The Effects of Lead in Drinking Water on Education Outcomes: Evidence from the Flint Water Crisis

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September 2019

Acknowledgements

This work has been supported (in part) by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1656518 and by the Institute of Education Sciences under Grant No. R305B140009. We are grateful to Carolyn Hoxby, Sean Reardon, Eric Bettinger, and Ben Domingue for helpful comments. We also wish to Jasmina Camo-Biogradlija, Kyle Kwaiser, and the Education Policy Initiative staff for assisting with access to Michigan's restricted-use educational data. This research used data structured and maintained by the MERI-Michigan Education Data Center (MEDC). MEDC data is modified for analysis purposes using rules governed by MEDC and are not identical to those data collected and maintained by the Michigan Department of Education (MDE) and/or Michigan's Center for Educational Performance and Information (CEPI). Results, information and opinions solely represent the analysis, information and opinions of the authors and are not endorsed by, or reflect the views or positions of, grantors, MDE and CEPI or any employee thereof.

Abstract

In April of 2014, the town of Flint, Michigan switched its municipal water source from Lake Huron to the Flint River as a cost saving measure. The corrosive river water was improperly treated, causing lead from aging service lines to leach into the city's drinking water. In this paper, we quantify the causal effects of the Flint Water Crisis on educational outcomes. We match Michigan's universe of longitudinal, student-level education records with a unique parcel-level service line dataset collected by Flint city officials tasked with pipe inspection and replacement following the crisis. We employ two parallel methodological approaches to estimate (a) the effect of the Flint Water Crisis overall and (b) the effect of exposure to lead poisoning from lead plumbing. Preliminary results suggest that the Flint Water Crisis caused a large decrease in academic achievement for all students living in Flint and that students living in homes with lead pipes experienced an increase in absences compared to students living in homes with copper pipes.

1. Introduction

In January of 2016, the eyes of the nation were fixed firmly upon Flint, Michigan. National news reports came out that Flint's water supply was contaminated with high levels of lead. After months of state officials insisting the tap water was safe to drink, Michigan Governor Rick Snyder declared a state of emergency and called in the National Guard to distribute bottled water. A couple of weeks later, President Barack Obama classified the Flint Water Crisis as a federal disaster and authorized 5 million dollars in emergency aid (AP 2016). Meanwhile, the Environmental Protection Agency (EPA) declared "imminent and substantial endangerment" and took over management of the Flint water supply (EPA 2016). By then, the roughly 100,000 citizens of Flint had been exposed to contaminated water for over a year and a half. The once little-known, majority black, industrial city quickly became a national symbol for governmental negligence and racial injustice.

Lead primarily effects the brain and is especially dangerous to children (Lidsky and Schneider 2003). A substantial epidemiological literature exists documenting the relationship between exposure to lead in childhood and future negative cognitive and behavioral outcomes. A burgeoning body of economics research documents the important role of childhood conditions in shaping human capital accumulation across the life course (Almond and Currie 2011; Almond, Currie, and Duque 2018), making lead exposure a potentially fruitful target for policymakers interested in reducing inequality and promoting economic efficiency. However, much of the existing literature is correlational and suffers from confounding due to omitted variables, such as socioeconomic status. More recently, a body of causal work examining lead exposure has accumulated, centered primarily on the leading source of childhood lead poisoning in America: lead paint. Nonetheless, there exists a dearth of rigorous studies exploring the effects of lead from other sources. Precious little is known about the social and economic burden of lead plumbing in America today. This lack of knowledge is alarming, given that an estimated 19 million Americans, approximately 6% of the population, still receive their water supply through lead service lines (Cornwell, Brown, and Via 2016).

Unfortunately, lead poisonings through tap water like the one in Flint are not uncommon. Lead in water contributes up to 20% percent of lead poisonings in the US and is the leading source of lead exposure for infants (Zartarian et al. 2017). Academic studies have noted similar water contaminations occurring in Rhode Island, Oregon, North Carolina, Maine, Philadelphia, Milwaukee, and, most famously, DC in the last twenty years alone (Renner 2010, 2009; Bryant 2004; Edwards, Triantafyllidou, and Best 2009; Troesken 2006). Moreover, the rates of lead poisoning in these cases were often more extreme than what happened in Flint. The national news media has begun highlighting the hundreds of water systems serving millions of Americans that failed to meet EPA lead standards from 2002 through 2015 (Ungar 2016).

There is, however, at least one important dimension of Flint's water contamination that differs from the others; the Flint Water Crisis began discretely at a well-known moment in time, a desirable property for a natural experiment. In April of 2014, hoping to cut city costs for water, Flint's emergency city manager ordered that the flow of water from Detroit, which had supplied water from Lake Huron to Flint's residents for the past 50 years, be shut off in favor of water from the Flint River, a small river which runs through the heart of the city. Flint's Water Service Center was woefully ill-prepared for the switch, leaving the Flint River's corrosive water unproperly treated. This untreated water caused lead from Flint's plumbing system to leach into the tap water. Within weeks, Flint residents began to complain about the color, taste, and odor of their drinking water (Masten, Davies, and McElmurry 2016).

In this paper, we quantify the causal effects of the Flint Water Crisis on educational outcomes. We first match the Michigan Department of Education's universe of longitudinal, student-level education records with a unique parcel-level service line dataset collected by Flint city officials tasked with pipe inspection and replacement following the Flint Water Crisis. We then take two methodological approaches to estimate (a) the effect of the Flint Water Crisis overall and (b) the effect of exposure to lead poisoning from lead plumbing. For both approaches, we consider a range of student educational outcomes, including academic achievement, attendance, and high-school drop-out.

To measure the overall impact of the Flint Water Crisis, we use augmented synthetic control analyses (Ben-Michael, Feller, and Rothstein 2018) to compare changes in outcomes over time between treated students living in Flint and control students living in other Michigan districts. These models aim to obtain estimates of the causal effects of the Flint Water Crisis, broadly defined, on the academic outcomes of affected students. The potential mechanisms of these broad effects include lead exposure as well other health effects (e.g. Legionnaires Disease) and social responses (e.g. protests, civil detachment, social stigma).

To measure the specific effect of exposure to lead plumbing, we employ difference-in-difference analyses that compare changes in outcomes for Flint children living in homes with lead pipes to Flint children living in homes with copper pipes. These models isolate the narrow effect of lead exposure from lead pipes on academic outcomes.

Preliminary results suggest that the Flint Water Crisis caused a large decrease in academic achievement for all students living in Flint and that students living in homes with lead pipes experienced an increase in absences compared to students living in homes with copper pipes. Our work contributes to the literature in several ways. First, we quantify the educational costs of a famous case of government mismanagement. Second, we provide the first quasi-experimental evidence that lead pipes remain an economic and social burden in the U.S today. Third, we show that lead exposure can have negative effects on children above the age of five. Fourth, we improve upon previous studies of lead exposure by using a treatment indicator (home service line material) that is free of measurement error. Finally, we are the first quasi-experimental study to examine high school drop-out and daily attendance rates as outcomes of lead exposure.

2. Background on Lead

2b. Lead Pipes

Lead has been a common material used in plumbing for over a thousand years. In 1900, of the forty-six largest cities in the U.S. for which data is available on piping material, thirty-nine used lead pipes (Troesken 2006). Lead pipes were preferred because, while costly, they lasted longer and were more malleable than alternative materials, making them easier to bend around existing structures. Tragically, lead pipes were the most likely to be used in regions with the most corrosive water, where alternative pipes (typically copper or galvanized steel) were eaten away by the water at the fastest rate. Although lead pipes are relatively more resilient to the water's corrosiveness, lead particulates would leach into the water. We use combination of features for causal identification: for substantial amounts of lead to contaminate tap water, there must both be lead pipes supplying the water *and* water corrosive enough to break down the interior of the pipes and cause leaching.

Lead pipes have long been recognized as a threat to public health. In Massachusetts, as early as 1890, the State Board of Health recommended that municipalities abandon lead pipes. Recognizing lead pipes as a cause of lead poisoning, many other cities and towns similarly began prohibiting their use. Nonetheless, partly due to a campaign by the Lead Industries Association extolling the positive qualities of lead, the use of lead pipes persisted in parts of America well into the twentieth century (Rabin 2008).

Today, 30% of the community water systems use some lead pipes (Cornwell, Brown, and Via 2016). The most recent surveys suggest that 6.7 million homes, approximately 19 million Americans, are supplied by lead service lines across the country. Furthermore, though most homes have their water supplied through "lead-free" pipes, they are not entirely without risk. Lead-free pipes can contain up to 8% lead, which has caused lead poisoning in cities that supposedly never had lead pipes (Renner 2010). In most cases, the exact location of lead service lines within a water service system is largely unknown (and would be very costly to determine), though there are some exceptions. Recent data released by the DC Water and Sewer Authority shows the location of at least 12,000 buildings that rely on public lead pipes for their water (DC Water 2016).

Although lead pipes were recognized as a substantial cause of morbidity in the U.S. at one point, a shift of focus of occurred in mid-1980. The Cincinnati Lead Study drew attention to the significant negative impact of lead paint and dust, causing lead pipes to largely be forgotten by policymakers interested in reducing children's exposure to lead (Renner 2010). Recent events in Flint, Michigan and Newark, New Jersey have brought lead plumbing back into the national attention (Leyden 2018). Lead in water is uniquely difficult to contain; while most contaminants can be filtered out at the water plant, lead usually gets into drinking water at the end of the system through individual houses' lead service lines.

2a. Epidemiological Literature

There is no known safe level of lead exposure. Over the last half-century, the Center for Disease Control has repeatedly decreased the "level of concern" amount of lead that can be in the body for children ages one to five, first from 20 µg/dL to 10 µg/dL and then finally to 5 µg/dL (CDC 2013). Substantial evidence suggests that even amounts of lead below these thresholds can lead to intellectual and behavioral impairment (Canfield et al. 2003; Winter and Sampson 2017; Reuben et al. 2017). While the overall exposure of children to lead has dramatically fallen over the past 40 years, as we learn more about the nuances of lead's toxic effects, it is clear that millions of children around the country remain at risk. Over 500,000 children under the age of five in the United States have levels of lead in their blood greater than 5 µg/dL and many more are exposed to lower amounts of lead. The elimination of elevated blood lead levels in children is among the objectives of Healthy People 2020, a ten-year federal Public Health Service campaign aimed at improving the general health of Americans ("Healthy People Leading Health Indicators" 2010).

Lead poisoning primarily effects the brain and is thought to be particularly dangerous to children, for two main reasons (Lidsky and Schneider 2003). First, a child's size makes them more susceptible to small amounts of lead, and second, early childhood is a critical period for neurological development. Importantly, the half-life of lead in the brain is estimated to be about two years, meaning that the detrimental effects of lead can continue long after exposure. Further, if the effects of lead stem neurodevelopment during a critical period, they may persist throughout the life course. While children ages one to five are known to be especially at risk, the extent to which lead is associated with negative outcomes in children who are exposed at ages greater than five is less well understood.

During childhood, lead exposure is associated with increased anxiety (Winter and Sampson 2017), behavioral problems (Washerman et al. 1998), body mass index (Winter and Sampson 2017), and decreased academic achievement (Amato et al. 2012). In adulthood, individuals exposed to lead as a child have decreased brain volume (Cecil et al. 2008), higher rates of criminal offending (Beckley et al. 2018), and decreased social mobility in adulthood (Reuben et al. 2017). Unfortunately, much of this epidemiological literature presents only correlational analyses and, therefore, suffers from confounding due to omitted or poorly measured variables, such as socioeconomic status.

2c. Economic Literature

A growing quasi-experimental literature documents the causal effects of lead on downstream health and human capital accumulation. Much of the extant research focuses on the effects of lead exposure resulting from lead paint, the leading source of childhood lead poisoning in America (Zartarian et al. 2017). This work largely leverages exogenous variation in exposure to lead as a result of public health programs that test children's blood and screen homes for exposed lead paint. Billings and Schnepel (2018) and Aizer et al. (2018) combine individual-level blood lead measures with administrative school data to show a negative relationship between childhood exposure to lead and future math and reading test scores. Billings and Schnepel (2018) further show large decreases in antisocial behavior, consistent with the epidemiological finding that lead affects brain-functioning beyond intelligence in the form of self-regulation and executive functioning (Canfield, Gendle, and Cory-Slechta 2004). Using a similar methodology with aggregate school data, Sorensen et al. (2019) find that lead hazard control grants reduce lead poisoning incidents by roughly 70%, increase overall academic achievement, and decrease racial achievement gaps.

Although the existing economics studies that use measures of blood lead levels for individuals are compelling, they are not without challenges; measurement of lead is complicated by the fact that the amount of lead in the blood can fluctuate wildly and is often not a reliable signal of the amount of lead in an individual's body (Lidsky and Schneider 2003). Additionally, because the lead paint-based public health interventions often target the neighborhoods and homes most at risk, the treated and control units risk confounding by socioeconomic status. Further, such programs often bundle multiple treatments together, making it hard to isolate the effects of lead remediation specifically.

Another strategy to identify the causal effects of lead is to exploit large, regional changes in the exposure to lead to obtain population-level estimates of its effects. Some studies leverage decreases in lead exposure to a population, such as the decrease in lead exposure due to the de-leading of gasoline. Reyes (2007) shows that the removal of lead from gasoline in the late 1970s as a result of the Clean Air Act explains part of the decrease of violent crime witnessed in the 1990s. Using individual data in the NLSY79, Reyes (2015) confirms her population-level findings and extends the causal effects of lead to other sorts of antisocial risky behavior in adolescence. Aizer and Currie (2017) use a similar approach to show that lead exposure in childhood increases future suspensions and incarceration.

Despite the important contributions that prior studies have made to understand the effects of lead exposure coming from paint or gasoline, no contemporary quasi-experimental studies have looked at the impact of lead pipes on child development. Though lead in water contributes up to 20% of lead poisoning in the US and is the leading exposure source for infants, there exists a paucity of research exploring the effects of lead poising from water sources in contemporary times. What we do know about the causal effects of lead pipes mostly comes from a literature in economic history. Troesken (2008) shows that the use of lead pipes was strongly associated with infant mortality around the turn of the 20th century. Similarly, Ferroe et al. (2012) exploit geographic variation in the corrosivity of water as a proxy for lead exposure among World War II enlistees and show large tests score gaps between the areas more and less at risk for lead poisoning. Finally, Feigenbaum and Muller (2016) utilize the introduction of lead pipes in the early twentieth century to show that the cities that installed lead service pipes experienced a considerable lagged rise in homicide rates.

3. The Flint Water Crisis

By the turn of the twenty-first century, Flint, a mid-sized industrial city in east-central Michigan, had faced severe economic decline. The once-booming birthplace to General Motors, Flint's now dwindling population was known for its high rates of crime. In 1960 Flint had over 200,000 residents, but Flint now has fewer than 100,000. In 2011, with Flint's government bankrupt, Michigan's governor Rick Snyder appointed the first of a long string of emergency city managers tasked with sorting out the city's budget troubles.

In April of 2014, to reduce costs, emergency manager Darnell Earley ordered that the flow of water from Detroit, which had supplied water from Lake Huron to Flint's residents for the past 50 years, be shut off and replaced by the Flint River, a small river which runs through the heart of the city. The Flint's Water Service Center was not prepared for the switch; for the past half-century it had been maintained as a backup water treatment facility, treating Flint River water only a few times a year for periods of a couple days. The most recent pilot test had been conducted over 10 years prior. Even if there had been adequate time to prepare, water from the Flint River is considered to be a challenge to treat, as it has "high bacteria and high carbon concentrations" that "fluctuate depending on rain events" (Masten, Davies, and McElmurry 2016). The facility's supervisor warned the Michigan Department of Environmental Quality against the switch, but his words fell on deaf ears. On April 25th, Flint's residents were drinking water from the Flint River.

A large fraction of Flint's service lines are made of lead, an artifact of 1897 city ordinance requiring that "all connections with any water mains be made with lead pipe" (Masten, Davies, and McElmurry 2016). The water from the Flint River was both corrosive and unproperly treated. This, alongside the prevalence of lead in Flint's plumbing system, created the perfect storm: high levels of lead leached into the tap water rom the pipes' inner walls (Pieper, Tang, and Edwards 2017). Almost immediately, Flint residents began to complain about the color, taste, and odor of their drinking water.

In February of 2015, the City of Flint sampled resident Lee Ann Walters' home and found lead in her water at a concentration over 100 μg/L, almost seven times the EPA legal limit. In September of that year, local pediatrician Mona Hanna-Attisha announced that the percentage of children with elevated blood lead levels had doubled. On October 16th, 2015, the city switched back to water from Detroit, but the water remained potentially unsafe to drink, as a protective mineral film needed to develop over time inside the pipes to prevent further leaching.

By the time that Michigan Governor Rick Snyder declared a state of emergency and called in the Michigan National Guard to distribute clean water, the citizens of Flint had been exposed to contaminated water for a year and a half. Since then, criminal charges have been filed against nine mid-level bureaucrats in the Michigan state government as a result of the Flint Water Crisis (Goodnough and Haimerl 2016). The ramifications of the Flint water crisis for affected citizens are only beginning to be explored; an existing study has suggested that the Flint Water Crisis negatively affected fertility (Grossman and Slutsky 2018), though this result has been disputed (Gómez et al. 2019). If and to what extent the Flint Water Crisis affected the development of children remains to be explored.

4. Data

4a. Michigan Longitudinal Administrative Education Records

We use longitudinal, student-level, administrative data from the Michigan Department of Education and the Michigan Center for Educational Performance and Information from 2006-2018. We use these data to identify all Michigan students attending public schools who lived in Flint each year. The state database contains information on all students, from kindergarten through high school, in Michigan public schools linked by a common student identifier. The data also contains student outcomes such as standardized tests scores, daily attendance, and high-school drop-out as well as student characteristics such as race, ethnicity, gender, and eligibility for subsidized meals.

4b. Flint Geo-Spatial Service Line

We also use cross-sectional, parcel-level, service-line inspections data by Flint's Fast Action and Sustainability Program (FAST Start). FAST Start is a small team of city- and state-appointed officials who were tasked with managing lead service line replacement following the Flint Water Crisis. Members of our research team partnered with the FAST Start team to help with data management and prediction (Abernethy et al. 2018). They created an online data-collection platform for FAST Start contractors to record the service-line materials (either copper, lead, or galvanized steel) observed at each inspected home in Flint using a mobile web application. This resulted in an address-specific database of home service-line inspections and replacements. Using each parcel's unique tax identification number, we merged the inspection data with other parcel-level information we received directly from government officials and public websites.

5. Methods

5a. Research Questions

1. What was the effect of the Flint Water Crisis on educational outcomes of children living in Flint compared to comparable children in Michigan?
2. What can we learn from the Flint Water Crisis regarding the health burden of lead pipes in America today? Specifically, how did educational outcomes differ for children living within Flint who lived in homes with lead pipes compared to those who did not?
3. Is lead exposure harmful to children above the age of five? Do children of different ages experience different effects?

We take two distinct approaches to separately estimate the effect of the broad Flint Water Crisis and the narrow effect of exposure to lead poisoning via lead pipes. For both approaches, we consider a wide range of student educational outcomes, including academic achievement, attendance, disciplinary actions, drop-out rates, and high-school graduation rates.

5b. Comparing Flint Students to Students in Other Michigan Districts

First, we conduct between-district analyses using recently developed augmented synthetic control methods (Ben-Michael, Feller, and Rothstein 2018). These augmented synthetic control analyses compare changes in outcomes over time between students living in Flint and students living in a weighted set of control school districts (i.e. all other districts in Michigan). In doing so, these models obtain estimates of the causal effects of the Flint Water Crisis, broadly defined, on the educational outcomes of affected students. The mechanisms of these broad effects of the Flint Water Crisis could include lead exposure as well other health consequences of the Flint Water Crisis (e.g. Legionnaires Disease) and social responses (e.g. protests, civil detachment, stigma).

Under the Rubin potential outcomes framework (Rubin 2005), in order to calculate the causal effect of the Flint Water Crisis on some outcome Y_{it} for district i in time t, we must identify the difference between what was observed in Flint, $Y_{1t}(1)$, and the potential outcome that we would have observed if Flint had not undergone the Flint Water Crisis, $Y_{1t}(0)$.

$$ATE_t = Y_{1t}(1) - Y_{1t}(0)$$
$$ATE = \frac{1}{4}\sum_{z=1}^{4} ATE_t$$

(5b.i)

ATE_t: Average treatment effect of the Flint Water Crisis in year t
ATE: Average treatment effect of the Flint Water Crisis from years T_1 through T_4
$Y_{1t}(1)$: Potential outcome for Flint (i.e i=1) in year t when $W_i = 1$
$Y_{1t}(0)$: Potential outcome for Flint (i.e i=1) in year t when $W_i = 0$

Unfortunately, however, we do not observe both $Y_{it}(1)$ and $Y_{it}(0)$ for any district (in particular, we observe Yit(1) for Flint and Yit(0) for others). However, we do observe T time periods of Y_{it}, from $t = 1, \dots, T_0, \dots, T_4$, for N school districts including Flint. We denote these as follows:

$$Y_{it} = \begin{cases} Y_{it}(0)\ if\ W_i = 0\ or\ t \leq T_0 \\ Y_{it}(1)\ if\ W_i = 1\ and\ t > T_0 \end{cases}$$

(5b.ii)

Y_{it}: Educational outcome for district i in time t
W_i: Binary variable indicating district i was treated
T: Scalar for total number of time periods observed
T_0: Scalar for year of treatment
T_4: Scalar for fourth year posttreatment
N: Number of total districts in our data

In many cases, a simple difference-in-difference methodology is a credible way to obtain $\hat{Y}_{1t}(0)$, an estimate of $Y_{1t}(0)$ and thereby estimate the causal effects of an event like the Flint Water Crisis. However, finding a valid counterfactual for Flint is incredibly difficult. Flint is unique: it is a mid-size city with residents who are disproportionately black and extremely poor and its schools vastly underperform the rest of Michigan. To address the problem of that lack of a clear counterfactual district, we use synthetic controls. Earlier iterations of this method were developed by Abadie and Gardeazabal (2003) and Abadie, Diamond, and Hainmuller (2010). We follow the approach recommended by Ben-Michael, Feller, and Rothstein (2018) to adopt an augmented synthetic control methodology. Synthetic control methodologies have the advantage of obtaining improved pretreatment fit (often referred to as "common trends" in the difference-in-difference literature) and also allow for a more transparent counterfactual selection process, leaving fewer "researcher degrees of freedom."

Using our augmented synthetic control estimator, we obtain $\hat{Y}_{1t}(0)$ using a weighted average of any number of untreated units. Thus, our estimating equation becomes:

$$ATE_t = Y_{1t}(1) - \hat{Y}_{1t}(0) = Y_{1t}(1) - \sum_{i=2}^{N} w_i^{\mathrm{A}}\, Y_{it}$$

(5b.iii)

w_i^{A}: Augmented synthetic control weight for district i

Our data is structured as the following $N \times T$ matrix:

$$\begin{matrix} Flint \\ Detroit \\ \vdots \\ Lansing \end{matrix} \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1T_0} & Y_{1T_1} & \cdots & Y_{1T_4} \\ Y_{21} & Y_{22} & \cdots & Y_{2T_0} & Y_{2T_1} & \cdots & Y_{2T_4} \\ \vdots & & & & & & \vdots \\ Y_{N1} & Y_{N2} & \cdots & Y_{NT_0} & Y_{NT_1} & \cdots & Y_{NT_4} \end{bmatrix} = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1T_0} & Y_{1T_1} & \cdots & Y_{1T_4} \\ X_{21} & X_{22} & \cdots & X_{2T_0} & Y_{2T_1} & \cdots & Y_{2T_4} \\ \vdots & & & & & & \vdots \\ X_{N1} & X_{N2} & \cdots & X_{NT_0} & Y_{NT_1} & \cdots & Y_{NT_4} \end{bmatrix} = \begin{bmatrix} \boldsymbol{X_1} & \boldsymbol{Y_1} \\ \boldsymbol{X_0} & \boldsymbol{Y_0} \end{bmatrix}$$

$\boldsymbol{X_1}$: A $1 \times T - 4$ row of pretreatment outcomes for Flint
$\boldsymbol{X_0}$: An $N - 1 \times T - 4$ matrix of pretreatment outcomes for control Michigan districts
$\boldsymbol{Y_1}$: A 1×4 row of posttreatement outcomes for Flint
$\boldsymbol{Y_0}$: An $N - 1 \times 4$ matrix of posttreatment outcomes for control Michigan districts

We first construct the vector of basic synthetic control weights, $\boldsymbol{w^S}$, by solving for the values that minimizes the squared distance between pretreatment outcomes for Flint and pretreatment outcomes for the other districts. Specifically, we solve:

$$\begin{aligned} \min_{\boldsymbol{w^S}} \quad & ||\boldsymbol{X_1} - \boldsymbol{X_0'}\boldsymbol{w^S}||_2^2 \\ \text{subject to} \quad & \sum_{i=2}^{N} w_i^{\mathrm{S}} = 1 \\ & w_i^{\mathrm{S}} \geq 0, i = 2, \ldots, N \end{aligned}$$

(5b.iv)

$\boldsymbol{w^S}$: $N - 1 \times 1$ vector of basic synthetic control weights w_i^{S} from $\mathrm{i} = 2, \ldots, \mathrm{N}$

We then fit ridge regression to obtain $\hat{\boldsymbol{\eta}}$, the matrix of coefficients of our outcome model.

$$\min_{\hat{\eta}} \quad ||\boldsymbol{Y_0} - \boldsymbol{X_0'}\hat{\boldsymbol{\eta}}||_2^2 + ||\lambda\hat{\boldsymbol{\eta}}^2||_2^2$$

(5b.v)

$\hat{\boldsymbol{\eta}}$: $T - 4 \times N - 1$ matrix of outcome model coefficients
λ: Ridge regression pentalty hyperparameter

We then augment these basic synthetic control weights using the results from our ridge regression model to obtain our final weights, w_i^{A}. Augmenting synthetic control estimates debiases them from imperfect fit in the pretreatment period.

$$\hat{Y}_{1t}(0) = \sum_{i=2}^{N} w_i^{\mathrm{A}}\, Y_{it} = \sum_{i=2}^{N} w_i^{\mathrm{S}}\, Y_{it} + (\boldsymbol{X_{1t}} - \sum_{i=2}^{N} w_i^{\mathrm{S}} X_{it}) \cdot \hat{\boldsymbol{\eta}}$$

(5b.vi)

The augmented synthetic control method has the desirable property of double robustness (Imbens and Rubin 2015). That is to say, the augmented synthetic control estimator is consistent if either the outcome model is correctly specified *or* if the weights are properly chosen (consistency does not require both conditions to be satisfied). While many improvements of the basic synthetic control method have been proposed, only one other shares this double-robustness property (Arkhangelsky et al. 2018), though no software package for implementation is currently available.

Because this augmented synthetic control approach has a dual representation as a weighting estimator (Ben-Michael, Feller, and Rothstein 2018), standard errors are derived analytically. We estimate these models using the publicly available R package `augsynth`.[1] We also add district-level covariates to our outcome model to increase precision. Finally, as a test for heterogeneity, we fit the models again separately for students who were in younger grades (i.e., K through grade 4) at the time of treatment and students who were in older grades (i.e., grade 5 to 12) at the time of treatment.

5c. Comparing Students Within Flint

Next, we conduct within-district analyses using a difference-in-difference approach. Using only a sample of children living in Flint at the time of the crisis, our difference-in-difference models compare changes in outcomes of children living in homes with lead pipes (i.e. treatment group) and children living in homes with copper pipes (i.e. control group). In doing so, these models isolate the narrow effect of the lead exposure due to lead pipes on academic outcomes.

Specifically, we estimate the following model for each child i in grade g living in census tract c at time t:

$$Y_{icgt} = \beta_1 Lead_i + \beta_2(Lead_i * Post_t) + \boldsymbol{X_i}\widehat{\boldsymbol{\Theta}} + \gamma_c + \tau_g + \pi_t + \epsilon \tag{5c.i}$$

Y_{icgt}: Educational outcome for individual i in grade g living in census tract c at time t
$Lead_i$: Binary variable indicating the home of student i during the 2013-2014 school year had lead pipes
$Post_t$: Binary variable indicating $t > T_0$
γ_c: Census tract c fixed effect
τ_g: Grade g fixed effect
π_t: Time t fixed effect
$\boldsymbol{X_i}$: Vector of student-level demographic controls (e.g. race, age, SPED status, LEP status, etc.)

We also fit a similar model to test by for heterogeneity by grade at treatment.

$$Y_{icgt} = \beta_1 Lead_i + \beta_2(Lead_i * Post_t) + \beta_3 Old_i + \beta_4(Old_i * Post_t) + \beta_5(Lead_i * Post_t * Old_i) + \boldsymbol{X_i}\widehat{\boldsymbol{\Theta}} + \gamma_c + \tau_g + \pi_t + \epsilon \tag{5c.ii}$$

Old_i: Binary variable indicating the student was in grade 5 or greater at treatment

Finally, we can fit a similar model with a student fixed effect, which causes a lot of the other variables in our regression to fall out:

$$Y_{icgt} = \beta_2(Lead_i * Post_t) + \boldsymbol{X_i}\widehat{\boldsymbol{\Theta}} + \mu_i + \tau_g + \pi_t + \epsilon \tag{5c.iii}$$

μ_i: Student i fixed effect

[1] Available at https://github.com/ebenmichael/augsynth/blob/master/vignettes/augsynth-vignette.md.

In Equations 5c.i, 5c.ii, and 5c.iii, our parameter of interest is β_2. The identifying assumption required to interpret β_2 as a causal effect is that, conditional on all of our covariates and fixed effects, there are no time varying differences that affect outcomes of students with lead pipes but not students with copper pipes. This is synonymous to saying that, in the absence of treatment, conditional on our controls, the students with lead pipes and students with copper pipes would have had identical trends in the outcome variable.

An advantage of the individual fixed effect model, presented in Equation 5c.iii, is that it accounts for time invariant differences between students that might contribute to differences in trends (and therefore violate our identifying assumption). However, a downside of the student-level model is that the student fixed effect requires that we have within-student variation in treatment in order to identify β_2. Because only a fraction of all students are observed at least once in the pre-treatment period ($t \leq T_0$) and at least once in the post-treatment period ($t > T_0$), the student fixed effect specification is more limited in terms of statistical power. The limited power is more exacerbated for outcomes like academic achievement, which we observe only students in grades 3-8 and in grade 11, than it is for attendance, which we observe for students during all their years in Michigan public schools.

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