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Review

Troubled waters? The disproportionate impact of lead water pollution: Evidence from three American communities

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Abstract: Although water is considered essential to life and an important natural resource, disadvantaged communities, such as low-income and minority communities, are disproportionately burdened by lead exposure in drinking water. In this paper, we highlight case studies that have received national press coverage as well as recent examples of community lead poisoning hazards that are still ongoing across various regions of the US. We show through these three case studies of Flint, Michigan, Washington, D.C., and Birmingham, Alabama, that the severity and frequency of this pervasive public health problem are highly concentrated in minority and low-income populations, and thus they bear the brunt of the socio-economic impacts. We identify the use of sensors to improve detection of hazardous materials and decrease inequities in drinking water contamination. To address water-related equity issues, we call for a sustainable community capacity approach that consists of shared governance between those who live in a community and stakeholders, such as businesses and health services, who have vested interests in it. We conclude by highlighting ways that a community could build collective social capital, safeguarding its environment from lead poisoning through health literacy education. Promoting water literacy is highly significant since water knowledge is crucial towards achieving water sustainability and equity.

Keywords: lead poisoning; water quality; environmental justice; community engagement; community building capacity; water sustainability; environmental hazards; health literacy

1. Introduction

Lead, historically, has been one of the most versatile and useful metals across the globe. Lead decorative items predate civilization itself. Lead has also been used in water distribution systems since ancient times. Even though lead's toxicity has been known for decades, lead-bearing units are still common in drinking water distribution systems worldwide. Any distribution system with elements installed before 1941 will likely have at least lead service lines [1].

Lead contaminates the environment via fossil fuel burning, mining, agriculture, and manufacturing. It is also used in lead-acid batteries, solder, metal pipes, and electronic devices. Furthermore, 16.4 million US homes (~25%) have a substantial amount of lead-based paint [2]. Ingestion of lead paint chips and dust is the largest source of lead poisoning in children. Additionally, the aging US water infrastructure releases lead into tap water, which has reached hazardous levels in many cities, such as Flint, MI [3]. Adults absorb 35% to 50% of this heavy metal through drinking water, and in children, absorption may exceed 50% [4]. Ingested lead is highest in the kidney, followed by the liver, heart, and brain [5,6]. Notably, the nervous system is the most susceptible to lead poisoning. Moreover, according to the US Environmental Protection Agency (EPA), there is no known "safe" level of lead for children [4]. The wide-ranging effects of lead toxicity create significant societal burdens, especially in communities that are ill-equipped to provide services to people who are adversely affected [7].

Adverse health effects identified with lead contamination [8,9] include increased blood pressure and other cardiovascular effects, decreased kidney function, and anemia in adults. Furthermore, lead accumulation in bones can accelerate osteoporosis [10]. For men, elevated lead levels can reduce sperm count. For pregnant women, lead exposure can result in reduced growth of the fetus and increased chances of miscarriage and premature birth [8,9]. Chronic effects of lead in children include decreased, delayed, or impaired neurobehavioral development, a decrease in intelligence quotient, speech and language deficits, anti-social behaviors, and a poor attention span [7,11].

The World Health Organization estimates that nearly one million people die every year due to lead poisoning [12], with millions more (many who are children) exposed to low levels of lead causing life-long health problems. Populations at higher risk for lead contamination include children, immigrant and refugee children, pregnant women, and people who work in lead-related industries [13].

The Safe Drinking Water Act (SDWA) was passed by the United States (US) Congress in 1974, with amendments added in 1986 and 1996, to protect our drinking water. Under the SDWA, the EPA sets the standards for drinking water quality and monitors states, local authorities, and water suppliers who enforce those standards [14]. In 1986, Section 1417 of the federal SDWA was amended to limit the content of lead in pipes and other materials used in water supplies, defining "lead-free" as being less than 8% lead in pipes and fixtures and less than 0.2% in solder.

In 1991, the US Environmental Protection Agency (EPA) established the Lead and Copper Rule (LCR) to "protect public health and reduce exposure to lead in drinking water". Revisions to the LCR took place in 2000, 2004, 2007, and 2021. The Maximum Contaminant Level Goal is zero due to there being no level of exposure to lead that is without risk. The treatment technique for the rule requires systems to monitor drinking water at customer taps; action levels occur if the lead concentration exceeds 15 parts per billion (ppb). Since its implementation, lead level exceedances have decreased by over 90% [15], see above.

Primary sources of lead in drinking water include copper pipe with lead solder, lead water service lines, faucets, galvanized pipe, and lead goosenecks [16]. The release of lead into water systems is affected [17] by the acidity or alkalinity of the water, the types and amounts of minerals in the water, the amount of lead that the water comes into contact with, the water temperature, the amount of wear in the pipes, how long water stays in pipes, and the presence of protective scales or coatings in the pipes.

The EPA has estimated that there are at least 6 to 10 million lead service lines, and a 2021 Natural Resources Defense Council (NRDC) survey found that this number could be 12 million or more. The practice of using lead-based solders was not abandoned until 1986 [1]. Any brass fixture with less than 8% brass was considered to be "lead free" under federal government regulation before 2014. So, any brass plumbing fixtures in the US can contain up to 8% lead. Although lead is ubiquitous in most US water systems, it remains dormant in stable systems. Whenever a utility changes or adjusts its source water, changes its finished water chemistry, or employs different treatment or distribution strategies, the lead in pipe scales can be disturbed, resulting in high lead residuals in a community's water. Without careful testing and sampling, disasters can happen. One such disaster played out in Flint, Michigan, from 2014 to present. Flint, MI, made headlines in 2016 when it was revealed that blood levels in children had nearly doubled since the city started pumping in drinking water from a new source without properly treating it [18]. The inadequate treatment and testing of the water resulted in a number of water quality and health issues. Citizens complained of foul-smelling, discolored, and off-tasting water for more than 18 months. Even as late as 2020, Flint, MI, does not have safe drinking water [19].

2. Case studies

We examine three case histories of lead contamination in water sources: Flint, MI; Washington, D.C.; and Birmingham, AL. High lead levels have been found in tap water in other US metropolitan areas, including Baltimore, MD; Detroit, MI; Milwaukee, WI; New York, NY; Pittsburgh, PA; Chicago, IL; Washington D.C. [18], Durham, NC; Greenville, NC; and Lakeland Acres, ME [20,21]. A map indicating the extent of lead contamination in water is shown in **Figure 1**, while **Figure 2** shows the number of lead service lines in each of the states in the US. Approximately 20% of US water systems have tested above the 15-ppb action level [22]. NRDC reports that 56% of the US population drinks from water systems with detectable levels of lead. The extent of lead contamination is not confined to major cities; NRDC reports that lead service lines are likely in use in every US state; many states and utilities do not know where their lead service lines are located [18]. In fact, the US Government Accountability Office [23] reports that less than 20 of the largest water systems have data publicly available related to their lead in drinking water.

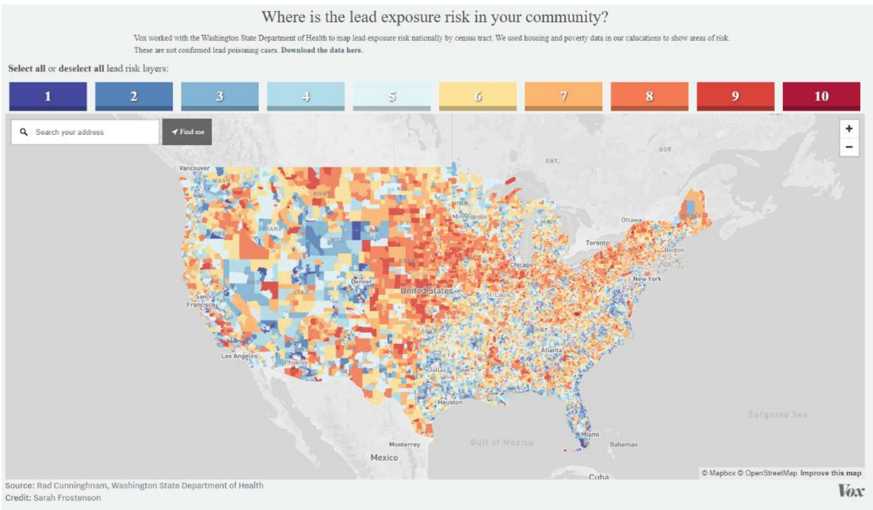

Figure 1. Map showing US lead exposure risk [24].

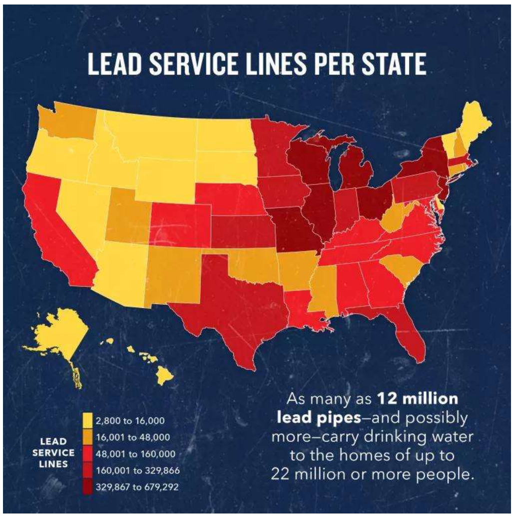

Figure 2. Lead service lines per state in the US [18].

2.1. Incident in Flint, Michigan

The Flint disaster represented a failure on all government levels, resulting in tragic implications for thousands of predominately poor, mostly minority residents in Flint, Michigan. A city manager was appointed in late 2011 by the State of Michigan in an attempt to reduce costs of city operations. One of the areas targeted for cost reduction was drinking water. The Flint city manager suspended the purchase of Detroit city water and approved the use of water from the Flint River [25]. An aqueduct to Lake Huron was still under construction and was not an option. On 25 April 2014, Flint River water was introduced into the city distribution system. Within days, the first customer water quality complaints were lodged [26].

When Flint, Michigan, switched to the Flint River as a temporary drinking water source, it did so without implementing corrosion control. Ten months later, lead concentrations in collected water samples progressively increased (104, 397, and 707 mg/L). This coincided with increasing water discoloration. All samples collected had lead concentrations exceeding the 15-ppb action level, and several samples had lead concentrations exceeding 5000 ppb. The US EPA has estimated that the blood lead level in a child will increase 1 mg/dL for every 5 mg/L lead increase in water [27]. The lead concentration (90th percentile) was 31.7 ± 4.3 mg/L [25].

By August 2014, boil orders were issued to Flint residents. Notably, boiling water has no effect on lead levels. Olson et al. [28] observed that the pipe scale was relatively depleted of lead compared to the scale from 26 public utilities. The stripping of scales by the relatively more corrosive Flint River water resulted in high bacterial counts. E. coli counts increased and Legionnaire’s disease cases were recorded. Additional chlorine was added, resulting in increases of disinfection by-products (DBP’s), a known carcinogen. A high DBP warning was issued in January 2015.

By 1 October 2014, General Motors suspended use of Flint City water due to its corrosiveness. On 9 January 2015, the University of Michigan at Flint discovered lead concentrations in Flint’s drinking water above allowable federal levels. By 9 September 2015, high lead levels were discovered in the blood of Flint residents. Later that month, a lead advisory was issued. On 1 October 2015, a public emergency was declared. The following day, the governor of Michigan, Rick Snyder, blamed the high lead levels on household plumbing, despite overwhelming contrary evidence. Later in October, Flint reconnected to Detroit water. Despite this, another state of emergency was declared on 14 December 2015. The National Guard was activated on 12 January 2016 to distribute bottled water to Flint residents. Well into 2017, Flint residents were still without safe drinking water from their water taps [26].

The raw water from the Flint River was considerably more corrosive than the Detroit city water. This is possibly due to the high concentration of chlorides used in road salts. However, the Flint River water might have been usable if the corrosion inhibitor applied in previous treatments had not been suspended. It is unknown if the suspension of the corrosion inhibitor was intended as a cost-saving maneuver. The City of Flint and the Michigan Department of Environmental Quality (DEQ) did not address the suspension of corrosion inhibitors until two months after the switch to Flint water. Over a year and a half after the switch to Flint River water, the DEQ acknowledged that it misinterpreted a rule on water treatment. The DEQ admitted in an e-mail that they should have required the city to implement corrosion control during the switch and afterward. It has been speculated that if the corrosion inhibitors were applied, the Flint disaster would have never happened [29]. Regardless, no pilot testing was performed before a major change was implemented in the Flint water treatment and distribution system. This is a dangerous practice regardless of the activity. For Flint, hundreds of millions of dollars in permanent damage was done to the distribution system, likely because a few hundred dollars worth of chemical additives was eliminated. The distribution pipe corrosion is permanent, and the damage will likely result in a complete rehabilitation and replacement of the drinking water distribution system. However, the cost to human health and dignity may never be fully realized [26].

Phosphate-based corrosion inhibitors

For decades, hexametaphosphates were the primary phosphate-based corrosion inhibitors used in water distribution systems. The effectiveness of hexametaphosphates was largely determined by their ability to reduce “red water” (iron staining and discoloration) complaints. However, hexametaphosphates likely increase the release of both particulate and soluble lead [30,31]. Phosphate corrosion inhibitors arrest metal corrosion in two ways; by sequestration and passivation. Sequestration is the prevention of metallic ion precipitation by forming a compound that remains dissolved in water. Since the compound remains in solution, no discoloration from precipitation occurs. Passivation is the formation of an inorganic film, which essentially coats the inner surface of a metal component, much like paint applied for surface protection [32,33]. Sequestration is a problematic strategy with dissolved metals that are toxic at relatively low concentrations. This is why hexametaphosphates should never be used to prevent lead corrosion.

Three commonly used phosphate-based inhibitors are polyphosphate, poly-phosphate blends (blends), and orthophosphate. Hexametaphosphates are the active ingredient in polyphosphates. Phosphoric acid is the active ingredient in orthophosphate. Blends are made of a mixture of polyphosphates and orthophosphates and have the advantage of the passivation chemistry of orthophosphate and the sequestration properties of polyphosphates. Blends are generally described as a percentage of polyphosphate versus orthophosphate [32]. Several studies have suggested that polyphosphates and polyphosphate blends should never be used to prevent lead corrosion. In fact, polyphosphates and blends may actually cause increased lead residuals [31,34–38].

The crisis in Flint, Michigan, killed 12 people, according to data from the Michigan Department of Health and Human Services [39]. Five officials, including the head of the state's health department, were charged with involuntary manslaughter on 14 June 2017.

2.2. Washington, D.C.

More than a decade before the Flint, MI, case, a lead contamination crisis occurred in Washington, D.C. Over 157 households had lead levels exceeding 300 ppb, with thousands exceeding the 15-ppb action level. In 2001, the Washington Aqueduct and the District of Columbia Water and Sewer Authority switched from chlorine to chloramines as the disinfectant for their water system. The change was made to minimize the formation of DBPs [22]. Replacing free chlorine with chloramines changes the chemistry by raising the pH and lowering the water's oxidizing potential. Increased lead content in water may have been caused by increased corrosion related to the introduction of chloramines. Two-thirds of the households tested (4075 homes) in summer 2003 had lead levels exceeding the 15-ppb action level [40].

In the past, lead oxide (PbO_2) scales formed due to the high oxidizing potential of their water. As long as the water remains highly oxidizing, the lead oxide scales are stable and insoluble. With the shift to chloramines, the water's oxidizing potential decreased, which meant that the water could dissolve the PbO_2 scale, thereby raising the water's lead concentration. Renner indicated that the change in water chemistry and old lead pipes was the source of the crisis. Furthermore, chloramines may be prone to mobilizing lead from brass [21]. Additionally, insufficient monitoring to address the LCR, gaps in controlling corrosion and leaching of lead, and poorly designed lead sampling and testing programs exacerbated the problem [21,41]. Washington, D.C., is still working to fix this problem [18].

To reduce the exposure to lead, the Washington Aqueduct used source and treated water containing very low lead levels. Brown et al. [42] observed that when chloramine alone was used to disinfect the water in Washington, D.C., the risk for blood lead levels was greater than when chlorine or chloramine with orthophosphates were used. Changes in water disinfection can enhance the effect of blood lead levels. Washington, D.C., now utilizes corrosion control treatment (maintaining constant pH and addition of orthophosphate), monitors the source and treated waters, and reports results to the EPA [43].

Figure 3 shows the effect of implementing orthophosphate treatment to control corrosion in Washington, D.C. In January 2015, the District of Columbia reported that 90% of the water samples had lead levels of 4 ppb or less [43]. Independent testing at six Washington, D.C., public schools in 2008 indicated that problems with elevated lead persisted at 2% to 41% of taps in each school [44]. The highest lead concentration detected in the public schools was 1987 mg/L, significantly higher than the 15-ppb action level.

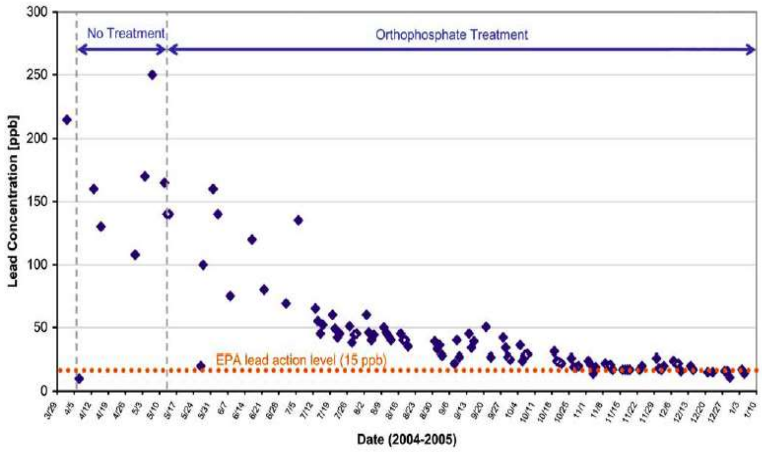

Figure 3. Lead concentration in water decreased markedly after implementing orthophosphate treatment to control corrosion in Washington, D.C. [43].

Incidence in elevated blood levels exceeding 10 mg/dL in Washington, D.C., for children less than 1.3 years old increased more than fourfold for 2001–2003, when lead in their water was high, versus in 2000, when lead levels in the water were low [45]. Guidotti et al. [46] reported that of 2342 children aged 6 months to 6 years in age, 65 had blood lead levels exceeding 10 mg/dL, and the highest blood level was 68 mg/dL. Additionally, two nursing mothers had blood lead levels exceeding 10 mg/dL.

2.3. Birmingham Water Works Board (BWWB) pilot study

One particularly dramatic illustration of the ineffectiveness of polyphosphate blends in preventing lead corrosion was discovered during a pilot study by the Birmingham Water Works Board in Birmingham, Alabama (BWWB). In an attempt to determine if a switch from chlorine to chloramines would have detrimental effects on the distribution system, a pilot study was conducted using elements harvested from the BWWB distribution system and brass hardware. A flow-through system was constructed equipped with cast iron, brass, and lead piping and fixtures. The apparatus was designed to mimic a distribution system with twelve-hour flow (approximately 3000 gallons) and twelve hours of stagnation (zero flow condition, **Figure 4**). Finished water and phosphate-based corrosion inhibitors were introduced to the pipe rack. Weekly samples were collected from the brass fixtures, cast iron, and lead pipes and analyzed for total and dissolved lead [38]. The brass hardware in this study was produced before 2014. Until 2014, brass fixtures were legally sold with up to 8% lead content. None of the effluent reached the distribution system and was discharged to wastewater.

Figure 4. BWWB flow through system [38].

The pipe rack was divided into five sections, each consisting of one ten-foot unlined cast iron pipe (two-inch inner diameter), three 2.5-foot pipes of lead service line (one-inch inner diameter), and an assembly of brass fixtures. The cast iron pipes were designated Cast Iron 1-5 from the top of the rack to the bottom. The lead pipes were labeled Lead 1-1, Lead 1-2, Lead 1-3, Lead 2-1, ... Lead 5-3. The brass fixture assemblies were labeled Brass 1-5 (**Figure 5**). Each section was tapped with sampling valves. Additional valves separated the pipes during sampling. Valves were installed between each pipe section for pressure release during sampling. The flow-through design was intended to give the best possible approximation of settings and materials found in the BWWB distribution system [47].

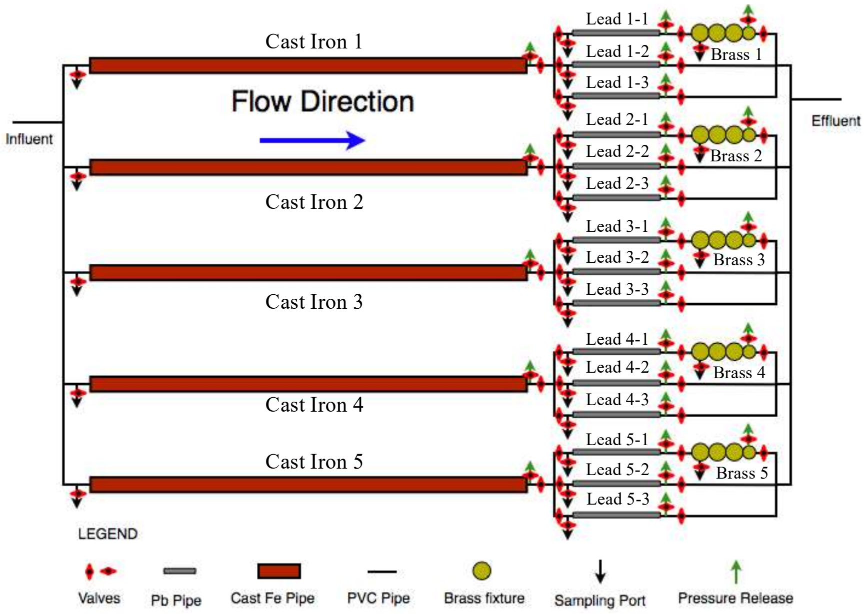

Figure 5. H. Y. Carson Filter Plant (CFP) pipe rack schematic [48].

Findings of the BWWB study

The management at the BWWB was aware of the 2004 incident that occurred in Washington, D.C., where high levels of lead were discovered in city drinking water. The suspected cause was the change in primary disinfectant from chlorine to chloramines. To avoid this, the BWWB selected a corrosion inhibitor recommended by a consultant. The corrosion inhibitor was marketed for its professed ability to "reduce lead corrosion". The chemical selected was a polyphosphate blend of 70% polyphosphate and 30% orthophosphate (70/30). Pure orthophosphate was rejected due to a reputation (largely contradicted in peer-reviewed literature) for exacerbating "red-water". The 70/30 was introduced to chlorinated water entering the flow-through at 4 parts per million (ppm) after six months without any corrosion inhibitor in chlorinated water [47].

Within two weeks, total lead concentrations in samples collected significantly increased. After the concentration of 70/30 was doubled, lead concentrations spiked 1500% in samples collected from the lead pipes. Lead concentrations exceeding 6000 ppb following the introduction of polyphosphate blends were obtained [47]. All cast iron pipes and brass fixtures showed concentration levels significantly higher than the maximum allowable limit of 15 ppb. The lead concentrations in Section 4 of the flow-through, which consistently showed higher turbidity, were even greater. The 70/30 was replaced with a 30/70 blend, increasing the concentration of orthophosphate by 40% relative to the polyphosphates. There was no measurable reduction in lead residuals as lead concentrations continued to reach over 10 ppm in the lead pipes (even greater in the high turbidity Section 4). The BWWB replaced the blends with orthophosphate, and within weeks the lead concentrations in all sections and materials stabilized to concentrations below original levels. After chloramines were introduced, lead residuals continued to decrease in all sections and all arterials. By the end of the study, all sample lead concentration levels were consistently below 15 ppb [47].

Other cities in Alabama, such as Leeds, Alabama, have reported blood levels of lead in the range of 10.86 ± 4.14 mcg/dL [49]. In addition, Casey Toner [50] reported that there were more than 24,000 cases of young children from 595 Alabama zip codes with lead in their blood. This information was submitted to the Alabama Department of Public Health from 2010 to 2014. Furthermore, the counties of Choctaw, Sumter, Mobile, Monroe, Morgan, Limestone, and Montgomery reported the highest number of children under five years of age who were diagnosed with lead health issues. Notably, Cabrera [51] points out that no amount of lead exposure is safe.

2.4. Techniques to reduce exposure to lead in drinking water

The Pennsylvania Department of Environmental Protection [25] has identified several techniques to reduce lead exposure:

- Run water to flush out lead;
- Use cold water for cooking and preparing baby formula;
- Do not boil water to remove lead (lead concentrations in water will increase with increases in temperature);
- Test the water for lead;
- Identify if the plumbing fixtures contain lead.

3. Socio-economic impact of environmental hazards

A body of literature on the social, health, and economic impact of environmental hazards on individuals and communities has been established. There has been a recognition of social disparities associated with the impacts of environmental toxins, with race and class as greater predictors of exposure to toxins. A fact sheet from the Environmental Defense Fund notes that children and racial minorities bear a disproportionate burden of lead exposure because of poverty and substandard housing [52]. The impact of contaminated drinking water, particularly the presence of lead, has been highlighted in the literature. However, the magnitude and extent of this entered the public discourse with the Flint water crisis, which attracted a great deal of attention. The contamination of residential water supply in Flint, Michigan, violated the right to clean water [53].

The incident in Flint exposed how significantly the lead crisis disproportionately impacts marginalized communities (mostly racial minorities and low-income neighborhoods). Empirical researchers such as Hannah-Attisha et al. [54] estimated that the change in the water source in the Greater Flint area caused an increase in the incidence of elevated blood levels from 2.4% to 4.9% ($p < 0.05$) in children. They also conducted a spatial analysis, which revealed that children in low-income communities experienced the greatest increase in blood lead levels. The 2018 NRDC report [52] reveals that about 45% of the Flint population lived below the poverty line with majority black populations. The report further documents that the Michigan Civil Rights Commission established that the poor response from the state government was a "result of systemic racism". Children are at a particular disadvantage when it comes to lead pollution because it leads to health, behavioral, and social impairments [55]. Hanna-Attisha et al. [54], who studied blood lead levels in children, concluded that the percentage of children with elevated blood lead levels increased after water source changes, particularly in socioeconomically disadvantaged neighborhoods. They also noted that water is a growing source of childhood lead exposure due to an aging water supply infrastructure.

Researchers, including Schaider et al. [56], have revealed that low-income and minority communities are impacted disproportionately by high pollutant exposures. The extent to which residential segregation is linked with lead exposure has further been investigated by Murray [57]. The study discovered that neighborhoods with higher proportions of Black and Hispanic residents were associated with an increased percentage of elevated blood lead levels. Marshall et al. [58] corroborated these findings in a research article that utilized the Adolescent Brain Cognitive Development study. This is a US-based, large-scale study of brain development and child health funded by the National Institutes of Health. Their research on a sample of 9712 children between the ages of 9 and 10 showed that children from lower-income neighborhoods have a higher risk of lead exposure. They also found that these children suffer more from distortions in their brain development, as evidenced by their lower cognitive test scores, smaller cortical volumes, and smaller cortical surface area. Although access to drinking water is a universal human right, there are several challenges surrounding drinking water systems in the US. They include aging infrastructure and polluted source water [59]. Nonetheless, the burdens are not equally distributed [60]. Despite the link between socio-demographic characteristics and water contamination, particularly drinking water quality, there is less attention paid to drinking water systems and more research directed at agricultural water use or environmental water quality of rivers, streams, and aquifers [61].

The active and growing literature on disparities in drinking water violations and compliance reflects the extent of these inequities. Research has identified types of communities disproportionately burdened by water contaminants. An analysis of community water systems in the U.S. from 2011 to 2015 reveals that counties with a disproportionate percentage of minorities had a higher percentage of drinking water violations [62]. Switzer and Teodoro [63] capture this trend by showing that racial/ethnic and income composition of populations predict drinking water quality and are therefore more likely to violate the Safe Drinking Water Act (SDWA) compliance. The findings particularly highlight the fact that there is a strong prediction that there will be SDWA violations for Black and Hispanic populations. Research across the Southeastern region of the United States maintains that minority and low-income communities have poor ambient water quality [64]. Bae and Lynch's analyses of safe drinking water violations from 2016–2018 conclude that socio-economic factors impact the distribution of SDWA violations in the US [59]. Their research notes that concentrated poverty negatively impacts access to safe drinking water and that racial minorities, as well as low-income populations, are disproportionately exposed to unsafe drinking water and have more safe drinking water violations. Blair's [65] research demonstrates this trend by showing that cities with higher minority populations are three times more likely to have a water standard violation. Addressing disparities associated with water infrastructure has not been equitable as well. A study published by the Environmental Defense Fund [66] and the School of Public Health in Washington, D.C., reveals that Lead Service Line Replacement programs are not equitable and benefit mostly wealthy and advantaged populations. In low-income and black-dominated communities, only 0.1% of residential service lines were voluntarily replaced. The results of the study show significant correlations between median household income and identification of residents as African Americans.

The recognition of these inequalities has expanded the range of scholars interested in studying the impact of environmental contaminants on humans. The environmental justice/racism movement has been crucial in highlighting inequities in terms of the impact of environmental hazards. Balazs [61,67] however argue that there is a paucity of information about inequities in drinking water contamination in the environmental justice literature, as opposed to the plethora of studies about the extent and causes of the disproportionate burden of environmental hazards.

3.1. Community empowerment

One important solution the environmental justice movement has advanced to addressing disproportionate access to clean water is to eschew top-down initiatives that do not influence the growth of community capacity nor long-term sustainability and replace them with bottom-up approaches. The Biden-Harris administration has established the "Get the Lead Out Partnership" as of 27 January 2023 to replace lead water pipes within 10 years. The partners in this campaign include state, city, county, and national water organizations in cities and rural areas, as well as non-governmental organizations [66]. The active engagement of communities and grassroots organizations in addressing environmental issues will ensure community involvement in deciding, planning, and evaluating projects. Involving the community includes engaging all stakeholders, recognizing their expertise, and allowing them to come up with solutions to addressing environmental problems. Williams et al. [68] note the importance of including diverse voices, especially those from underrepresented groups, to effectively engage in water dialogues. One way to prioritize disadvantaged communities impacted by poor water quality is to have community members and stakeholders advocate for the funding of grassroots and local organizations who are actively involved in ensuring water equity but encounter financial barriers to achieving clean water in their communities [69].

3.2. The opportunity cost of environmental crises

Environmental crises have a direct impact on health. Resolving them is, therefore, usually prioritized, and the process often calls for large funding. These funds represent an "opportunity cost" for underprivileged communities. When resources are limited and choices need to be made, the opportunity cost of a choice represents the best alternative forgone. The funds could potentially be used to significantly improve the lives of the aforementioned low-income communities. However, they are used for the resolution of the crisis.

In the case of the Flint, Michigan, crisis, the total expenditure directed towards the resolution of the crisis was significant. For example: (1) the city received $100 million through the EPA [70]; (2) the state of Michigan increased its budget by over $350 million for water quality improvement and pipe replacement, among others [71]; (3) the crisis cost the state $626 million in settlements [72]. This non-exhaustive list of taxpayer dollars utilized for the resolution of the crisis amounts to over $1 billion. This represents an important opportunity cost for underprivileged communities, as approximately 40% of the population of Flint, Michigan, lives in poverty [73]. The water crisis had other economic effects. Christensen et al. [74] found evidence that the housing market was greatly affected. They estimated a decrease in the value of the housing stock by $520 million and determined that home prices remained depressed for 16 months even after the water was declared safe for consumption. Moreover, there is evidence that small businesses in the city were significantly impacted, which prompted the US Small Business Administration to provide an economic relief package [75].

4. Call to action for community empowerment

Exposing to environmental hazards is an ongoing challenge and one that must be actively addressed. The negative health outcomes of lead-contaminated water poisoning, especially in racial and ethnic minority communities [76], received heightened attention after Flint, Michigan, exposed the seriousness of environmental racism [77]. Low-income racial ethnic communities across the US have had the unpleasant experience of confronting the fear of exposure to toxic chemicals in their water supply with no solution in sight [78].

Also, the mounting cognitive and physical health burdens that come with these environmental hazards negatively affect community residents throughout their life span [51]. After the crises in Flint, Michigan, a sustained focus on this particular event and ensuing health risks to community residents became the prime example that spearheaded national attention to the environmental racism and associated health implications that had long been underacknowledged [77].

The national media coverage that followed the water crisis in Flint further legitimized environmental activists claims regarding excessive exposure to lead poisoning in impoverished racial ethnic communities. The Flint water crisis also strengthened alliances between community activists and health policy experts. These partnerships with local community groups and public health practitioners catalyzed bolder and more effective outcomes in confronting EPA legislation that had been in the making for decades. With this greater backing, increased momentum and sustained attention regarding environmental hazards in low-income, black, and brown communities took hold [52,79]. Environmental activists now have more social and political power to intervene and prevent the problems of high exposures of lead contamination in community water supply systems. Although many positive strides have been made on behalf of disenfranchised communities, there is still much more work to be done in the area of environmental justice, especially as it relates to lead poisoning in racially segregated communities.

Realizing the urgent needs of these communities, health protection agencies at the local, state, and national level are creating more academic space through interdisciplinary partnerships. These partnerships will enable us to better support vulnerable communities and work alongside them in understanding the problem and how to prevent further health problems through culturally tailored interventions that welcome community participation and knowledge of local community health issues that have long been ignored or poorly addressed. Educating community members about technological advances will also improve their health literacy and drive the community's engagement toward greater investment in their health outcomes through the use of interventions such as point-of-use sensor technology that could be used to detect lead-based water contamination.

The problems of lead contamination in water supply systems have been under the radar of environmental protection agencies and public health scientists for over 15 years. Interdisciplinary research scientists at the National Institute of Aging are also raising the alarm about the effects of lead toxicity in water and related exposome risks on brain and physical health [79]. This highlights the importance of research that also addresses environmental exposures linked to cognitive health outcomes across the life span. For example, lead poisoning has been associated with cognitive development problems in young children, resulting in lower school performance and test scores [80] and cognitive impairment in older adults [81]. Hence, there is a pressing need for public health and environmental community health agencies to collaborate together for sustained community action and engagement to prevent unsafe exposures such as these in human population environments, which are disproportionately black and brown [51].

A community's collective social capital is its' resource

Community social capital is a powerful resource in racially segregated communities and is vital to a community's empowerment at combating environmental injustice issues such as lead water contamination and related exposome threats to its' resident's health outcomes [82]. Racial ethnic communities in low-income segregated areas are most often cut off from mainstream sources of power and access to local government authorities, including water municipal companies, business districts, local civic governments, and council leaders with agency, that could provide effective solutions [83]. When a community has nowhere else to turn, its' only hope and ironically the greatest source of collective strength is in the social capital that its' community residents possess. In fact, social capital is a "vital component and characteristic of the community itself" [84], and it is through this type of community empowerment that black and brown low-income residents could actively demand environmental justice around lead-contaminated water problems and ongoing exposomic risks to its health [85].

The collective unity that a community's social capital could bring is needed to build alliances around racial and ethnic local community problems [86], such as lead-contaminated water and exposome risks that affect human health outcomes [79]. The human health effects of contaminated drinking water and other environmental hazards require that local community agencies also actively participate in its' demand for safe drinking water and removal of toxic dumping sites where residents reside [82]. Community grass roots organizing and partnering public health and environmental sustainability programs are needed to help communities address the cognitive and physical health implications of lead-contaminated water and exposome threats that are lurking at disproportionately higher levels in impoverished racial and ethnic communities across the United States.

Developing cost-effective sensors and related technology that easily detect noxious chemicals in the water and air could reduce human environmental health hazards and decrease neurological diseases and cancers. This technology could also support the long-standing environmental justice efforts to address environmental racism and the declining health and well-being of black and brown communities across the US [87].

5. Can technology help?

Lead can be measured in blood, urine, saliva, and other tissues [4,88,89]. However, the measurement methodologies associated with using these bodily fluids/tissues often include lengthy sample preparation and laboratory testing. Similarly, measuring heavy metals in water supplies entails time-consuming collection and sample preparation. Currently, accurate detection of heavy metals in fluid samples relies on expensive atomic absorption spectroscopy or inductively coupled plasma mass spectrometry in commercial testing laboratories operated by highly skilled staff [90]. It takes time to ship samples, run the tests, and send the results. The cost of $100 or more per test is prohibitive for many individuals and for communities that must sample water at numerous points in their water systems. Furthermore, in the two weeks, or more, that it takes to receive results, people remain at risk [79].

Enabling communities to directly monitor lead concentration in their municipal and agricultural water supplies would enable them to know if and when lead levels reach the point where action is required. In addition, people in the community need to know if they have ingested high levels of lead. Having reliable data will empower them to seek assistance in protecting themselves and their communities. They need an economical, easy-to-use method of detecting lead that will tell them if their water level exceeds the actionable level set by the EPA of 15 ppb and if individuals have high levels of lead.

We envision the creation of two types of point-of-use sensors that would optimally monitor the situation in low-resource communities. This would avoid the expense and time delays of sending samples to a lab for analysis, both of which would be burdens for communities with little or no ability to pay for expensive sample collection and lab services. The first type would be used to frequently measure lead levels in water sources for domestic and farm use. The second would be for human use. Community screening events could be held that would both train residents to sustainably manage their environmental safety and identify individuals at risk, including children. As residents are trained, they could even perform the tests in their own homes, similar to COVID tests. These tests could also identify potential hot spots for lead exposure that would warrant immediate action, such as changing their water treatment methods.

6. Conclusion

Three case histories have been presented in which elevated lead concentrations were observed in municipal water systems: Flint, MI; Washington, D.C.; and Birmingham, AL. Issues impacting the increased lead concentrations included changes in the water supply sources, aging infrastructure, changes in the disinfection systems used, and inadequate corrosion control. The elevated lead concentrations in the municipalities resulted in elevated blood lead levels, impacting the health of their residents. The disproportionate impact of aqueous lead pollution on low-income and minority communities has been described, and poor responses from the state regulatory agencies exacerbated the problems created by lead contamination. Failing to address the environmental lead contamination crisis has a direct negative impact on public health. Children and racial minorities often bear the brunt of lead contamination exposure. Concentrated poverty negatively impacts public access to safe drinking water throughout people's lifespan. Several techniques were presented for reducing exposure to lead in drinking water. Additionally, we proposed the creation of low-cost, point-of-use sensors that could provide a faster and more frequent means for low-resource communities to monitor lead levels and to act before widespread harm ensues. Lastly, to address these issues, community involvement of the stakeholders involving public alliance partnerships is required.

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