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IEUBK Modeling of Children's Blood Lead Levels in Homes Served by Private Domestic Wells in 3 Illinois Counties

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Abstract: Lead is known to impair neurocognitive development in children. Drinking water is routinely monitored for lead content in municipal systems, but private well owners are not required to test for lead. The lack of testing poses a risk of lead exposure and resulting health effects to rural children. In three Illinois counties we conducted a cross-sectional study (n=151) examining water lead levels, water consumption, and water treatment status to assess risk of lead exposure among residents using private water wells. Since blood lead levels were not available, Integrated Exposure Uptake Biokinetic (IEUBK) modeling was used to estimate the contribution of water lead levels to blood lead levels. Nearly half (48.3%) of stagnant water samples contained measurable lead ranging from 0.79-76.2 µg/L. The median Pb was 0.537 µg/L. Deciles were used to estimate BLLs change from 10th to 90th percentiles. IEUBK modeling of water lead levels estimated that compared to children with 10th percentile (0.54) water lead levels, those with 90th percentile (4.88 µg/L) levels would have blood lead levels that were 0.3 to 0.4 µg/dL higher. Based on IEUBK modeling 18% of children with water leader levels at the 10th percentile would have BLLs above 3.5 µg/dL compared to 27.4% of those with water lead levels in the 90th percentile. These findings suggest that the consumption of unfiltered well water likely results in increases blood lead levels in children.

Keywords: epidemiology; health disparities; social determinants of health

1. Introduction

Lead (Pb) exposure is associated with negative neurocognitive health effects in children on memory, gross motor skills, attention and IQ[1–5] as well as physical effects such as stunted growth. [6] Studies have shown that even low levels of water lead levels (WLLs) (3.3 µg/L or greater) are associated with elevated blood lead levels (BLLs) in 1-5 year old children (adjusted odds ratio [OR] 4.7, 95% confidence interval [CI] 2.1-10.02).[7] In Flint, Michigan the increase in WLLs led to an increase in the frequency of BLLs >5 µg/dL among children, from 3% to 5%.[8] Drinking water is estimated to account for up to 20% of total Pb exposure in the US, but the risk is higher for infants who rely on formula; in fact, water can account for 45 - 60% of infants' daily Pb exposure.[9] Community water supply systems are regulated by the Lead and Copper Rule, which specifies an action level of 15 µg/L. If WLLs exceed the action level, actions are required to reduce exposures to water Pb[10]. Owners of private domestic wells (PDWs) must measure WLLs for real estate transactions only in Rhode Island [11]; in other states, WLL testing is voluntarily and infrequent.[10] Studies have shown that children who rely on PDWs are more likely to have elevated BLLs. A recent study found that among North Carolina children, those on PDWs were 20% more likely to have an elevated BLL than children on community water sources.[12] Despite this information, there is still very little data on the association between BLLs of children who rely on PDWs for water and WLLs. Over 13 million private wells in the US are the primary source of drinking water for an estimated 44 million people.[13,14] Thus, children who live in homes with PDW water may be at risk for ingestion of Pb, but because of the lack of water Pb testing, the scale of this public health threat is not known.

Pb in drinking water from PDWs is especially concerning in rural areas of the United States. A study combining USGS data and U.S. census data showed PDWsare more prevalent in areas of low housing density.[15] CDC recommended blood Pb testing data may also not sufficiently capture this risk. From 2011 to 2016 in North Carolina less than a third of children born in the state had both BLL screenings at 1 year and 2 years of age.[16] In rural areas where there are fewer health facilities, BLL screening compliance may be lower. This in addition to the lack of regular water testing pose a significant risk to the health of children in rural areas. Typical Pb sources in water tend to be Pb water service lines and other lead components in plumbing. Even Pb soldering materials can contribute to Pb in tap water. Corrosive water aids with Pb particulate shedding from the piping and can lead to particulate Pb. Particulate Pb is associated with higher elevations in BLLs than dissolved Pb.[17]

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The health effects of elevated BLLs Is are well known. Children exposed to Pb are known to be more likely to have neurodevelopmental delays, lower scholastic performance, attention deficits, hyperactivity, and increased psychological mood disorders.[18–21] The effects of chronic exposure to Pb has been shown to negatively affect children's IQ and the deficits continue with lower vocabulary and academic performance and a greater risk of not completing high school, which is associated with lower socioeconomic status in the future .[22,23] Bone Pb concentration in children 12-18 is also associated with juvenile delinquency.[24] Even Pb blood levels below the reference value of 3.5 μg/dL have been shown to have effects on IQ and behavior. BLLs as low at 1.2 μg/dL can have effects on IQ.[25] These effects are especially concerning in rural population which are already at risk for earlier mortality due to low SES and the gap is growing each year compared to urban areas.[26] Chronic Pb exposure, reduced socioeconomic opportunity due to poor school performance could potentially reduce the ability of children to be able to gain opportunities through education which would allow them to leave areas which are consider low opportunity. Pb exposure above 3.3 μg/L has been shown to significantly increase the odds of a child having an elevated BLL.[7]

We have previously reported WLLs in 151 Illinois homes that rely on PDWs for drinking water.[27] In that study, Pb was detectable in nearly 50% of homes, and 3% of homes had WLLs that exceeded the 15 μg/L action level that applies to community water systems. The primary goal of this study was to assess the likely contribution of drinking water to BLLs among children residing in homes supplied by PDWs in three Illinois counties.

2. Materials and Methods

2.1. Setting

In a cross-sectional study, two kitchen tap water samples from 151 households in three Illinois counties--Kane, Jackson, and Peoria--were collected by home residents based on the guidelines set by the Lead and Copper Rule.[28] Local health department environmental health staff conducted in-home water sampling training with participants. After at least a 6-hour period of no water use, stagnant and flushed (1st and 7th liter, respectively) water samples were returned to the Illinois State Water Survey to be analyzed for Pb and corrosivity properties. Total Pb was analyzed using graphite furnace atomic absorption. Samples with Pb > 2 μg/L were passed through a 0.45 μm filter and analyzed for dissolved Pb. Sulfate and chloride were measured using ion chromatography and alkalinity was measured by titration. Corrosivity was determined using the Larson-Skold Index (LSI): LSI = (epm chloride + epm sulfate)/(epm alkalinity) where epm = equivalents per million.

2.2. Questionnaire

Participants completed a 32-item questionnaire to collect information on demographics and potential Pb exposure risk factors such as plumbing materials, well maintenance, and water treatment. The questionnaire was based on several national surveys and those used in previously published research.[29–35] The questions address water use, plumbing infrastructure, water treatment devices, primary drinking and cooking water sources, fixtures, plumbing maintenance, housing characteristics, and water safety perceptions. For items about water safety, a 5-point Likert scale was used to assess personal safety perceptions. The other questions were structured in a multi-choice format or as a yes or no question.

2.3. Blood Lead Level Modeling

The primary aim of this study was to estimate the contribution of drinking water to BLLs of children (BLLs were not measured). We accomplished this by using the EPA's Integrated Exposure Uptake Biokinetic (IEUBK) Model Version 2.[36] IEUBK was developed using data mainly from Pb superfund sites to model risk to children. Geometric mean (GM) BLLs can be modeled using air, dietary, maternal, soil and dust, and water Pb concentrations from sites where data are available. [36] Because our interest was in the contribution of PDW water to BLLs, sources and pathways included in IEUBK except for water exposure were set to IEUBK default values (the IEUBK model does not include input terms for paint Pb, other than through a dust Pb exposure pathway). Differences in estimated BLLs between those with observed 90th and 10th percentile water lead levels. We used the default values for dust, dietary, maternal, soil and air. The only output changed was WLLs based on the data collected. The aim was to estimate the effect WLLs have on total BLLs, not directly simulate exact BLLs of children on PDWs in the 3 counties. Calculations were based on WLLs from all homes in the study, regardless of whether children lived in these homes or not. For undetectable Pb levels (levels <0.76 μg/L), Pb presence was determined using (0.76 μg/L)/(√2), Distribution of BLLs was calculated using IEUBK software. Geometric standard deviation (GSD) was left at 1.6 based on the IEUBK user manual guidance. For statistical analysis STATA (STATACorp LLC College Station, TX) was used.

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3. Results

Table 1 shows key characteristics of the three counties. In Jackson County, about 30% of housing is rural with 60% built before 1980. By comparison, 25%f the housing in Kane is pre-1980, and the same is true of about half the housing stock in Peoria. The percentage of children under 18 years ranged from 18.4 (Jackson) to 25.0 (Kane).[13] Details on demographics and the study methodology have been previously published.[27]

Table 1. Characteristics of study sample by county.

		Jackson	Kane	Peoria
Population, n (%)				
	Under 5 years	3,129 (5.4)	32,962 (6.2)	12,555 (7.0)
	5 to 9 years	2,544 (4.4)	32,638 (6.1)	11,115 (6.2)

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Under 18 years	10,646 (18.4)	132,979 (25.0)	42.236 (23.6)
Total Population*n*	57,977	532,403	179,179
Rural Housing, %	30	11	17
Housing before 1980, %	60	75	50.5
Estimated PDWs, n	1,900	7,100	18,000

Table 2 shows Pb concentrations in the 1st liter (stagnant) and 7th liter (flushed) sample. Measurable Pb was present in 73 (48.3%) of 1st liter samples. Measurable Pb in 5 (3.3%) of 1st liter samples had Pb concentrations >15 µg/L (the EPA action level for community water systems). The highest Pb concentration was 76.2 µg/L, 5 times higher than the EPA action level for community water systems. 5 samples had Pb levels above the action level. Measurable Pb was present in 34 (22.5%) of the 7th liter samples, but none had Pb >15 µg/L.

Table 2. Measurable Pb Concentrations by County for 1st and 7th liters.

	Samples with detectable Pb (n)	Pb Concentration (µg/L) Minimum Detectable	Maximum	Median	IQR
1st Liter					
Jackson(n=38)	20	0.83	76.2	0.85	1.62
Kane(n=62)	27	0.83	47.0	0.54	1.62
Peoria(n=51)	26	0.79	15.4	0.79	1.12
All (n=151)	51	0.79	76.2	0.54	1.60
7th Liter					
Jackson(n=38)	11	0.89	3.93	0.54	0.46
Kane(n=62)	8	0.86	3.37	0.54	0
Peoria(n=51)	15	0.77	5.00	0.54	0.37
All (n=151)	34	0.77	5.00	0.54	0

** interquartile range IQR is the measure of the spread of the middling values of the data*

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Table 3 shows housing age and presence of detectable Pb. Though a majority of the houses that had Pb present were built prior to 1980. There were homes that were built after 1980 with detectable Pb(27.9% of Pb containing samples). However, out of the homes surveyed, a majority of the Pre-1950 and 1970-1979 water samples contained Pb.

Table 3. Housing Age and Detectable Pb.

Year House Built	Measurable Pb n (%)	Undetectable Pb n (%)	Total n
Pre-1950	10(71.4)	4(28.6)	14
1950-1969	15(50.0)	15(50.0)	30
1970-1979	24(63.2)	14(36.8)	38
1980 to Present	19(31.7)	41(68.3)	60

Table 4 shows results from 150 households that returned the questionnaire (99.3% response rate). From the questionnaire, several questions detailed participant water usage, treatment equipment, and perceptions of water safety. Most respondents either strongly agreed or somewhat agreed that tap water is safe to drink (75.7%) and the vast majority were not concerned about Pb in water (76.8%). Of the participants who answered the question about the primary water source at home, 31.5% used tap water that was not treated with any device. The only item with significant differences across groups was "Amount spent on Well Upkeep Annually," where a higher percentage of those with detectable Pb (14.3%) spent greater than $100 per year on well upkeep than those with no detectable Pb (3.9%) (odds ratio 0.25 (95% CI 0.04-1.02).

Table 4. Water Perception and Use Between Measurable and Undetectable Pb Groups.

Question/Answer	Measurable Pb n (%)	Undetectable Pb n (%)	Total n (%)
Amount Spent on Well Upkeep Annually (n=146)			
< $100	60 (85.7)	73 (96.1)	133 (91.1)
> $100	10 (14.3)	3 (3.9)	13 (8.9)
*p=0.028**			
My tap water is safe to drink (n=148)			
Strongly agree	32 (45.7)	41 (52.6)	73 (49.3)
Agree somewhat	23 (32.9)	16 (20.5)	39 (26.4)
Neither agree nor disagree	10 (14.3)	10 (12.8)	20 (13.5)
Disagree somewhat	4 (5.7)	8 (10.3)	12 (8.1)
Disagree strongly	1 (1.4)	3 (3.8)	4 (2.70)
p=0.370			
Concern about lead in well water after learning about the Flint water crisis (n=138)			
Yes	18 (26.9)	14(19.7)	32 (23.2)
p=0.320			
Primary source of water (n=149)			
Tap Water	25 (35.2)	22 (28.2)	47 (31.5)
Bottled Water	21 (29.6)	20 (25.6)	41 (27.5)
Treated Tap Water	15 (21.1)	26 (33.3)	41 (27.5)
Multiple Sources	3 (4.2)	1 (1.3)	4 (2.7)

Other	7 (9.9)	9 (11.5)	16 (10.7)
p=0.393			
Water Treatment devices (point of use or point of entry) (n=106)			
Reverse osmosis	8 (17.4)	12 (20.0)	20 (18.9)
Ultraviolet light system	0 (0)	1 (1.7)	1 (0.9)
Water Softener	30 (65.2)	37 (61.7)	67 (63.2)
Multiple Devices	8 (17.4)	10 (16.7)	18 (17.0)
p=0.820			
Amount of Tap Water Consumed Daily by Drinking (n=149)			
1-3 cups	12 (16.9)	9 (11.5)	21 (14.1)
4-7 cups	23 (32.4)	26 (33.3)	49 (32.9)
8 or more cups	23 (32.4)	27 (34.6)	50 (33.6)
None	13 (18.3)	16 (20.5)	29 (19.5)
p=0.822			
Cooking Water Source (n=148)			
Unfiltered tap water	46 (64.8)	47 (61.0)	93 (62.8)
Filtered tap water	5 (7.0)	6 (4.11)	11 (7.4)
Bottled water	4 (5.6)	2 (1.0)	6 (4.1)
Other	16 (22.5)	22 (14.99)	38 (25.7)
p=0.688			

Chi-squared test used to calculate p-values. * denotes significance at the $p<0.05$ level.

Using deciles of 1^{st} liter Pb concentration, we estimated the WLL effect on geometric mean (GM) of BLLs among children aged 6 months to 7 years who are served by a PDW (Table 4). The difference in BLL between those with a 90^{th} percentile value and a 10^{th} percentile

value in water lead level was estimated to be 0.4 µg/dL. Children 0.5 to 2 years of age have the highest simulated GM BLLs. For children in that age category, a difference in estimated BLL for those in the 90^{th} and the 10^{th} percentile was 0.37 µg/dL.

Table 5. IEUBK Modeled BLLs by age group.

WLL μg/L (WLL percentile)	**BLL in μg/dL by Age Group in Years**						
	0.5-1	**1-2**	**2-3**	**3-4**	**4-5**	**5-6**	**6-7**
0.54 (10-50th)	3.0	3.0	2.4	2.1	2.1	1.9	1.7
1.07 (60th)	3.0	3.0	2.4	2.1	2.1	1.9	1.8
1.65 (70th)	3.1	3.1	2.5	2.2	2.1	2.0	1.8
2.50 (80th)	3.2	3.1	2.5	2.3	2.2	2.0	1.9
4.88 (90th)	3.4	3.3	2.7	2.5	2.4	2.2	2.1

The IEUBK probability distributions from the deciles can be seen in **Figure 1**. The cutoff point was set at 3.5 μg/dL, the current CDC reference level for BLLs, with acknowledgement that no Pb level is thought to be entirely safe.[37] Based on the cutoff, the percentage of children above this point can be estimated from all Pb sources in the model. As water WLL inputs increased from 0.54 μg/L to 4.98 μg/L, the probability of a child having a IEUBK estimated BLL above 3.5 μg/dL increased from 18.0 to 27.4%.

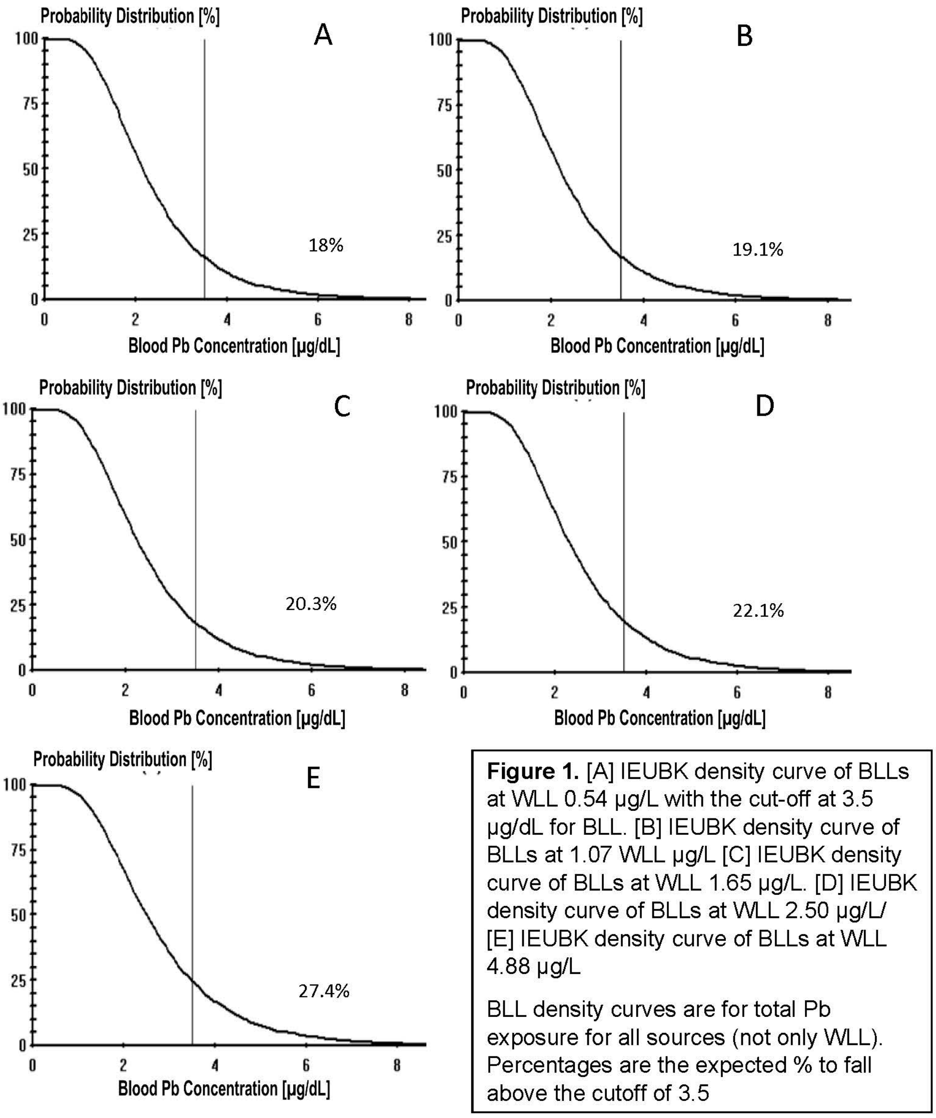

Figure 1. [A] IEUBK density curve of BLLs at WLL 0.54 μg/L with the cut-off at 3.5 μg/dL for BLL. [B] IEUBK density curve of BLLs at 1.07 WLL μg/L [C] IEUBK density curve of BLLs at WLL 1.65 μg/L. [D] IEUBK density curve of BLLs at WLL 2.50 μg/L/ [E] IEUBK density curve of BLLs at WLL 4.88 μg/L

BLL density curves are for total Pb exposure for all sources (not only WLL). Percentages are the expected % to fall above the cutoff of 3.5

Figure 1. [A] IEUBK density curve of BLLs at WLL 0.54 μg/L with the cut-off at 3.5 μg/dL for BLL. [B] IEUBK density curve of BLLs at 1.07 WLL μg/L. [C] IEUBK density curve of BLLs at WLL 1.65

µg/L. [D] IEUBK density curve of BLLs at WLL 2.50 µg/L. [E] IEUBK density curve of BLLs at WLL 4.88 µg/L. BLL density curves are for total Pb exposure for all sources (not only WLL). Percentages are the expected % to fall above the cutoff of 3.5.

4. Discussion

This study highlights the risks of Pb exposure among children living in homes with PDWs. Participants reported that 31.5% relied on tap water without any filtration treatment as their source of drinking water, and 62.8% used untreated tap water for cooking. Children who drink untreated tap water or infants who have formula prepared using it are at risk of Pb exposure. Although the observed 90th percentile WLL water lead level was below the EPA community system action level of 15 µg/L, modeled BLLs indicate that children consuming tap water at the 90th percentile value would have BLLs approximately 0.3-0.4 µg/dL greater than those who consume tap water with Pb level at the 10th percentile value. This highlights the fact that even WLLs below 15 µg/L have the potential to elevate BLLs, which would be expected to impair neurodevelopment. The EPA action level is not a health-based standard.

During the COVID-19 pandemic rural children in Illinois experience a 26.9% decrease in BLL testing.[38]Prior to the pandemic, it had already been seen in South Carolina that rural children are at risk of elevated BLLs and that BLLs increased from ages <1 to 2 years of age when screened.[39] With the reduction in testing seen in Illinois, more children may be at risk of having elevated BLLs which have not been discovered due missing one or both of the typically screenings.

Other studies have used IEUBK to model BLLs based on water Pb intake. However, inputs for other Pb exposure sources for the IEUBK model vary. A previous study has used default inputs for other exposures and only alter the WLL category, like the method for the current study.[40,41] Deshommes et al. (2013) estimated BLLs in children in relation to WLL in homes with Pb service lines using IEUBK.[42] In that study, WLLs were measured, and model inputs for other Pb sources were either default IEUBK values, Health Canada values, or values from other studies. To confirm the accuracy of the IEUBK models, simulated BLLs were compared to available BLLs from Montreal children from homes with and without Pb service lines. IEUBK estimates were found to be consistent with actual BLLs. For our study, however, BLLs were not measured. Thus, our modeled BLLs could be over- or under-estimates.

Several studies have used Stochastic Human Exposure and Dose Simulation (SHEDs) which is based on a probabilistic Monte Carlo exposure. This method considers how likely the source is to be the main exposure pathway and helps create a better estimate of metabolizing Pb. These exposure values are then used in the IEUBK parameters to model GM BLLs from varying WLL exposures.[43,44] The SHEDs-IEUBK model allows for greater specificity when modeling GM BLLs by predicting the dominant route of exposure and simulating the resulting BLL based on that particular exposure route. With the correct medium of exposure identified, IEUBK-modeled BLLs closely resemble the BLLs seen in geographic areas available through NHANES data[42]. Zartarian et al. (2017) suggested that SHEDs IEUBK models should be used when determining costs and benefits of interventions to mitigate Pb. Since the IEUBK models simulated for this study do not take into account other source and pathways of Pb exposure such as paint Pb, we may be over- or under-estimating the contribution of water Pb to BLLs.

This study has several strengths. One of these strengths was participant compliance with instructions. This metric can be seen in the fact that participants overwhelmingly completed the study questionnaire with a 99.3% response rate. Another strength is the ability to compare people's self-reported perceptions of their water safety to the actual WLL in their homes. Another strength is that through IEUBK software, changes in WLLs below the limits set by the Lead and Copper rule were able to be related to the percentage of children whose simulated BLLs would fall above 3.5 µg/dL limit. This study was able to estimate that 18% of children will have BLLs above the reference value at Pb levels at the 50th percentile for 1st liter water samples collected during the study. Also, since participants were able to have health department staff members deliver their kits and demonstrate in their homes sampling methods and samples were returned through shipping, participants in remote rural areas of the counties were able to participate in the study. Particularly, participants who may not have other health services near them were able to provide water samples, which may help capture risk to children living in remote rural areas. It also may capture children who may have missed BLLs at 1 and 2 years of age.

Despite these strengths, this study has several limitations. Even with site specific modeling, IEUBK is only an estimate of BLLs. BLLs in combination with Pb levels in paint, dust, and soil, which are known to be the most common exposure sources, would provide the best analysis of risk. Without this data we are only able to estimate the effect water levels could have on overall change in BLL and not direct effects. Another limitation of our study is sample size. With only 151 homes in 3 counties, our findings are not representative of these counties or of the state of Illinois. For example, Peoria County has approximately 18,000 PDWs in total, of which we sampled 52. This small sample size combined with the fact that nearly half of the houses were built after 1980 may have not captured the true risk of Pb in PDWs in these three counties. Filtration systems also may impact the Pb levels, however; we did not collect samples which both included filtration and ones that bypassed filtration. Where the source of Pb in these water systems is not known. It could be from the home's plumbing, the well, or from other parts of the water system.

Future studies of WLLs should include BLLs and other common Pb exposures to accurately assess the risk of Pb in PDWs. As seen in other studies, when more site-specific data or population-specific data are included, IEUBK modeling can be adjusted to provide more accurate BLLs resulting from specific exposures. Since the default IEUBK inputs are from superfund sites, the true Pb levels in homes from various sources may have smaller or larger impacts on overall BLLs based on age of housing, presence of Pb paint, and other exposure factors across environmental media on average. Future studies should work to confirm accuracy of IEUBK simulation of BLLs for homes on PDWs with increased sample size and more detailed Pb data for other environmental media. Another consideration is that the source of the Pb is not known. Future studies should involve measuring Pb directly from PDWs and from taps to determine whether the well components or the plumbing is driving WLLs seen in homes, especially since several homes in this study that were built post 1980 had measurable WLLs. The effectiveness of Pb filtration systems should also be considered when taking future water samples.

5. Conclusions

The findings suggest that children who consume well water containing measurable Pb levels likely experience increased BLLs. The Lead and Copper Rule does not require owners of PDWs to test their drinking water for Pb. Since PDWs are mostly in less dense population areas, children living in the rural United States are particularly at risk of having elevated BLLs due to Pb expose in well water. Policies to encourage and financially support testing of tap water in homes with PDWs are needed. Priority should be given to those homes in which children and women of childbearing age reside or are expected to reside, as well as homes built before 1986. Mitigation of Pb in water from PDWs should be adequately funded. Based on our simulation, changes in WLL that remain below the EPA action level for community water systems are associated with increases in BLLs among young children. Children should not be exposed to Pb in drinking water due to the known effects on neurodevelopment at any level.

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D Geiger; Resources, Walton Kelly; Writing – original draft, Sarah Keeley and Sarah D Geiger; Writing – review & editing, Sarah Keeley, Samuel Dorevitch, Walton Kelly, David E Jacobs and Sarah D Geiger; Supervision, , Samuel Dorevitch and Sarah D Geiger; Project administration, , Samuel Dorevitch and Sarah D Geiger. All authors have read and agreed to the published version of the manuscript.

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References

1. Liu J, Li L, Wang Y, Yan C, Liu X. Impact of Low Blood Lead Concentrations on IQ and School Performance in Chinese Children. Sun Q, ed. *PLoS ONE*. 2013;8(5):e65230. doi:10.1371/journal.pone.0065230
2. Liu J, Liu X, Wang W, et al. Blood Lead Concentrations and Children's Behavioral and Emotional Problems: A Cohort Study. *JAMA Pediatr*. 2014;168(8):737. doi:10.1001/jamapediatrics.2014.332
3. NTP monograph on health effects of low-level lead. *NTP Monogr*. 2012;(1):xiii, xv-148.
4. Min JY, Min KB, Cho SI, Kim R, Sakong J, Paek D. Neurobehavioral function in children with low blood lead concentrations. *NeuroToxicology*. 2007;28(2):421-425. doi:10.1016/j.neuro.2006.03.007
5. Mason LH, Harp JP, Han DY. Pb Neurotoxicity: Neuropsychological Effects of Lead Toxicity. *BioMed Research International*. 2014;2014:1-8. doi:10.1155/2014/840547
6. Gleason KM, Valeri L, Shankar AH, et al. Stunting is associated with blood lead concentration among Bangladeshi children aged 2-3 years. *Environ Health*. 2016;15(1):103. doi:10.1186/s12940-016-0190-4
7. Levallois P, St-Laurent J, Gauvin D, et al. The impact of drinking water, indoor dust and paint on blood lead levels of children aged 1–5 years in Montréal (Québec, Canada). *J Expo Sci Environ Epidemiol*. 2014;24(2):185-191. doi:10.1038/jes.2012.129
8. Kennedy C, Yard E, Dignam T, et al. Blood Lead Levels Among Children Aged <6 Years — Flint, Michigan, 2013–2016. *MMWR Morb Mortal Wkly Rep*. 2016;65(25):650-654. doi:10.15585/mmwr.mm6525e1
9. U.S. EPA. Basic Information About Lead in Drinking Water. Published online January 27, 2023. https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water
10. US EPA. Lead and Copper Rule. Published November 28, 2023. Accessed February 16, 2024. https://www.epa.gov/dwreginfo/lead-and-copper-rule
11. Rhode Island Department of State. Private Drinking water systems (216-RICR-50-05-2.12). Accessed November 21, 2023. https://casetext.com/regulation/rhode-island-administrative-code/title-216-department-of-health/chapter-50-environmental-health/subchapter-05-water-quality/part-2-private-drinking-water-systems-216-ricr-50-05-2/section-216-ricr-50-05-212-mandatory-testing-requirements-for-private-water-supplies
12. Gibson JM, Fisher M, Clonch A, MacDonald JM, Cook PJ. Children drinking private well water have higher blood lead than those with city water. *Proc Natl Acad Sci USA*. 2020;117(29):16898-16907. doi:10.1073/pnas.2002729117
13. U.S. Census Bureau. American Housing Survey (AHS)—AHS Table Creator. Accessed April 6, 2022. https://www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html?s_areas=00000&s_year=2019&s_tablename=TABLE4&s_bygroup1=1&s_bygroup2=1&s_filtergroup1=1&s_filtergroup2=1&s_show=SO
14. Dieter CA, Maupin MA, Caldwell RR, et al. *Estimated Use of Water in the United States in 2015.*; 2018:76. doi:10.3133/cir1441
15. Johnson TD, Belitz K, Lombard MA. Estimating domestic well locations and populations served in the contiguous U.S. for years 2000 and 2010. *Science of The Total Environment*. 2019;687:1261-1273. doi:10.1016/j.scitotenv.2019.06.036
16. Kamai EM, Daniels JL, Delamater PL, Lanphear BP, MacDonald Gibson J, Richardson DB. Patterns of Children's Blood Lead Screening and Blood Lead Levels in North Carolina, 2011–2018—Who Is Tested, Who Is Missed? *Environ Health Perspect*. 2022;130(6):067002. doi:10.1289/EHP10335
17. Deshommes E, Laroche L, Nour S, Cartier C, Prévost M. Source and occurrence of particulate lead in tap water. *Water Research*. 2010;44(12):3734-3744. doi:10.1016/j.watres.2010.04.019

18. Hou S, Yuan L, Jin P, et al. A clinical study of the effects of lead poisoning on the intelligence and neurobehavioral abilities of children. *Theor Biol Med Model*. 2013;10(1):13. doi:10.1186/1742-4682-10-13
19. Needleman HL, Gunnoe C, Leviton A, et al. Deficits in Psychologic and Classroom Performance of Children with Elevated Dentine Lead Levels. *N Engl J Med*. 1979;300(13):689-695. doi:10.1056/NEJM197903293001301
20. Miranda ML, Kim D, Galeano MAO, Paul CJ, Hull AP, Morgan SP. The Relationship between Early Childhood Blood Lead Levels and Performance on End-of-Grade Tests. *Environ Health Perspect*. 2007;115(8):1242-1247. doi:10.1289/ehp.9994
21. Nicolescu R, Petcu C, Cordeanu A, et al. Environmental exposure to lead, but not other neurotoxic metals, relates to core elements of ADHD in Romanian children: Performance and questionnaire data☆, ☆☆☆Study approval: This study has been reviewed and approved by the Ethics Committee of the "Romanian College of Physicians". *Environmental Research*. 2010;110(5):476-483. doi:10.1016/j.envres.2010.04.002
22. Needleman HL, Schell A, Bellinger D, Leviton A, Allred EN. The Long-Term Effects of Exposure to Low Doses of Lead in Childhood: An 11-Year Follow-up Report. *N Engl J Med*. 1990;322(2):83-88. doi:10.1056/NEJM199001113220203
23. Needleman HL. Lead at low dose and the behavior of children. *Acta Psychiatr Scand*. 1983;67(s303):26-37. doi:10.1111/j.1600-0447.1983.tb00939.x
24. Needleman HL, McFarland C, Ness RB, Fienberg SE, Tobin MJ. Bone lead levels in adjudicated delinquents: A case control study. *Neurotoxicology and Teratology*. 2002;24(6):711-717. doi:10.1016/S0892-0362(02)00269-6
25. Jakubowski M. Low-level environmental lead exposure and intellectual impairment in children — The current concepts of risk assessment. *International Journal of Occupational Medicine and Environmental Health*. 2011;24(1):1-7. doi:10.2478/s13382-011-0009-z
26. Long AS, Hanlon AL, Pellegrin KL. Socioeconomic variables explain rural disparities in US mortality rates: Implications for rural health research and policy. *SSM - Population Health*. 2018;6:72-74. doi:10.1016/j.ssmph.2018.08.009
27. Geiger SD, Bressler J, Kelly W, et al. Predictors of Water Lead Levels in Drinking Water of Homes With Domestic Wells in 3 Illinois Counties. *Journal of Public Health Management and Practice*. Published online November 27, 2020. doi:10.1097/PHH.0000000000001255
28. US EPA R 08. Lead and Copper - Suggested Directions for Homeowner Tap Sample Collection Procedures. Published May 29, 2019. Accessed July 10, 2023. https://www.epa.gov/region8-waterops/lead-and-copper-suggested-directions-homeowner-tap-sample-collection-procedures
29. Erinosho TO, Pinard CA, Nebeling LC, et al. Development and Implementation of the National Cancer Institute's Food Attitudes and Behaviors Survey to Assess Correlates of Fruit and Vegetable Intake in Adults. Rezzani R, ed. *PLoS ONE*. 2015;10(2):e0115017. doi:10.1371/journal.pone.0115017
30. Hargrove W, Juárez-Carillo P, Korc M. Healthy Vinton: A Health Impact Assessment Focused on Water and Sanitation in a Small Rural Town on the U.S.-Mexico Border. *IJERPH*. 2015;12(4):3864-3888. doi:10.3390/ijerph120403864
31. Jones AQ, Dewey CE, Doré K, et al. Public perceptions of drinking water: a postal survey of residents with private water supplies. *BMC Public Health*. 2006;6(1):94. doi:10.1186/1471-2458-6-94
32. McLeod L, Bharadwaj L, Waldner C. Risk Factors Associated with the Choice to Drink Bottled Water and Tap Water in Rural Saskatchewan. *IJERPH*. 2014;11(2):1626-1646. doi:10.3390/ijerph110201626
33. Merkel L, Bicking C, Sekhar D. Parents' Perceptions of Water Safety and Quality. *J Community Health*. 2012;37(1):195-201. doi:10.1007/s10900-011-9436-9
34. Onufrak SJ, Park S, Sharkey JR, Sherry B. The relationship of perceptions of tap water safety with intake of sugar-sweetened beverages and plain water among US adults. *Public Health Nutr*. 2014;17(1):179-185. doi:10.1017/S1368980012004600
35. U.S. Census Bureau. American Community Survey (ACS). Accessed December 18, 2021. https://www.census.gov/programs-surveys/acs
36. U.S. EPA. Lead at superfund sites: software and users' manuals for IEUBK model. Retrieved December 18, 2021, from U. S. EPA. (2021) Lead at superfund sites: software and users' manuals for IEUBK model. Accessed December 8, 2021. https://www.epa.gov/superfund/lead-superfund-sites-software-and-users-manuals
37. U.S. CDC. Blood Lead Reference Value | Lead | CDC. Published online December 2, 2022. https://www.cdc.gov/nceh/lead/data/blood-lead-reference-value.htm
38. Fokum FD, Entezar T, McAfee K. Effect of the COVID-19 Global Pandemic on Illinois Children Tested for Blood Lead Level and Exposure. *Am J Public Health*. 2023;113(1):89-95. doi:10.2105/AJPH.2022.307109
39. Aelion CM, Davis HT. Blood lead levels in children in urban and rural areas: Using multilevel modeling to investigate impacts of gender, race, poverty, and the environment. *Science of The Total Environment*. 2019;694:133783. doi:10.1016/j.scitotenv.2019.133783
40. Akers DB, MacCarthy MF, Cunningham JA, Annis J, Mihelcic JR. Lead (Pb) Contamination of Self-Supply Groundwater Systems in Coastal Madagascar and Predictions of Blood Lead Levels in Exposed Children. *Environ Sci Technol*. 2015;49(5):2685-2693. doi:10.1021/es504517r
41. Jarvis P, Quy K, Macadam J, Edwards M, Smith M. Intake of lead (Pb) from tap water of homes with leaded and low lead plumbing systems. *Science of The Total Environment*. 2018;644:1346-1356. doi:10.1016/j.scitotenv.2018.07.064
42. Deshommes E, Prévost M, Levallois P, Lemieux F, Nour S. Application of lead monitoring results to predict 0–7 year old children's exposure at the tap. *Water Research*. 2013;47(7):2409-2420. doi:10.1016/j.watres.2013.02.010

43. Zartarian V, Xue J, Tornero-Velez R, Brown J. Children's Lead Exposure: A Multimedia Modeling Analysis to Guide Public Health Decision-Making. *Environ Health Perspect*. 2017;125(9):097009. doi:10.1289/EHP1605
44. Stanek LW, Xue J, Lay CR, et al. Modeled Impacts of Drinking Water Pb Reduction Scenarios on Children's Exposures and Blood Lead Levels. *Environ Sci Technol*. 2020;54(15):9474-9482. doi:10.1021/acs.est.0c00479