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Water purification efforts and the black-white infant mortality gap, 1906–1938

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A R T I C L E I N F O

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A B S T R A C T

According to Troesken (2004), efforts to purify municipal water supplies at the turn of the 20th century dramatically improved the relative health of Blacks. There is, however, little empirical evidence to support the Troesken hypothesis. Using city-level data published by the U.S. Bureau of the Census for the period 1906–1938, we explore the relationship between water purification efforts and the Black-White infant mortality gap. Our results suggest that, while water filtration was effective across the board, adding chlorine to the water supply reduced mortality only among Black infants. Specifically, chlorination is associated with a 9 percent reduction in Black infant mortality and a 10 percent reduction in the Black-White infant mortality gap. We also find that chlorination led to a substantial reduction in the Black-White diarrhea mortality gap among children under the age of two, although this estimate is measured with less precision.

1. Introduction

Today in the United States, Black infants are more than twice as likely to die within the first year of life than their White counterparts (Aron 2013; Riddell et al., 2017). Although the Black-White infant mortality gap has existed since at least the turn of the 20th century, when reliable mortality data by race first became available, its causes are still being researched and debated today (Ewbank 1987; Collins and Thomasson 2004; Almond et al. 2006; Elder et al., 2016; Speights et al., 2017; Anderson et al., 2020a).

This study is the first to explore whether the adoption of clean water technologies (i.e., water chlorination and filtration) at the municipal level can explain the evolution of the Black-White infant mortality gap during the first decades of the 20th century, a period when urban mortality rates—especially infant mortality rates—were in steep decline (Cutler and Miller 2005; Anderson et al. forthcoming). Previous studies provide evidence that the construction of filtration plants led to substantial reductions in infant mortality (Cutler and Miller 2005; Anderson et al. forthcoming), but these studies do not provide estimates by race.

In *Water, Race, and Disease*, Troesken (2004) famously hypothesized that, because urban Blacks and Whites lived in close proximity to each other at the turn of the 20th century and drew upon the same sources of drinking water, the adoption of clean water technologies led to an improvement in the relative health of Blacks.[1] The negative and statistically significant association between water filtration and typhoid mortality among Blacks living in major American cities documented by Troesken (2002, 2004) supports this hypothesis, but typhoid deaths were only a small proportion of total deaths during the first decades of the 20th century and never amounted to more than half of mortality

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[1] Specifically, Troesken (2004, p. 2004) wrote that because “there was limited discrimination in the provision of public water and sewer lines...blacks benefited more than whites, in terms of disease reduction, from investments in water and sewer lines and water purification systems” (Troesken 2004, p. 204). For reviews of *Water, Race, and Disease*, see Kiple (2005), Harper (2007) and Humphreys (2007).

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from diarrhea/enteritis (Anderson et al. forthcoming), the leading cause of infant mortality. Whether, and the extent to which, water purification efforts contributed to the evolution of the Black-White infant mortality gap is still an open question.

Using newly transcribed infant mortality data by race on 17 major American cities for the period 1906–1938, we find mixed evidence with regard to the Troesken hypothesis. Specifically, we observe a strong negative association between water filtration and infant mortality among both Blacks and Whites. By contrast, there is no evidence that chlorination reduced White infant mortality; among Blacks, however, chlorination is associated with a 9% reduction in infant mortality. Adding chlorine to the water supply is also associated with a 10% reduction in the Black-White infant mortality gap and a 22% decrease in the Black-White diarrhea/enteritis mortality gap among children under the age of two, although it should be noted that this latter estimate is not statistically significant at conventional levels.

The remainder of the paper is organized as follows. In the next section, we provide historical context and discuss the relevant literature, focusing on the contributions of Troesken (2002, 2004). In Sections 3 and 4, we describe our data and empirical strategy, respectively. We report our results in Section 5. Section 6 concludes.

2. Background and previous studies

Public health experts at the turn of the 20th century recognized that the infant mortality rate was much higher among Blacks than Whites (Billings 1883; Du Bois 1899; Miller 1906). The reasons for this discrepancy, however, were fiercely debated. For instance, in an infamous treatise published by the American Economic Association, Hoffman (1896, p. 69) argued that "excessive infant mortality among the colored population is largely the result of individual neglect, as well as in part due to inherited organic weakness…" Hoffman (1896, p. 329) went on to recommend that philanthropic efforts not be directed toward reducing the Black infant mortality rate for fear that such efforts would make Blacks "even more dependent on the white race at the present time than…previous to emancipation."

Other public health experts during this era argued that the Black-White infant mortality gap was due to "matters of condition" as opposed to "racial traits and tendencies" (Miller 1906, p. 90). For instance, Miller (1906, p. 90) listed several factors that could explain why Black children in Philadelphia were not as healthy as their White counterparts. Among them were "unwholesome food," "poor training," and lack of education. Miller also believed that contaminated drinking water contributed to the relatively poor health of Black children living in Philadelphia.

Indeed, the water supply of Philadelphia—like other major American cities—was unquestionably contaminated at the time Miller was writing. An extensive system of underground sewers carried human and industrial waste into the Schuylkill River, from which the city's drinking water was drawn, and waterborne diseases, including dysentery and typhoid, were rife (Condran et al., 1984; McCarthy 1987; Levine 2010). Between 1900 and 1911, several filtration plants and pumping stations were constructed, costing the city $28 million (an enormous sum at the time), and chlorine, a powerful disinfectant, was continuously added to the Philadelphia water supply beginning in 1910 (West 1914; McCarthy 1987; Levine 2010).

Evidence on the effectiveness of water purification efforts such as those undertaken by the city of Philadelphia comes from Cutler and Miller (2005) and Anderson et al. (forthcoming). Using data on 13 major American cities for the period 1900–1936, Cutler and Miller (2005) found that the building of a water filtration plant led to a 35 percent reduction in infant mortality. Using data on 25 American cities for the period 1900–1940, Anderson et al. (forthcoming) found that water filtration led to an 11–12 percent reduction in infant mortality.[2] Although Cutler and Miller (2005) and Anderson et al. (forthcoming) found no evidence that adding chlorine to the water supply improved the health of infants, neither provided estimates by race.

2.1. Water purification efforts and the Troesken hypothesis

Troesken (2004, p. *xv*) observed that urban Blacks and Whites lived in close proximity to each other ("almost side by side") at the turn of the 20th century.[3] He argued that, because of this lack of residential segregation, it was costly to deny Blacks access to clean water and sewerage, and hypothesized that Blacks should have benefited disproportionately from municipal efforts to clean the water supply.[4] According to Troesken (2002, p. 748), the fear of waterborne diseases spreading from Blacks to Whites also "played a role in motivating cities to install relatively equitable sewer and water systems." In other words, given that Blacks and Whites lived in such close proximity to each other, if municipal authorities denied Blacks access to clean water and sewerage, they risked widespread infections among Whites.

To test the hypothesis that Blacks should have benefited disproportionately from water purification efforts, Troesken estimated the relationship between filtration and typhoid mortality using data from 33 US cities for the period 1890–1920.[5] Typhoid mortality is often used by researchers as a proxy for water quality and to track diarrheal deaths (Cutler and Miller 2005; Ferrie and Troesken 2008; Clay et al., 2014). Troesken (2002, 2004) found that filtering water was associated with a 53 percent reduction in the Black typhoid mortality rate and a (statistically insignificant) 16 percent reduction in the White typhoid mortality rate. He interpreted this pattern of results as evidence "against the hypothesis that cities systematically denied African Americans access to public water systems" (Troesken 2002, p. 750) and concluded that "blacks benefited more than whites from the installation of filters" (Troesken 2004, p. 127).[6]

Relatedly, drawing upon data from 14 North Carolina municipalities for the period 1889–1908, Troesken (2001) found that switching from

[2] Anderson et al. (forthcoming) showed that, when a series of transcription errors were corrected, Cutler and Miller's (2005) infant mortality estimate fell by two-thirds. Studies on the relationship between early water purification efforts and infant/child mortality outside the United States include Knutsson (2017) and Ogasawara et al. (2018). Anderson et al. (forthcoming) also found that the building of a water filtration plant led to a 14 percent reduction in the diarrhea/enteritis mortality rate.

[3] In 1890, the average Black person in an American city lived in a ward that was only 20 percent Black; by 1970, the average Black person lived in a ward that was 70 percent Black (Troesken 2002). Residential segregation laws generally postdated the construction of water and sewer systems (Troesken 2002).

[4] Blacks stood to benefit disproportionately from municipal efforts to clean the water supply because they "did not have the resources to purchase expensive bottled water or acquire information on appropriate sanitary practices such as boiling potentially contaminated drinking water" Troesken (2004, pp. 52-53).

[5] Most of these cities contributed 15 years of data to Troesken's analysis (1906-1920). Three cities (Charleston, SC; Charlotte, NC and Pittsburgh, PA) contributed 31 years of data (1890-1920). Thirteen of the 17 cities in our sample are included in Troesken's (2002, 2004) sample. The exceptions are: Cleveland, OH; Detroit, MI; Indianapolis, IN and Newark, NJ. Troesken (2002, 2004) also included data from: Atlanta, GA; Augusta, GA; Birmingham, AL; Charleston, SC; Charlotte, NC; Columbus, OH; Covington, KY; Jacksonville, FL; Kansas City, KS; Lynchburg, VA; Memphis, TN; Montgomery, AL; Nashville, TN; Newport, KY; Norfolk, VA; Richmond, VA; San Antonio, TX; San Francisco, CA; Savannah, GA and Wilmington, DE.

[6] Additional evidence comes from the experiences of Memphis, TN and Savannah, GA (Troesken 2002, 2004). Memphis, which was the more racially integrated of the two cities, began construction on a sewer system two years after the 1878 yellow fever epidemic. The system eventually consisted of 40 miles of mains and all but one neighborhood (Chelsea, whose residents were predominantly Black) gained access. Savannah also suffered through several yellow fever outbreaks but was much slower in providing sewerage to its residents. Twenty-two years after the last major yellow fever outbreak in Savannah, 30 miles of mains were constructed but several predominantly Black neighborhoods did not gain access. More evidence on this issue comes from Alesina et al. (1999), who found that shares of spending on productive public goods (e.g., roads and sewers) were inversely related to the degree of ethnic fragmentation in U.S. cities. See also Alesina et al. (2001) for an excellent discussion on racial animosity and redistribution in the United States versus Europe.

Table 1
Municipal Water Purification Dates and Years of Data Availability.

City and state	Year city began filtering water supply	Year city began chlorinating water supply	Years covered for infant mortality counts by race	Years covered for diarrhea/enteritis mortality counts by race
Baltimore, MD	1915	1911	1906–1938	1906–1910, 1912–1937
Boston, MA	…	1928	1908–1922, 1937–1938	1908–1909, 1913–1915, 1918, 1937
Chicago, IL	…	1912	1908–1938	1908–1910, 1912–1937
Cincinnati, OH	1907	1918	1908–1938	1908–1910, 1912–1937
Cleveland, OH	1918	1911	1920–1938	1920–1937
Detroit, MI	1923	1913	1920–1938	1920–1937
Indianapolis, IN	1904	1909	1908–1938	1908–1910, 1912–1937
Kansas City, MO	1928	1911	1906–1938	1906–1910, 1912–1937
Los Angeles, CA	…	1925	1910–1938	1914, 1915, 1918–1937
Louisville, KY	1909	1913	1906–1938	1906–1910, 1912–1937
New Orleans, LA	1909	1915	1906–1938	1906–1910, 1912–1937
New York, NY	…	1911	1908–1938	1908–1910, 1912–1937
Newark, NJ	…	1921	1920–1922, 1930–1938	1930–1937
Philadelphia, PA	1906	1910	1908–1938	1908–1910, 1912–1937
Pittsburgh, PA	1908	1910	1908–1938	1908–1910, 1912–1937
St. Louis, MO	1915	1913	1908–1938	1908–1910, 1912–1937
Washington, D.C.	1905	1923	1906–1938	1906–1910, 1912–1937

privately to publicly owned water companies narrowed the Black-White waterborne-disease mortality gap, where waterborne-disease mortality was defined as the sum of deaths due to cholera, diarrhea, dysentery and typhoid. Specifically, among Blacks, public ownership was associated with a substantial reduction in waterborne-disease mortality; among Whites, public ownership was associated with a much smaller (and statistically insignificant) reduction in waterborne-disease mortality Troesken (2001).

3. Data

Infant mortality counts by race at the city-year level for the period 1906–1938 come from *Mortality Statistics* and *Vital Statistics of the United States*, both of which were published annually by the U.S. Census Bureau.[7] These data sources have been used by previous researchers interested in exploring the causes of the mortality transition (Cutler and Miller 2005; Anderson et al., 2019a, 2020b, forthcoming), during which infant mortality rates fell precipitously (Cutler and Miller 2005; Anderson et al. forthcoming).[8] Our focus is on 17 of the most populous American cities as of 1910 (Table 1).[9] These cities accounted for nearly 16 percent of the total US population in 1910.

Because data on births at the municipal level are not available for this period, crude infant mortality rates (CIMRs) are calculated per 100,000 of the race-specific population. Previous studies on city-level mortality during this period calculated infant mortality rates in a similar fashion (Cutler and Miller 2005; Clay et al., 2014; Komisarow 2017; Anderson et al. forthcoming). *Mortality Statistics* began reporting live births in 1915, but only at the state level and only for registration states (Linder and Grove 1947, Table 44).

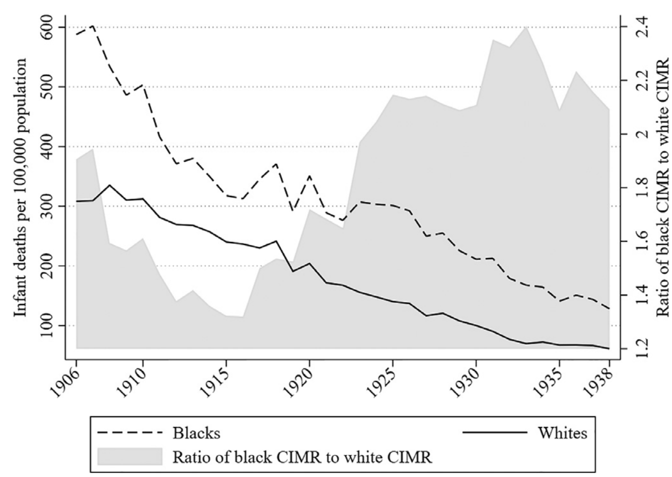

Fig. 1. Crude Infant Mortality Rates by Race, 1906–1938.

Fig. 1 shows the Black CIMR, the White CIMR and the Black-White CIMR ratio for the years 1906–1938.[10] CIMRs fell dramatically among both Blacks and Whites during these years. At first, the Black CIMR fell faster than the White CIMR, leading to a substantial reduction in the Black-White CIMR ratio. Specifically, between 1906 and 1916, the Black-White CIMR ratio fell from 1.91 to 1.32, or 30.9 percent. This

[7] Historical evidence and recent research suggest that the infant mortality counts published in *Mortality Statistics* and *Vital Statistics of the United States* were reported with minimal bias (Grove 1943; Eriksson et al. 2018). Births, however, often went unregistered, and under-registration was particularly severe among Blacks in the South (Eriksson et al. 2018).

[8] Anderson et al. (forthcoming) used city-level mortality data for the period 1900-1940. Our sources do not provide city-level infant mortality data by race for the years 1900-1905 or 1939-1940.

[9] Each of these cities had a population greater than 200,000 as of 1910 and reported mortality counts by race. We chose to focus on the largest American cities for which infant mortality counts by race were available because finding intervention dates for smaller cities proved to be exceedingly difficult. For many of these smaller cities, we could not determine whether chlorine was ever added to the water supply during the period 1906-1938. It is worth noting, however, that small- to medium-sized American cities did not adopt filtration and chlorination technologies as quickly as their larger counterparts (Melosi 2008), where the mortality transition was most pronounced (Haines 2001; Cain and Hong 2009). As late as 1939, only one-third of all U.S. waterworks used chlorine (Melosi 2008, p. 139).

[10] City-level infant mortality counts by race (i.e., "White" versus "Nonwhite") are from *Mortality Statistics* for the period 1906-1936 (U.S. Bureau of the Census 1908-1938) and from *Vital Statistics of the United States* for the period 1937-1938 (U.S. Bureau of the Census 1939-1940). Because 97 percent of the Nonwhite population in the 17 cities under study was Black, we use the term "Black" instead of "Nonwhite" throughout the analysis. In Los Angeles, roughly half of the Nonwhite population was Black. The estimates reported below are robust to dropping Los Angeles from the sample. City-level populations by race come from the decennial census; intercensal population estimates were produced by linear interpolation. *Mortality Statistics* and *Vital Statistics of the United States* often reported mortality rates per 100,000 population. However, Anderson et al. (2019b) showed that the intercensal population estimates used to calculate these rates were often wildly inaccurate. We view using linear interpolation to produce intercensal population estimates as the best available option.

Table 2
Water Purification Efforts and Infant Mortality by Race, 1906–1938.

	(1) ln(*White CIMR*)	(2) ln(*Black CIMR*)	(3) $\ln(\frac{Black\ CIMR}{White\ CIMR})$
Filtration	−0.133*	−0.174***	−0.057
	(0.063)	(0.050)	(0.092)
	{0.127}	{0.031}	{0.654}
Chlorination	0.015	−0.092**	−0.108**
	(0.049)	(0.041)	(0.050)
	{0.771}	{0.052}	{0.033}
Mean of Dependent Variable	162.6	275.6	1.83
N	478	478	478
R^2	0.983	0.900	0.732

*Statistically significant at 10% level; ** at 5% level; *** at 1% level.
Notes: Based on annual data from *Mortality Statistics* and *Vital Statistics of the United States* for the period 1906–1938, published by the U.S. Bureau of the Census. Each column reports estimates from a separate OLS regression. In columns (1)-(2), the dependent variable is equal to the natural log of the number of race-specific infant deaths per 100,000 of the relevant population in city *c* and year *t*, and the regressions are weighted by the relevant city population. In column (3), the dependent variable is equal to the natural log of the ratio of *Black CIMR* to *White CIMR*, and the regression is weighted by city population. Controls include the city-level demographic characteristics and other public health interventions listed in Online Appendix Table 1, city fixed effects, year fixed effects and city-specific linear time trends. Standard errors, corrected for clustering at the city level, are in parentheses. P-values from wild cluster bootstrap procedure are in curly brackets and are based on 1,000 replications. Means of the dependent variable (without taking the natural log) are reported.

trend reversed after 1916 and the Black-White CIMR ratio increased to 2.09 by 1938, or 58.3 percent.[11]

Table 1 provides chlorination and filtration dates for each of the 17 cities that contributed data to the analysis. These dates correspond to those used by previous researchers and were obtained from a mix of primary and secondary sources.[12] Filtration technology was developed as a method of reducing the turbidity and improving the taste of drinking water. It became more popular as the study of bacteriology advanced and municipal governments came under pressure to protect their citizens from waterborne diseases, especially typhoid. Filtering the municipal water supply was, however, often prohibitively expensive (Melosi 2008, pp. 92–95) and several cities in our sample—including Boston, Chicago, and New York—had not built water filtration systems by 1938, the last year of our analysis. Adding chlorine to the water supply, by contrast, was relatively inexpensive and every city in our sample adopted this technology at some point during the period under study.[13]

4. Empirical strategy

We begin our examination of whether water purification efforts contributed to the trends documented in Fig. 1, by estimating the following regression by race:

$$\ln\left(CIMR_{ct}\right) = \beta_0 + \beta_1 Filtration_{ct} + \beta_2 Chlorination_{ct} + \mathbf{X}_{ct}\boldsymbol{\beta}_3 + \upsilon_c + w_t + \Theta_c \cdot t + \varepsilon_{ct}, \quad (1)$$

where *c* indexes cities and *t* indexes years. Our primary interest is in the indicators *Filtration* and *Chlorination. Filtration* is equal to 1 if city *c* was filtering its water supply in year *t* (and is equal to 0 otherwise); *Chlorination* is equal to 1 if city *c* was adding chlorine to its water supply in year *t* (and is equal to 0 otherwise).[14]

The vector of controls, $\boldsymbol{X}_{ct}$, is composed of city demographics (i.e., percent female, Nonwhite, foreign born, under 15 years of age, 15–44 years of age and 45 years of age or older) taken from the 1900–1940 Censuses and linearly interpolated for intercensal years.[15] In addition to these demographics, we control for other public health interventions that could have impacted CIMRs. These interventions, which are described by Anderson et al. (forthcoming), include an indicator for whether sewage was treated before its discharge into rivers and lakes, and indicators for municipal-level efforts to provide clean milk.[16] Online Appendix Table 1 presents descriptive statistics and definitions of the variables contained in $\boldsymbol{X}_{ct}$.

Finally, city fixed effects (υ_c) control for city-level determinants of race-specific CIMRs that were constant over time and the year fixed effects (w_t) control for common shocks such as changes in medical knowl-

[11] It is important to note, however, that these CIMR trends could have been driven by changes in race-specific fertility as opposed to race-specific infant mortality. In the United States, the fertility transition among Whites began in the early 1800s, while the fertility transition among Blacks did not begin until roughly 1880 and lasted through the 1930s (Tolnay 1981; Haines and Hacker 2006; Haines et al. 2020). Perhaps due to a dearth of well-defined natural experiments, it has proven difficult to pinpoint the causes of the fertility transition among either Blacks or Whites. Using data from the 1910 census, Haines (1989) concluded that the total fertility rate among Black mothers ages 15-49 was approximately 25 percent higher than the fertility rate among their White counterparts. Aaronson et al. (2014) found that rural Black women who were exposed to Rosenwald schools during childhood were less likely to have children on both the extensive and intensive margins.

[12] For the list of sources, see the appendices in Anderson et al. (2020b) and Anderson et al. (forthcoming). In Table 1, we report the years for which infant mortality counts were available for each city in the analysis. Seven cities contributed data before and after the construction of a water filtration plant, while 15 cities contributed data before and after chlorine was added to the water supply.

[13] While both filtration and chlorination are effective against bacteria, chlorination appears to be better at eliminating viruses (Centers for Disease Control 2012, 2014). See the National Center for Environmental Health (1999), Melosi (2008) and Anderson et al. (forthcoming) for more information on the history and technical aspects of chlorination and filtration.

[14] When the exact date was available, these indicators were set equal to the proportion of the year during which the water supply was filtered/chlorinated.

[15] Because municipal efforts to clean the water supply could have been correlated with changes in the demographic composition of cities, it is important to include these Census-based controls on the right-hand side of equation (1). Several cities in our sample were important destinations during the Great Migration and it is possible that Blacks were attracted to cities that had adopted clean water technologies. Beach et al. (2016) found evidence that early-life exposure to clean water (as proxied by typhoid rates) increased geographic mobility as an adult. In an effort to explore this issue further, we regressed *% Nonwhite* on the filtration and chlorination indicators, along with the full set of controls. We found no evidence that the adoption of clean water technologies was predictive of city-level racial composition. In a separate exercise, we fixed each city's population to its 1900 level when constructing the race-specific CIMRs. The results based on this exercise were qualitatively similar to those presented below.

[16] Anderson et al. (forthcoming) also included an indicator for whether a city completed a large-scale project to deliver clean water from further afield (e.g., aqueducts and water cribs). We do not include this indicator in our analysis because only two cities in our sample contributed infant mortality data before and after the construction of a clean water project (Los Angeles, CA and Newark, NJ).

edge and technology.[17] City-specific linear time trends ($\Theta_c \cdot t$) account for the possibility that race-specific CIMRs evolved differently across the cities in our sample. Although it would have been preferable to use race-specific infant mortality rates (with births in the denominator instead of population), there is little reason to believe that the adoption of clean water technologies was systematically correlated with fertility.

After estimating the baseline regression described above for Whites and Blacks separately, we replace the CIMR with the Black-White infant mortality gap, measured as $\ln(Black\,CIMR/White\,CIMR)$, to estimate the following regression :[18]

$$\ln\left(\frac{Black\,CIMR_{ct}}{White\,CIMR_{ct}}\right) = \alpha_0 + \alpha_1 Filtration_{ct} + \alpha_2 Chlorination_{ct} + \mathbf{X}_{ct}\boldsymbol{\alpha}_3 + \upsilon_c + w_t + \Theta_c \cdot t + \varepsilon_{ct}. \quad (2)$$

Our interest is in the estimates of α_1 and α_2. Negative and statistically significant estimates of α_1 and α_2 would lend support to Troesken's (2002, 2004) hypothesis.

5. Results

In columns (1) and (2) of Table 2, we report estimates on the relationship between infant mortality and water purification efforts by race. Standard errors are corrected for clustering at the city level (Bertrand et al., 2004).[19] Filtering drinking water is associated with a 12.5 percent reduction ($e^{-0.133} - 1 = -0.125$) in the White crude infant mortality rate, and a 16 percent reduction ($e^{-0.174} - 1 = -0.160$) in the Black crude infant mortality rate. While the effect for Blacks is over 20 percent larger than for Whites, we cannot formally reject the hypothesis that the estimated coefficients are equal. By contrast, adding chlorine to the water supply appears to have only been effective at reducing the Black CIMR. The estimated coefficient on *Chlorination* is small, positive and statistically indistinguishable from zero for White infants; for Black infants, chlorination is associated with a 9 percent reduction in the CIMR.[20]

The third column of Table 2 shows the associations between water purification efforts and $\ln(Black\,CIMR/White\,CIMR)$, our measure of the Black-White infant mortality gap. Chlorination is associated with a 10 percent decrease in the Black-White CIMR ratio, while the association between filtration and the Black-White CIMR ratio is statistically insignificant.[21,22]

5.1. Water purification and the diarrhea mortality gap

During the period under study, diarrhea/enteritis was the leading cause of death among infants and the vast majority of total diarrheal deaths were among children under the age of two (Anderson et al. forthcoming). Furthermore, Black children were much more likely to die from diarrheal diseases, including "cholera infantum" and "summer complaint," than their White counterparts (Billings 1883; Du Bois 1899; Miller 1906).[23] Although myriad factors likely contributed to the Black-White diarrheal mortality gap, our focus is on municipal water purification efforts. Specifically, we estimate the modified version of Eq. (1) by race:

$$\ln\left(Diarrhea_{ct}\right) = \beta_0 + \beta_1 Filtration_{ct} + \beta_2 Chlorination_{ct} + \mathbf{X}_{ct}\boldsymbol{\beta}_3 + \upsilon_c + w_t + \Theta_c \cdot t + \varepsilon_{ct}, \quad (3)$$

where the CIMR is replaced by diarrhea/enteritis deaths among children under the age of two per 100,000 of the race-specific population.[24] We also estimate a modified version of Eq. (2):

$$\ln\left(\frac{Black\,Diarrhea_{ct}}{White\,Diarrhea_{ct}}\right) = \alpha_0 + \alpha_1 Filtration_{ct} + \alpha_2 Chlorination_{ct} + \mathbf{X}_{ct}\boldsymbol{\alpha}_3 + \upsilon_c + w_t + \Theta_c \cdot t + \varepsilon_{ct}, \quad (4)$$

where the Black-White infant mortality gap is replaced by the Black-White diarrhea mortality gap, measured as $\ln(\frac{Black\,Diarrhea}{White\,Diarrha})$.[25]

Estimates of Eq. (3) are reported in the first two columns of Table 3. These estimates provide evidence that the relationship between chlorination and the Black-White infant mortality gap documented in Table 2 is, at least in part, driven by the impact of chlorination on diarrheal diseases. Specifically, we find that chlorination is associated with a 17 percent reduction in the diarrhea/enteritis mortality rate among Black children under the age of two. The estimated effect of chlorination on diarrhea mortality among White children, while negative, is small in magnitude and nowhere near statistically significant. There is little evidence that filtration led to reductions in diarrhea/enteritis mortality among either White or Black children.

In the last column of Table 3, we report the estimated effects of water purification efforts on the Black-White diarrhea/enteritis mortality ratio. Chlorination is associated with a 22 percent reduction in the Black-White diarrhea mortality gap, but this estimate is not statistically signifi-

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[17] For instance, during the period under study there was "great progress in understanding fluid and electrolyte therapy," which likely contributed to the sharp decline in infant mortality from diarrheal diseases (Wegman 2001, p. 404S).

[18] Similarly constructed outcomes have been used by previous researchers interested in exploring the determinants of other types of Black-White gaps (LaFree et al. 2010; Quillian et al. 2017; Myers et al. 2018).

[19] P-values calculated from the wild cluster bootstrap procedure suggested by Cameron et al. (2008) and Cameron and Miller (2015) are reported in curly brackets.

[20] It is worth noting, however, that we cannot formally reject the hypothesis that the estimated chlorination effects are equal for Blacks versus Whites (p-value = 0.110).

[21] In the online appendix, we report event-study estimates of the effects of filtration and chlorination on race-specific CIMRs. Replacing *Filtration* with a series of mutually exclusive leads and lags produces no evidence of pre-treatment trends (Online Appendix Figures 1-3), suggesting that the parallel trends assumption is satisfied. Likewise, replacing *Chlorination* with a series of mutually exclusive leads and lags produces no evidence of pre-treatment trends (Online Appendix Figures 4-6). In Online Appendix Table 2, we show the coefficient estimates for the other public health interventions contained in $\boldsymbol{X}_{ct}$. In general, there is little evidence that efforts to clean the municipal milk supply reduced mortality among either White or Black infants. However, sewage treatment is associated with a 13 percent reduction in the White CIMR. Anderson et al. (forthcoming) found no evidence that building a sewage treatment plant reduced CIMRs in their sample of 25 cities for the period 1900-1940. Using data on municipalities in Massachusetts for the period 1880-1920, Alsan and Goldin (2019) examined the effects of clean water and access to a regional sewerage system on infant and child mortality. These authors found that the interaction of clean water and sewerage explained roughly one-third of the observed decline in child mortality and nearly one-half of the observed decline in infant mortality. Using data from Paris for the period 1880-1914, Kesztenbaum and Rosenthal (2017) found that the provision of sewerage to a neighborhood increased the life expectancy of its residents by several years.

[22] We also explored whether the effects of filtration and chlorination were strongest in cities with the least residential segregation. Specifically, using data from the 1900 Census, we constructed isolation and dissimilarity indices proposed by Bell (1954) and Duncan and Duncan (1955), respectively, and described by Cutler et al. (1999, pp. 458-459). Estimates based on interacting *Filtration* and *Chlorination* with these indices were decidedly mixed: some were consistent with Troesken's hypothesis, while others were not. In hindsight, these results, which are available from the authors upon request, are not surprising given the limited number of cities in our sample combined with the relatively little variation in the indices.

[23] The label "cholera infantum" was often applied to particularly virulent episodes of diarrhea that struck infants and children in the summer months (Anderson et al. 2020b). Physicians used the term "summer complaint" to refer to a "form of bowel disorder of infants characterized usually by diarrhea, sometimes by constipation, and accompanied by more or less well-marked symptoms traceable to the central nervous system" (Christopher 1893, p. 250).

[24] City-level counts of diarrhea/enteritis deaths among children under the age of two by race (i.e., White versus Nonwhite) are from *Mortality Statistics* for the period 1906-1936 (U.S. Bureau of the Census 1908-1938) and from *Vital Statistics of the United States* for the year 1937 (U.S. Bureau of the Census 1939). These counts, which are listed under the title "diarrhea and enteritis," include deaths due to cholera infantum, colitis, diarrhea, enteritis, enterocolitis, gastroenteritis, summer complaint and other similar causes (United States Bureau of the Census 1910). In Table 1, we report the years for which diarrhea/enteritis mortality counts were available for every city in our sample. City-level counts of diarrhea/enteritis deaths are not available for 1938.

[25] $Black\,Diarrhea_{ct}$ is equal to the number of diarrhea/enteritis deaths among Black children under the age of two per 100,000 Black population and $White\,Diarrhea_{ct}$ is equal to the number of diarrhea/enteritis deaths among White children under the age of two per 100,000 White population. Because the Black diarrhea/enteritis mortality count is equal to 0 for three observations, we add 1 to $Black\,Diarrhea_{ct}$ before taking its natural log. The estimates presented below are similar if we simply drop the zeros from the sample or use the quartic root function, rather than take the natural log. The quartic root function has been used by Thomas et al. (2006), Tarozzi et al. (2014) and Ashraf et al. (2015), among others, to deal with zeros.

Table 3
Water Purification Efforts and Diarrheal Mortality Among Children Under the Age of Two by Race, 1906–1937.

	(1) ln(*White Diarrhea*)	(2) ln(*Black Diarrhea*)	(3) $\ln(\frac{Black\ Diarrhea}{White\ Diarrhea})$
Filtration	−0.162	0.093	0.294
	(0.132)	(0.097)	(0.177)
	{0.355}	{0.348}	{0.182}
Chlorination	−0.027	−0.191**	−0.254
	(0.129)	(0.084)	(0.163)
	{0.875}	{0.013}	{0.123}
Mean of Dependent Variable	39.9	56.1	1.88
N	431	431	431
R^2	0.970	0.880	0.605

*Statistically significant at 10% level; ** at 5% level; *** at 1% level.
Notes: Based on annual data from *Mortality Statistics* and *Vital Statistics of the United States* for the period 1906–1937, published by the U.S. Bureau of the Census. Each column represents the results from a separate OLS regression. In columns (1)-(2), the dependent variable is equal to the natural log of the number of race-specific diarrhea/enteritis deaths among children under the age of two per 100,000 of the relevant population in city *c* and year *t*, and the regressions are weighted by the relevant city population. In column (3), the dependent variable is equal to the natural log of the ratio of *Black Diarrhea* to *White Diarrhea*, and the regression is weighted by city population. Controls include the city-level demographic characteristics and other public health interventions listed in Online Appendix Table 1, city fixed effects, year fixed effects and city-specific linear time trends. Standard errors, corrected for clustering at the city level, are in parentheses. P-values from wild cluster bootstrap procedure are in curly brackets and are based on 1,000 replications. Means of the dependent variable (without taking the natural log) are reported.

Table 4
Water Purification Efforts and Infant Mortality by Race, 1906–1938: Exploring Interactive Effects.

	(1) ln(*White CIMR*)	(2) ln(*Black CIMR*)	(3) $\ln(\frac{Black\ CIMR}{White\ CIMR})$
Filtration	−0.147*	−0.045	0.087
	(0.076)	(0.067)	(0.107)
	{0.196}	{0.490}	{0.521}
Chlorination	0.009	0.013	−0.042
	(0.074)	(0.059)	(0.068)
	{0.898}	{0.815}	{0.571}
Filtration*Chlorination	0.016	−0.176**	−0.174
	(0.076)	(0.079)	(0.111)
	{0.842}	{0.083}	{0.257}
Mean of Dependent Variable	162.6	275.6	1.83
N	478	478	478
R^2	0.983	0.901	0.733

*Statistically significant at 10% level; ** at 5% level; *** at 1% level.
Notes: Based on annual data from *Mortality Statistics* and *Vital Statistics of the United States* for the period 1906–1938, published by the U.S. Bureau of the Census. Each column reports estimates from a separate OLS regression. In columns (1)-(2), the dependent variable is equal to the natural log of the number of race-specific infant deaths per 100,000 of the relevant population in city *c* and year *t*, and the regressions are weighted by the relevant city population. In column (3), the dependent variable is equal to the natural log of the ratio of *Black CIMR* to *White CIMR*, and the regression is weighted by city population. Controls include the city-level demographic characteristics and other public health interventions listed in Online Appendix Table 1, city fixed effects, year fixed effects and city-specific linear time trends. Standard errors, corrected for clustering at the city level, are in parentheses. P-values from wild cluster bootstrap procedure are in curly brackets and are based on 1,000 replications. Means of the dependent variable (without taking the natural log) are reported.

cant at conventional levels.[26] The estimates shown in Table 3 provide no evidence that filtration contributed to the narrowing of the Black-White diarrhea mortality gap.[27]

5.2. Interactive effects

In the early 20th century, public health experts often disagreed as to whether it was necessary to chemically treat water that had already been filtered and vice versa (Hill 1911; Orchard 1917; Race 1918; Kienle 1919; Stein 1919; Clark 1921). Modern-day researchers have come to different conclusions with regard to the direction and importance of these interactive effects. For instance, Cutler and Miller (2005, p. 11) concluded that "filtration and chlorination were substitute technologies," while Troesken (2004), who focused on the experience of Washington D.C., found that the combination of filtration and chlorina-

[26] The standard p-value and the p-value from the wild cluster bootstrap procedure are equal to .138 and .123, respectively.

[27] In Online Appendix Table 3, we show the coefficient estimates on the other public health interventions that compose the vector $\boldsymbol{X}_{ct}$. In general, there is little evidence that sewage treatment or efforts to clean the municipal milk supply reduced diarrhea/enteritis mortality among White or Black children.

tion was more effective at reducing typhoid than filtration alone. Finally, Anderson et al. (forthcoming) found that interacting their filtration and chlorination indicators produced a negative, but statistically insignificant, estimated effect on infant mortality.

Our results, which are reported in Table 4, provide evidence that, when combined, chlorination and filtration were particularly effective at reducing mortality among Black infants. The estimated coefficient of the interaction term is negative, large in magnitude, and statistically significant at the 5 percent level. Taken at face value, it suggests that the interaction of chlorination and filtration led to a 16.1 percent reduction in the Black CIMR.[28]

6. Conclusion

Whether health inequalities are exacerbated or diminished by technological innovation is theoretically ambiguous. Expensive, private technologies can be prone to "elite capture," while there is evidence that less expensive "breakthrough" technologies disproportionately benefit poorer, underprivileged members of society (Alsan et al. 2019).

Our estimates suggest that adding chlorine to the water supply, which was relatively inexpensive, had no appreciable effect on the White crude infant mortality rate (CIMR), but led to a 9 percent reduction in the Black CIMR and a 10 percent reduction of the Black-White CIMR ratio, our measure of the Black-White infant mortality gap. The adoption of water filtration technology, by contrast, seems to have been effective at reducing infant mortality among both Blacks and Whites: it is associated with an almost 13 percent reduction in the white CIMR and a 16 percent reduction in the Black CIMR.[29]

Chlorination appears to have narrowed the Black-White infant mortality gap, at least in part, through its effect on diarrheal diseases. We find that chlorination led to a 17 percent reduction in diarrhea/enteritis mortality among Black children under the age of two for the period 1906–1937. Although the estimated effect of chlorination on diarrhea mortality among White children is also negative, it is small and statistically insignificant at conventional levels. We find little evidence to suggest that filtration led to reductions in diarrhea/enteritis mortality among either White or Black children under the age of two.

In *Water, Race, and Disease*, Troesken (2004) observed that, at the turn of the 20th century, urban Blacks and Whites lived in close proximity to each other and drew upon the same sources of drinking water. According to Troesken (2004), when municipalities purified the water supply, this had the effect of improving the health of Blacks relative to Whites. The negative association between adding chlorine to municipal water supplies and the Black-White infant mortality gap lends support to his often-cited and well-known argument.

Why would adding chlorine to the water supply affect Black, but not White, infant mortality? One possibility is that chlorination mattered more for Black families because, on average, their children were more likely to suffer from nutritional deficiencies and, thus, were less able to cope with waterborne infections. Another possibility is that Black families did not have the resources to disinfect or boil their water prior to chlorination (Troesken 2004).[30] Indeed, Troesken (2004, p. 167) found a stronger positive association between bacteria counts in municipal water supplies and waterborne-disease mortality among Blacks than among Whites, suggesting that "African-American households were less able than White households to engage in the personal precautions necessary to prevent typhoid." Lastly, an effective treatment for infant diarrhea had been developed by the early 1900s, and it is possible that physicians and midwives who served White communities prior to chlorination were simply better equipped to treat diarrheal diseases than their counterparts who served Black communities.[31]

Credit author statement

All authors contributed equally to the production of this manuscript.

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Supplementary materials

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[28] The estimated coefficient of the filtration-chlorination interaction is actually positive (but small and statistically insignificant) when ln(*White CIMR*) is the dependent variable. The estimated coefficient of the filtration-chlorination interaction is equal to −0.174 when the Black-White infant mortality gap is on the left-hand side of the regression, but it is not statistically significant at conventional levels.

[29] It is worth noting again that we cannot formally reject the hypothesis that the estimated effects of filtration on Black and White infant mortality are statistically equivalent. These estimated effects are of similar magnitude to those reported by Anderson et al. (forthcoming). As noted above, these authors found that water filtration was associated with an 11-12 percent reduction in the infant mortality rate. Because Anderson et al. (forthcoming) did not explore effects by race, they were able to analyze more years of data (i.e., 1900-1940 vs. 1906-1938) for a larger set of cities (i.e., 25 vs. 17 cities).

[30] Because chlorination appears to be better at eliminating viruses than filtration, it could have been particularly important for families that were unable to disinfect their drinking water (Centers for Disease Control and Prevention 2012, 2014).

[31] For example, a popular textbook used by midwives during the early 1900s taught the use of albumin water to treat severe diarrhea in children (Johnstone 1913). Han et al. (2009, p. 444) found that normal saline solution and albumin were equally effective for "initial hydration therapy for dehydrated term infants…due to acute diarrhea."

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