Social and Built Environmental Correlates of Predicted Blood Lead Levels in the Flint Water Crisis

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Objectives. To highlight contextual factors tied to increased blood lead level (BLL) risk following the lead-in-water contamination in Flint, Michigan.

Methods. Using geocoded BLL data collected in 2013 and 2015 and areal interpolation, we predicted BLLs at every residential parcel in the city. We then spatially joined social and built environmental variables to link the parcels with neighborhood-level factors that may influence BLLs.

Results. When we compared levels before and during the water crisis, we saw the highest estimates of predicted BLLs during the water crisis and the greatest changes in BLLs in neighborhoods with the longest water residence time in pipes ($\mu = 2.30$ µg/dL; $\Delta = 0.45$ µg/dL), oldest house age ($\mu = 2.22$ µg/dL; $\Delta = 0.37$ µg/dL), and poorest average neighborhood housing condition ($\mu = 2.18$ µg/dL; $\Delta = 0.44$ µg/dL).

Conclusions. Key social and built environmental variables correlate with BLL; such information can continue to guide response by prioritizing older, deteriorating neighborhoods with the longest water residence time in pipes. (*Am J Public Health.* 2017;107:763–769. doi:10.2105/AJPH.2017.303692)

See also Galea and Vaughan, p. 646.

In the seminal report on the Flint Water Crisis (FWC), our team identified a spatial pattern in blood lead levels (BLLs), linking the water source change to an increase in the proportion of children with elevated BLLs (EBLLs).[1] This work has subsequently had immense currency in emergency response, but many questions remain regarding the influence of various social and built environmental characteristics on predicted BLLs and the ability to apply this work to identify children at greatest risk for lead exposure.

In this report, we build on our initial work and ask, what social and built environmental variables are most strongly associated with predicted postswitch pediatric BLLs (i.e., after the change in water source) and with predicted change in pediatric BLLs from the preswitch to the postswitch period in Flint, Michigan, during the FWC? We characterize the neighborhoods where public health response was most needed (those with the highest change in values), and also illustrate the types of neighborhoods where lead remediation programs should be targeted first (those with the highest postswitch values).

Despite a precipitous decline in lead poisoning in the United States over the past several decades, lead exposure remains a critical public health concern because of its irreversible neurotoxicological effects and its disparate impact on low-income, predominantly minority children.[2] Widespread lead-in-water contamination is increasingly recognized as a source of lead exposure[3] because of the ubiquity of lead in plumbing and the lax and outdated regulation of lead in water.[4] Lead in water is particularly troubling because it disproportionately affects the most developmentally vulnerable population—the unborn and infants[5,6]—and the short detection window of BLLs underestimates peak waterborne exposure based on routine BLL screening done at 1 and 2 years of age.

Both the Centers for Disease Control and Prevention[7] and the American Academy of Pediatrics[8] have reiterated that there is no safe level of lead, and have renewed the call for primary prevention: eliminating children's exposure to lead from all sources. To eliminate exposure, however, multifactorial models must be built to predict and minimize risk.

Our research focus—Flint, Genesee County, Michigan—is the center of a postindustrial region of nearly 500 000 people that has struggled economically for several decades, in part because of broader shifts in economic policy and industrial production. Flint lost 77% of its manufacturing employment and 41% of employment overall between 1980 and 2009.[9] Children's health indicators and measures of poverty, unemployment, crime, drug use, and violence remain among the worst in the state.[10,11]

Many disparities stem from a range of social and environmental injustices, which create an added and disproportionate burden for Flint residents. Explicit racial discrimination in housing up to the 1960s set the stage for negative attitudes toward integration and later spurred White flight.[12] The consequently fragmented urban governance diluted the tax base and amplified inequalities present in the city of Flint.[12,13] Majority Black neighborhoods continue to face a disproportionate

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burden of deteriorating housing conditions and high vacancy rates.[14]

Within this clearly demarcated, economically distressed, and racially segregated area, democracy was usurped by state-appointed emergency management and the drinking water source was changed to the Flint River. Without the addition of necessary corrosion control, the water system began leaching iron, lead, and other contaminants into the drinking water. Iron corrosion is of concern because of its connection to *Legionella* bacteria,[15] and lead corrosion has been linked to subsequent increases in the proportion of children with EBLLs. We examine additional relationships between social and built environmental variables and predicted BLLs in children, as previously defined.[1] This is an important next step in environmental health research because implicating built environmental characteristics in increased water-based exposure to lead during a lead leaching event is less well established.

METHODS

This retrospective study used spatially interpolated surfaces derived from our original article, which were created from a sample of all children younger than 5 years who had a BLL test processed through Hurley Medical Center's laboratory. The time periods are identical to those in the original report: the preswitch time period (before the water source change) was January 1, 2013, to September 15, 2013, and the postswitch time period (after the water source change) was January 1, 2015, to September 15, 2015 (the water source was changed on April 25, 2014).

We operationalize 2 dependent variables. First, we derived the predicted BLL at every residential parcel in the city (n = 41 058) from the ordinary Kriging result of our sample of 737 children from Hurley Children's Hospital,[1] whereby we generated unknown BLL values from known values, with nearer values playing a stronger role in the prediction. Second, we obtained the change in predicted BLLs at every residential parcel by a map algebra equation calculating the difference between predicted BLL in 2013 (derived from n = 736) and predicted BLL in 2015 (included as an appendix in our earlier report[1]). The benefit of using these Kriged surfaces is that they offer a predicted value for each parcel individually and thus represent the entirety of the city, limiting spurious conclusions based on potential biases from clustered sampling.

We constructed independent variables from several city and community data sets that span the entirety of the city of Flint, including vacancy rate, house age, and demolition density (Genesee County Land Bank Authority Dept of Planning & Neighborhood Revitalization, unpublished data, 2016); socioeconomic distress level and percentage of Black residents[16]; and neighborhood housing condition, land use mix, residence time in pipes, and water line composition (City of Flint Dept of Planning and Development, unpublished data, 2016). In this study, we have included many variables on the basis of their demonstrated associations to pediatric BLLs in past research.[17,18] We have included other variables (e.g., land use mix) to test assumptions about lead exposure.

Vacancy rate is a block-level continuous variable from the City of Flint referring to the percentage of vacant parcels within the block. A constructed categorical variable includes break points at 10%, 25%, and 50%. Vacancy rates have previously been used as a proxy for lead-based paint deterioration, since high vacancy rates are associated with high lead exposure as properties become less well maintained.[19]

Socioeconomic distress is a census block group–level continuous variable referring to the level of material and social deprivation (a construct of rates of lone parenthood, poverty, low educational attainment, and unemployment combined into an unweighted z-score sum),[20] in which higher numbers signify increasingly higher distress. We constructed a categorical variable using quintiles.

Percentage of Black residents is a census block group–level continuous variable referring to the percentage of the neighborhood that is composed of Black residents. We constructed a categorical variable with 20% break points. Both measures of socioeconomic distress and racial composition have been associated with disparities in BLLs,[17,19] with Black residents being more likely to have higher BLLs.

Neighborhood housing condition is a continuous variable derived from the average condition of houses within the same block; it is based on a city assessment of the condition of homes on a 4-point scale (1 = good, 2 = fair, 3 = poor, 4 = structurally deficient). City workers trained raters to evaluate homes on the basis of the same set of guidelines. The categorical variable equivalent has break points at 1.25, 1.50, 2.00, and 2.50, encapsulating neighborhoods ranging from good to poor condition. Overall housing condition has been shown to be important in predicting pediatric BLLs.[21]

House age is an integer variable referring to the year in which the house was built. The categorical variable has break points at 1920, 1940, 1960, and 1986, signifying periods of Flint development as well as the year when the use of lead in pipes was restricted. Researchers have implicated house age as a primary determinant of lead exposure[22] because of the use of lead paint. Of note here is that 99.1% of housing in Flint was constructed before lead in paint was banned in 1978.

Land use mix is a continuous variable based on an entropy index showing how "diverse" an area is in terms of residential, commercial, and industrial land uses. Higher scores signify mixed land uses, whereas lower scores signify segregated land uses. The categorical variable has 20% break points. Although land use mix is more commonly used in transportation and walkability studies,[23] we use it here as a proxy for legacy commercial and industrial uses and high traffic areas where baseline soil lead levels may be higher.[24,25]

Demolition density is a continuous variable referring to the number of demolitions within 400 feet of the parcel in the past 2 years. The categorical variable has break points at 0, 100, and 300 demolitions per square mile. Research has shown that demolitions are important to lead exposure risk up to a 400-foot dust fall range.[26] Although the Genesee County Land Bank has stringent guidelines on mitigating dust fall impacts during demolition, we included this variable to ensure that it was not playing a significant role in lead exposure risk.

Residence time in pipes is a categorical variable in which higher numbers signify water that has been resident in the water distribution system for longer periods of time. Preestablished break points were set at 24, 72, and 144 hours. Its inclusion is based on research showing that longer residence time in pipes is associated with water corrosivity and thus with increased lead leaching.[27]

Water line composition (used only in ANOVA) is a categorical variable referring to the composition of the water service line at the corresponding parcel (includes lead, no lead, or unknown); it is included because of the well-defined causal link of lead service lines to high water lead levels and increased lead exposure risk.[28,29] It does not capture lead in premise (household) plumbing.

We conducted Pearson *R* correlations and forward stepwise regressions to determine the most salient predictor variables of BLLs; we conducted ANOVA on the categorical versions of these variables to test differences in means.

RESULTS

As a frame of reference, we note some descriptive statistics for predicted BLL (in μg/dL) at every parcel in Flint (n = 57 165) and in Genesee County not including Flint (Genesee County non-Flint; n = 134 935). The universal predicted BLL before the water source change was 1.74 (Flint) versus 1.21 (Genesee County non-Flint) micrograms per deciliter. After the change, this disparity increased to 1.82 (Flint) versus 1.13 (Genesee County non-Flint) micrograms per deciliter, widening the overall gap between Flint and Genesee County non-Flint from 0.54 to 0.69 micrograms per deciliter. All differences are statistically significant. To provide a further frame of reference, descriptive statistics for social and built environmental variables are shown in Table 1.

We do not reference Genesee County throughout the balance of this report; the values in the previous paragraph are given merely to contextualize the meaning of the ensuing results. In addition, because social and built environmental data sets were not available for the entire county, we performed analysis at the city level. Focus is thus given to how the postswitch and change in predicted BLLs in Flint vary across different social and built environments. This has the added benefit of controlling for only those places that received Flint water.

We initially ran Pearson *R* correlations between the aforementioned variables and the postswitch and change raster values assigned to each residential parcel in the city of Flint to determine how closely each variable was related postswitch and change values. The 3 strongest variables correlated to predicted BLL were house age (postswitch = –0.491; change = –0.417), neighborhood housing condition (postswitch = 0.428; change = 0.474), and residence time in pipes (postswitch = 0.387; change = 0.400), signifying that older homes, homes in neighborhoods in poorer condition, and homes in which water had a longer residence time in pipes were more likely to have high predicted BLL rates and to have experienced a large change in predicted BLLs. High socioeconomic distress (postswitch = 0.351; change = 0.402) and high vacancy rates (postswitch = 0.307; change = 0.295) were also moderately correlated to higher postswitch and change BLLs.

TABLE 1—Descriptive Statistics for Social and Built Environmental Variables: Flint, MI, 2013–2015

Variable	Mean (95% CI)
Vacancy rate,[a] %	13.84 (13.68, 14.00)
Socioeconomic distress[b]	1.98 (1.95, 2.01)
% of Black residents	50.57 (50.19, 50.96)
Housing condition[c]	1.57 (1.57, 1.58)
Year house was built	1941.53 (1941.35, 1941.70)
Land use mix,[d] %	48.98 (48.76, 49.21)
Density of demolitions, per sq mi	130.61 (128.54, 132.68)
Residence time in pipes (water age zone)[e]	2.35 (2.34, 2.36)

Note. CI = confidence interval. For all variables, the number of residential parcels was 41 058.
[a]Percentage of vacant parcels within the block.
[b]A construct of rates of lone parenthood, poverty, low educational attainment, and unemployment combined into an unweighted *z*-score sum,[20] in which higher numbers signify increasingly higher distress.
[c]Average condition of houses within the same block based on a city assessment of the condition of homes on a 4-point scale (1 = good, 2 = fair, 3 = poor, 4 = structurally deficient).
[d]Based on an entropy index showing how "diverse" an area is in terms of residential, commercial, and industrial land uses.
[e]Categorical variable (1–4) in which higher numbers signify water that has been resident in the water distribution system for longer periods of time. Preestablished break points were set at 24, 72, and 144 hours.

Two variables with lower correlations than expected were percentage of Black residents (postswitch = 0.145; change = 0.268) and demolition density (postswitch = 0.287; change = 0.321). These results are encouraging, as they suggest only a modest relationship of higher BLLs to neighborhoods with a higher proportion of Black residents and a higher concentration of recent demolitions. (Even so, the broader environmental injustice should not be overlooked: Black residents remain disproportionately inside the city of Flint.) Finally, the small negative relationship with land use mix (postswitch = –0.176; change = –0.266) suggests that more homogenous neighborhoods were loosely associated with higher postswitch and change in predicted BLLs.

Because of the potential for collinearity—for our purposes, whether certain social and built environmental variables were essentially describing the same association to postswitch and change in predicted BLLs—we also conducted a regression analysis with collinearity diagnostics. For brevity, we note here only that the variance inflation factors (or the extent to which any 2 variables may predict the same part of a regression model) for each set of variables were well within acceptable limits (minimum = 1.100; mean = 1.598; maximum = 2.316), and thus did not suggest significant collinearity.

We ran forward stepwise regression analyses for the 2 outcome variables: postswitch predicted BLL and change in predicted BLL. This iterative analysis entailed the addition of predictor variables to a model one at a time based on which most improved the model. We cut off models at 5 variables for each model, as r^2 values increased at a rate of less than 0.005 per additional variable after that point. In the postswitch predicted BLL model (Table 2), house age was the strongest determinant, with an r^2 value of 0.241 on its own. The r^2 value increased to 0.364 when we included residence time in pipes, and it leveled off at 0.458 with the inclusion of neighborhood housing condition, socioeconomic distress, and percentage of Black residents.

In the change in predicted BLL model (Table 3), neighborhood housing condition was the strongest determinant, with an r^2 value of 0.225 on its own. As with the postswitch predicted BLL model, residence time in pipes was the next most important predictor, and its inclusion increased the

TABLE 2—Associations With Postswitch Blood Lead Levels: Flint, MI, 2015

Model	b (SE)	B	P
(Constant)	19.33 (0.21)		< .001
House age	−0.01 (0.00)	−0.35	< .001
Residence time in pipes	0.17 (0.00)	0.36	< .001
Neighborhood housing condition	0.22 (0.01)	0.24	< .001
Socioeconomic distress	0.03 (0.00)	0.19	< .001
% of Black residents	−0.00 (0.00)	−0.14	< .001

Note. "Postswitch" refers to the period after the change in water source.

r^2 value to 0.356. Adding house age, socioeconomic distress, and land use mix brought the r^2 value up to 0.450.

As an alternative test of determining the influence of variables on postswitch and change in predicted BLLs, we also used ANOVA to highlight relationships between categories of social and built environmental characteristics and postswitch and change in predicted BLLs (Table 4). Here, we add in water line composition (unknown, not lead, and lead) to further contextualize these relationships. To determine the subcategories that caused significant differences in ANOVA scores, we also ran Tukey's posthoc test for each. For brevity, only the mean values and confidence intervals are shown.

Significant results from Tukey's test can be inferred from observing the nonoverlapping confidence intervals within each variable. For example (and most prominently), the mean postswitch and change in predicted BLLs with residence time in pipes of more than 144 hours (postswitch = 2.30 µg/dL; 95% confidence interval [CI] = 2.28, 2.31; change = 0.45 µg/dL; 95% CI = 0.44, 0.46) is significantly different from other residence times in pipes (e.g., for residence time < 24 hours, postswitch = 1.68 µg/dL; 95% CI = 1.68, 1.69; change = –0.12 µg/dL; 95% CI = –0.12, –0.11). That this contrast exhibits the largest intergroup variation highlights the importance of residence time in pipes on postswitch and change in predicted BLLs.

Such significant differences are common throughout the subdivisions. Of note (and not observable in linear regression) is that percentage of Black residents has a parabolic relationship with postswitch and change in predicted BLLs, such that integrated neighborhoods (41%–60% Black) have the highest postswitch (2.35 µg/dL) and change in (0.32 µg/dL) predicted BLLs, whereas more segregated neighborhoods tend to have lower postswitch and change in predicted BLLs. A similar but inverted pattern is seen for house age, with the oldest (postswitch = 2.22 µg/dL; change = 0.37 µg/dL) and newest (postswitch = 2.04 µg/dL; change = 0.12 µg/dL) homes receiving high scores. The presence of higher postswitch and change in predicted BLLs in the newest homes may be because they are present on redevelopment sites in older parts of the city, which thus have legacy infrastructure that predicts lead exposure.

Other large changes include the predicted BLLs seen in areas with vacancy rates of 50% or more (0.29 µg/dL), very high socioeconomic distress (0.32 µg/dL), poor neighborhood housing condition (0.44 µg/dL), and high demolition density (0.31 µg/dL).

TABLE 3—Associations With Change in Blood Lead Levels: Flint, MI, 2013–2015

Model	b (SE)	B	P
(Constant)	12.32 (0.17)		< .001
Neighborhood housing condition	0.20 (0.00)	0.26	< .001
Residence time in pipes	0.13 (0.00)	0.32	< .001
House age	−0.01 (0.00)	−0.29	< .001
Socioeconomic distress	0.02 (0.00)	0.14	< .001
Land use mix	−0.17 (0.01)	−0.10	< .001

DISCUSSION

Our intention was to contextualize the social and built environmental variables with which predicted BLLs may be associated in the context of the FWC. Although previous studies have conducted spatial analyses of such variables, they have focused more closely on more typical sources of lead[30] or only conducted estimates rather than determining relationships to BLLs.[31] We have shown that, in the context of the FWC, residence time in pipes (longer time in distribution system), neighborhood housing condition (poorer housing condition), and house age (older homes) are most strongly and consistently related to higher postswitch and change in predicted BLLs. This has critical implications for future public health response: it not only further implicates the corroded lead plumbing as vectors of lead exposure, but it also shows that children living in older homes in neighborhoods of generally poorer housing condition have been disproportionately affected by higher rates and greater increases in pediatric BLLs during this water lead–leaching event. This outcome makes sense given that such homes more commonly have lead in paint and plumbing, but it is important because the connection between water lead levels and social and built environmental variables had not yet been established since the outbreak of the FWC. From the regression analyses and ANOVA, a few variables stood out as of great importance to the consideration of spatially targeted public health response. The strong relationship between poorer neighborhood housing condition and larger postswitch and change in predicted BLLs suggests that the general deterioration of neighborhoods can be a risk factor for lead exposure from pipes.

Directly related to our central concern of lead in pipes, the fact that residence time in pipes was a top determinant in both regression models and saw the largest difference in mean values in the ANOVA suggests a critical link between the time water spends in the distribution system and postswitch and change in predicted BLLs. The association of high postswitch and change in predicted BLLs to house age shows that the deterioration process at the individual level has a direct effect on lead exposure from pipes. Though intuitive, this finding is still important, as it signifies a baseline inequity in lead exposure and supports other work showing links to lead exposure from soils and paints in older homes.[32]

One finding of interest is the association of areas with little land use mix to greater postswitch and change in predicted BLLs. The functional meaning is that residential areas isolated from other uses (i.e., deep in neighborhoods) are more likely to have higher postswitch and change in predicted BLLs. The causal mechanism behind this is unclear, particularly because it is opposite of the result we expected, given the well-established link between commercial land

TABLE 4—Stratified Social and Built Environmental Variables and Association to Postswitch and Change in Blood Lead Levels (BLLs): Flint, MI, 2013–2015

Variable Categories	No. of Residential Parcels	Mean Predicted Postswitch BLL, µg/dL (95% CI)	Mean Predicted Change in BLL, µg/dL (95% CI)
Vacancy rate, %			
< 10	22 735	1.65 (1.65, 1.66)	−0.06 (−0.07, −0.06)
10–24	9 873	1.82 (1.81, 1.83)	0.10 (0.09, 0.11)
25–49	6 360	2.01 (2.00, 2.02)	0.23 (0.21, 0.23)
≥ 50	2 090	2.08 (2.06, 2.10)	0.29 (0.27, 0.30)
Socioeconomic distress[a]			
Very low	10 906	1.56 (1.59, 1.60)	−0.14 (−0.15, −0.14)
Low	9 852	1.55 (1.55, 1.56)	−0.15 (−0.15, −0.14)
Average	7 656	1.90 (1.89, 1.91)	0.16 (0.15, 0.17)
High	6 905	1.94 (1.92, 1.95)	0.22 (0.21, 0.23)
Very high	5 739	2.09 (2.08, 2.10)	0.32 (0.30, 0.33)
% of Black residents			
0–20	16 537	1.69 (1.68, 1.69)	−0.07 (−0.08, −0.07)
21–40	3 588	1.66 (1.64, 1.67)	−0.12 (−0.13, −0.10)
41–60	472	2.35 (2.29, 2.41)	0.32 (0.28, 0.36)
61–80	3 091	1.92 (1.90, 1.94)	0.15 (0.14, 0.16)
> 80	17 370	1.83 (1.82, 1.84)	0.15 (0.14, 0.16)
Housing condition[b]			
1–1.24 (good)	14 388	1.55 (1.55, 1.56)	−0.15 (−0.15, −0.14)
1.25–1.49	8 252	1.64 (1.63, 1.65)	−0.10 (−0.11, −0.09)
1.50–1.99 (fair)	9 359	1.93 (1.92, 1.94)	0.17 (0.16, 0.18)
2.00–2.49	6 332	2.02 (2.00, 2.03)	0.28 (0.27, 0.29)
2.50–4.00 (poor)	2 727	2.18 (2.16, 2.20)	0.44 (0.42, 0.46)
Year house was built			
< 1920	4 354	2.22 (2.20, 2.23)	0.37 (0.36, 0.39)
1920–1939	13 145	1.97 (1.96, 1.98)	0.18 (0.17, 0.19)
1940–1959	18 501	1.59 (1.59, 1.60)	−0.09 (−0.09, −0.08)
1960–1986	4 849	1.48 (1.47, 1.49)	−0.18 (−0.18, −0.17)
1987–present	209	2.04 (1.98, 2.09)	0.12 (0.06, 0.17)
Land use mix,[c] %			
0–19	5 544	1.89 (1.13, 3.07)	0.22 (−0.45, 1.12)
20–39	9 304	1.85 (1.09, 3.07)	0.13 (−0.87, 1.15)
40–59	11 849	1.77 (1.06, 3.07)	0.01 (−0.67, 1.23)
60–79	10 468	1.65 (1.01, 3.34)	−0.06 (−0.76, 1.14)
80–100	3 893	1.73 (1.02, 3.01)	−0.07 (−0.78, 1.06)
Density of demolitions, per sq mi			
0	18 587	1.66 (1.65, 1.67)	−0.06 (−0.06, −0.05)
1–99	7 498	1.73 (1.72, 1.74)	0.00 (−0.01, 0.01)
100–299	8 431	1.84 (1.83, 1.85)	0.08 (0.07, 0.09)
≥ 300	6 542	2.04 (2.03, 2.05)	0.31 (0.30, 0.32)

Continued

uses such as gas stations and lead.[33] Rather, this may be a result of the colocation of isolated residential areas with other variables, especially high residence time in pipes.

The high postswitch and change in predicted BLLs in neighborhoods with high vacancy rates, very high socioeconomic distress, and high demolition density are likely attributable to their association to deteriorating neighborhood housing condition and house age, as the aforementioned variables themselves were not strong correlates in the regression analyses. Although these variables were not predictive of higher predicted BLLs, their relationship to such levels means that residents in poorer neighborhoods with poorer housing conditions and older homes are still at risk, amplifying the disadvantage they experience by living in such conditions.

Conversely, the presence of specific subgroups of neighborhoods in areas with low postswitch predicted BLLs and low change in predicted BLLs highlights how these neighborhoods may be somewhat buffered from the most extreme issues associated with lead exposure. These include neighborhoods with the following characteristics: houses built between 1960 and 1986 (postswitch = 1.48 µg/dL; change = −0.18 µg/dL), very good housing condition (postswitch = 1.55 µg/dL; change = −0.15 µg/dL), and low socioeconomic distress (postswitch = 1.55 µg/dL; change = −0.15 µg/dL) or very low socioeconomic distress (postswitch = 1.60 µg/dL; change = −0.14 µg/dL). These differences could be a result of higher income groups being better equipped to buffer against lead exposure through, for instance, improved nutrition, home improvements of lead in paint, decreased exposure to lead in soil, or ability to afford water alternatives or filters at the onset of the water source change.

The change variable is of particular interest because it illustrates not only areas where high BLLs were a continual concern, but also areas where conditions changed significantly between 2013 and 2015. If legacy lead concerns were the primary issue, no significant changes would have been expected from 2013 to 2015 (the period during which the water source changed). The presence of significant relationships in the change in predicted BLL stratified by neighborhood further contextualizes how the water source change increased EBLLs among Flint children in 2015.[1] As with the postswitch variables, neighborhoods with higher vacancy rates, higher socioeconomic distress, poorer housing condition, and less land use mix experienced the greatest increases in predicted BLL. The housing variables themselves are important because of

TABLE 4—*Continued*

Variable Categories	No. of Residential Parcels	Mean Predicted Postswitch BLL, µg/dL (95% CI)	Mean Predicted Change in BLL, µg/dL (95% CI)
Residence time in pipes (water age zone), h			
< 24	9 381	1.68 (1.68, 1.69)	−0.12 (−0.12, −0.11)
24–72	15 337	1.62 (1.61, 1.63)	−0.02 (−0.03, −0.01)
73–144	8 842	1.67 (1.66, 1.68)	−0.04 (−0.05, −0.03)
> 144	7 498	2.30 (2.28, 2.31)	0.45 (0.44, 0.46)
Water pipe composition			
Unknown	7 764	1.86 (1.85, 1.87)	0.11 (0.10, 0.12)
Not lead	30 202	1.72 (1.72, 1.73)	0.01 (0.00, 0.01)
Lead	3 092	1.98 (1.96, 2.00)	0.19 (0.18, 0.21)

Note. CI = confidence interval. "Postswitch" refers to the period after the change in water source; "change" denotes change from the preswitch to the postswitch period.

[a]A construct of rates of lone parenthood, poverty, low educational attainment, and unemployment combined into an unweighted *z*-score sum,[20] in which higher numbers signify increasingly higher distress.

[b]Average condition of houses within the same block based on a city assessment of the condition of homes on a 4-point scale (1 = good, 2 = fair, 3 = poor, 4 = structurally deficient).

[c]Based on an entropy index showing how "diverse" an area is in terms of residential, commercial, and industrial land uses.

the issues of fluctuating water lead levels in homes that have been vacant for even a modest period of time.

This report serves as a follow-up to our earlier study[1] by further contextualizing the types of neighborhoods in which children were predicted to experience the greatest increases in BLLs in the wake of the FWC. Such information has been guiding emergency response efforts, and it provides further contextualization of the increase in EBLL proportion as a result of the water source change. With this knowledge in hand, we can continue to shape efforts to target lead-mitigating programs and child development–promoting programs toward the most vulnerable children in our city, not only where endogenous lead in soil and paint creates greater risk but where the uptick in lead in water exacerbated that risk the most during the FWC.

Our report implicates additional variables that may play an additive or synergistic role in children's lead exposure. In Flint, the widespread water-based lead contamination was exacerbated in neighborhoods where water was resident in the pipes for the longest period of time, and compounded in neighborhoods known to have higher lead risks, including older homes in poor condition. These factors synergistically increased children's lead exposure.

We recognize that error could have been introduced through our use of interpolated values from 2 Kriging exercises designed to model the spatial distribution of BLLs in Flint children. Using these values, however, allowed us to demonstrate clear links between social and built environmental variables and predicted BLLs, thereby increasing the citywide utility of the mapping conducted in our earlier report.[1] Kriging also afforded us better individual estimates than would have been possible with aggregated area-based estimates, which are more prone to the ecological fallacy. Additionally, potential bias may exist in our data because our sample is smaller and likely more socioeconomically disadvantaged than a broader, statewide sample. But our data may also hold several advantages over larger data sets because they were collected from 1 laboratory, values were not rounded up to the nearest integer in micrograms per deciliter (as they are in state data), and venous tests were used over capillary tests when available.

Other researchers and communities can use this analysis as a template for discerning the spatial relationships between BLLs and social and built environmental variables. The patterns are likely to be similar in other communities, but making such patterns explicit and using this information to increase community capacity in lead prevention efforts is essential for working toward the goal of eliminating pediatric lead exposure, especially for our most vulnerable children. AJPH

CONTRIBUTORS

R. C. Sadler conducted analyses and drafted the Results and Discussion sections. J. LaChance and M. Hanna-Attisha drafted the literature and background. All authors conceptualized the study and also contributed to and approved all components of the final draft.

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HUMAN PARTICIPANT PROTECTION

No human participants were involved in this study. It is impossible to identify individual-level data from the raster surfaces of predicted blood lead levels used as the basis for analysis in this report.

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