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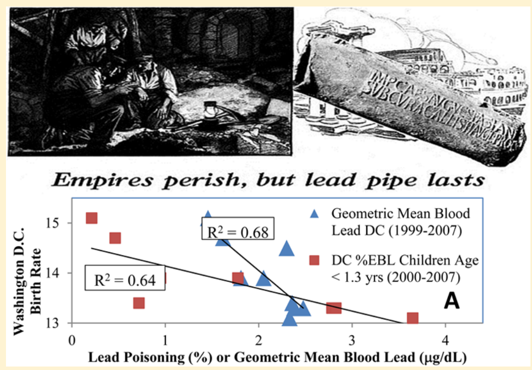
Fetal Death and Reduced Birth Rates Associated with Exposure to Lead-Contaminated Drinking Water

Marc Edwards*

Civil and Environmental Engineering Department, Virginia Polytechnic Institute and State University, 418 Durham Hall, Blacksburg, Virginia 24061, United States

Supporting Information

ABSTRACT: This ecologic study notes that fetal death rates (FDR) during the Washington DC drinking water "lead crisis" (2000−2004) peaked in 2001 when water lead levels (WLLs) were highest, and were minimized in 2004 after public health interventions were implemented to protect pregnant women. Changes in the DC FDR vs neighboring Baltimore City were correlated to DC WLL (R^2 = 0.72). Birth rates in DC also increased versus Baltimore City and versus the United States in 2004−2006, when consumers were protected from high WLLs. The increased births in DC neighborhoods comparing 2004 versus 2001 was correlated to the incidence of lead pipes (R^2 = 0.60). DC birth rates from 1999 to 2007 correlated with proxies for maternal blood lead including the geometric mean blood lead in DC children (R^2 = 0.68) and the incidence of lead poisoning in children under age 1.3 years (R^2 = 0.64). After public health protections were removed in 2006, DC FDR spiked in 2007−2009 versus 2004−2006 ($p < 0.05$), in a manner consistent with high WLL health risks to consumers arising from partial lead service line replacements, and DC FDR dropped to historically low levels in 2010−2011 after consumers were protected and the PSLR program was terminated. Re-evaluation of a historic construction-related miscarriage cluster in the USA Today Building (1987−1988), demonstrates that high WLLs from disturbed plumbing were a possible cause. Overall results are consistent with prior research linking increased lead exposure to higher incidence of miscarriages and fetal death, even at blood lead elevations (≈5 μg/dL) once considered relatively low.



INTRODUCTION

The Washington DC (DC) "lead in drinking water crisis" caused an increased incidence of elevated blood lead (EBL) in children at thresholds >5 μg/dL and also >10 μg/dL.[1−3] The "lead crisis" was inadvertently triggered in 2000 by a switch in drinking water disinfectant from chlorine to chloramine (Table 1) to reduce regulated disinfection byproducts, but the switch also caused an unintended release of lead from plumbing materials to drinking water.[1−6] Consumers had no warning of high water lead levels (WLLs) until late-2002, and the true extent of the hazard was not publicly revealed until a front page investigative Washington Post report in January 2004.[2,7] Unprecedented interventions by the DC Department of Health (DC DOH) were then implemented to protect the general public and especially sensitive populations of pregnant women including written and broadcast (radio, television) alerts to avoid tap water, use utility provided water lead filters or enhanced flushing of pipes.[1,4,7,8] These interventions dramatically reduced the incidence of childhood lead poisoning (i.e., blood lead >10 μg/dL for children under age 6) in DC from 2004 onward.[2]

Exposure to lead has been associated with spontaneous abortion, stillbirth and high rates of infant mortality.[9,10] Lead abortion pills with 32 μg lead each (256 μg Pb per day for the recommended dose of 8 pills) were used in the early 1900s, and use of new lead pipe in potable water systems for cities without corrosion control increased fetal mortality 300−400%.[9,10] On this basis a significant elevation in miscarriage and fetal death rates would be predicted in Washington, DC from late 2000 through 2003. For instance, analysis of thousands of samples collected by the District of Columbia Water and Sewer Authority (DC WASA) in 2003 from homes with lead pipe, revealed median daily consumer exposure of 70 μg Pb/day assuming 2 L tap water exposure per day from a 50:50 mixture of first draw:flushed water. The same type of analysis indicates that greater than 15% of these consumers had daily exposure exceeding that from 1900s lead abortion pills (256 μg Pb/day).[2,9,10] The presumed historical success of the lead abortion pills via acute lead exposure, highlights concerns about adverse pregnancy outcomes from short-term exposure of pregnant women in Washington, DC to elevated WLLs.

More recent research demonstrated that every 5 μg/dL increase in maternal blood lead resulted in a 180% increased

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Table 1. Demarcation of Washington DC Lead in Water Risks into Calendar Years for Consideration of Impacts on Fetal Death, Birth Rates and General Fertility

calendar year time period	consumer risk to elevated lead in water
1997−1999	**low.** low water lead when chlorine was disinfectant.
2000	**uncertain.** chloramine only dosed part of the year and no lead in water samples were taken during that time.
2001−2002	**highest.** very high lead in water and no public information of health risks until 10/2002.
2003	**high.** high lead in water and ineffective public education from 10/2002 to late 2003.
2004−2006	**low.** high lead in water, but intense public education, congressional intervention, provision of lead filters and enhanced flushing instructions protected population.
2007−2009	low general lead in water risks due to corrosion control, but high PSLR activity and removal of public health protections created **very high risk in PSLR**[a] homes.
2010−2011	**very low.** low water lead due to corrosion control, low risks in PSLR homes due to CDC health advisory issued 1/2010 and provision of lead filters.

[a]PSLR= partial service line replacement.

risk of miscarriage (defined herein as death of an embryo from pregnancy up to 20 weeks gestation).[11,12] While statistically robust records of maternal blood lead in DC are not available for analysis, it is likely that the increased incidence of childhood blood lead over thresholds of 5 and 10 μg/L (lead poisoning)[1−3] during the lead crisis is a reasonable proxy for trends in maternal blood lead, for which each 10 μg/dL increase would raise miscarriage rates by about 360%.[11,12]

While problems with elevated WLLs throughout DC were largely controlled after 2006 by dosing of an orthophosphate lead corrosion inhibitor (Table 1), more than 13 000 homes where lead pipes were disturbed had unusually high risk of elevated WLLs from 2004 to 2011.[3,7,8,13−15] Specifically, after the water utility cut lead service pipes to implement partial service line replacements (PSLR) under mandates of the U.S. Environmental Protection Agency (EPA) Lead and Copper Rule or through their own voluntary program from mid-2006 to 2009, consumer collected water samples often contained over 100 μg/L and as much as 190 000 μg/L lead.[8,13,14] The WLL remains elevated in the PSLR homes for a few months or years after cutting the pipe.[16] Although the Centers for Disease Control (CDC) identified increased risk of childhood lead poisoning risk incidence in DC PSLR homes in late 2007, the public was unaware of any problem until a Washington Post article in 2008, which revealed the serious spikes in WLLs and the utility began to scale back the PSLR program.[7,8,14] But consumers were not adequately protected from high WLLs until the CDC issued a public health advisory regarding an increased incidence of childhood lead poisoning in PSLR homes in January 2010, the utility provided consumers water lead filters, and the health risks were reinforced by congressional hearings and extensive media coverage (Table 1).[14,15,17] CDC eventually reported 330% increased incidence of childhood lead poisoning in PSLR homes versus DC homes without lead pipe.[3]

This research examines whether expectations of adverse pregnancy outcomes are evident in fetal death and birth rate data for Washington, DC from 2001 to 2003 when WLLs were elevated throughout the city and consumers were unprotected, and if there are also links between fetal death rates and PSLR activities from 2007 to 2009 before public health interventions protected the public from high WLLs (Table 1). To enhance the analysis, a general approach used in prior studies of infant mortality due to arsenic exposure in Chile drinking water was followed,[18] by comparing Washington, DC to neighboring Baltimore City, MD which had relatively low WLLs from 1997 to 2011. Baltimore City has a number of similarities to Washington, DC.(Table 2) and both cities are part of the same combined statistical area (CSA) census department designation due to social and economic ties, as well as geographical proximity.[19,20] The comparison to Baltimore City can eliminate many localized confounding factors that could impact comparisons between Washington, DC and the United States. A final phase of research applies an evolving understanding of consumer lead exposure that arises from disturbed lead plumbing, to a historic 1987−1988 Washington, DC area "USA Today Building" miscarriage cluster, where very high WLLs and proximity to renovation disturbances were initially implicated as a causal factor.[21−26]

Table 2. Representative Demographic Data for Washington DC, Baltimore City and the United States

parameter	Washington, DC	Baltimore City	United States
population	601 723	620 961	308 700 000
average family size	3.15	3.14	3.14
median household income ($)	61 835	40 00	52 762
% population in poverty	18.2	22.4	14.3
% population African American	50.7	63.7	12.6
% population women age 15−44	27.0	23.4	20.2
total housing units	296 719	296 685	131 034 946
%Pop <9th grade education	5.0	6.6	6.1

MATERIALS AND METHODS

WLL and PLSR Replacement Data. DC WLL samples collected for EPA compliance monitoring (1997−2011) were organized into calendar year time periods,[2,6] for which corresponding incidence of fetal death, live birth and other data were also compiled (Table 3). The 90th percentile (90th %) water DC WLL data from 1997 to 2000 were derived from a U.S. EPA report,[6] data from 2001 to 2007 were derived from Edwards et al.,[2] and data for 2008−2011 were obtained from DC WASA consumer confidence reports.[27] Since chloramine was only dosed in part of 2000, and no WLL data were collected for that time period (and the data were subject to revision and controversy),[6] year 2000 data was excluded from any correlations between WLLs and adverse pregnancy outcomes. DC WASA provided data on PSLRs from 2003 to 2011 (Table 3) and incidence of lead pipes by neighborhood or ward.[28] Baltimore City WLL data were obtained from consumer confidence reports (2001 onward) and from the U.S. EPA before 2001 (1997−2001).[29,30]

Blood Lead Trends for Washington, DC, Baltimore City, and the United States. Washington, DC blood leads were derived from prior published independent data due to acknowledged problems with the CDC data set and DC DOH reporting.[2,7,31] Baltimore City and U.S. data on incidence of childhood lead poisoning were compiled from Baltimore City Health Department records or CDC's lead surveillance data.[32−34]

Fetal Deaths and Live Births. Data for miscarriages <20 weeks gestation are not systematically compiled and reported in

Table 3. Lead in Water, Incidence of Elevated Blood Lead (EBL), Fetal Death Rate (FDR), Birth Rate, General Fertility Rate (GFR),@ and Partial Service Line Replacements (PSLR) in Washington D.C (DC), Baltimore City (BC) and the United States (U.S.)

	Washington, DC							Baltimore City, MD					United States			
year	DC 90th% Pb[a]	% EBL DC	% EBL DC Age <1.3 yr	PSLR	FDR DC	birth rate DC	GFR DC	BC 90th% Pb[b]	% EBL BC&	FDR BC	birth rate BC	GFR BC	% EBL U.S.&	FDR U.S.	birth rate U.S.	GFR U.S.
1997	7			na	9.7	15	61.6	13		17.1	14.1	60.0	7.6	6.8	14.2	63.6
1998	7			na	9.5	14.7	60.7	8		16.9	14.9	63.0	6.5	6.7	14.3	64.3
1999	12.5	5.5		na	7.9	14.5	59.9	10	16.7	16.9	15.4	66.0	5.0	6.7	14.2	64.4
2000	34	3.8	0.71	na	10.8	13.4	53.3	12	12.1	14	14.8	63.1	4.0	6.6	14.4	65.9
2001	79	3.2	2.78	na	12.9	13.3	52.9	11	9.5	15.2	14.1	60.7	3.0	6.5	14.1	65.1
2002	45	4.2	3.65	na	10.4	13.1	52.8	8	9.4	16.3	14.2	61.5	2.6	6.4	14	65.0
2003	51.5	3.9	2.82	373	8.9	13.3	55.1	10	6.4	13	14.4	63.0	2.3	6.3	14.1	66.1
2004	59	2.7	1.78	1745	7.1	13.9	58.3	11	6.2	13.1	14.4	64.6	1.8	6.3	14	66.4
2005	15	2.7	0.95	3210	8.2	13.9	58.4		4.8	13.3	14.4	65.1	1.5	6.2	14	66.7
2006	11	1.7	0.46	3312	7.5	14.7	58.4		4.3	11.4	15.5	69.3	1.2	6.1	14.3	68.6
2007	10.5	0.9	0.21	3430	9.9	15.1	60	7	3.4	10.9	15.5	68.8	0.9		14.3	69.3
2008	7			2442	10.1	15.4	61.4			10.3	15.6	69.5	0.7		14	68.1
2009	8			411	8.2	15.1	59.7	8		10.6	14.9	63.7	0.6		13.5	66.2
2010	5			229	7.4	15.2	56.4			10.9	14.4	61.2	0.6		13	64.1
2011	5			123	6.5	15	55.9	5[b]		10.9	14.3	61.6	0.6		12.7	63.2

[a]90th% EPA Lead and Copper Rule data adjusted to calendar year from prior work[2,6] except for 2000, a year in which chloramine was first dosed and also includes a sampling round where high lead samples were illegally invalidated. The U.S. EPA issued a revised calculation for July 2000-June 2001 of 34 ppb.[6] [b]Baltimore has been on reduced monitoring since 2004 and only samples for lead in water every 3 years. Data in Table for Baltimore City in year 2011, is that reported in the 2012 Consumer Confidence report, to indicate trends from 2009 to 2011. [c]Fetal death rates (FDR) per thousand births are calculated for DC and Baltimore City using a standard formula [FDR = (no. fetal deaths)/(live births + fetal deaths)] × 1000; birth rates are live births per thousand population, general fertility rate (GFR) is number of live births per thousand women aged 15−44.

the U.S., but total fetal deaths (over 20 weeks gestation) and live births for Washington, DC are compiled and reported annually by the DC DOH to Vitalstats Online.[35] Total fetal deaths (over 20 weeks) in Washington, DC reported and compiled by DC DOH, were taken from Vitalstats (1997−2005) and DC DOH reports (2003−2011).[35−37] Data on Washington, DC birth rates, general fertility rates, and births by ward (neighborhood) were obtained from DC DOH reports or Vitalstats.[35−38] Fetal death rates, birth rates and general fertility rates for Baltimore City 1997−2011 were obtained from annual Maryland Vital Statistics reports,[39] and similar data for the United States were obtained from National Vital Statistics reports when available.[35,40,41]

Effects of Renovation Activity on Lead Release from Soldered Plumbing. Trends in lead release to potable water occurring as a result of vibrations during renovations were investigated experimentally. Six 0.6 m long copper pipes (1.9 cm diameter) with a single central joint and a 6″ bead of 50:50 Pb:Sn solder were created and exposed to simulated source water for the USA Today building (synthesized Potomac River water).[2] The pipes were first conditioned in a continuous recirculation mode for 3 months using a 150 L reservoir to allow development of a lead corrosion product (rust) layer, that might be mobilized to water during physical disturbances.[42] Water in the reservoir was completely changed each month throughout the study. Thereafter, baseline lead release to the recirculating reservoir was quantified for each pipe after 1 month exposure, using a representative premise plumbing flow regime of 15 s flow every 8 h at 0.66 m/sec. The pipes were then gently placed directly on a concrete pad at distances of either 3 or 15.2 m from a conventional jackhammer, weighed down with 20 kg masses to hold the pipes firmly in place, and the jackhammer was operated 30 s to generate representative vibrations that arise during renovation. The pipes were then placed back into the recirculation reservoir which was sampled (as before) at 1 and 4 months after the vibration disturbance (months 2 and 3 were not sampled).

Statistical Methods and Error Bars. Correlations, statistical testing, and upper and lower confidence intervals were calculated using a standard Microsoft EXCEL 2010 program with an assumption that data were normally distributed. All error bars in graphs represent 95% confidence intervals.

■ RESULTS

After reviewing temporal trends in DC fetal death rates from 1997 to 2011 as a function of WLL risk (Table 1), a similar analysis was conducted for birth rates. Results of a simulation experiment quantifying trends in lead release to water from pipes disturbed during construction renovation are then described, providing a basis for reconsidering the possible role of elevated WLLs in the USA Today miscarriage cluster.

Changes in Fetal Death Rates: Washington, DC, 1997−2011. The 90th percentile WLL in DC (Table 3) spiked over 40 μg/L from 2001 to 2004 after the switch to chloramine disinfectant, with a peak WLL of 79 μg/L in calendar year 2001.[2] Prior work indicated that during 2001, incidence of childhood lead poisoning (blood lead >10 μg/dL) increased from 0.5% up to 4.8% for children less than 1.3 years of age.[2] The DC fetal death rates declined from 9.7 down to 7.9 per thousand births in the years 1997−1999 before chloramine was dosed to water (Table 3), but increased 32−63% when WLL was high in 2001 (Figure 1A). Fetal death rates remained high in 2002, and did not drop below those of 1999 until public health interventions in 2004 decisively limited exposure of pregnant women to high WLLs.[2,7] Applying a dummy variable of 90th% lead of 10 ppb to reflect lower exposure due to the consumer public health protections from 2004 to 2006,

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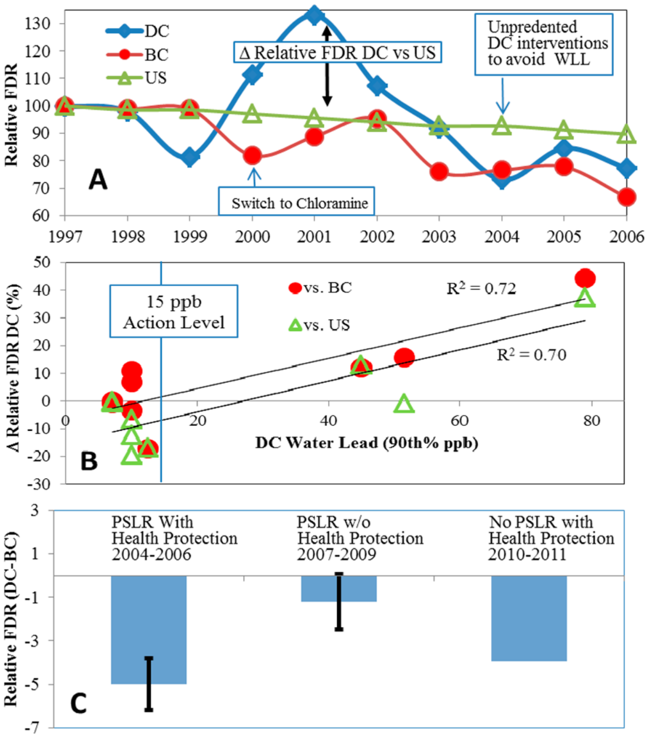

Figure 1. Relative fetal death rates (1997 = 100%) trended downward in the U.S. and in Baltimore City (BC) from 1997 to 2006, but exhibited a spike in DC around 2001 when lead in water was high (A). The change in relative fetal death rates (FDR) for DC versus BC or versus the U.S. was strongly correlated to water lead level (B; Figure excludes transition year of 2000). In years with partial lead service line replacements (PSLR) and no public health protections in 2007–2009, fetal death rates rose in DC to the point they were not statistically different from BC, before dropping back when PSLRs were discontinued and public health protections were offered residents in 2010–2011 (C).

indicates that higher WLL correlated to higher fetal death rates from 1997 to 2006 (R^2 = 0.60; data not shown excluding year 2000).

WLLs in Baltimore City (BC) declined steadily from 1997 to 2012 from 13 ppb down to 5 ppb (Table 3), along with incidence of childhood lead poisoning (16.7% in 2000 to 3.4% in 2011) and fetal death rates (17.1 down to 10.9 per thousand births). U.S. fetal death rates (6.8 to 6.1 per thousand births) and lead poisoning incidence (7.6 to 1.2%) also declined steadily from 1997 to 2006 (Table 3). After normalizing fetal death rates in DC, BC, and the U.S. by setting 1997 rates to 100% (Figure 1A), the 2000–2003 trend in DC is observed to be anomalously high. The higher rate of fetal deaths in DC versus either the U.S. or BC correlates (R^2 = 0.70–0.71) to the DC 90th% lead level (assuming 10 ppb lead as a dummy variable reflecting lower WLL exposure in 2004–2006 and excluding year 2000; Figure 1B). The correlation does not change significantly if years 2004–2006 are simply excluded from the analysis (R^2 = 0.70–0.72; data not shown). If the relative fetal death rate is calculated on an absolute rather than a percentage basis, a significant but somewhat lower correlation with DC 90th% WLL is observed (SI Figure 1; R^2 = 0.45 DC versus BC; R^2 = 0.68 DC vs U.S.). The correlation improves if years 2004–2006 are excluded from the analysis rather than using a dummy variable to reflect lower WLL exposure (R^2 = 0.62 DC versus BC; R^2 = 0.82 DC vs U.S.).

After DC experienced 3 years of relatively low fetal death rates (7.1–8.2 per thousand births) from 2004 to 2006 when the public health protections for high WLLs were in place (Table 1; Table 3), fetal death rates rose 21–42% to 9.9–10.1 per thousand births in 2007–2008 when risks of high WLLs in PSLR homes were highest and consumer public health protections were removed. DC fetal death rates declined smoothly from 2008 to 2011 as the PSLR program was phased out and public health protections were reinstituted in early 2010. During this same time period 2004–2011, fetal death rates declined or remained stable in BC. Analysis of relative fetal death rates confirm an adverse change in DC from 2007 to 2009, as DC fetal death rates rose to the point they were not statistically different from those in BC. DC fetal death rates are much lower than in BC in either 2004–2006 (p < 0.05) or in 2010–2011 when public health protections were in place (Figure 1C).

Changes in Birth and General Fertility Rates: Washington, DC, 1997–2006. Birth rates in DC decreased from 1997 to 1999 to 2001–2003 as WLLs rose during the lead crisis, and then increased by more than 0.6 births per thousand residents (p < 0.05) after public health protections were implemented from 2004 to 2006 (Table 3). Birth rates in DC continued to rise steadily from 2006 to 2009. Incidence of childhood lead poisoning and median child blood lead are possible proxies for trends in maternal blood lead (Table 3), and the DC birth rate was inversely correlated to both parameters (Figure 2A; R^2 = 0.64–0.68).

A neighborhood (ward) analysis indicated that the higher birth rates for 2004 vs 2001 in DC, were highly concentrated in the wards of the city with the highest incidence of lead pipe and WLL exposure. The presence of a lead service pipe increased

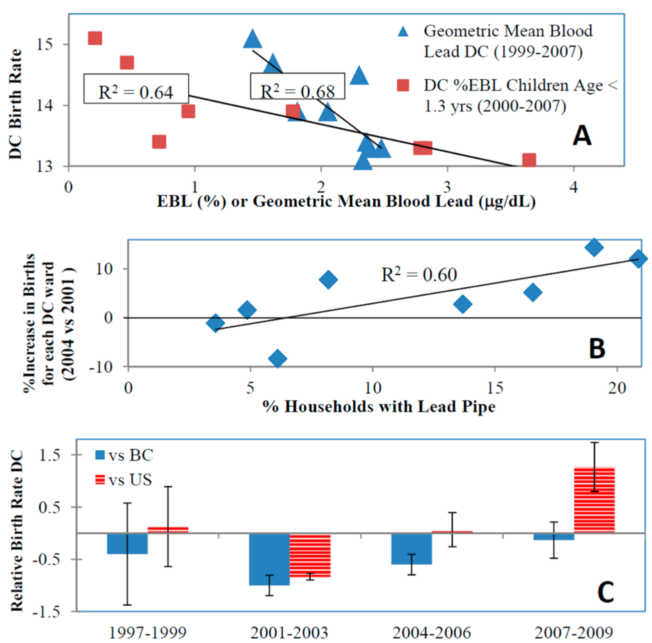

Figure 2. The birth rate in DC was inversely correlated with geometric mean blood lead and the percentage of children <1.3 years of age with blood lead over 10 μg/dL (A). Increased birth rates in each DC ward for 2004 versus 2001, was correlated to the percentage of lead pipes within each ward (B). Birth rates in Washington, DC relative to Baltimore City or the U.S., decreased during the lead crisis 2001–2003, and then increased in 2004–2006 when public health protections were implemented (C).

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the likelihood of high WLLs and incidence of childhood lead poisoning during the lead crisis.[1,3,6] Specifically, the two wards with greater than 19% incidence of lead pipe observed a greater than 12% increase in births for 2004 versus 2001, whereas the three wards with less than 6% incidence of lead pipe all had less than a 1.5% increase in births (or even declining birth rate) during the same time period (Figure 2B) . The percent increase in birth rate comparing 2004 vs 2001 for each ward was correlated to the incidence of lead pipe in that ward (Figure 2B; $R^2 = 0.60$).

Birth rates nationally were relatively constant in the range of 13.5−14.7 from 1997 to 2009 (Table 3), and the national birth rate actually declined slightly to 14.0 from 14.1 in 2004 vs 2003, respectively. Birth rates were unchanged in Baltimore City from 2004 vs 2003 (Table 3). The calculated changes in birth rate for DC versus either BC or the U.S. illustrated a consistent trend, with a relative reduction in birth rates for DC in 2001−2003 when WLLs are low, and relative increases in birth rates (after 2004) when the population was protected by either public health interventions or corrosion control (Figure 2C). Taking a larger perspective using National Vital Statistics data for other U.S. states and territories,[35] the 4.8% increase in DC birth rates reported in 2004 versus 2003 was the highest among U.S. states and territories reporting more than 2000 births. Likewise, the 11% increase in DC birth rates comparing 2006 versus 2003, was matched or exceeded only in Wyoming, Thus, while the changes observed in DC are not unprecedented, they were also highly unusual compared to other states and territories.

Changes in birth rates can be a strong function of demographics; for example, if DC had a lower population of women aged 15−44 in 2004−2006 versus 2001−2003, the observed increase in birth rate starting in 2004 might have nothing to do with WLL exposure. When DC DOH trends in reported general fertility rates were examined using the same approach as for Figure 2A, DC general fertility rates were inversely correlated to both incidence of childhood lead poisoning age <1.3 years and median blood lead (SI Figure 2; $R^2 = 0.49−0.53$). Repeating the analysis of Figure 2C for changes in general fertility rates in DC versus both BC and the U.S., revealed the same trend as was observed for the birth rate (SI Figure 3). Thus, changes in demographics do not seem to be a likely explanation for the observed anomalies in DC birth rates.

There was also a reasonable inverse correlation, between DC fertility rates and DC fetal death rates (SI Figure 4; $R^2 = 0.38$). The slope of that curve implies an increase in births of 300 per year when the cases of fetal death are reduced by 30 cases per year, which roughly approximates to the actual data for DC in 2004 versus 2001 when live births increased by 308 and fetal deaths decreased by 34. If this change reflects changes in WLL exposure and its associated effect on spontaneous abortion incidence,[9−12] then decreased fetal deaths account for only about 10% of the observed increase in birth rate and the remaining 90% would be attributed to miscarriages. A ratio of 1 fetal death for every 9 miscarriages was expected based on prior research.[43] Overall, observations in DC are consistent with predictions of higher miscarriage incidence at less than 20 weeks gestation at times with high WLLs and higher maternal lead exposure, which translates to reduced birth rates as expected given the presumed successful use of 19th century lead abortion pills.[9−12]

Revisiting the 1987−1989 USA Today Miscarriage Cluster. A National Institute for Occupational Safety and Health (NIOSH) report summarized a 16-month health hazard investigation for a high profile miscarriage cluster in what was once the USA Today Building complex in Rosslyn, VA.[22] This building receives water from the same source as Washington, DC. A 100% incidence of miscarriages (eight miscarriages for eight pregnancies) was confirmed among women working on two specific floors of one building that underwent renovation during 1988, an activity which was noted to have disturbed the existing copper−lead solder plumbing system to the point that joints failed and "dripping from overhead pipes <was> common."[21] The miscarriages were associated with "working in an area under renovation during the first 20 weeks of pregnancy" (RR = 2.52; 95% CI = 1.43−4.48).[22]

Extensive testing many months after the miscarriages revealed nothing unusual except for very high WLLs (up to 1300 μg/L), with mean lead in first draw drinking water fountain samples of 100 μg/L and mean lead levels after flushing 5 min of 50 μg/L. But the two floors with the renovations and highest incidence of miscarriages had ***anomalously low*** detected WLLs (mean lead of 20 μg/L first draw and 11 μg/L after flushing), WLLs that were 80% lower than in other areas of the building with lower incidence of miscarriages ($p < 0.05$). This finding, coupled with low levels of blood lead for 39 women tested after March 1989, was used to rule out WLLs as a factor contributing to the cluster.[22,23] Expert consensus at the time was that "no matter how much water you would drink here, that by itself would not be sufficient to increase the level of lead in the body of an adult very much at all."[24]

Re-evaluation of the NIOSH logic and closer examination of the raw data reveals substantial uncertainty in the conclusions regarding the effect of high WLL. First, recent reports have demonstrated that physical disturbances to pure lead pipe can sometimes create massive water lead spikes over a duration of weeks to months, before eventually improving.[13−16,44] The experimental testing simulating impacts of disturbances during renovations on WLL exposure for occupants on the two floors of the USA Today building conducted for this work, revealed that before the physical disturbance lead release in the two sets of pipes were identical (Figure 3). But after just 30 s of vibrations at 3 m distance from the pipes, WLL increased over hazardous waste criteria (>5000 μg/L) for cumulative composite samples collected for the 1 month after the disturbance. Consuming even a small amount of water containing >5000 μg/L lead would greatly exceed the dose from 1900s lead abortion pills. The same vibrations 15 m distant from the pipes had nearly no effect on WLLs (Figure 3). Importantly, three months after the vibration had ceased, the pipes closest to the vibration had 88% ***lower*** lead release than

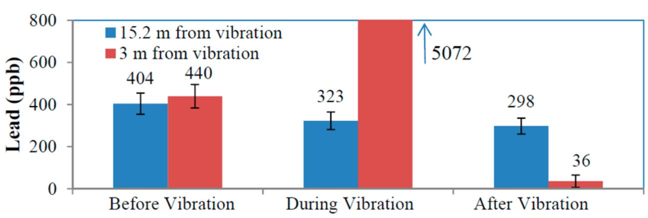

Figure 3. A simulation of construction vibration impacts for the USA Today building, illustrates massive release of lead to water for the month immediately after vibrations, and much lower water lead 2−3 months afterward for disturbed lead pipes.

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more distant pipes not impacted by the vibration ($p < 0.05$), consistent with the notion that removal of a lead rust reservoir during the prior disturbance effectively cleaned out lead from the pipes (Figure 3). Hence, the anomalously low WLLs detected on the two floors with renovation and higher miscarriages in the USA Today building months after the adverse pregnancy outcomes and renovations, is completely consistent with much higher consumer lead exposure on the same floors during the construction.

Further considering that the FOIA revealed the following: (1) only two of the reported low blood lead tests in the NIOSH report were of women on the floors where the miscarriages occurred, (2) more than seven blood lead half-lives had passed from the time of the renovation in early 1988 to the time blood lead was drawn, which would have left little trace of a spike in blood lead if it had occurred,[2,45] and (3) WLLs throughout the building are in a range known to be sufficient to cause elevated blood lead and adverse pregnancy outcomes as indicated in this report and elsewhere.[9−13] Hence, the renovation and possible exposure to the high WLLs, was a possible causal factor in the USA Today miscarriage cluster.

■ DISCUSSION

Limitations and Strengths. Inherent limitations to the ecologic study design and the data used in this work, do not allow causal relationships between WLL exposure and adverse pregnancy outcomes to be established. Further research beyond the scope of work presented herein, such as attempting to link addresses of fetal death cases to homes with lead pipe or PSLRs from 2007 to 2009, could increase the strength of the analysis and conclusions associated with this research. Such work was recently called for by an EPA Science Advisory Board, in order to more carefully examine the relationship between PLSRs and incidence of lead poisoning for DC children.[16]

On the other hand, this evaluation also has unique strengths in terms of the following: (1) widespread water lead exposure in a large city with over a half million people, for over a 3 year duration, during a time period when blood lead levels were low by modern standards and influences of other major lead sources such as leaded gas, leaded dust and lead paint were largely under control, (2) presence of a nearby comparison city with similar population and other demographic similarities to eliminate some confounding factors,[18] and (3) availability of over a decade of data synthesizing hundreds of thousands of water lead, blood lead, pregnancy outcomes, and demographic data, collected using modern instrumentation and comparable methods from both cities. The very high statistical power inherent in some aspects of this ecologic study allowed strong temporal associations to be revealed with relatively simple statistical methodology. The observed associations are also consistent with expectations based on a prospective study, which demonstrated that even relatively modest elevations in blood lead (≈ 5 μg/dL) would increase the likelihood of miscarriage.[11,12]

Ecologic study designs are susceptible to numerous biases and possible confounding factors. At least two are worth noting explicitly herein. First, there is no clear consensus as to the effects of chloramine versus chlorine disinfection on pregnancy outcomes. Early work suggested that a change from chlorine to chloramine would reduce miscarriage rates, whereas several recent studies have indicated that these benefits are not significant, perhaps because certain chloramine disinfection byproducts may be more toxic than previously suspected.[46−49] In Washington, DC., it is clear that hoped for improvements in pregnancy outcomes, which have been cited as a major justification for changing from chlorine to chloramine in 2000,[47] were not realized over the time period of this study. If anything the opposite trend was observed during the time WLLs were elevated. It is also possible that any possible benefits from switching to chloramine after 2000 were overwhelmed by the adverse consequences of very water high lead.

Second, the historical lows in DC fetal death rates during 2004−2006 and 2010−2011 and the rise in birth rates starting in 2004, occurred after or during periods of intense adverse publicity about tap water safety in Washington, DC (Table 1). At these times many consumers were explicitly directed to avoid tap water, use bottled water or install lead filters distributed by the water utility. Because prior research has indicated that avoiding tap water (and using bottled water) can sometimes significantly decrease risk of miscarriages,[50] this factor might confound any attribution of pregnancy outcome trends to WLL exposure alone. However, the strong correlation between maternal blood lead proxies and the measured changes in birth rate, along with the prior research establishing links between modestly elevated blood lead and higher miscarriages, supports the hypothesis that at least some of the improved pregnancy outcomes are due to reduced WLL exposure.

Implications for Policy. From a policy perspective, it is encouraging that most of the data suggest relatively small increases to fetal death rates or reduced birth rates if water was maintained below the 90th% EPA action level of 15 μg/L (Figure 1B), or if public health interventions limit consumer exposure to elevated WLLs when the lead action level was exceeded such as in 2004−2006 or 2010−2011 (Figure 1A; Figure 1C; Table 1). At the same time, the 15 μg/L EPA action level provides little or no safety factor relative to adverse pregnancy outcomes. This point was supported by biokinetic modeling of continuous exposure of 1 year olds to water lead at 7 μg/L, for which 25% of exposed children are predicted to exceed a blood lead level of 5 μg/dL.[51] A one-time acute exposure to a single 250 mL glass of water with about 2500 μg/L Pb, was predicted to increase blood lead of a typical 5 year old child from 0 to 5 μg/dL.[51] Because these trends are likely to hold for adults as well, and these types of WLL exposure occur routinely in cities with lead plumbing or after PSLRs,[44,52] public health concern over lead in tap water for pregnant women seems to be justified.[9−13] It is noteworthy that the most recent data has indicated that U.S. fetal death rates have essentially plateaued since 2003 at a level which is higher than for other industrialized countries, and that the reasons for relatively high U.S. fetal death rates are not fully understood and remain a topic of active research.[53,54]

The data presented herein suggest a very high risk for elevated lead (and by extension adverse pregnancy outcomes) in PSLR homes from 2007 to 2009. Brown et al. (2011) reported a 360% increase in lead poisoning incidence for children living in PSLR homes versus typical homes in the city using data collected from 2004 to 2006, and this was when public health protections were in place throughout DC (Table 1). After 2006 the public health protections were removed and the utility stopped collecting water samples after PSLR in consumer homes. Thus, the time period examined by Brown et al. was actually relatively low risk to consumers, compared to the 2007−2009 time period examined in this report. Further support for very high risks after 2006 was obtained during an analysis of DC DOH Freedom of Information Act (FOIA) data for 2007, which revealed that >12% of cases of lead poisoned children (>5 of 40) lived in DC PSLR homes, even though less than 1% of DC housing units had PSLRs each year.[55] The 2007 FOIA data and that from the CDC through 2006, are also dominated by analysis of children aged 1.5−6 years, whose blood lead levels are generally dominated by lead paint exposure.[2,56] Maternal blood lead can be expected to have a greater proportion of total lead exposure from water than from lead paint when compared to children age 1.5−6 years. For instance, Fertmann et al. (2004) noted that young women reduced their blood lead by 37% if tap water was completely avoided in a city with WLL exposure much lower than in DC PSLR homes.[57] The implication is that very high risk of adverse pregnancy outcomes is possible in the small subset of PSLR homes, providing a practical basis for the spiking fetal death rates in Figure 1C and Table 1 from 2007 to 2009, even when blood lead was declining rapidly and birth rates were increasing throughout the rest of the city.

This work also reinforces the basis for health concerns and warnings associated with lead spikes arising from disturbing old lead plumbing.[3,8,15,44] This evolving knowledge base parallels prior experience with lead paint remediation and renovations, during which careless disturbances created short-term lead health hazards that were ultimately regulated.[58] At present there is no requirement to even notify consumers of voluntary PLSR replacements by water utilities, which represent a majority of PLSRs occurring in practice.[16] Implementation of modest health protections for consumers in homes subject to voluntary PLSR including (1) clear notification that their pipe is being disturbed, (2) the fact that serious health hazards may be created for residents, or (3) providing relatively inexpensive (≈$30) water lead filters seems desirable. Indeed, implementation of these steps by DC Water in 2010, reinforced by the CDC health alert and heavy media coverage regarding possible health risks from PSLR during public hearings in DC and in Congress,[7,8,17] may have helped to achieve historically low fetal death rates in Washington, DC in 2011 (Table 3). Re-examination of the miscarriage cluster in the USA Today building and an associated experiment simulating lead release during renovation, extends the recent concerns with PLSRs to disturbances of lead plumbing within buildings.[44] The same procedures effectively protecting residents in PSLR homes could also be implemented to protect these consumers.

■ ASSOCIATED CONTENT

Supporting Information

One Table and 4 Figures providing additional analysis on fetal death and birth rates have been developed. This information is available free of charge via the Internet at http://pubs.acs.org/

■ AUTHOR INFORMATION

Corresponding Author

*Phone: (540) 231-7236; fax: (540) 231-7916; e-mail: edwardsm@vt.edu.

Notes

The authors declare the following competing financial interest(s): The author has been subpoenaed to testify in lawsuits of children who were lead poisoned in Washington D.C. from 2001-2004. He has received no financial compensation for his testimony. DC Water was a financial contributor to a Robert Wood Johnson Foundation grant which supported this research..

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