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ORIGINAL PAPER

Something in the pipe: the Flint water crisis and health at birth

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Abstract
In 2014, the city of Flint, MI, in the USA changed its public water source, resulting in severe water contamination and a public health crisis. Using the Flint water crisis as a natural experiment, we estimate the effect of in utero exposure to polluted water on health at birth. Matching vital statistics birth records with various sources of data, we use the synthetic control method to identify the causal impact of water pollution on key birth outcomes. Our results suggest that the crisis modestly increased the rate of low birth weight (LBW) by 1.8 percentage points (or 15.5%) but had little effect on the length of gestation or rate of prematurity. However, these effects are larger among children born to black mothers, as indicated by an increase in the rate of LBW by 2.5 percentage points (or 19%). Children born to white mothers exhibit, on average, a 30.1-g decrease in birth weight. We find little evidence that the male-to-female sex ratio declines in the overall population, suggesting that the in utero scarring effect of the Flint water crisis may dominate the channel of mortality selection. However, we observe a slight decline in the sex ratio among children born to black mothers. Finally, we find no notable change in the fertility rates of either black women or white women in Flint. These results are robust to a rich set of placebo and falsification tests.

Keywords Water pollution · Lead exposure · Flint water crisis · Infants · Low birth weight

JEL classification I14 · I18 · Q53 · Q58

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1 Introduction

In the USA, pollution of drinking water is a major long-term environmental concern that poses significant threats to public health. Unsafe drinking water in Flint, MI, has recently received considerable attention, but the problem is widespread. According to the US Environmental Protection Agency (EPA), a fifth of the US population has been exposed to unsafe water more than once during the 2010s. Nearly 3000 recently tested municipalities recorded peak-level lead poisoning rates at least double those in Flint, MI, and more than 1100 of these communities reported blood tests with elevated lead levels approximately four times the rate of that in Flint (Centers for Disease Control and Prevention 2012, 2016; Pell and Schneyer 2016). As a long-overdue move, in 2021, President Joseph Biden proposed a $55 billion plan to replace the country's aging, lead-laced water systems. In contrast to the burgeoning economics literature on air pollution and pediatric health (e.g., Currie and Neidell 2004; Currie et al. 2009), much less attention has been given to the impact of contaminated drinking water on pediatric health (Currie et al. 2013).

Little is known about the causal relationship between lead or other pollutants in water and adverse fetal or neonatal outcomes. Environmental and epidemiological studies find that maternal lead exposure is associated with negative fetal outcomes, such as preterm birth (Zhu et al. 2010) and fetal death (Edwards 2014). Furthermore, lead ingested by the mother can cross the placenta and potentially poison the fetus (Taylor et al. 2015). A few recent studies aim to establish causal relationships between lead exposure and reduced fertility rates (Grossman and Slusky 2019), educational outcomes (Sauve-Syed 2018), maternal stress (Danagoulian and Jenkins, 2021), birth outcomes (Dave and Yang 2020), and bottled water sales (Christensen et al. 2018). Other pollutants in drinking water, such as trihalomethanes (THMs), coliform bacteria, and *Legionella* bacteria (the causative pathogen of Legionnaire's Disease), are associated with health at birth.[1] As changes in the color, taste, and odor of local drinking water indicate simultaneous changes in other pollutants besides lead, attributing the main adverse birth effects of polluted water consumption to lead may overestimate its effect.

This paper offers novel evidence on the effect of in utero exposure to contaminated municipal tap water on health at birth in the context of the Flint water crisis (the crisis hereafter) in Flint, MI. Very few studies have examined the causal effect of this serious public health crisis on birth outcomes (Abouk and Adams 2018; Grossman and Slusky 2019). More scientific evidence is required given that the crisis still affects the lives of local residents with potential latent health effects for the local newborns.

To identify the effect of drinking water pollution on health at birth, we use variations in water quality caused by a change in the municipal tap water source in Flint as a natural experiment. In 2014, the city of Flint switched its main drinking water

[1] Byproducts of chlorinated disinfectants, such as THMs, are associated with negative outcomes such as small for gestational age (SGA), low birth weight, and spontaneous abortion (Gallagher et al. 1998; Waller et al. 1998).

source from Lake Huron via a supplier in the city of Detroit to the considerably more corrosive water of the Flint River (see the timeline in the Appendix Fig. 7). The change in water source led to significant increase in multiple contaminants, reports, and complaints of changes in the color, taste, and odor of the water.[2] In our analysis, we leverage this change in the water supply in Flint but not elsewhere in the state of MI or other cities in the USA. Using all birth records filed in the city of Flint from 2008 to 2015, our empirical strategy allows us to compare birth outcomes across groups of children exposed to differing levels of drinking water contaminants while in utero (treatment and control groups). Applying the synthetic control method (SCM), we use a rich set of measured variables to best match Flint with a large set of candidate cities in the USA (i.e., the synthetic Flint). Our results hold even after a large set of placebo tests and robustness checks.

Our findings suggest that drinking water contamination in Flint after the water switch has a modest effect on the general population of newborns. Specifically, relative to the control cities, the frequency of low birth weight (LBW) increased by 1.8 percentage points (or 15.5%) in Flint after the crisis. Moreover, we find larger and more significant effects on the probability of LBW among infants born to black mothers compared with those born to white mothers. This finding differs from the null effect on infants of black mothers in Abouk and Adams (2018). Like Grossman and Slusky (2019), who observe only a 0.12 percentage point reduction in the male-to-female sex ratio after controlling for city-specific time trends, we find an indistinguishable decline in the sex ratio, suggesting that overall, the scarring effect may be stronger than mortality selection in terms of the observed birth outcomes. However, we observe a small but significant decrease in the male-to-female sex ratio among children born to black mothers after the crisis. We observe little evidence of a change in the length of gestation, likelihood of prematurity, or rate of fertility after the crisis.

Our findings may represent conservative estimates of the outcomes of the crisis. First, our analysis identifies an average treatment effect for all mothers living in Flint, which involves those who were able to avoid polluted water source partially or completely due to mitigation investments, such as through residential selection or purchasing bottled water. Our estimates should therefore be interpreted as intention-to-treat effects, as not every mother in Flint was exposed to contaminated water. Second, our datasets do not include direct information on avoidance actions

[2] In August and September 2014, coliform bacteria were detected in Flint water, representing a violation of the Safe Drinking Water Act. To eliminate these bacteria, additional chlorine was added; however, this caused another violation of the same Act due to the total level of THMs in the water. In October 2014, the local General Motors plant stopped using Flint tap water because the high concentration of chlorine was corroding engine parts. Ferric chloride was added to reduce the THM levels in the water, resulting in water that was 19 times more corrosive than the Detroit-supplied water. This increased level of corrosivity facilitated the leaching of lead from lead pipes into the drinking water supplied to roughly 40% of Flint homes. In six of the nine city wards, 20 to 32% of homes had tap water with lead levels greater than 15 ppb, a concentration that triggers remedial action under the Safe Drinking Water Act's Lead and Copper Rule. In some homes, the lead levels exceeded 1000 ppb (90th percentile = 25 ppb) (Bellinger 2016).

taken by residents. Therefore, the identified biological effects may be partially offset by the effects of avoidance behavior.[3] Third, we identify the effects of exposure to polluted water on surviving children (i.e., the scarring effect), whereas other studies focus on children who were selected out via reduced fertility rates (e.g., Grossman and Slusky 2019). Fourth, latent health effects of the crisis may manifest later in life as poor health, low educational attainment, poor labor market performance, and increases in behavioral problems and criminal activity (e.g., Almond et al. 2017; Aizer and Currie 2019).[4]

Our paper highlights key methodological issues relevant to the study of a broad range of fetal and infant health effects. First, to better approximate the real Flint in absence of the crisis, our counterfactual Flint is carefully constructed using a much larger set of candidate cities across the USA than those used in other studies (Abouk and Adams, 2018; Grossman and Slusky 2019). This larger set of donor pool cities, which includes those used in previous studies, expands the choice set for SCM algorithms and thus tends to improve the efficiency and reliability of the optimization process. This change may at least partially explain the differences in our estimates. Second, as women exposed to pollutants differ from their non-exposed counterparts in both observable and unobservable ways, we implement state-of-the-art designs to account for these differences and correct bias in the estimates. For example, as Flint had not violated the Safe Drinking Water Act (SDWA) prior to the crisis, we therefore exclude cities with such violations before the crisis from the counterfactual Flint to ensure better matching. Third, we examine both the overall effects and heterogeneous effects by maternal race. Unlike Abouk and Adams (2018), who observe a larger effect of polluted water on birth weight among children born to white mothers, or studies that do not focus on differential effects by maternal race/ethnicity (Sauve-Syed 2018; Grossman and Slusky 2019), our identified effect is driven by children born to black mothers. Finally, we use quarterly/semiannual data to obtain more precise estimates than those resulting from the annual data used by Abouk and Adams (2018).

We provide new evidence on the inequality of health at birth that may help to formulate public policy, thus improving the safety of the water supply or, more generally, the provision of public goods that are key to child development and the reduction of health inequality at birth. We demonstrate that maternal disadvantage may worsen health inequality at birth. Fortunately, knowledge about the determinants of infant health and how to apply these determinants to infant health-focused policy practice has generated tremendous benefits over the past decades (Aizer and Currie, 2014). We find that a widening wealth gap in the parental generation has not led to an increased child health gap. Rather, we observe a significant convergence of health

[3] For example, if women avoided pregnancy due to their concern over water pollution, the affected infants in our sample would be fewer than the potentially affected infants if there were no pregnancy avoidance. Similarly, if pregnant women drink bottle water instead of tap water, the effect we found would be smaller than the effect without avoidance behaviors.

[4] While Michigan expanded Medicaid over this time period, we find no evidence of increase in the proportion of births covered by Medicaid. The use of prenatal care during this time period decreases. Therefore, Medicaid coverage is unlikely to attenuate our results.

at birth or in early life that is mostly attributable to the provision of effective public programs and public goods.

The remainder of the paper proceeds as follows. In Section 2, we lay out our empirical strategy. In Section 3, we present our data. In Section 4, we report and discuss the results. In Section 5, we conclude and discuss future research directions.

2 Empirical strategy

The birth outcomes in Flint were significantly worse than those in other cities throughout the studied period. Additionally, the averaged birth outcomes are much smoother in the other 162 cities than in Flint. We use an SCM to identify the "best" counterfactual version of Flint (i.e., "synthetic Flint") among the untreated cities and then compare the birth outcomes in Flint and synthetic Flint to identify the effect of the crisis.

According to Abadie et al. (2003, 2010), we assume that the observed birth outcomes in city i at time t are as follows:

$$Y_{it} = Y_{it}^N + \alpha_{it} D_{it}, \tag{1}$$

where Y_{it}^N represents the birth outcomes that would be observed for infants in city i at time t in the absence of the crisis, and D indicates whether city i experienced the crisis; $t = 1, \ldots, T_1$ is split into periods before $(t = 1, \ldots ..T_0)$ and after the crisis $(t = T_0 + 1, \ldots, T_1)$. Because only Flint experienced the crisis beginning in May 2014 (denoted by T_0), $D_{it} = 1$ if i represents Flint and $t > T_0$, and 0 otherwise.

Let Y_{1t}^I be the health outcomes observed in Flint during period t $(t > T_0)$, which corresponds to the crisis. Then, the effect of the crisis is expressed as follows:

$$\alpha_{1t} = Y_{1t}^I - Y_{1t}^N \tag{2}$$

Next, we estimate Y_{1t}^N, which is unobserved. If we assign a set of nonnegative weights $\left(w_2^*, \ldots, w_{J+1}^*\right)$ and $w_2 + \cdots + w_{J+1} = 1$ to the covariates for control city j, such that the characteristics of synthetic Flint optimally resemble those of Flint in the pre-treatment period $(\widehat{Y}_{1t}^N = \sum_{j=2}^{J+1} w_j^* Y_{jt})$, then the estimated crisis effect is $\widehat{a}_{it} = Y_{1t} - \sum_{j=2}^{J+1} w_j^* Y_{jt}$.

In the first empirical step, we identify the predictors for the SCM. In addition to maternal characteristics, we use the average number of births and birth outcomes in the period before the crisis as predictors to adjust for differences in birth outcomes between Flint and synthetic Flint.[5] In Flint, the average birth weight decreased and

[5] In the matching process, it is common to include outcomes that occurred during part of the pre-treatment period to adjust for heterogeneity in the observed and unobserved factors that affect the outcomes of interest (Abadie et al., 2003; Abadie et al. 2015). However, if we include the outcomes during each pre-treatment period, the effects of other predictors are eliminated with barely apparent weights. Therefore, we only include the birth outcomes corresponding to part of the pre-treatment period in the main analysis but implement a separate robustness check using the health outcomes during all pre-treatment periods.

the probability of LBW increased sharply from 2010 to 2012, indicating an unobserved shock on birth outcomes before the crisis. To capture the effect of this shock, we include birth outcomes during this period among our predictors.

Next, we identify a set of potential control cities as the "donor pool" from which we construct synthetic Flint. To avoid potential downward bias, cities that experienced similar crises or pollution incidents at any time during the studied period should be excluded. Although Flint is the only city that experienced a disclosed crisis, it is not the only city that experienced water pollution during our study period. At least 10% of Americans regularly drank unhealthy water, and around 50 million Americans drank water containing industrial solvents or other chemicals with known health risks. Over 20% of the US water treatment systems violated key provisions of the SDWA during 2000–2005 (Fung et al. 2007), and we observe over 150 major US cities with health-based drinking water violations of the SDWA from 2008 to 2015. Therefore, we only include cities with no health-based drinking water violations of the SDWA during the study period; however, we test robustness using the whole set of donor pool cities.

Following Abadie et al. (2003, 2010) and McClelland and Gault (2017), we then conduct a series of placebo tests by iteratively applying the SCM to every other city in the donor pool. According to the distribution of the post/pre-crisis root mean square prediction error (post/pre RMSPE) ratios generated for Flint and cities in the donor pool using placebo tests, we calculate a permutation *p*-value to assess the significance of the difference between Flint and synthetic Flint.

3 Data

This study relies on three sources of data: Centers for Disease Control and Prevention (CDC) vital statistics natality records (birth certificates), the American Community Survey, and drinking water violations in cities across the USA from 2008 to 2015.[6] Birth certificate data include a record of every birth, which contains information about health at birth, gestational age, and maternal characteristics (including race, education, age, prenatal care, and health). Birth certificates also contain record the mother's resident city, enabling us to match these data with other datasets. Our treatment group comprises children born to mothers residing in Flint prior to or after the crisis.[7] Our analysis focuses on singleton birth records.[8] We obtain city-level population data from the American Community Survey.

The Safe Drinking Water Information System (SDWIS), which is managed by the US EPA, reports all types of drinking water violations incurred by both active

[6] Flint switched back to Detroit water in October 2015, reflecting government intervention in the crisis. To exclude the effects of various government actions, we drop data recorded after October 2015.

[7] One limitation of our CDC natality data is the use of mothers' reported residences, rather than geocoded residences, to assign resident cities. Therefore, the reported residences may involve errors. Specifically, our dataset may contain mothers who live in a municipality near Flint but not in the city Flint.

[8] Twin births account for approximately 4% of the sample.

and inactive water systems nationwide.[9] Violations are categorized as either health-based violations, such as improperly treated water or a contaminant level exceeding safety standard, or non-health-based violations, such as a failure to adhere to mandatory guidelines regarding sample collection or reporting requirements. As Flint had not incurred any drinking water violations before the change in water source, we carefully select control cities that incurred no health-based drinking water violations between 2008 and 2015.[10] We exclude births without geographic identifiers from our analysis, as their residences cannot be matched to water systems and water quality data.[11]

Our main SCM analysis aggregates individual-level birth data to the city level in each semiannual period. The donor pool comprises 162 control cities. Our treatment group includes all Flint singleton births between January 2008 and September 2015, of which 12,788 and 2637 are categorized into the pre- and post-treatment periods, respectively (Table 5 of the Appendix). As not all homes in Flint were supplied by polluted water pipes, our sample includes mothers living and not living in areas with polluted water pipes.[12] This sample allows us to evaluate the combined effect of the crisis on birth outcomes, including direct biological effects, such as those due to exposure to lead or microorganisms, and indirect effects, such as psychological shocks. Figure 1 maps the locations of Flint and the 162 cities in the donor pool of the SCM analysis, while Table 5 of the Appendix presents summary statistics of the observable characteristics of these cities. Compared with the donor pool cities, Flint has worse birth outcomes, including lower birth weights, shorter gestation periods, and higher LBW and prematurity rates. Furthermore, mothers in Flint are less likely to be white, older than 35 years, married, or hold at least a bachelor's degree and more likely to be adolescents, black, and less educated.

4 Results

4.1 Main results and robustness

As explained above, we construct synthetic Flint by assigning weights to candidate control cities to ensure the closest possible resemblance to specific birth outcomes in Flint prior to the crisis. Four to eight control cities are given positive weights,

[9] For cities in which SDWIS does not provide related water system information, we first identify all of the water systems in the respective counties using SDWIS and then match the water system to the city through a Google search.

[10] We perform three robustness checks: one includes all possible donor cities, and the other two exclude cities with health-based drinking water violations during the pre- or post-period. Our results are robust.

[11] Births without geographic identifiers occurred either in small cities or towns, which have better average birth outcomes and demographics than big cities.

[12] The polluted water pipes in Flint crisis are mainly lead pipes. The use of lead pipes in construction has been illegal since 1986. For details, see the map created by Marty Kaufman and Troy Rosencrants of the University of Michigan–Flint Geographic Information Systems Center at https://www.fondriest.com/news/amid-flint-water-crisis-gis-effort-maps-citys-pipes.htm.

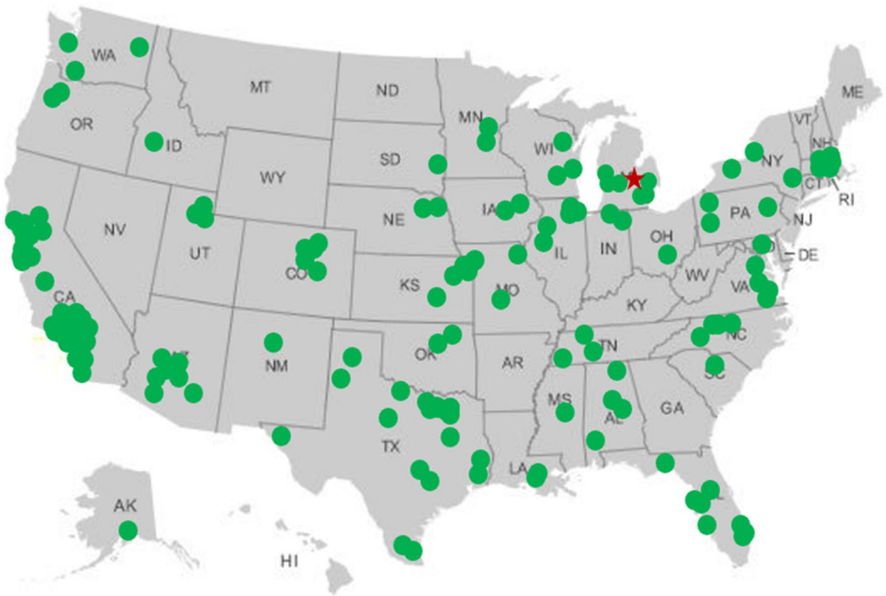


Fig. 1 Spatial distribution of donor pool cities. Notes: Flint is represented by a red star, and the 162 cities in the donor pool of our SCM estimations are in green

depending on specific birth outcomes. Table 1 displays the control cities with positive weights used to construct synthetic Flint for each birth outcome measure. Some control cities appear more than once across various health outcomes in the generation of synthetic Flint.

Table 2 compares the pre-treatment characteristics of Flint with those of each synthetic Flint and the average of the 162 cities in the donor pool. Flint is more similar to all synthetic Flints than to the 162-city donor pool, although Flint differs from synthetic Flints with respect to maternal characteristics. Specifically, the synthetic Flints have fewer mothers younger than 18 but more mothers older than 35 years, more black mothers, more married mothers, more mothers with bachelor's degrees, and more births compared with Flint.

Figure 2 displays the birth outcomes in Flint and synthetic Flints from 2008 to 2015. As shown in Fig. 2a, Flint and synthetic Flint initially have similar trends in average birth weight but divergent trends after the crisis. The average birth weight in Flint sharply declined within the first year after the crisis but recovered in late 2015. Figure 2b shows that before the crisis, the LBW rate trajectory of synthetic Flint closely tracks that of Flint, whereas these trajectories diverge after the crisis (~ 11.8% and 13%, respectively), suggesting that the crisis led to a higher rate of LBW. In Fig. 2c, d, and e, the trends in the probability of very LBW (VLBW), length of gestation, and rate of prematurity are less visibly different between Flint and synthetic Flint after the crisis, suggesting that infants near the LBW cut-off were mainly affected. Figure 8 of the Appendix supports this conclusion. Compared with the four cities weighted in the synthetic control analysis, the distribution of birth

Table 1 Weights of synthetic control cities

City	Weights
Outcome: birth weight (g)	
Memphis, TN	0.534
Jackson, MS	0.237
Tulsa, OK	0.184
Arvada, CO	0.035
Beaumont, TX	0.010
Outcome: probability of low birth weight	
Memphis, TN	0.384
Jackson, MS	0.379
Arvada, CO	0.121
Tulsa, OK	0.116
Outcome: probability of very low birth weight	
Jackson, MS	0.515
Lancaster, CA	0.267
Buffalo, NY	0.059
Mobile, AL	0.037
Tulsa, OK	0.035
Detroit, MI	0.033
Lansing, MI	0.029
Arvada, CO	0.024
Outcome: length of gestation (weeks)	
Detroit, MI	0.828
Tulsa, OK	0.172
Outcome: probability of prematurity	
Detroit, MI	0.481
Jackson, MS	0.342
Birmingham, AL	0.091
Springfield, IL	0.086

weight in Flint shifts leftward after the crisis, especially around the LBW cut-off, suggesting a greater density of infants with LBW.

To formally determine the significance of this effect on the rate of LBW, we implement two types of placebo test. In Fig. 3, we draw 162 solid gray lines representing differences in the probability of LBW between each city in the donor pool and its respective synthetic version. The black line denotes the effect of assigning Flint as the treatment city. The dashed red vertical line denotes the start of the crisis. Figure 3 shows that the effect size for Flint is greater than the sizes of most placebo treatment effect. Panel A includes some cities that are poor matches prior to the crisis; therefore, in panel B, we retain only more closely matched cities (i.e., those with a pre RMSPE within two times the pre RMSPE of Flint). Excluding those poorly fitted cities, the Flint line clearly rises above almost all of the gray lines during the post-treatment period. In the placebo tests,

Table 2 Mean of predictors for birth outcomes

Variable	Flint						Average of 162 control cities
	Real	Synthetic (BW)	Synthetic (LBW)	Synthetic (VLBW)	Synthetic (LG)	Synthetic (PP)	
% Younger than 18	0.059	0.052	0.052	0.048	0.058	0.053	0.028
% Older than 35	0.065	0.087	0.089	0.090	0.097	0.092	0.148
% Black	0.590	0.650	0.638	0.600	0.735	0.751	0.184
% Married mother	0.210	0.312	0.331	0.330	0.241	0.270	0.572
% Bachelor's degree or higher	0.053	0.192	0.228	0.235	0.073	0.213	0.301
Number of birth per month	168.096	561.069	447.999	239.496	752.209	511.230	334.938
Birth weight, first half-year of 2010	3162.920	3236.832					3288.303
Birth weight, first half-year of 2011	3118.376	3127.489					3286.773
Birth weight, first half-year of 2012	3074.068	3093.314					3291.358
Birth weight, first half-year of 2014	3143.358	3148.882					3291.258
% LBW, first half-year of 2010	0.102		0.105				0.065
% LBW, first half-year of 2011	0.119		0.116				0.067
% LBW, first half-year of 2012	0.133		0.130				0.065
% LBW, first half-year of 2014	0.096		0.097				0.062
% VLBW, first half-year of 2010	0.016			0.020			0.011
% VLBW, first half-year of 2011	0.021			0.020			0.012
% VLBW, first half-year of 2012	0.025			0.021			0.011
% VLBW, first half-year of 2014	0.011			0.013			0.011
Length of gestation, first half-year of 2010	38.134				38.249		38.699
Length of gestation, first half-year of 2011	38.519				38.382		38.722
Length of gestation, first half-year of 2012	38.214				38.221		38.731
Length of gestation, first half-year of 2014	38.242				38.333		38.751
% Prematurity, first half-year of 2010	0.199					0.171	0.102
% Prematurity, first half-year of 2011	0.154					0.169	0.101

Table 2 (continued)

Variable	Flint						Average of 162 control cities
	Real	Synthetic (BW)	Synthetic (LBW)	Synthetic (VLBW)	Synthetic (LG)	Synthetic (PP)	
% Prematurity, first half-year of 2012	0.190					0.176	0.100
% Prematurity, first half-year of 2014	0.185					0.162	0.095

According to different birth outcomes, we constructed five different synthetic Flint by using different birth outcomes in the pre-period as predictors. Synthetic BW represents the synthetic Flint generated to compare birth weight with birth weight in the pre-period as some predictors. Similarly, synthetic LBW, VLBW, LG, and PP represent the synthetic Flint generated to compare the probability of low birth weight, the probability of very low birth weight, length of gestation, and the probability of prematurity, respectively. Different from the definition for other "first half-year," "first half-year of 2014" ends on April 30, 2014, the beginning of the Flint water crisis.

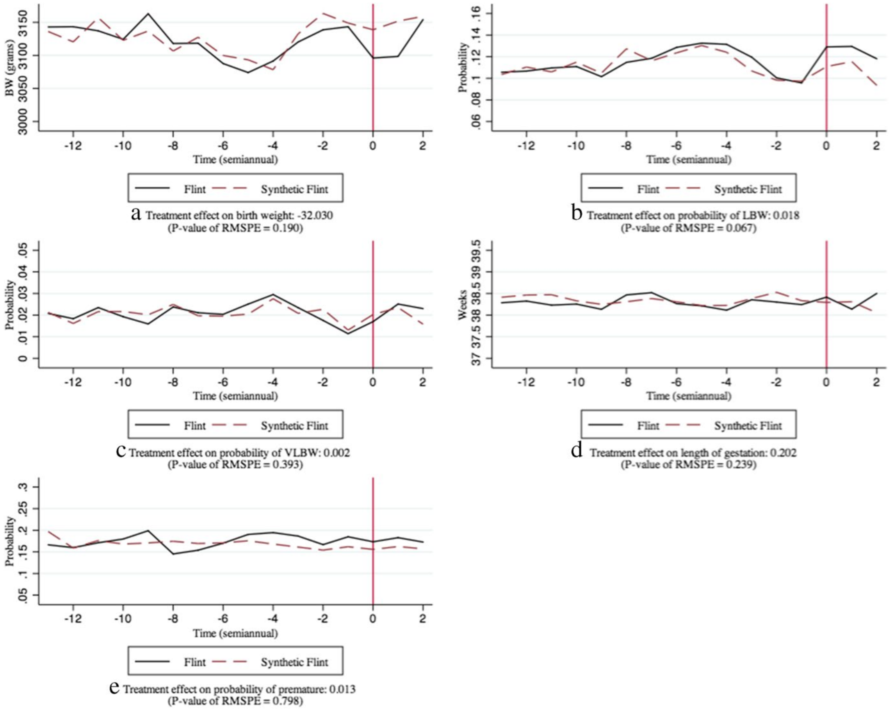
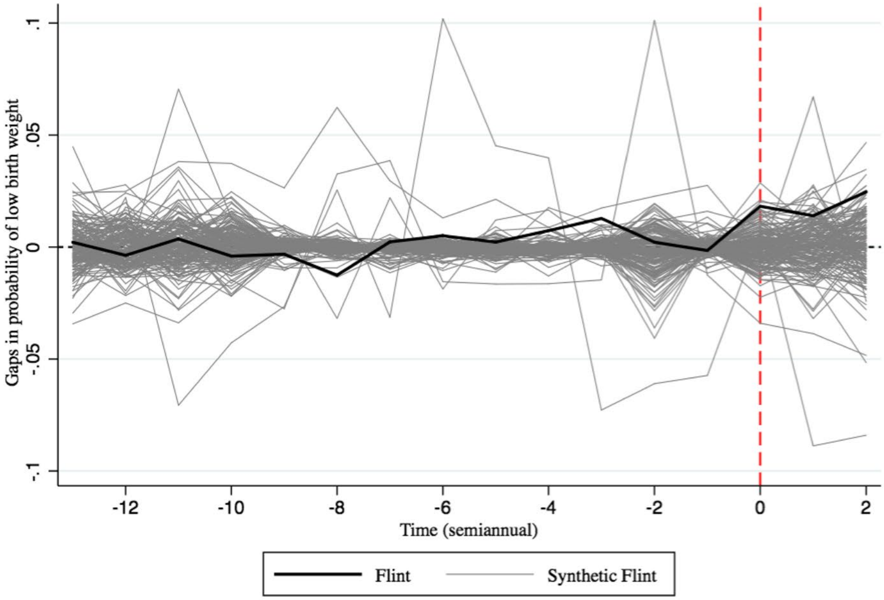


Fig. 2 Trends and SCM estimates on birth outcomes: Flint vs. synthetic Flint. *Notes:* The *X*-axis represents birth date relative to the Flint water crisis. The data points are measured in half-years prior to and after the water switch. The red vertical line (May 1, 2014) marks the beginning of the water switch

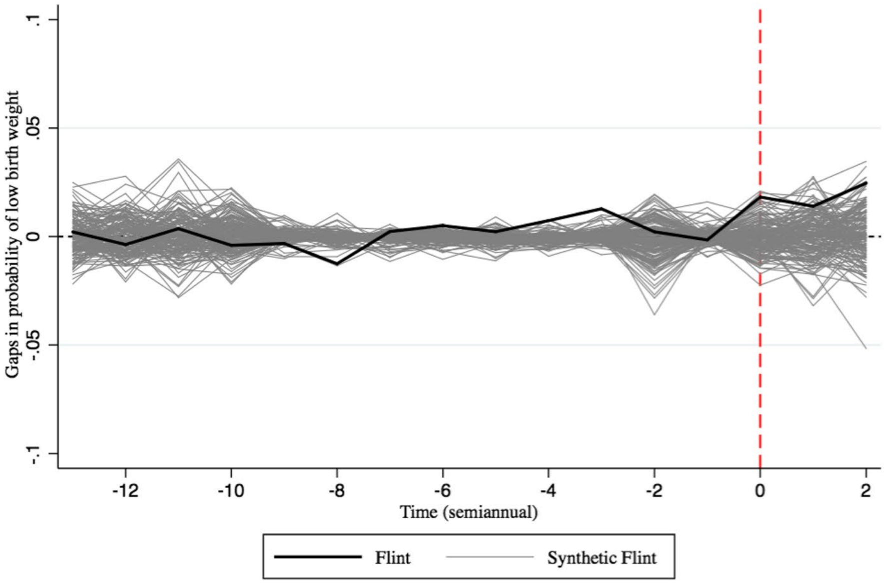
154 of 162 placebo cities have smaller post/pre RMSPE ratios relative to Flint, indicating that 94.5% of placebo treatment effects are smaller in size than the real treatment effect. In Table 3, we include only the pre-treatment sample and assign falsified cut-offs (i.e., July 1, 2013; January 1, 2013; and July 1, 2012) as the crisis start dates. We consistently obtain insignificant estimates, thus validating the lack of effect of placebo shocks.

To check whether our results are sensitive to cities in the donor pool, we construct different synthetic Flints by including different cities in the donor pool. Table 4 shows that our results are robust whether we include cities with health-based drinking violations in the pre-period, post-period, or both periods.

Following Abadie et al. (2015), we iteratively re-estimate the baseline model for our main findings. This is achieved by constructing a synthetic Flint that iteratively excludes, in a leave-one-out manner, each city that received a positive weight, such as Memphis, TN, or Jackson, MS, with the largest positive weights (Table 1). Despite sacrificing some goodness of fit, this sensitivity check allows us to evaluate to what extent our results are driven by a particular control city. However, our consistent estimates mitigate this concern and demonstrate the robustness of our results, as shown in Fig. 2b, where the black and maroon solid lines reproduce the



a Probability of low birth weight gaps in Flint and placebo gaps in all 162 control cities



b Probability of low birth weight gaps in Flint and placebo gaps in 154 control cities
(discarding cities with pre-RMSPE more than twice as high as Flint's)

Fig. 3 Placebo tests: gaps in rate of low birth weight. *Notes:* The *X*-axis represents birth date relative to the Flint water crisis. The data points are measured in half-years prior to and after the water switch. The red vertical line (May 1, 2014) marks the beginning of the water switch

Table 3 Robustness check: estimating pseudo shocks at time cutoffs before the Flint water crisis (SCM)

	(1) July 1, 2013	(2) Jan 1, 2013	(3) July 1, 2012
Birth weight (g)			
Treatment effects (−32.030)	−33.979	−20.024	−29.767
P-value of RMSPE (0.190)	0.227	0.331	0.245
Probability of low birth weight			
Treatment effects (0.018*)	0.013	0.049	0.008
P-value of RMSPE (0.067)	0.153	0.270	0.362
Probability of very low birth weight			
Treatment effects (0.002)	−0.001	0.001	0.001
P-value of RMSPE (0.393)	0.374	0.356	0.411
Length of gestation (weeks)			
Treatment effects (0.202)	−0.093	−0.157	−0.261
P-value of RMSPE (0.239)	0.491	0.233	0.153
Probability of prematurity			
Treatment effects (0.013)	0.021	0.023	0.021
P-value of RMSPE (0.798)	0.503	0.380	0.325
Cities in donor pool	163	163	163

Notes: This table restricts sample to pre-treatment data only and assigns falsified cut-offs, i.e. July 1, 2013, Jan 1, 2013, and July 1, 2012, as the starting dates of the crisis, respectively.

***Significant at the 1% level.

**Significant at the 5% level.

*Significant at the 10% level.

results and the dashed or dotted lines represent the leave-one-out estimates. In this analysis, the synthetic control that demonstrates the smallest effect of the crisis excludes Tulsa, OK. However, even this estimate reveals an apparent gap in the probability of LBW between Flint and synthetic Flint after the crisis. The other leave-one-out synthetic controls show similar effects to our original analysis.

To mitigate concern about bias caused by unbalanced covariates, we use the data-driven procedure proposed by Botosaru and Ferman (2019) to determine the relative importance of each predictor used in the estimations and ensure that only balanced covariates are included. Specifically, we include all pre-treatment outcome lags from 2008 to 2014 (i.e., a longer period before the treatment) in our list of potential covariates to achieve a better balance of the pre-treatment outcomes.[13] This largest set of pre-treatment outcome lags, with *no* covariates,

[13] Although achieving a good balance regarding each of the covariates has the advantage of providing tighter bounds, Botosaru and Ferman (2019) argue that the bias of the SCM estimator remains bounded when pre-treatment outcomes are well balanced, even if the relevant covariates are not perfectly balanced. We thank an anonymous reviewer for this constructive comment, which prompted us to leverage longer pre-treatment outcome lags in robustness checks to improve our estimation procedure when Flint and synthetic Flint are not well matched in some covariates.

Table 4 Robustness check: using different compositions of donor pool cities

	Sample 1: Keep all cities	**Sample 2:** Drop cities with violations before the crisis	**Sample 3:** Drop cities with violations after the crisis
Birth weight (g)			
Treatment effects (– 32.030)	– 30.313	– 32.954	– 27.523
P-value of RMSPE (0.190)	0.158	0.161	0.161
Probability of low birth weight			
Treatment effects (0.018*)	0.017*	0.018*	0.018*
P-value of RMSPE (0.067)	0.088	0.086	0.088
Probability of very low birth weight			
Treatment effects (0.002)	0.001	0.001	0.001
P-value of RMSPE (0.393)	0.633	0.305	0.663
Length of gestation (weeks)			
Treatment effects (0.202)	0.141	– 0.003	0.172
P-value of RMSPE (0.239)	0.293	0.206	0.114
Probability of prematurity			
Treatment effects (0.013)	– 0.002	0.014	– 0.002
P-value of RMSPE (0.798)	0.748	0.787	0.829
Cities in donor pool	215	174	193

Notes: The values in the brackets are for the control sample without a drinking water health-based violation before and after the crisis.

***Significant at the 1% level.

**Significant at the 5% level.

*Significant at the 10% level.

creates an alternative synthetic Flint similar to our baseline synthetic Flint before the crisis. After including the largest set of pre-treatment outcome lags, the two synthetic Flints almost fully overlap, regardless of whether we further add covariates to the SCM estimations. This finding verifies that covariates other than pre-treatment outcome lags contribute little to the construction of synthetic Flint. The SCM optimization procedure used to estimate synthetic Flint does not include information on all observed covariates to balance each of these variables. However, the pre-treatment outcome lags demonstrate strong predictive power and yield a well-matched synthetic Flint.

As an alternative strategy to mitigate concerns about bias resulting from unbalanced covariates, we directly remove the two least well-balanced covariates: number of births and maternal education. The resulting alternative synthetic Flint remains very similar to the real Flint prior to the crisis. The mean statistics of predictors of birth outcomes in Flint and synthetic Flint across covariates and pre-treatment outcomes suggest that our results cannot be attributed to the differences in some characteristics between Flint and synthetic Flint.[14]

[14] One caveat, however, is that these results also rely on the assumption that the unobserved covariates are largely balanced.

In addition to semiannual SCM estimates, we attempt to obtain even more precise quarterly SCM estimates, which demonstrates similar trend and marginally significant results for children born to black mothers. It is often more difficult to achieve a good fit using quarterly data than semiannual data because of larger fluctuations in the former datasets. The estimates generated using a narrower time window further differentiate our findings from the SCM estimates based on annual data in Abouk and Adams (2018).

4.2 Heterogeneous effects

Health inequality at birth can be exacerbated by environmental exposure. A full sample analysis may hide potentially larger effects among more vulnerable mothers who may practice less healthy behavior, have less access to medical care, and are at greater risk of exposure to harmful environments (Aizer and Currie, 2014). For example, a higher proportion of children with elevated blood lead levels in Flint live in disadvantaged neighborhoods (Hanna-Attisha et al. 2016).

As natality data do not include information about maternal income, we rely on maternal race to test the main results by vulnerability.[15] Table 5 of the Appendix shows the raw differences between black mothers and white mothers in Flint. Notably, the marriage rate among white mothers is three times that among black mothers. White mothers also generally have better birth outcomes than black mothers. However, children born to both groups of mothers demonstrated worse results in some birth outcomes after the crisis.

The SCM results are displayed separately for black mothers (Fig. 4) and white mothers (Fig. 9 of the Appendix). The trajectory of synthetic Flint tracks that of Flint very closely before the crisis for each birth outcome but deviates afterwards. Specifically, as shown in Fig. 4, the birth weight and length of gestation among Flint newborns to black mothers decline immediately after the crisis but return to the levels observed in synthetic Flint in late 2015. The trend of LBW rate in Flint increases relatively modestly after the crisis but declines sharply in synthetic Flint. The crisis has an effect size of 2.5 percentage points on the rate of LBW in Flint (statistically significant at the 5% level). In Fig. 9 of the Appendix, the same effect size of the crisis on the rate of LBW is observed among white mothers but with no statistically significant effect. Similarly, the crisis has little effect on the rates of VLBW and prematurity and only marginally significant effects on birth weight and the length of gestation.

4.3 Further discussion

One concern regarding our analysis is that the crisis may have caused mothers to leave Flint for areas with safe water; therefore, the observed Flint infants may be more likely to have been born to mothers who were unable to move, i.e., more

[15] We also tested results by maternal education, but Flint and synthetic Flint do not match well in the pre-treatment period for the two subsamples, which prevents us from identifying the effect of the crisis on birth outcomes by maternal education.

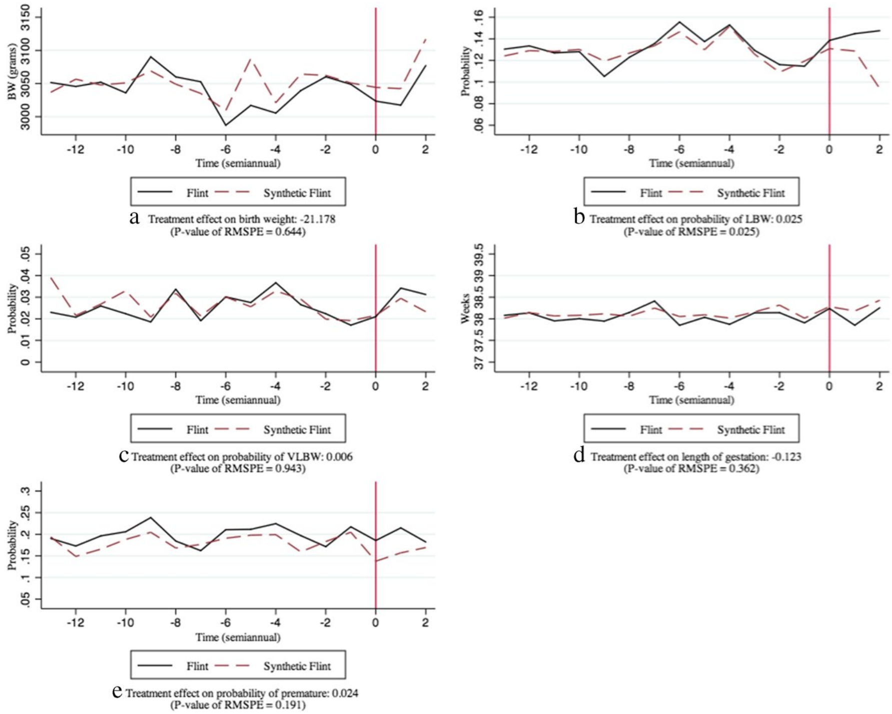


Fig. 4 Trends and SCM estimates on birth outcomes for children born to black mothers. *Notes:* The *X*-axis represents birth date relative to the Flint water crisis. The data points are measured in half-years prior to and after the water switch. The red vertical line (May 1, 2014) marks the beginning of the water switch

disadvantaged. This may have led to overestimation in our results. We address this concern by using SCM to estimate the effect of the crisis on the population of women aged 15–49 years in Flint. The crisis did not significantly reduce the cohort size of this population, suggesting that the migration of women of child-bearing age should not be a concern.

Another concern is that the crisis may have resulted in miscarriage or fetal death (via mortality selection), which would yield a sample comprising relatively healthier infants and lead us to underestimate the negative health effects. At the time of this study, the CDC has not yet released direct fetal death data after 2015; additionally, it is difficult to record the incidence of miscarriage. Instead, we implement two strategies to test this possibility. First, following Sanders and Stoecker (2015) and Grossman and Slusky (2019), we use the male-to-female sex ratio at birth to indirectly test fetal death under the premise that male fetuses in utero are often more vulnerable to negative health shocks than female fetuses. Potentially, the crisis may have resulted in more male fetal losses, thus reducing the rate of male births and the male-to-female ratio. We use SCM to estimate the effect of the crisis on sex ratios at birth in the full sample

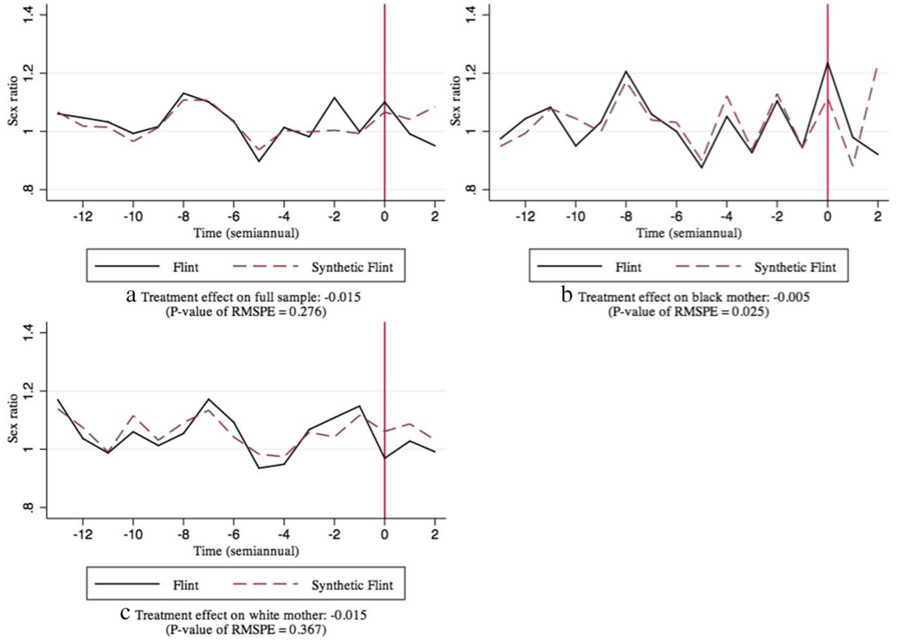


Fig. 5 Trends in male-to-female sex ratios for newborns. *Notes:* The *X*-axis represents birth date relative to the Flint water crisis. The data points are measured in half-years prior to and after the water switch. The red vertical line (May 1, 2014) marks the beginning of the water switch

and among infants born to black or white mothers. As shown in Fig. 5b and Fig. 5c, our results suggest that the sex ratios are similar between children born to black mothers and those born to white mothers prior to the crisis. After the crisis, the trend in sex ratios of children born to white mothers is largely smooth, whereas the trend for children born to black mothers decreases significantly by 0.005. However, we find no significant decline in sex ratios in the full sample (Fig. 5a).[16] Second, we test changes in the fertility rate. Figure 6 shows insignificant effects of the crisis on fertility in Flint, as measured by births per 1000 female population aged 15–49, in both the whole sample and in groups stratified

[16] This differs from Grossman and Slusky (2019), who find decreases in the sex ratio by 0.7 (1.3%) and 0.9 percentage points (1.8%), respectively. Some possible explanations of the more salient effect of the crisis on sex ratios identified by Grossman and Slusky (2019) compared with our work are as follows. (1) We use a larger set of cities in the donor pool. (2) Grossman and Slusky (2019) focus on mothers who live closer to lead pipes (i.e., larger probability of lead exposure) and have a larger biological effect, while we include all mothers living in Flint. (3) Due to residential selection by socioeconomic status, households closer to the contaminated water source may be poorer and less healthy and have less means to avoid the situation. (4) The intensified exposure among those living closer to contaminated water may increase their stress, even if they are not directly affected. (5) Grossman and Slusky (2019) note that proximity to a polluted water source more likely affected the water in places of employment.

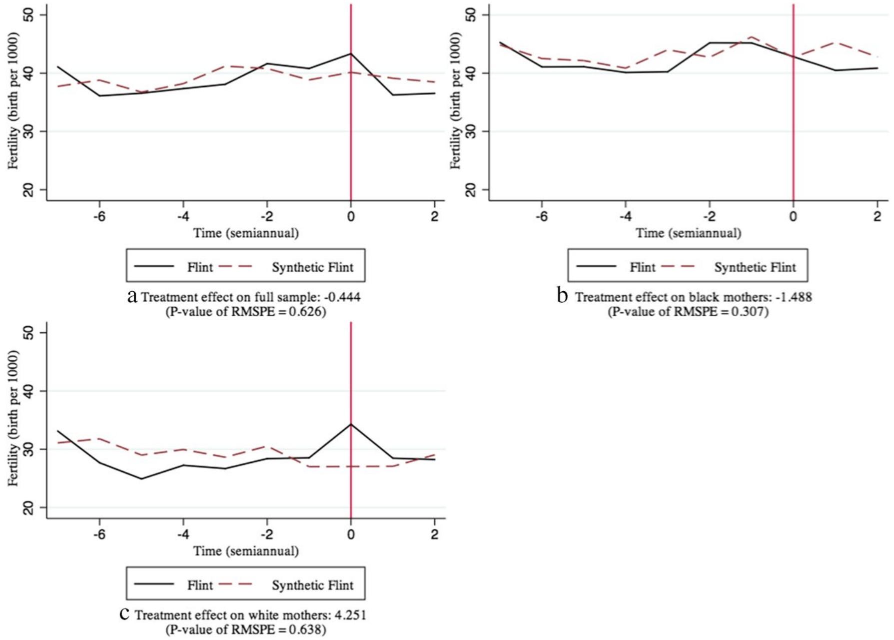


Fig. 6 Trends in fertility rates. Notes: The *X*-axis represents conception date relative to the Flint water crisis exposure. The second half-year of 2013 is the first conception half-year for infants born after the water switch, which is presented by the red vertical line. The fertility measure in city *c* and half-year *t* is calculated as $Fertility_{ct} = 1000 * \frac{TotalBirths_{ct}}{PopulationAged15{-}49_{ct}}$. To calculate fertility rates for black women and white women, the total number of births to black women and to white women are numerators, respectively, and the size of population aged 15–49 for black women and for white women are denominators

by maternal race. Specifically, the crisis is associated with only an indistinguishable reduction in the average fertility rate by 1.49 births per 1000 black women (Fig. 6b) and a very modest increase in fertility among white women (Fig. 6c). These consistent findings mitigate the concern that the effect of the crisis on mortality selection might be strong enough to cause underestimation bias. Overall, our findings indicate that the observed worse birth outcomes are attributable to a scarring effect.

At least three potential mechanisms—biological effects, maternal stress, and avoidance behavior—can jointly affect birth outcomes. In addition to biological effects due to exposure to lead or microorganisms, maternal stress during pregnancy may harm fetal development and birth outcomes (Walsh et al. 2019; Duncan et al. 2017). Local trends in Google searches, such as the search volume for the keyword “lead in water,” may provide an indication of trends in stress over time. Flint residents may vary in their ability to mitigate the negative effects of the crisis through residential sorting or other relevant mechanisms. For example, people in lower socioeconomic classes are more likely to live in cheaper, older housing stock, which more often contains polluted water pipes. Other populations may have the means to avoid polluted water pipes ex ante or ex post or take other avoidance actions, such as purchasing bottled water (Christensen et al. 2018). We have no firm way to isolate these actions and leave the determination of the exact mechanisms as a direction for future studies.

5 Conclusions

By matching vital statistics on all birth records in Flint with various sources of data, we are among the first to provide causal evidence of the short-term impact of drinking water contamination on birth outcomes. Our main results suggest that, on average, contaminated water modestly increased the rate of LBW by 1.8 percentage points (or 15.5%) and reduced birth weight by 32 g, but had little effect on the rates of VLBW or prematurity or the length of gestation. The observed effects are driven by black mothers. While we find no evidence that the crisis significantly reduced male-to-female sex ratios in the whole sample, suggesting a dominant scarring effect in utero, we observe a modest decline in the sex ratio among children born to black mothers. We do not observe significant reductions in fertility in the full sample or in subsamples by maternal race.

We suggest some directions for future studies. First, a better understanding of the physiological mechanisms may isolate the effect due to a surge in lead exposure from those attributable to simultaneous changes in other pollutants, both being caused by the change in municipal water in Flint. Such research requires precise, high-quality data on the levels of multiple dominant pollutants, preferably those measured in blood. While lead is likely to be a key contributor, it is still too early to conclude whether the effects are mainly due to lead contamination or proximity to polluted pipes. Second, the corrosive water in Flint leached lead not only from lead service lines outside of homes but also from brass fixtures inside homes. Richer data at the community or even finer levels could help to distinguish the effects of these different sources of lead contaminations. Third, the longer-term impact of the crisis on health and human development warrants further monitoring. Fourth, data on maternal stress during the crisis could help to elucidate potential psychological mechanisms of the observed effects. Finally, avoidance behavior data could help to distinguish the effects of biological factors from those of avoidance actions.

Appendix

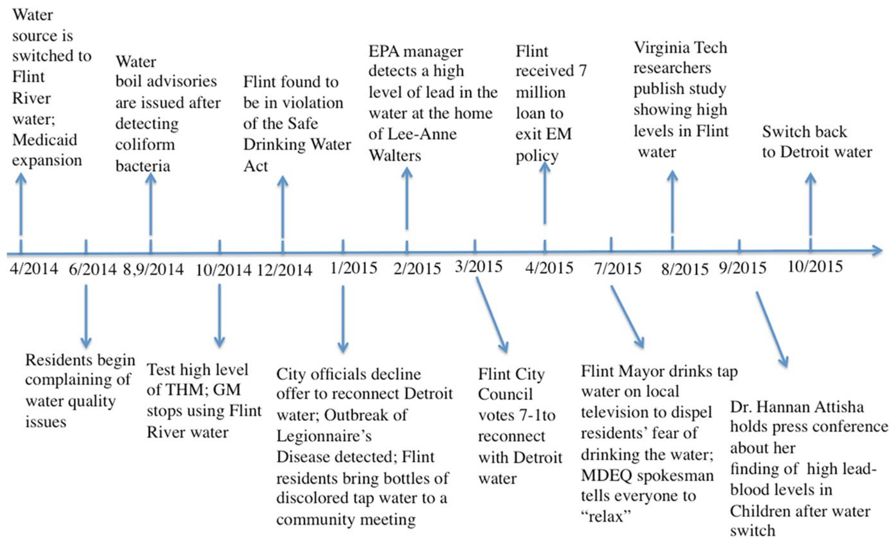


Fig. 7 Timeline of the Flint water crisis

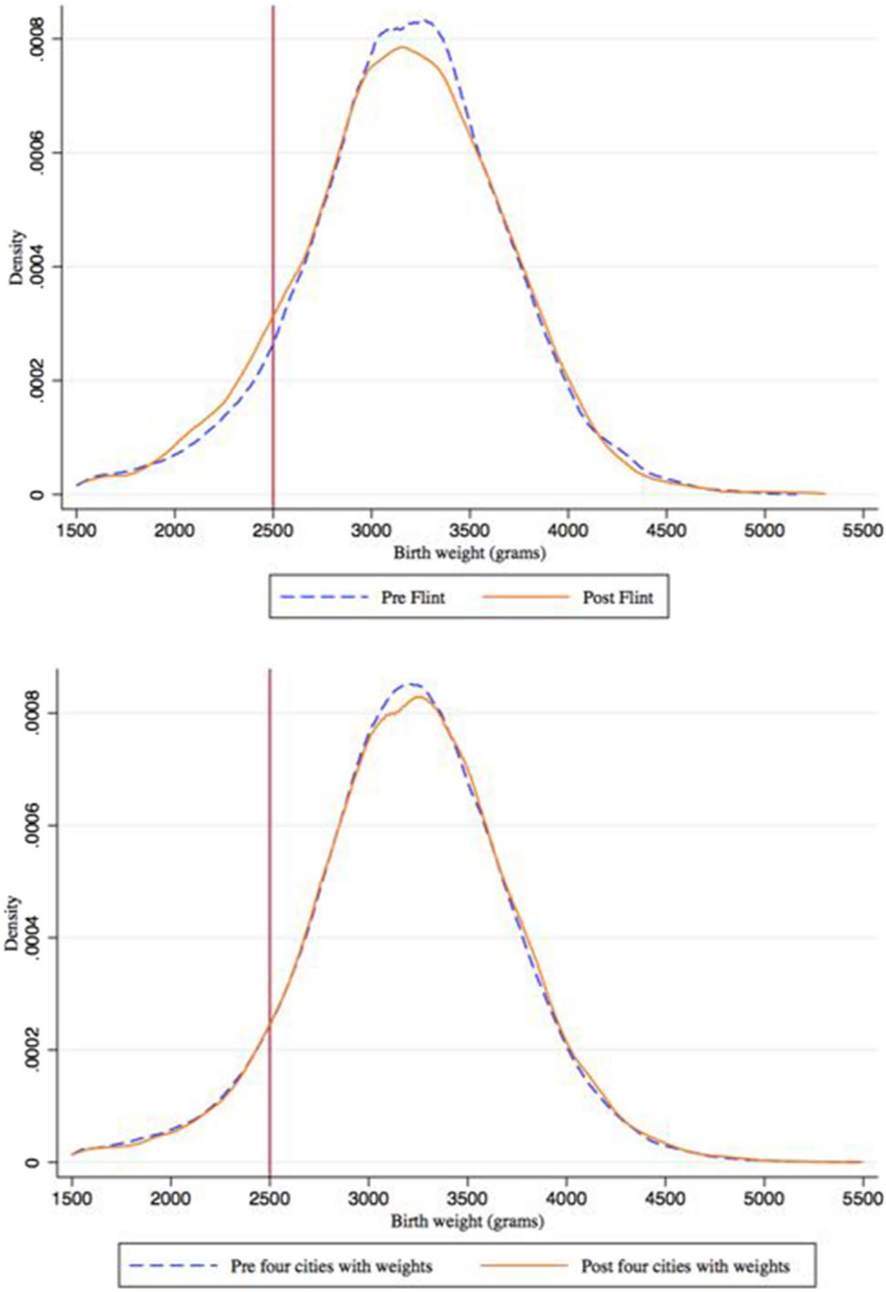


Fig. 8 The distributions of birth weight before and after the Flint water crisis. *Notes:* Four cities are those having positive weights using the synthetic control method (SCM). The vertical red lines correspond to birth weight being 2500 g

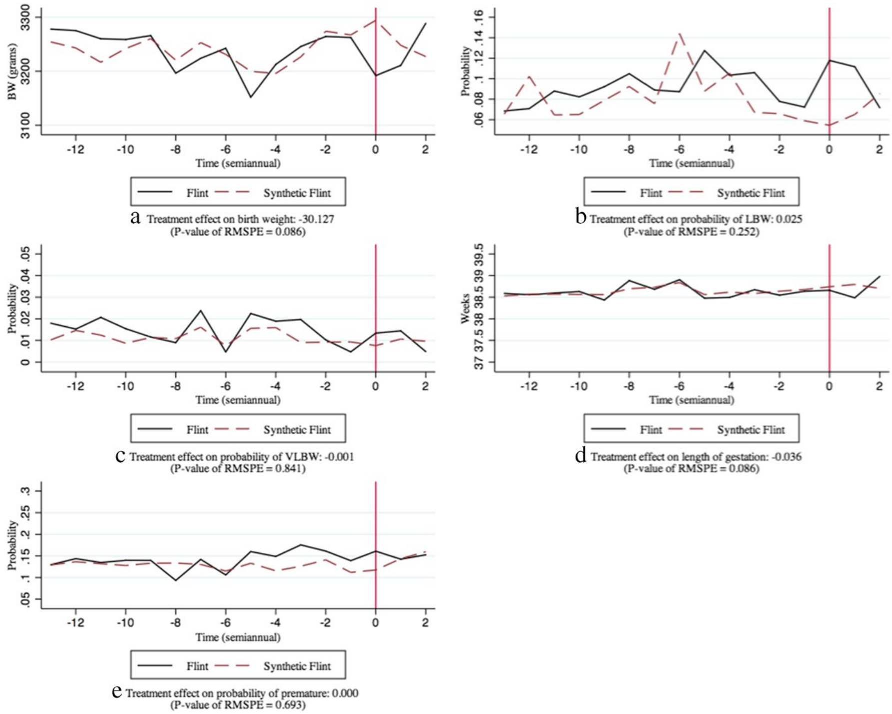


Fig. 9 Trends and SCM estimates on birth outcomes for those born to white mothers. *Notes:* The *X*-axis represents birth date relative to the Flint water crisis. The data points are measured in half-years prior to and after the water switch. The red vertical line (May 1, 2014) marks the beginning of the water switch

Table 5 Summary statistics for newborns in Flint and other 162 American cities

	162 cities in the USA	**Flint**	**Flint**			
		Full sample	Pre-treatment period		Post-treatment period	
			Black mother	White mother	Black mother	White mother
Birth outcome						
Birth weight	3273.386 (565.3924)	3121.291 (603.262)	3041.870 (59.049)	3240.851 (73.869)	3030.851 (54.284)	3215.687 (90.083)
% LBW	0.068 (0.252)	0.116 (0.320)	0.130 (0.033)	0.090 (0034)	0.142 (0.032)	0.107 (0.051)
% VLBW	0.021 (0.004)	0.021 (0.143)	0.025 (0.016)	0.015 (0.016)	0.027 (0.015)	0.012 (0.014)
Length of gestation	38.697 (2.403)	38.300 (3.029)	38.051 (0.334)	38.623 (0.375)	38.105 (0.393)	38.656 (0.440)
% prematurity	0.104 (0.305)	0.174 (0.379)	0.198 (0.043)	0.139 (0.047)	0.195 (0.038)	0.153 (0.047)
% male	0.512 (0.500)	0.508 (0.500)	0.504 (0.050)	0.514 (0.059)	0.519 (0.046)	0.498 (0.058)
Mother characteristics						
% younger than 18	0.030 (0.171)	0.057 (0.231)	0.080 (0.257)	0.031 (0.021)	0.050 (0.023)	0.026 (0.016)
% aged between 18 and 35	0.822 (0.383)	0.877 (0.329)	0.858 (0.029)	0.901 (0.032)	0.899 (0.029)	0.879 (0.037)
% older than 35	0.148 (0.355)	0.067 (0.249)	0.063 (0.021)	0.068 (0.028)	0.051 (0.022)	0.095 (0.038)
% White	0.690 (0.463)	0.402 (0.490)	N/A	N/A	N/A	N/A

Table 5 (continued)

	162 cities in the USA	**Flint**	**Flint**			
		Full sample	Pre-treatment period		Post-treatment period	
			Black mother	White mother	Black mother	White mother
% Black	0.208 (0.406)	0.587 (0.492)	N/A	N/A	N/A	N/A
% less than high school	0.208 (0.406)	0.279 (0.449)	0.300 (0.052)	0.263 (0.047)	0.249 (0.046)	0.253 (0.062)
% high school	0.264 (0.441)	0.324 (0.468)	0.324 (0.052)	0.311 (0.064)	0.353 (0.061)	0.342 (0.064)
% some college	0.261 (0.439)	0.343 (0.475)	0.342 (0.060)	0.349 (0.062)	0.356 (0.059)	0.334 (0.064)
% bachelor's degree	0.169 (0.375)	0.041 (0.197)	0.035 (0.017)	0.077 (0.031)	0.043 (0.029)	0.071 (0.030)
% graduate school	0.097 (0.296)	0.013 (0.112)	0.008 (0.009)	0.018 (0.015)	0.007 (0.010)	0.021 (0.020)
% married mother	0.541 (0.498)	0.210 (0.407)	0.114 (0.033)	0.346 (0.049)	0.119 (0.034)	0.327 (0.054)
Previous termination	0.238 (0.426)	0.293 (0.455)	0.307 (0.058)	0.273 (0.068)	0.303 (0.057)	0.301 (0.061)
Prenatal care	2.982 (1.598)	2.943 (1.698)	2.959 (0.225)	3.027 (0.253)	2.678 (0.256)	2.742 (0.289)
Weight gain	30.109 (14.520)	32.085 (16.762)	31.940 (1.778)	32.451 (2.206)	31.238 (1.970)	33.162 (2.509)
Observation						
Total births	5,476,852	15,425	7553	5125	1504	1071

Notes: The full samples of newborns in 162 cities (column 1) and Flint (column 2) include those born to mothers of all races/ethnicities.

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