincing evidence indeed.

Calculating mortality for the sewer lines is a more complex task that today would require some sophistication. A crude method that would have served in Snow's day would be to count deaths on streets proximate to the suspect post-1850 sewer lines, as well as the houses that lined the streets along which those sewers ran, to create a simple mortality ratio for those streets. We counted 219 houses on sewer-suspect streets on Snow's map. Among them were 139 cholera deaths in 73 houses, about 10% of the total number of houses. Mortality per house was 1.51, far lower than in Broad Street, and general mortality for these streets was calculated as 63.47 per 1000 persons. Analysed in this fashion, the apparent culpability of the sewer lines that Londoners commented on in the newspapers of the day could have been definitively denied.

The results appear to be definitive: the mortality ratio of the Broad Street service area was so much higher than that of any other catchment, or possible contagion site, as to strongly argue the likelihood that the Broad Street well was indeed the source of the outbreak. We believe these findings would have been convincing to Snow's contemporaries. Certainly they would have been more convincing than the argument Snow made in MCC2.

Discussion

It took us four or five days of intermittent labour to count the houses per street, transfer the old cemetery site to Snow's map, create the buffer, and trace the critical sewer lines to Snow's maps. With these data in place, the calculations, carried out by hand (but checked with an electric calculator), took perhaps two hours. We believe that Snow's contemporaries would have seen these results as, if not definitive, then certainly far more convincing than those Snow presented. We further believe that the questions asked by Snow's contemporaries were correct and deserved to be seriously considered.

The methodology we used in this study was one current in Snow's era and – given his frequent use of mortality ratios elsewhere in his work from 1849 through 1858 – clearly one he was familiar with. Why, then, did Snow not take the time to do the work that would have been convincing in the science of his day? We can only speculate. It may be that Snow believed his maps presented so clear and compelling a statement that no further calculation was necessary. Mapping was an accepted methodology whereby classes of disease events were first constructed and then compared to proximate environmental contaminants. In his maps Snow could see the suspect well and pump at the very epicentre of the mapped class of deaths. If Snow thought nothing more was needed to make his case, however, the reservations of his critics make clear that in this assumption he was wrong.

A more practical reason for Snow's reluctance to quantify his spatial data may be that he did not want to take the time. Simply, he was overextended: in 1854 Snow attempted simultaneously to investigate three separate cholera outbreaks (Deptford, Broad Street, and South London) while still practising as a physician, a specialist in anaesthesiology, during a period of ferocious epidemic disease. Because he tried to do too much, perhaps he had insufficient time to complete the analysis in any of his study projects.

Finally, it was Snow's habit to publish early and leave to later papers the accumulation of additional data to bolster an argument. He did this, as previously noted, with his 1849 pamphlet (MCC1) and in 1856, once the data were made available, in an attempt to improve his South London study (Koch and Denike 2006). Perhaps the real question is not why Snow published the Broad Street study without adequate calculation but why, given the concerns of critics, he did not use the mapped data presented by Cooper and Whitehead to go back and finish the "exact numerical investigation" later.

ESSENTIAL OR ILLUSTRATIVE

It is probably more important today to ask why some modern cartographers (Monmonier 2002) and public-health researchers (Brody and others 2000; Vinten-Johansen and others 2003) deny the evidentiary importance of the Broad Street map in which Snow's fundamentally spatial argument was lodged. Again, we speculate.

The insistence by some that Snow's maps did not serve important evidentiary and argumentative functions is a reflection not on Snow's map but on those commentators' lack of knowledge of mid-nineteenth-century medical science and perhaps, more generally, their ignorance of the history of maps as tools of substantive analysis and argumentation.

More important, perhaps, is the denigration by Snow's biographers, who dismiss both Snow's map and medical mapping in general. Epidemiology and public health are twentieth-century constructs that social epidemiologist Nancy Krieger (2000, 155) defines as "preconditional on the emergence of quantitative population sciences" and the "fundamental beliefs that intimate relations exist between mathematics and material reality." This "quantitative population science" has been relatively ignorant of spatial data in its analysis of epidemic incidence (Gould and others 1991). That ignorance includes both the history of disease mapping and the spatial analytics that, since at least the nineteenth centuries, have accompanied it (Koch 2009). Given Snow's centrality in the mythology of these disciplines and his failure to quantify his study, it is, we suspect, easier to blame the map than to blame the progenitor himself. Dismissing Snow's map as at best an illustrative afterthought allows them to dismiss mapping and the spatial analytic it presents as well. Clearly this dismissal of the map and its critical argument serves neither in this case nor across several hundred years of disease study, then to now (Koch 2004, 2005a, 2009). The dismissal of Snow's Broad Street map, in other words, says more about the critics than about Snow or the science of his day. Of course, not all public-health experts dismiss cartographic analytics; an example is John Krieger's treatment of the history of census tracts in health research and of modern disease mapping as a resource in epidemiology and public health (Krieger and others 2006; Krieger 2006).

MAP OR LEGEND

It also may be that over the last century Snow's map has come to *be* just a graphic, that the substantive instrument that Snow fashioned in his maps has been lost in its various appropriations (Koch 2004). In 1901 William T. Sedgwick redrew Snow's parish inquiry map to emphasize its irregular polygon for use in a textbook on "sanitary science," as public health was then called. His map, "After John Snow," was used to illustrate an inferential process of deduction that students were to employ in considering the logical relationship between spatially grounded data on disease incidence and environmental, principally water-borne, sites of suspected contagion.

Since 1901 a progression of illustrations based on Sedgwick's "After John Snow" that purport to *be* John Snow's have been constructed (see Koch 2005a). In the 1950s, for example, geographer E.W. Gilbert published as "Dr. John Snow's Map (1855) of Deaths" a simplified version of Sedgwick's rendition (he quotes Sedgwick, but not Snow) to argue the importance of medical cartography and geography. In this map Gilbert changed the symbology and removed streets – the essence of Snow's topography – to emphasize visually the centrality of the Broad Street pump. In the 1960s Gilbert's map was used as the template for another "Snow's Map" published by another geographer, L.D. Stamp (1964). This map, in turn, was the basis for another "Snow Map" by E.R. Tufte (1983) that, with Stamp's, was the basis for Mark Monmonier's

"Snow's Dot Map" (Monmonier 1996, 2005). Most egregious, perhaps, was the pruning of Snow's database of more than 100 cholera deaths in a digital version of Snow's Broad Street maps produced by the US Centers for Disease Control's EpiInfo mapping software (CDC 2000; see, e.g., Lang 2000).

It is typically these later versions, rather than Snow's own maps, that are referred to by many who critique (and many who laud) Snow's Broad Street study (see Granados 2009 for a recent example). These later versions were graphics, not elements of a sustained research program; they were crafted as advertisements promoting cartography, geography, and public health as disciplines, rather than as spatial arguments in which disease data are first categorized and then analysed. The analytic and evidentiary value of Snow's maps was lost in the propagandistic intent of these maps by later authors whose principal argument has been the importance of their own disciplines rather than a methodology of disease study.

Snow was correct: cholera is a water-borne disease. Science, however, is not about being "right." Rather, it is about convincing a jury of one's contemporaries of the correctness of a thesis on the basis of commonly accepted methodologies. This is what Snow attempted and failed to do. Snow's failure to quantify his spatial data or to give rigorous consideration to other possible sources of the Broad Street outbreak left questions unanswered.

This was not a failure of Snow's map, however. The map provided a crucial evidentiary base for a spatial argument that, given several additional days' consideration, could have been more convincing. Nor is it correct to lay the blame for Snow's failure to convince his contemporaries at the door of mapping generally. The means by which Snow could have answered his critics was lodged in other maps of the same outbreak to which he had access. Finally, to dismiss medical mapping on the basis of Snow's failure to adequately answer his colleagues signals a lack of both historical acumen and contemporary knowledge and awareness. As computerized cartographic approaches to spatial analysis of health have advanced, the mapped analysis of health data has become increasingly important (see, e.g., Krieger and others 2006). In precisely the same way that Snow ignored his contemporaries and the evidence they presented, those who insist upon the map as simply a graphic addendum ignore the reality of Snow's scientific method and the importance of the map in its analysis. To argue otherwise is to deny both history and the wealth of contemporary studies in which spatial arguments embedded in maps are presented in the arena of disease investigation.

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