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the requirements for the degree of Doctor of Philosophy

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Methods for Assessing Inequitable Social Impacts of Dam Failures on Marginalized Communities

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ABSTRACT

The rate of dam failures in the U.S. is alarming due to climate change and lack of regulation. Civil engineers rarely quantify the impact of dam failures, and when they do, it is limited to measuring loss of life and property. Although these are significant indicators of a dam failure's impact, indicators involving demographic disparities have not been explored. Environmental justice literature considers social disparities that result from dam construction. However, there is no mention of the harm dam failures in particular can pose on socially marginalized communities. As the risk of dam failures increases due to changing climate patterns, there needs to be preventive urgency in identifying methods that will regard race and class when assessing diverse forms of social impact. This dissertation consisted of three studies that introduce innovative approaches to assess the impact of dam failures on racially and/or economically marginalized populations. The first study presents a method that identifies inequity within disaster aid after a severe rainfall and dam failure event and uses Columbia, South Carolina as a case study for demonstrating the method. The second study uses geospatial data and methods to determine the vulnerability of buildings in a marginalized Birmingham, AL community if a nearby dam failed under extreme rainfall conditions. Finally, the third study investigates how tailings dams and rural healthcare access in Southeast Missouri could together exacerbate lead exposure risks for young children. Across these three studies, this dissertation advances understanding of the social and policy implications of dams, underscoring how dam regulation could be improved to ensure the safety of marginalized communities.

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INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), socially marginalized groups across the world are the most vulnerable to the financial, environmental, and health consequences of climate-related extremes [1]. In particular, those experiencing poverty and/or racial/ethnic discrimination have limited access to emergency preparation and disaster aid as they are socially restricted from public services, transportation, insurance, and healthcare [2], [3], [4], [5]. The IPCC also states that water-mitigation infrastructure in North America, specifically, is not designed to withstand current rainfall patterns, exacerbating the risk of flood disasters for many communities, including in the United States (U.S.).

The U.S. already has a history of prominent climate-related water infrastructure failures that worsened social injustices for economically and socially marginalized communities. Severe rainfall caused the historic Mississippi Flood of 1927, which led to massive levee failure across seven states along the Mississippi River [6], [7], [8]. After the levees failed, Black residents, who were already facing subjugation during the time, were denied evacuation assistance, forced to stay in deplorable refugee camps, and displaced into homelessness [6], [7], [8], [9]. In 1972, heavy rainfall in Logan County, WV and insufficient dam design resulted in a series of tailings (mine waste) dam failures that destroyed several rural coal-mining towns [10]. The disaster killed almost 130 civilians, left more than 4,000 people homeless, polluted the area's fishing source, and caused life-long psychological trauma for those impacted [10], [11], [12]. Another prominent disaster was Hurricane Katrina's impact on the city of New Orleans in 2005. The hurricane's storm surges and extreme rainfall superseded the design limits of levees, resulting in the severe flooding of adjacent low-income Black neighborhoods. These neighborhoods were already historically and purposely confined to lowlands that experienced swamp inundation [13], [14], [15], [16], [17], [18]. Considering this social inequality, it was inevitable that the levee failures led to the disproportionate death, trauma, and displacement of Black residents [13], [14], [16], [19].

Acknowledging these historical disasters and their social impacts, it is essential that the current state and potential effects of U.S.'s deficient water infrastructure systems be made more evident, especially when regarding its dams. In the U.S., The American Society of Civil Engineers has already deemed the majority of dams to be in poor condition and at a high risk of failing [20], [21]. From 2010 to 2020, the Association of State Dam Safety Officials (ASDSO) recorded an alarming 270 nationwide dam failures and 581 near-failures [22]. Even more unsettling, ASDSO reports that there is a lack of national funding to not only rehabilitate dams that are structurally inadequate, but also operate and preserve dams in general. Furthermore, ASDSO notes that 73% of U.S. dams will be over 50 years old by 2025, indicating that the majority of them were built assuming stationary rainfall conditions that no longer exist due to climate change [23]. The U.S. has experienced several catastrophic dams failures in the past five years and all were climate-induced [24], [25], [26], [27], [28]. All of these dams failed due to unexpected severe storms or snowmelt, and their failure was exacerbated due to aging (each ~100 years old) and insufficient maintenance and regulation. As dam failure disasters become more frequent due to these stressors, it is important to identify populations that will be impacted by them. It is also imperative to locate socially vulnerable populations specifically, as they are already more susceptible to the consequences of climate change and have less resources to be resilient against them.

LITERATURE REVIEW

In civil engineering literature, the discussion of quantifying the social impact of dam failures is rare and it has mostly been limited to measuring loss of life and/or building destruction. The Life Safety Model (LSM) is a simulator that models the interactions of people and buildings with flood events [29], [30], [31]. Lumbroso et al. used the LSM to accurately estimate the number of fatalities and buildings destroyed after the 1959 failure of the arch concrete Malpasset Dam in France [29]. LSM has also been used to simulate the Brumadinho Tailings Dam's 2019 failure in Brazil, estimating loss of life at different delayed response and warning times [30]. A study conducted in Peru implemented the LSM to predict the number of fatalities at different warning times if a tailings dam in the Pasco region failed [31].

Although loss of life and property damage are significant indicators of a dam failure's social impact, little has been discussed on defining and expanding on other indicators, especially in the U.S. Concha Larrauri et al. used geographical information systems (GIS) and multi-criteria decision analysis to quantify more micro-level impacts of dam failures in the U.S., specifically in the Cumberland River basin [32]. Such impacts included loss of utility services, transportation damage, commodity losses, and hazardous waste site damage. Dennis et al. conducted the only study that addressed potential social demographic disparities that could result from dam failures [34]. It was found that minority populations in Pennsylvania were disproportionately supplied water by dams that are older (50+ years) and not inspected frequently enough to combat cyber-physical attacks. Excluding Concha Larrauri et al. and Dennis et al., civil engineering literature overall has yet to consider alternative social impacts of dam failures, especially when regarding demographic disparities in the U.S.

Environmental justice (EJ) literature discusses social disparities of water infrastructure in the U.S., including those that result from dams. There is literature on the use of GIS to locate sewer and water supply service inequities in North Carolina, Michigan, and the U.S. in general [35], [36], [37]. GIS has also been utilized to pinpoint stormwater management disparities in New Orleans after Hurricane Katrina [38], [39], [40]. There are also studies where GIS was used to discover inequality in the development of green infrastructure for storm water mitigation in Pennsylvania [41], [42], [43]. When the focus is on U.S. dams, EJ literature discusses how they have displaced socially marginalized Native American populations and contaminated or depleted their food and water sources [44], [45], [46], [47], [48]. These are the only injustices that have been explored with regards to dams, excluding the harm dam ***failures*** in particular can also pose on socially marginalized communities.

CASE STUDIES

The aforementioned studies in civil engineering and EJ literature indicate that there is need for approaches that can assess diverse and specific forms of social impact for dam failures in the U.S., especially when regarding race and class**.** The following three case studies outline novel approaches that were used to highlight potential social inequities in different regions of the nation. The first case study is placed in Columbia, South Carolina where in 2015 an extreme rainfall event lead to the failure of three dams in addition to severe flooding. Social inequity was assessed by using FEMA claim data to determine the level of FEMA assistance each impacted census tract received after the disaster. The second case study touches on the difficulty of obtaining dam breach flood extents and the unknown flood risks that result. This is particularly the case in Alabama where there is no dam safety entity to create and publicize these flood extents. To overcome this challenge, the study aimed to use hydrologic/hydraulic fundamentals to demonstrate how much more buildings in a marginalized Birmingham, AL community could be impacted if a nearby dam failed under extreme rainfall conditions. Finally, Study 3 investigated how tailings dams and rural healthcare access in Southeast Missouri could together exacerbate lead exposure risks for young children and inequality in blood lead level testing.

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SOUTH CAROLINA & FEMA

Assessing Disaster Aid Disparities in Columbia

INTRODUCTION

As mentioned previously, socially marginalized groups are the most vulnerable to the financial, environmental, and health consequences of climate-related extremes [1]. In particular, those experiencing poverty and/or racial/ethnic discrimination have limited access to emergency preparation and disaster aid as they tend to be socially excluded from public services, transportation, insurance, and healthcare [2], [3], [4], [5]. In the U.S., specifically, there have been indications that disaster assistance from the Federal Emergency Management Agency (FEMA) is inequitable. For example, research indicates that FEMA has allocated higher payouts to more wealthy and white communities [6], [7], [8]. FEMA also has not implemented the over a decade-old requirement to include flood extents of dam breaches in its flood map products, which have already been reported to overlook and exclude high flood risk areas occupied by vulnerable communities [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20]. In addition, FEMA and other disaster mitigation agencies lack data analysis practices that assess equity in their recovery processes [21].

Acknowledging the aforementioned social disparities and oversights with FEMA's disaster mitigation, the objective of this study was to assess if there are social disparities in U.S. recovery assistance after climate-induced dam failures occur. The 2015 South Carolina flooding disaster was used as a case study for this assessment because flooding was partially caused and exacerbated by dam failures. This provided a perfect opportunity to quantify racial and economic equity of FEMA's National Flood Insurance Program (NFIP) for this disaster, giving insight to more potential inequities in the distribution of recovery assistance.

METHODS AND MATERIALS

Study Area

In early October 2015, Hurricane Joaquin resulted in a 1,000-year rainfall event in Columbia, South Carolina. Columbia is located in Richland County (**Fig. 1.**) which intersects with the Gills Creek watershed. **Fig. 2.** shows the locations of these dams at the intersection of Columbia and the watershed. All of the dams are nationally classified as high-hazard, meaning that their failure could cause loss of life [22]. **Table 1** reveals the conditions of the dams after the rainfall event. It also shows how all except two dams had ages significantly over 50 years, indicating that their designs are antiquated in the face of current precipitation patterns [23], [24]. As a result, four of these dams overtopped and another three completely failed [25]. Overtopping is when water spills over the dam's crest [26]. Overtopping is often a precursor to failure, which is when the dam can no longer retain water and releases large quantities of it as a result [26], [27].

The United States Geological Survey (USGS) digitally produced the inundation boundary that resulted, referencing quality high-water marks that were documented immediately after the rainfall event and dam incidents [28]. **Fig. 3.** (left) displays this boundary with respect to the locations of the dams. Dark gray indicates which 2010 census tracts in Columbia intersect with the inundation boundary [29]. **Fig. 3.** (right) also shows how these 16 census tracts were numerically labeled in order to simplify the process of corresponding their census tract ID number with their social demographic data (i.e. race and median household income).

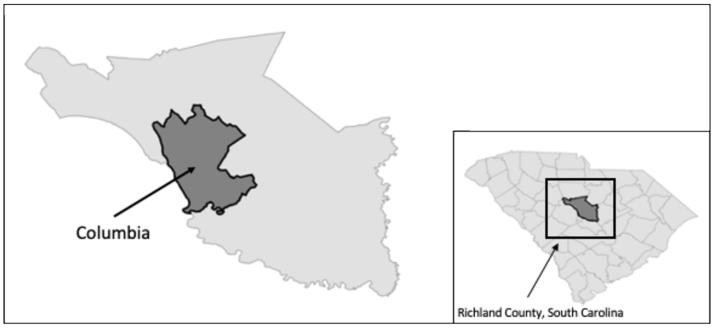

Fig. 1. Columbia subdivision in Richland County, South Carolina
[Source: U.S. Census Bureau]

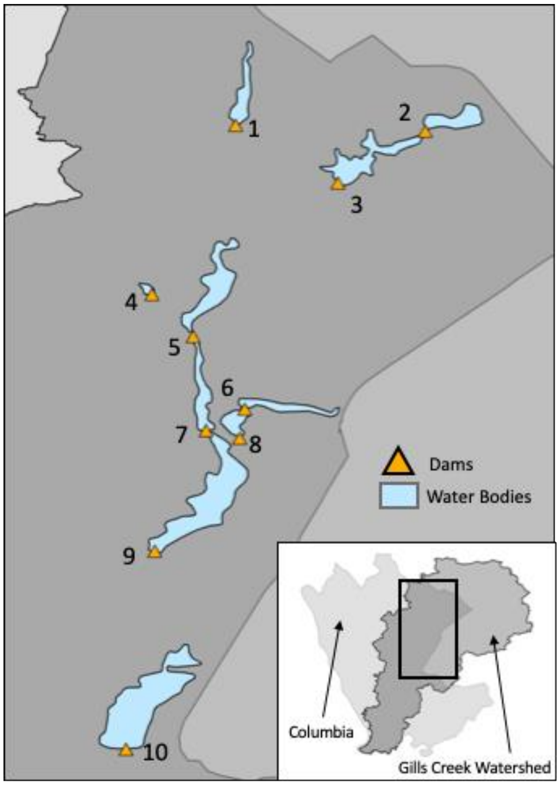

Fig. 2. Dams within the intersection of Columbia and the Gills Creek Watershed
[Sources: U.S. Census Bureau, SCDHEC, Esri]

Table 1. Corresponding dams to Fig. 2.

Number	Dam	Held, Overtopped, or Failed	Age in 2015 (years)
1	Springwood Lake	Held	61
2	Upper Windsor Lake	Held	50
3	Windsor Lake	Held	50
4	Arcadia Woods Lake	Overtopped	78
5	Carys Lake	Failed	77
6	North Lake	Failed	60
7	Spring Lake	Overtopped	115
8	Rocky Ford Lake	Failed	115
9	Forest Lake	Overtopped	115
10	Lake Katherine	Overtopped	74

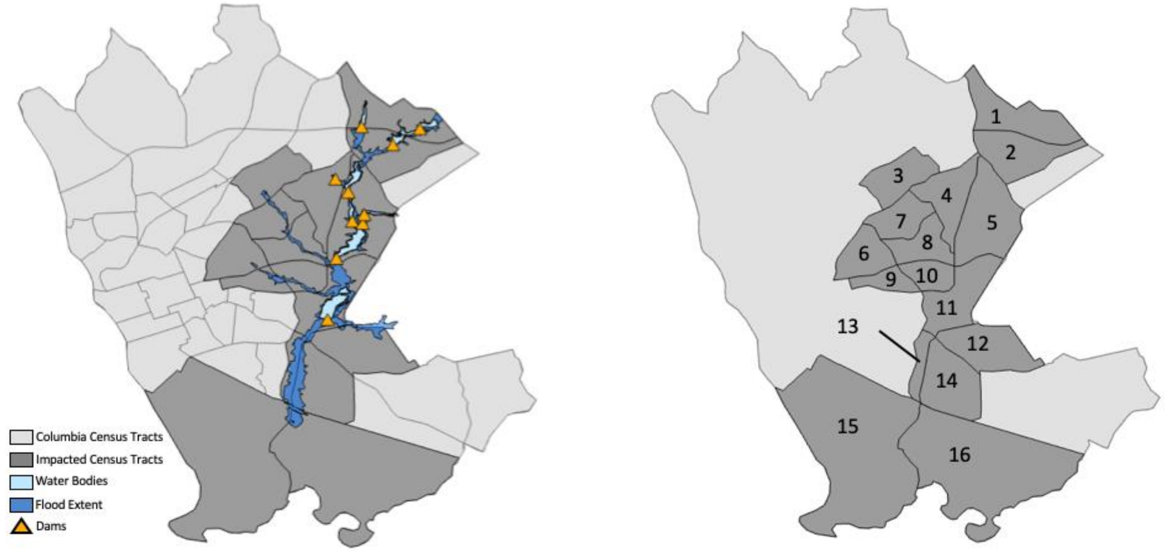

Fig. 3. Inundation boundary and census tracts (left) & census tracts numerically labeled (right) [Sources: U.S. Census Bureau, SCDHEC, Esri, USGS]

Data Preparation

FEMA's NFIP claims dataset contains claims filed from 2009 to when the dataset was retrieved [30]. For this study, the data was retrieved in March of 2022. Using R, the FEMA claims were filtered by date of loss which was October 2015 when the rainfall event occurred. The claims were then grouped by census tract, which was the smallest geographical unit available in the dataset due to anonymity purposes [29], [31]. This became an imperative limitation because having access to a smaller geographical level would have provided more geographical boundaries to analyze, giving the study a much bigger and suitable sample for a statistical analysis. Using the following assumptions and reasonings, a novel non-statistical method was developed instead to accommodate for this shortcoming and even others.

The first assumption was that a claim indicated definite impact of flooding to a building. Filing a FEMA claim can be arduous even for those with ample resources to do so, implying that survivors go through the process of filing a claim for an important reason. That reason being to get assistance with flood damage. The next assumption was that a building within the USGS flood extent did not guarantee that it was flooded and/or that a claim was filed for it. Microsoft's Building Footprints dataset consists of U.S. building outlines by state that were computer-generated from satellite imagery [32]. Building outlines for South Carolina were obtained and ArcGIS Pro was utilized to calculate the number of buildings within each census tract. However, without exact addresses (which the claims dataset does not include) and elevation data (which the building footprints do not have), it was difficult to determine with certainty if a building experienced flood damage and if a claim was filed as a result. This strengthens the reasoning behind following the first assumption because at least a claim can indicate a response to some form of flood damage.

Using R, the total number of claims along with the percent of claims FEMA reported as unpaid were calculated as well for each census tract. ArcGIS Pro was then used to link the census tracts in **Fig. 3.** to their respective claim data. Data on race in 2015 and median household income in 2015 were obtained by census tract and also linked to the census tracts [33], [34]. **Table 2** was generated in Excel to compare the census tracts by race (percentage of Black people and percentage of White people), median household income, percentage of buildings with claims (total number of claims divided by number of buildings), and the percentage of unpaid claims (number of unpaid claims divided by total number of claims). Acknowledging the two aforementioned assumptions, the percentage of buildings with claims was used to quantify flood impact for each census tract. An additional assumption was that the percentage of unpaid claims signaled which census tracts had the most survivors not receiving the aid to mitigate flood damage. This metric in particular was used to help determine inequity during the comparative analysis which is explained later on.

A threshold was created to control for census tracts that had such a small number of claims to where the percentage of unpaid claims where inflated, giving a false sense that the percentage of unpaid claims was considerably more than it was. For example, census tract 15 had three claims filed with one claim unpaid, making the percentage of unpaid claims 33%, compared to census tract 8 which had a relatively similar percentage of 29% but had 21 claims filed and six claims unpaid. Using this logic, census tracts that had percentages less than the threshold of 1% were eliminated, which in turn removed census tracts that had less than 15 claims. **Table 3** presents the remaining census tracts that were used later on for the comparative analysis.

Table 2. Census tracts and their corresponding race, income, and FEMA claim data

Census Tract No.	Census Tract ID	% White	% Black	Median Household Income	No. Buildings	No. Claims	% of Buildings w/ Claims	% Unpaid Claims
1	011303	27.6	56.5	$38,571	978	9	0.92	11
2	011304	32.0	56.4	$34,226	1,244	15	1.21	20
3	010804	7.3	91.6	$30,757	1,254	3	0.24	0
4	011102	84.7	12.5	$61,452	1,816	8	0.44	38
5	011301	61.9	34.1	$50,231	2,145	85	3.96	19
6	001100	50.1	48.2	$35,738	1,657	10	0.60	10
7	011101	61.2	35.0	$55,574	1,430	32	2.24	12
8	011202	71.6	18.6	$54,156	1,477	21	1.42	29
9	001200	92.1	6.6	$97,102	784	18	2.30	11
10	011201	90.8	7.1	$75,288	753	38	5.05	5
11	002400	84.5	4.0	$80,179	1,628	171	10.50	3
12	011603	75.8	18.5	$58,708	1,935	11	0.57	27
13	002604	35.3	54.2	$22,242	333	41	12.31	15
14	011604	84.4	9.2	$75,475	2,210	30	1.36	17
15	011701	69.3	26.5	$20,667	1,186	3	0.25	33
16	011702	11.8	85.5	$33,885	1,428	4	0.28	0

Table 3. Census tracts with percentage of buildings with claims more than 1%

Census Tract No.	Census Tract ID	% White	% Black	Median Household Income	No. Buildings	No. Claims	% of Buildings w/ Claims	% Unpaid Claims
2	011304	32.0	56.4	$34,226	1,244	15	1.21	20
5	011301	61.9	34.1	$50,231	2,145	85	3.96	19
7	011101	61.2	35.0	$55,574	1,430	32	2.24	12
8	011202	71.6	18.6	$54,156	1,477	21	1.42	29
9	001200	92.1	6.6	$97,102	784	18	2.30	11
10	011201	90.8	7.1	$75,288	753	38	5.05	5
11	002400	84.5	4.0	$80,179	1,628	171	10.50	3
13	002604	35.3	54.2	$22,242	333	41	12.31	15
14	011604	84.4	9.2	$75,475	2,210	30	1.36	17

The census tracts were then categorized by similarity in percentage of buildings with claims so that the scale of impact was similar, and thus controlled for. As shown in **Table 4**, census tracts that had percentages within 2% of each other were then grouped together so that a fair comparative analysis for each group could be implemented.

Table 4. Census tracts grouped by percentage of buildings with claims

Census Tract No.	Census Tract ID	% White	% Black	Median Household Income	No. Buildings	No. Claims	% of Buildings w/ Claims	% Unpaid Claims
13	002604	35.3	54.2	$22,242	333	41	12.31	15
11	002400	84.5	4.0	$80,179	1,628	171	10.50	3
10	011201	90.8	7.1	$75,288	753	38	5.05	5
5	011301	61.9	34.1	$50,231	2,145	85	3.96	19
9	001200	92.1	6.6	$97,102	784	18	2.30	11
7	011101	61.2	35.0	$55,574	1,430	32	2.24	12
8	011202	71.6	18.6	$54,156	1,477	21	1.42	29
14	011604	84.4	9.2	$75,475	2,210	30	1.36	17
2	011304	32.0	56.4	$34,226	1,244	15	1.21	20

Comparative Analysis

Race percentages, median income, and unpaid claims percentages were compared for each census tract group to access potential evidence of inequity. For consistency purposes, the subjective threshold of 3% was used throughout the analysis to indicate if the race, income, and unpaid claims differences between census tracts was notable enough to declare inequity. For example, if a census tract had a 2% higher Black population than the other, the comparison would signal that no racial inequity could be declared because the difference is less than 3%. Overall, inequity was determined by comparisons where there was at least a 3% difference in race/income AND the more socially marginalized (i.e. Blacker, lesser income) census tract had at least 3% higher unpaid claims.

RESULTS

Income

Out of the 12 possible comparisons that could be made, eight or two-thirds of them showed potential income inequity. **Table 5** includes the census tract pairings compared, each census tract's median household income (MHI) and percentage of unpaid claims, and the difference in MHI and percentage of unpaid claims between the tracts being compared. Referring back to

Table 5. Median household income comparisons

Census Tract Pairings	Median Household Income (MHI)	Difference in MHI	% Unpaid Claims	Difference in % Unpaid Claims	Inequity
13	$22,242	$57,937	15	12	Yes
11	$80,179		3		
5	$50,231	$25,057	19	14	Yes
10	$75,288		5		
2	$34,226	$21,348	20	8	Yes
7	$55,574		12		
2	$34,226	$19,930	20	9	No
8	$54,156		29		
2	$34,226	$62,876	20	9	Yes
9	$97,102		11		
2	$34,226	$41,249	20	3	Yes
14	$75,475		17		
7	$55,574	$41,528	12	1	No
9	$97,102		11		
7	$55,574	$19,901	12	5	No
14	$75,475		17		
8	$54,156	$1,418	29	17	No
7	$55,574		12		
8	$54,156	$42,946	29	18	Yes
9	$97,102		11		
8	$54,156	$21,319	29	12	Yes
14	$75,475		17		
14	$75,475	$21,627	17	6	Yes
9	$97,102		11		

how inequity was determined, pairings that have “Yes” in the “Inequity” column indicate that that there was at least a 3% difference in MHI between the census tracts and that the census tract with the lower MHI had at least 3% higher unpaid claims. Pairings that had “No” in the “Inequity” column did not fit both of these criteria. For example, census tract pairings 2-8 and pairing 7-14 had a higher percentage of unpaid claims for the census tract with the higher MHI (i.e. tracts 8 and 14). Pairing 8-7 had a 2.5% difference in MHI, which was less than the 3% threshold. Pairing 7-9 had a 1% difference in unpaid claims, which was also less than the threshold.

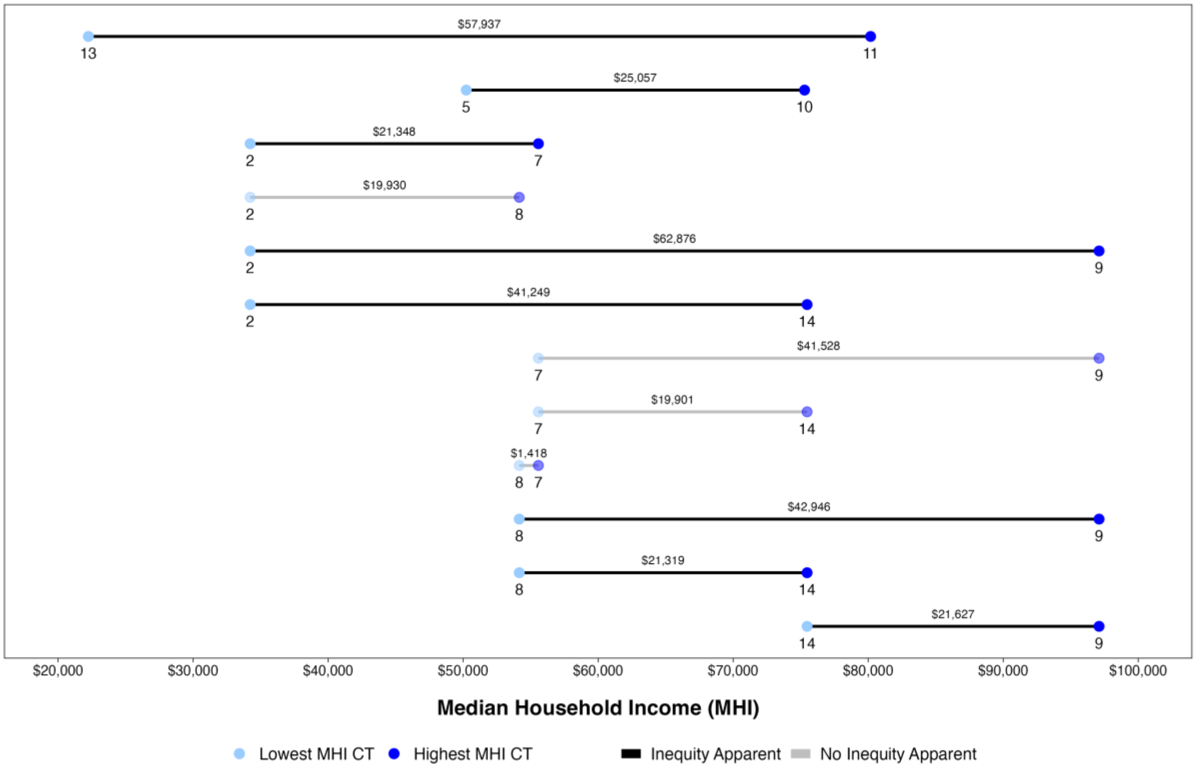

Fig. 4. Median household income (MHI) differences for census tract pairings

Fig. 4. exemplifies the MHI differences for each pairing. The light blue dots represent the census tracts with the lower MHI of each pairing, while the dark blue ones represent the census tracts with the higher MHI. The black line segments indicate pairings where inequity was declared apparent and the gray ones are pairings where inequity was not declared. The differences in MHI for pairings declared inequitable ranged from about $20,000 to a little over $60,000, with pairings 13-11 and 2-9 being on the highest end of the rage and pairings 2-7, 8-14, and 14-9 being on the lowest.

Fig. 5. exhibits the difference in unpaid claim percentages for each pairing. The faded bars correspond to the pairings where inequity was not declared. The orange bars indicate the census tracts with the higher unpaid claim percentage of the pairings, while the gray bars symbolize the census tracts that had the lower percentage. Pairings 8-9 and 5-10 had the highest percentage differences, while pairings 2-14 and 14-9 had the lowest.

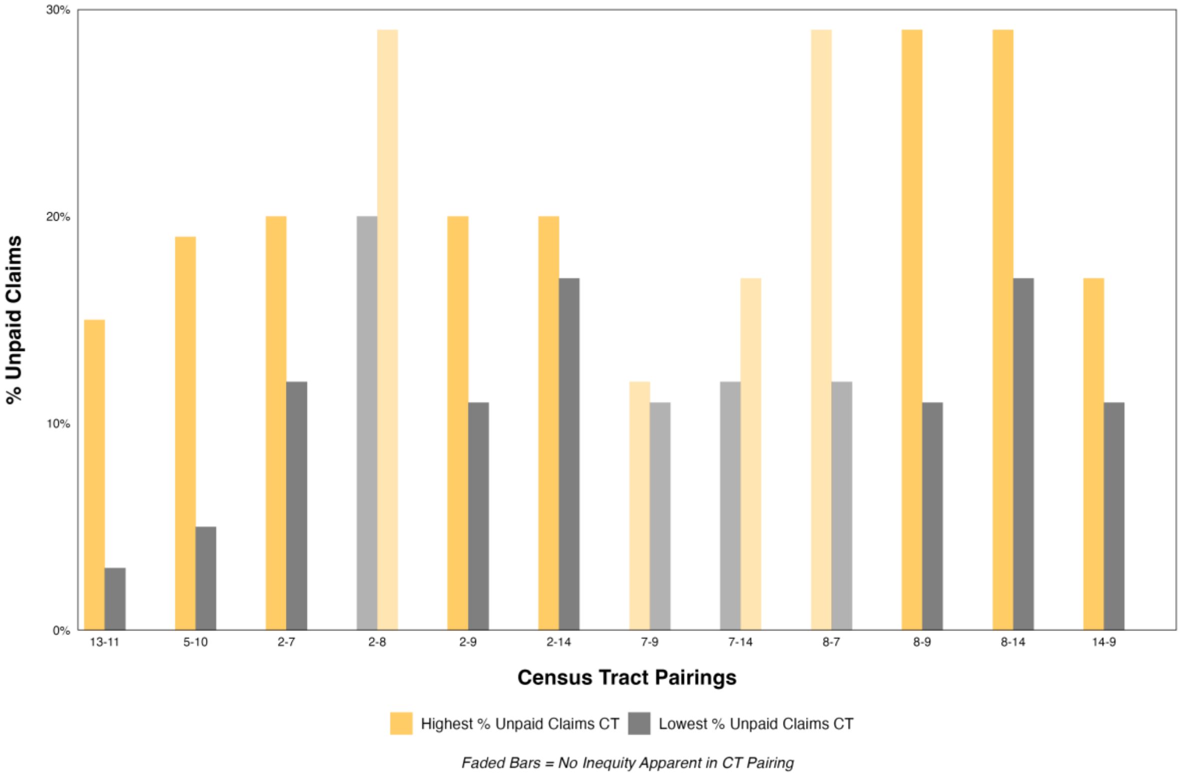

Fig. 5. Unpaid claim percentages for MHI comparisons

Race

Out of the same 12 possible pairings that could be made, seven or about three-fifths of them showed potential racial inequity. **Table 6** includes the census tract pairings compared, each census tract's Black population and unpaid claims percentages, and the differences of these percentages for each pairing. Similar to how income inequity was declared, pairings that have "Yes" in the "Inequity" column indicate that that there was at least a 3% difference in percent Black between the census tracts and that the census tract with the lower Black percentage had at least 3% higher unpaid claims. Pairings that had "No" in the "Inequity" column did not fit both of these criteria. The same pairings that were declared to not demonstrate income inequity were also declared to not show racial inequity. Again, pairing 7-9 (or 9-7) had a 1% difference in unpaid claims, which was less than the 3% threshold. The census tract with the lowest Black percentage in pairings 14-7, 8-7, and 8-2 (i.e. 14 and 8) had higher unpaid claim percentages. The only additional pairing that was not declared inequitable was 9-14, where there was only a 2.6% difference between the census tracts' Black populations, which is below the 3% threshold.

Table 6. Black population percentage comparisons

Census Tract Pairings	% Black	Difference in % Black	% Unpaid Claims	Difference in % Unpaid Claims	Inequity
11	4.0	50.2	3	12	Yes
13	54.2		15		
10	7.1	27.0	5	14	Yes
5	34.1		19		
9	6.6	28.4	11	1	No
7	35.0		12		
9	6.6	12.0	11	18	Yes
8	18.6		29		
9	6.6	2.6	11	6	No
14	9.2		17		
9	6.6	49.8	11	9	Yes
2	56.4		20		
14	9.2	25.8	17	5	No
7	35.0		12		
14	9.2	9.4	17	12	Yes
8	18.6		29		
14	9.2	47.2	17	3	Yes
2	56.4		20		
8	18.6	16.4	29	17	No
7	35.0		12		
8	18.6	37.8	29	9	No
2	56.4		20		
7	35.0	21.4	12	8	Yes
2	56.4		20		

Fig. 6. exhibits the Black percentage differences of each pairing. The light blue dots represent the census tracts with the lower Black population percentage of each pairing, while the dark blue ones represent the census tracts with the higher Black population percentage. Again, the black line segments indicate pairings where inequity was declared apparent and the gray ones are pairings where inequity was not declared. Along with having the highest MHI differences, pairings 13-11 (or 11-13) and 9-2 (or 2-9) also had the highest Black population percentage differences. Pairing 14-2 also had a relatively high Black population percentage difference, while pairings 9-8 and 14-8 had the lowest differences.

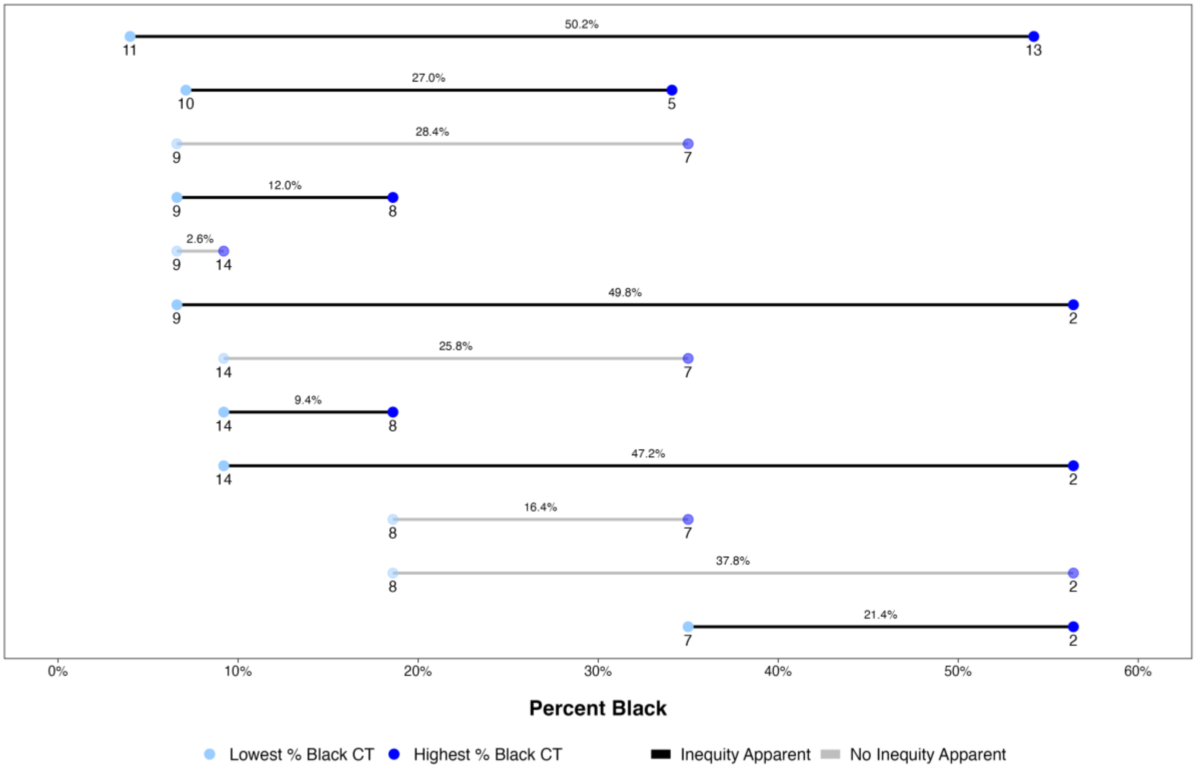

Fig. 6. Black population percentage differences for census tract parings

Like **Fig. 5.**, **Fig. 7.** shows the difference in unpaid claim percentages for each pairing. However, this time the bars for pairing 14-9 (or 9-14) is faded out because it did not demonstrate racial inequity. This now made 14-2 (or 2-14) and 7-2 the pairings with the lowest unpaid claim percentage differences.

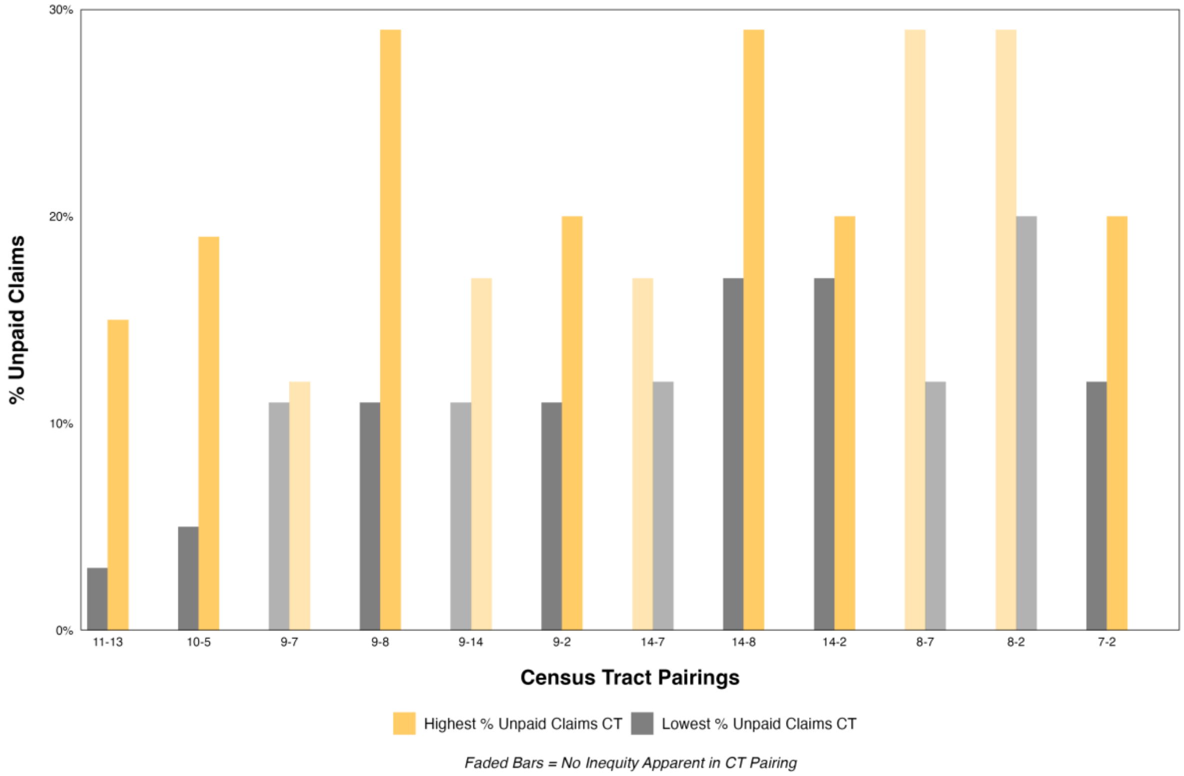

Fig. 7. Unpaid claim percentages for Black population percentage comparisons

Overall

There were 24 total comparisons made – 12 for MHI and 12 for Black population percentage. Out of the 24 comparisons, 15 or around 60% were declared either economically or racially inequitable. **Table 7** summarizes the outcome of comparing each pairing. All but five pairings showed potential for both income and racial inequity. One pairing, 9-14, only showed possible income inequity.

Table 7. Summarization of comparisons

Census Tract Pairings	Income Inequity	Race Inequity
11, 13	Yes	Yes
5, 10	Yes	Yes
2, 7	Yes	Yes
2, 8	No	No
2, 9	Yes	Yes
2, 14	Yes	Yes
7, 9	No	No
7, 14	No	No
7, 8	No	No
8, 9	Yes	Yes
8, 14	Yes	Yes
9, 14	Yes	No

DISCUSSION

When regarding unpaid claims, most of the pairings showed evidence of potential racial and income inequity, indicating that FEMA's distribution of aid after the 2015 rainfall event and dam incidents in Columbia, SC could have been inequitable. This especially could be the case for pairings 13-11 and 9-2, where the considerably Blacker and lower-income census tracts had noticeably more unpaid claims. Although more work needs to be done to be certain inequity was present, the results still spark important insights on how FEMA assistance can be inequitable. FEMA's NFIP claims dataset does not notate reasons for a claim being unpaid and there are a few policy implications related to FEMA that could explain these potential inequities, exposing more systemic social issues in disaster mitigation [30]. These implications include lack of recognition of heirs' property and high claim denial rates.

In order to receive most types of FEMA assistance for property damaged by a disaster, survivors need proof of ownership [35], [36]. Heirs' property is property that has been inherited without a legal document proving ownership such as a will [37], [38]. FEMA implemented a policy change in 2021 where additional types of documentation can be used to prove property ownership, making rebuilding assistance more accessible to those with heirs' property [37], [39]. However, before this point, FEMA claim denial rates were significantly high for heirs' property survivors of natural disasters such as Hurricane Katrina and Hurricane Maria. Heirs' property is prominent in racially minoritized and/or low-income communities because historical social marginalization has led these communities to distrust and be excluded from the U.S. legal system [40], [41], [42]. After Hurricane Katrina, nearly 20,000 heirs property owners were denied FEMA assistance due to property title issues, thwarting rebuilding efforts in New Orleans' predominantly Black, low-income communities [37], [42]. At the time Hurricane Maria struck Puerto Rico in 2017, FEMA's property ownership policy did not coincide with Puerto Rico's legal recognition of heirs' property owners, which is rooted in the country's history and culture [43]. The number of claims denied after the hurricane due to property title issues is unknown because FEMA has yet to make this information public [43]. However, the Puerto Rican organization, Ayuda Legal Huracán María, has a record of 48,000 instances where survivors had untitled property and were denied assistance [43]. Overall, FEMA's lack of historical and cultural awareness when validating property ownership has led to the exclusion of marginalized communities from disaster aid and recovery, possibly explaining the disparity in unpaid NFIP claims found in this study.

Another explanation for disproportionate unpaid claims rates within marginalized communities could be inequity in FEMA's building inspections after disasters. The NFIP claim process requires that insured survivors have building inspections to assess damage after a disaster [44]. Insureds file a claim with their NFIP provider, which initiates an adjuster visiting the building to inspect it and provide the insurer with a damage estimate. However, it has been reported that inspections introduce inequity for low-income and racially minoritized insureds. The inspections process can be slow and entails disaster survivors to manage the logistics of the adjuster's visit (e.g. contacting the adjuster, scheduling the visit, directing them to damage) [41]. This can be challenging for the insured, especially if they have been displaced to another area that is farther away and/or has limited transportation and communication (e.g. phone, email) options after the disaster – all of which would make meeting with the adjuster difficult. Due to social and financial barriers, marginalized communities have significantly less shelter, transportation, and communication alternatives. These limitations are exacerbated if they have been interrupted or destroyed during a disaster. For example, after Hurricane Harvey in 2017, data showed that claims filed by lower-income households were disproportionately declared ineligible by FEMA due to an inspector's inability to contact a survivor or the survivor missing their visiting appointment [45], [46]. Furthermore, inspectors have disproportionately misattributed damage of low-income homes as "deferred maintenance," declaring claims as ineligible due to "insufficient damage" and implying that the home was in poor condition before the disaster [41], [47]. Following Hurricane Ike in 2008, over 100,000 claims were denied by FEMA because of "insufficient damage," most of which were concentrated in low-income and racially minoritized neighborhoods in Houston [41]. Even if survivors wanted to appeal a claim denial, the process is lengthy and ambiguous, especially for marginalized survivors as they could lack the means to afford proper legal resources and/or the time to navigate such an arduous process [41]. This can in turn deter survivors from appealing, leaving them with an unpaid claim and thus without disaster aid to recover. Overall, the social inequity demonstrated throughout the inspection process provides another possible explanation for the unpaid claim disparities shown in this study.

Limitations

The term "impacted" used in this study is not all-encompassing and thus cannot capture the presence of inequity in its entirety. There could have been people impacted by resulting floods of this disaster but did not, for some reason, file an NFIP claim with FEMA. This brings into question how far-reaching FEMA assistance is and who is being excluded from it. There are also limitations related to the NFIP dataset used in this study itself, which made identifying and measuring this exclusion, or social inequity, more challenging.

A major documented shortcoming of FEMA's is that its FIRMs are not inclusive of all flood-prone communities, especially ones that are socially marginalized. The U.S. Government Accountability Office (GAO) not only found that FEMA's flood mapping investments were lower for communities with higher underserved populations, but also that these communities had more unmapped areas, less mapped areas that met FEMA's technical credibility standard, and longer mapping process cycles [48]. Supporting these findings, Flores et al. revealed that almost 1 million residents in the Greater Houston area are excluded from FEMA's 100-year flood zones, with racially minoritized groups being disproportionately overlooked [11]. FIRMs are used to assess flood risks, guide flood management, and create flood insurance rates for communities so that they have flood damage coverage [49], [50]. If flood maps for marginalized communities are non-existent and/or take longer to create, then they are not efficiently getting the information and assistance they need to prepare and recover from floods, which includes getting adequate flood damage coverage. As stated before, dam breaches are also not included in FEMA's flood maps. In addition to FEMA being more than 10 years behind on its requirement to include these inundations, state and local dam regulators, which are typically understaffed and underfunded, are expected to create and publicize dam breach inundation zones [10], [51], [52], [53]. The absence of dam breach inundations on FEMA's flood maps could further exclude communities, jeopardizing their safety and opportunities for appropriate flood preparation and recovery.

Exclusion of marginalized communities also arises from the administrative burden related to filing FEMA claims. Analyzing NFIP data from 1973 to 2019, Kruczkiewicz et al. discovered that non-White census tracts had disproportionately fewer NFIP claims, stating that lack of trust in and accessibility to the NFIP could be the reason [54]. After Hurricane Hugo in 1989, rural survivors in the Carolinas did not receive timely FEMA assistance due to mistrust and social barriers such as illiteracy, rural isolation, and lack of electronic media access [55]. High claim rejection rates can also dissuade other survivors from applying and trusting the assistance process, especially when FEMA does not clearly explain the reason for the rejection and/or is not consistent in explaining assistance protocols [56]. As mentioned before, this becomes an administrative burden for survivors who do not have the means to dedicate time and/or money to navigate FEMA's complex claim filing process. This supports why it was found that many low-income and Black survivors of Hurricane Harvey reported that they would need the most help with applying for disaster assistance and repairing home damage [57]. This need further indicates how exclusionary FEMA assistance can be and how that can be reflected in the NFIP dataset where there can be impacted individuals missing.

Another limitation of the NFIP dataset is the geographical level in which claims were recorded. For anonymity purposes, FEMA restricted the NFIP claim dataset to the census tract level [30], [31]. This in turn prohibited a robust statistical analysis as there were only nine census tracts that were used in this study compared to the numerous block groups that could have been used to indicate statistical significance between race, income, and unpaid claims data. Having a closer geographical level could have also resulted in a more thorough spatial analysis that could have better displayed the level of racial and economic disparities and more accurately pinpointed those who were impacted. Although the restrictions of this geographical level made the study's equity analysis more challenging, it led to a creative and alternative way of analyzing the claim data when statistical analysis was not a viable option. It also led to valuable insights that can be used to determine statistical possibilities for future research.

Policy Suggestions

As a form of dam failure prevention, FEMA should revise its dam funding protocol so that states can support private dam owners, who comprise 65% of dam ownership and owned the dams that overtopped and failed during the 2015 rainfall event [22], [58]. Until 2019, FEMA only funded federal dams. Now, FEMA has the High Hazard Potential Dam (HHPD) Grant Program, allowing states to apply for dam funding [59]. However, in 2020, the South Carolina Department of Health and Environmental Control (SCDHEC) claimed that funding was still an issue, preventing financial support for private dam owners [60]. Although FEMA is receiving over $600 million from the 2021 Infrastructure Investment and Jobs Act for the HHDP, it still prohibits private dam owners from being subrecipients of states awarded HHDP grants [61]. If FEMA continues to exclude private dam owners from funding, the safety of communities across the nation, including those who do not have flood preparation and recovery resources, could be jeopardized.

FEMA has made recent efforts to make disaster mitigation equitable, but more can be done to ensure true equity. In May 2022, FEMA declared that it intends to collect race and ethnicity data from survivors applying for assistance to help assess disparities and identify barriers for underserved communities [62], [63]. However, it is unclear if this data will be made public and when FEMA will start collecting it. FEMA has also expanded its ownership eligibility policies in 2021 to include more forms of documentation as proof, anticipating that this will reduce administrative burden on a low-income and rural applicants and better ensure they get assistance [63], [64]. Although this effort will make aid more accessible and inclusive, it is not known if it will be retroactive for survivors of disasters prior to 2021. A 2020 bill codifying retroactivity was reintroduced to the House of Representatives in 2022, but there have not been updates since [65], [66]. In its 2022-2026 Strategic Plan, FEMA mentions that it is prioritizing efforts for its caseworkers to contact applicants deemed ineligible for assistance and help them navigate the claims application process. This action will further address concerns with administrative burden and FEMA's claims application process [64]. It does not, however, disclose if it will thoroughly investigate prior issues with high and inequitable rejection rates. Doing so would also demonstrate retroactive justice and support for past survivors who could have been unrightfully denied assistance, especially if they are from underserved communities.

CONCLUSION

The 2015 rainfall event and dam incidents that occurred in Columbia, SC illustrated how lack of dam regulation and severe storms can lead to a disaster. Although FEMA assistance was present after this disaster, there was evidence of inequity which could have excluded racially and economically marginalized survivors from obtaining adequate recovery aid. This study used ArcGIS Pro and R to visualize and quantify the distribution of NFIP claims for the severe 2015 rainfall event and concurrent dam incidents. A comparative analysis was then conducted to identify noticeable sociodemographic similarities and differences among census tracts that were impacted. Results revealed that when the proportion of buildings with claims was similar, census tracts that were Blacker and lower-income tended to have higher percentages of unpaid NFIP claims. Although not a definite indication of inequity, the signs of inequity should encourage future research to identify how dam failures can exacerbate the impacts of flooding on marginalized communities, especially as severe storms worsen and become more frequent.

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ALABAMA & DAM SAFETY

Assessing an Additional Flood Risk in Birmingham

INTRODUCTION

When assessing the impact of a dam failure, it is desirable to have the resulting flood extent. There have been a few efforts in making the creation of these flood extents possible and more accessible. The Decision Support System for Water Infrastructural Security (DSS-WISE) was created to make dam and levee breach flood modeling and mapping open-source, more consistent, and faster [1]. However, for security reasons, it relies on state and federal dam regulatory officials to approve the user for modeling, which could take a long time. Also, there could be regulatory bodies that do not have the same resources available in DSS-WISE to make modeling more robust or possible at all. Dam regulatory agencies in California, Kentucky, South Carolina, Virginia, and Rhode Island have created their own online and downloadable dam breach inundation maps, a couple of which have used DSS-WISE to do so [2], [3], [4], [5], [6]. Other states may have these maps within Emergency Action Plans, which are documents used to identify at-risk downstream populations and how to evacuate them if the dam fails [7], [8]. However, most states do not have EAPs publicized because not every dam has one and their creation is dependent on a very arduous process that dam owners must adhere to [7]. To address these shortcomings, a universal database for dam failure inundations would be advantageous. But the closest entity the U.S. has to that could be FEMA's flood mapping products, which, as stated in the previous chapter, are more than 10 years behind in including dam breach inundations. This is mainly due to the time and resources necessary for FEMA to complete such a task.

Overall, flood extents are difficult to create for dam failures due to time, financial, and regulatory limitations. This difficulty can be compounded for states that do not have the dam safety infrastructure dedicated to create them. Alabama was the only state without dam safety program until 2023 when one was signed into law [9]. It will probably take a while before the program is running since as of March 2024 there is no direct point of contact for or additional information about the program [10]. Not having a dam safety program limits the availability of information on a state's dams, and that includes inundation maps. Without inundation maps for dam failures, additional flood risks for downstream communities can be overlooked, especially marginalized ones that already tend to be excluded in FEMA's flood maps [11], [12]. Making a predominately Black and low-income area in Birmingham, Alabama as the area of focus, the following analysis aims to implement a simpler, yet logical, way to predict additional flood risks if a nearby dam were to fail under extreme rainfall conditions.

MATERIALS & METHODS

Study Area

Birmingham, Alabama was urbanized and industrialized for its steel industry during the late 1800s through early 1900s. This resulted in more impervious surfaces that exacerbated flooding in the already naturally flood-prone region [11], [12]. As steel companies developed towns for their workers, Black workers and their families were restricted to buying houses in the most undesirable, low-lying, flood-prone areas [11], [13]. The East Lake Park Dam is located in the Village Creek watershed, which can be seen in **Fig. 1.** along with the watershed's 100-year floodplain. **Fig. 2.** shows that the majority of this floodplain is in predominately low-income, Black communities (pink). In Birmingham, the East Lake Park Dam is one of the oldest dams present, with an age that exceeds 100 years [14]. It is also classified as high-hazard (meaning it can cause loss of life) and has no associated evacuation plan, no known last inspection date, and no listed inspection frequency [15]. These facts become more alarming when considering there is no dam safety program to monitor the dam, as Alabama is the only state in the country to not have one implemented yet. If this dam were to fail, it would contribute to more catastrophic flooding for the Black community downstream that has been unfairly confined to this flood-prone area for decades. This makes the area an ideal area of study because it is urgent and necessary that the area have a flood risk assessment that considers the flooding outcome of the East Lake Park Dam.

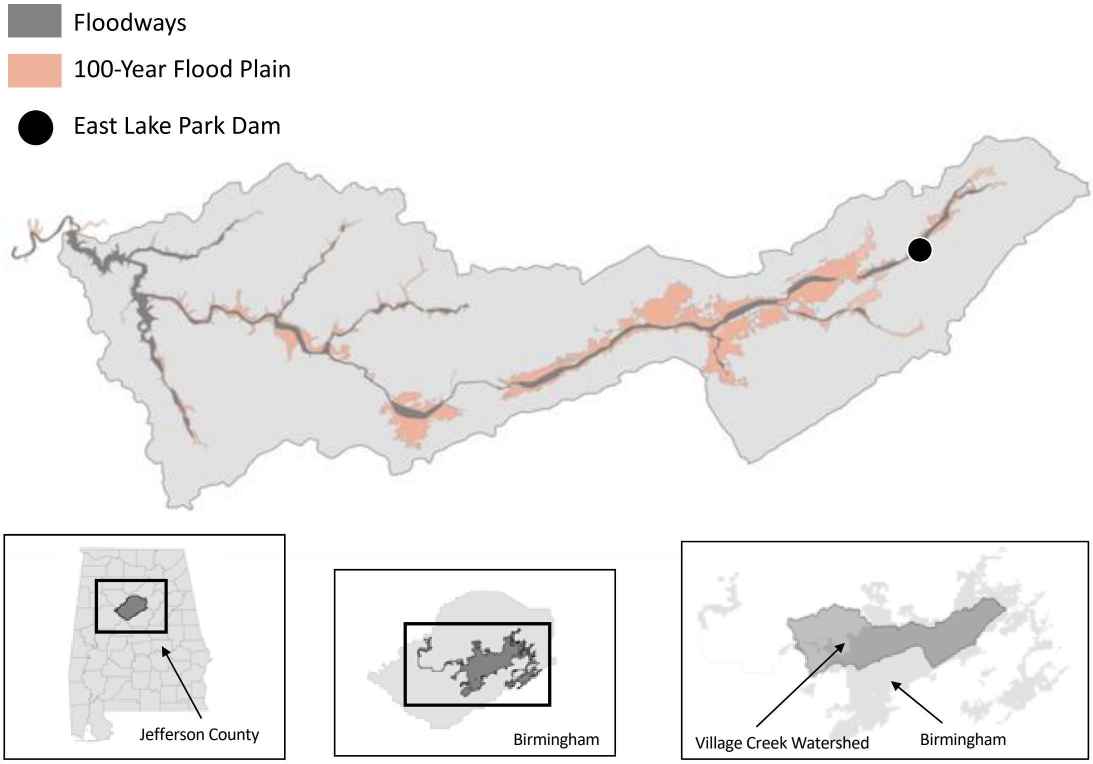

Fig. 1. Village Creek Watershed [Sources: ArcGIS Online, National Inventory of Dams, U.S. Department of Agriculture, U.S. Census Bureau]

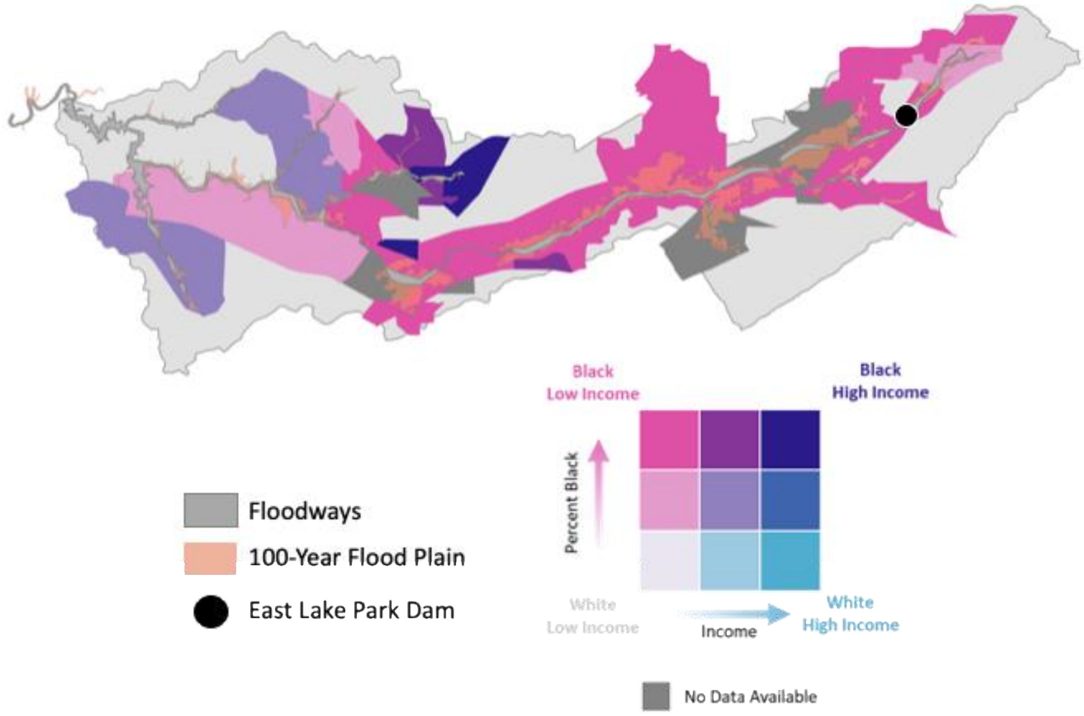

Fig. 2. Race and income demographics along 100-year floodplain
[Sources: U.S. Census Bureau, Social Explorer]

Analysis

A few reasonable assumptions were made to simplify hydrologic and hydraulic considerations and make this study possible. The first assumption is that the study area is relatively flat, indicating that elevation is similar throughout. This is supported by the topographic contours of the area which are very far apart from each other, showing that the area is mostly flat [16]. The next assumption is that enough water from the East Lake Park Dam's failure and a 100-year storm event could make the area's floodplain spread further. This is indeed possible due to Birmingham's history of severe flash floods, flood maps being outdated for current climate conditions, and there being limited dam regulation in Alabama to prepare for these conditions [17], [18], [19]. The final assumption is that the land will be flat and saturated enough during the dam failure and storm event, making floodwater easier to spread and rise. While recognizing hydrologic/hydraulic fundamentals, these assumptions set a rational foundation for determining in a simpler way to estimate which and how many buildings in the study area could be at risk of flooding.

Microsoft's Building Footprints dataset consists of U.S. building outlines by state that were computer-generated from satellite imagery [20]. Building outlines for Alabama were obtained and imported into ArcGIS Pro. **Fig. 3.** shows the building footprints in the study area that were subjectively chosen for the analysis. The buildings were selected based on their downhill proximity to the East Lake Park Dam and being along the floodway and 100-year floodplain boundaries [21]. After importing the digital elevation model (DEM) raster for the area, the

Zonal Statistics as Table tool was used to estimate the elevations (in meters) of the buildings within and outside of the floodplain and floodway boundaries [22]. This tool interpreted the building footprints as "zones", using the raster to calculate multiple statistics (i.e. maximum, median, range, etc.) for the footprints' elevations and outputting them into a table [23]. The minimum elevation was recorded for each building to be conservative and then was organized in a separate table in Excel so that it was suitable for analysis in R. Along with the elevation data for each building, the table included each building's corresponding identification number and if the building was located inside of the floodway, inside of the floodplain, or outside of both.

Fig. 3. Building footprints downstream of East Lake Park Dam and along floodway and 100-year floodplain [Sources: Microsoft, National Inventory of Dams, ArcGIS Online]

Using R, boxplots were created to represent each boundary, as shown in **Fig. 5.** The median elevation of buildings within each boundary was calculated and plotted as dashed lines. These lines served as thresholds to determine which buildings outside of the floodway and floodplain boundaries could be at the same elevation, thus susceptible to flood risk based on the assumptions explained earlier. In other words, if "Outside" buildings were within the (green and red) median thresholds of 188.97 m and 190.18 m, they were considered vulnerable to the floodway. If they were within the (red and blue) thresholds of 190.18 m and 193.78 m, they were declared vulnerable to the floodplain. The applicable "Outside" buildings had their boundaries relabeled to their newly declared ones and were imported into ArcGIS Pro to be color coded accordingly. **Fig. 4.** shows the buildings color coded before the analysis while **Fig. 6.** shows the color coding after it.

RESULTS

The analysis revealed that a total of 118 more buildings could be susceptible to flooding based on the assumptions made. Before the analysis, 235 buildings were in neither of the floodway and floodplain (i.e. Outside buildings), 54 were in the floodway, and 63 were in the floodplain. After the analysis **(Fig. 6.**), 11 Outside buildings were considered to be vulnerable to the floodway, while 107 were declared vulnerable to the floodplain. **Fig. 5.** shows that about half of the Outside buildings were around the same elevations as Floodplain buildings that are above the floodplain's median building elevation. **Fig. 5.** also shows that the building elevations are fairly close in value, supporting the assumption that the area could be relatively flat. The median elevation of Outside buildings was 193.78 m, which is almost 4 m above the median floodplain building elevation and about 5 m above the median floodway building elevation. The median elevation of Floodplain buildings is a about 1 m over the median floodway building elevation.

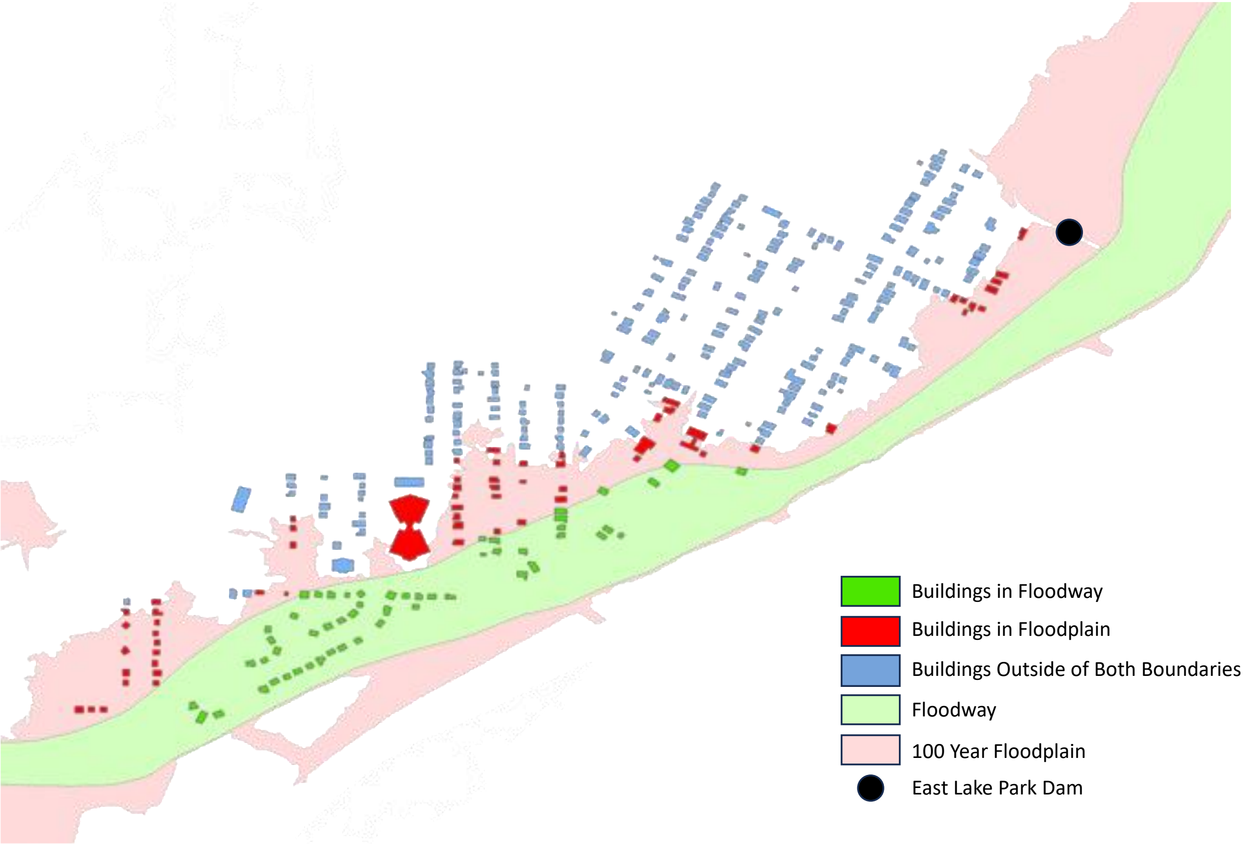

Fig. 4. Buildings color-coded by boundaries

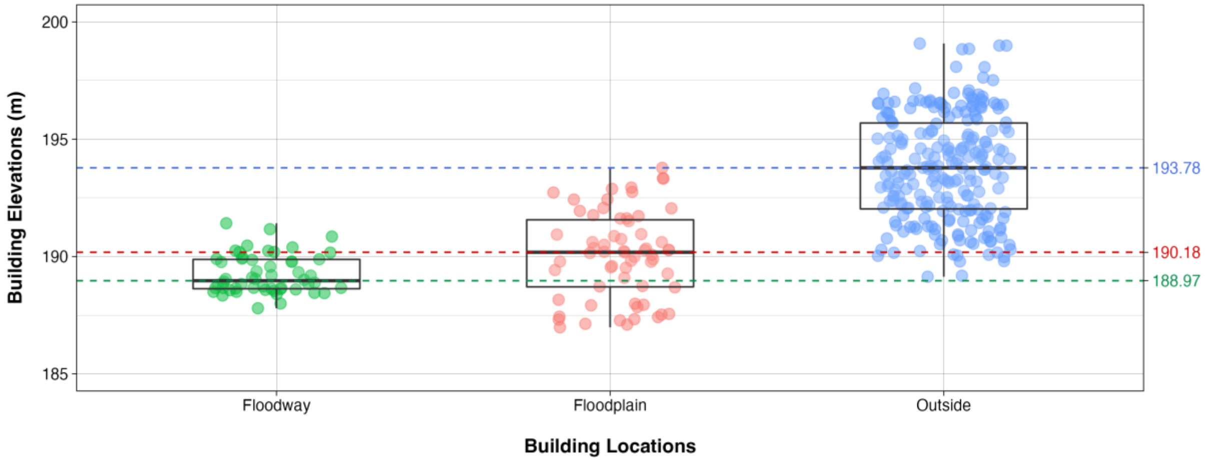

Fig. 5. Boxplots of building elevation distribution for each boundary

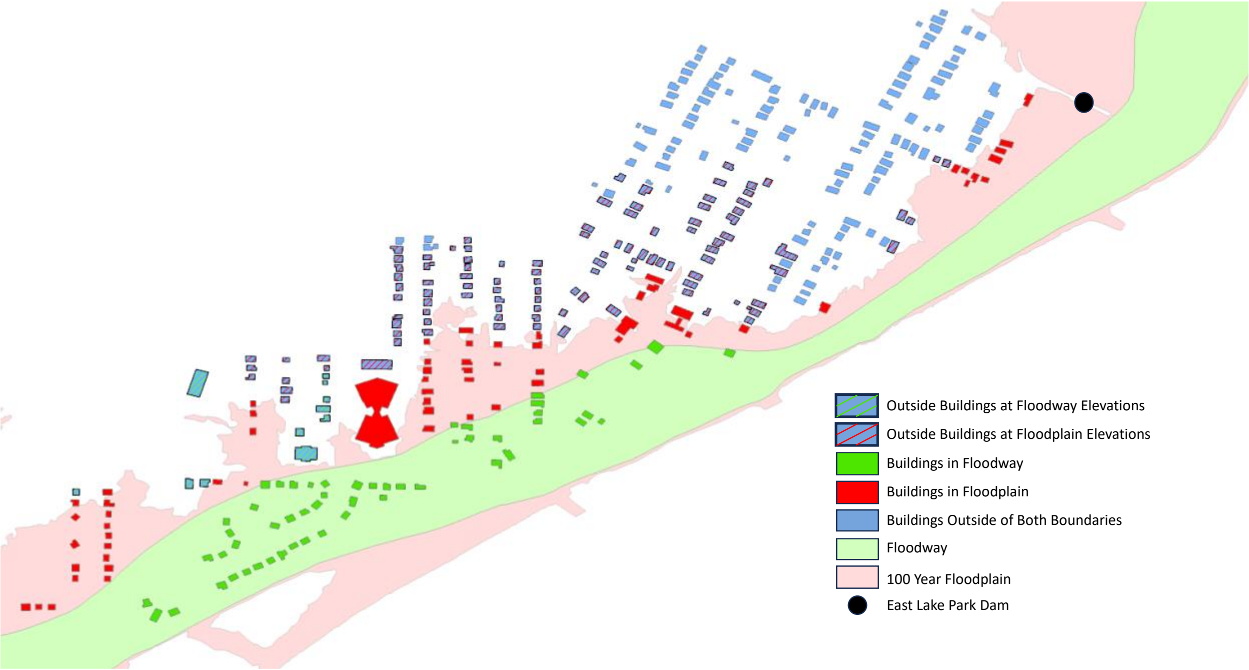

Fig. 6. Buildings color-coded after analysis

DISCUSSION

Given the aforementioned assumptions, the results of the analysis indicate that considerably more buildings downhill of the East Lake Park Dam could be vulnerable to flooding. Although not definite, this observation can provide insight on the consequences that could arise from such a situation. As mentioned before, this area is predominantly Black and low-income, suggesting that the residents there could already face financial barriers. Flood damage can quickly become expensive and arduous to repair, leaving impacted low-income communities with little choices to recover. This in turn can unjustly lead to displacement, homelessness, and stress-induced mental and physical health problems – all of which worsen financial burden [24]. The results could also indicate that more buildings should probably be within the floodplain/way, especially if climate change worsens severe storms and makes them more frequent. Exclusion from these boundaries can lead to residents being unaware that they need flood insurance, which is crucial for getting adequate flood damage assistance. However, another financial barrier would be costs as more Americans have been finding flood insurance unaffordable, especially after disasters in 2023 [25], [26], [27], [28].

Although the assumptions made make studying potential flood impact more accessible, they also simplify the complex nature of hydrologic/ hydraulic analysis. This study should in no way be used to replace the rigor and accuracy that goes into hydrologic/ hydraulic analysis. This is especially since the direction, speed, and depth of flooding – all of which determine the severity of flooding – is not accounted for in this study. If the financial and time means were available, a certified specialist would be used to create a flood extent for the hypothetical 100-year rainfall event and dam failure assumed in this study. An accurate creation of this flood extent would also be used to validate if the same buildings highlighted in this study could be impacted.

To assist in the development of universal dam breach modeling for Alabama, a policy suggestion would be to incorporate such a task in its upcoming dam safety program. Alabama is in the process of establishing its dam safety program and has even passed a bill in May 2023 that established requirements for privately-owned dams to be voluntarily inspected [29], [30]. In February 2024 there was another bill passed to enforce regular inspection of state-owned dams [29]. However, East Lake Park Dam is neither privately nor state-owned as it is owned by the city of Birmingham, which indicates local government ownership [31]. It is unclear if dam inspection provisions will be passed for local governments, but until that is apparent the East Lake Park Dam could remain uninspected. This, along with the absence of a dam breach model, prevents early detection of potential failure risks, prolonging the flooding vulnerability of the community downstream.

CONCLUSION

This analysis used fundamental hydrologic and hydraulic considerations to develop a hypothetical dam failure scenario that could result from a 100-year rainfall event. Although not definite, the results of the analysis revealed that more than 100 hundred buildings outside of the floodway/plain in a downstream Black and low-income area could be at risk for flooding. Given the hydrologic and hydraulic limitations of the scenario, more thorough analysis can be done to confirm that these buildings will in fact be impacted by flooding. Regardless, this analysis emphasized the importance of considering social inequities when creating flood maps and implementing dam regulation. If the appropriate measures are not taken to acknowledge socially marginalized groups in this regard, these groups can become susceptible to additional flood risks and the consequences that come with them.

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MISSOURI & TAILINGS DAMS

Assessing Lead Exposure for Children in Washington County

INTRODUCTION

Tailings dams are impoundments created to indefinitely store mine waste. Not much is known about tailings dams in the United States (U.S.), including where all of them are located. **Fig. 1.** is a map of known tailings dam locations sourced from several databases that record their geographical coordinates [1], [2], [3], [4]. It is not an extensive map, as each source contributes locations that the others do not have. There are also sources that report that a tailings dam exists but do not have coordinates for them. For example, the Mine Safety and Health Administration has recorded more than 1,100 sites with tailings dams with some having more than one tailings dam, pushing the total number of dams to over 1,800. The Environmental Protection Agency's (EPA) Facility Registry Service has 189 tailings dams recorded, but only 150 of them have known locations. In sum, the U.S. does not have a holistic database of tailings dam locations, potentially making it difficult to assess the effects of them on communities if they were to fail.

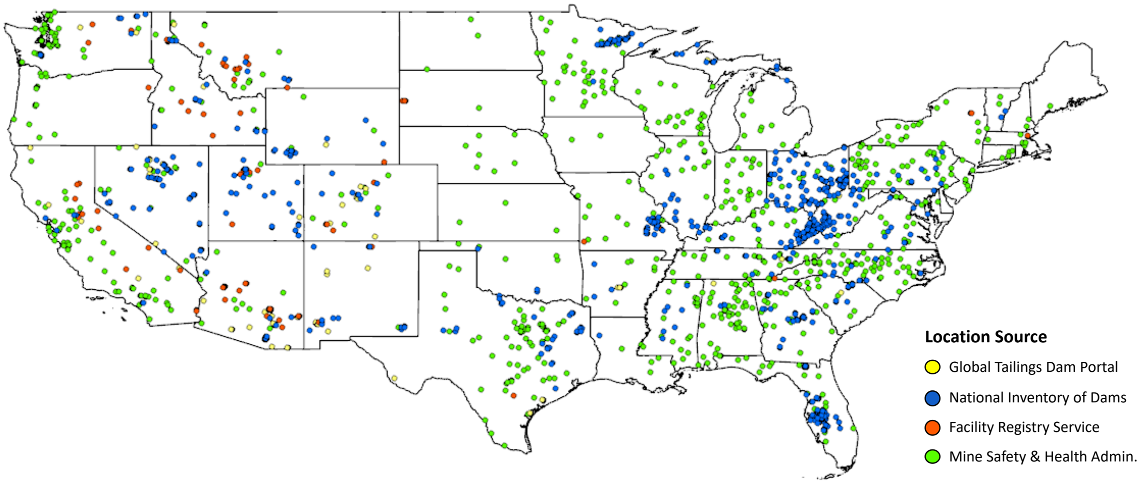


Fig. 1. Non-extensive map of tailings dam locations in the U.S.
[Sources: U.S. Census Bureau, GRID-Arendal, U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, Mine Safety and Health Administration]

Along with causing significant loss of life and property destruction, tailings dam failures can release contaminants that pollute water and soil, ruining necessary food sources and impacting human health [5], [6], [7]. However, the health risks of tailings dams are rarely considered outside of death, leaving other potential health impacts alarmingly unstudied. Furthermore, with locations of all tailings dams unclear, the connections between health and their presence are made more difficult to investigate. Southeast Missouri was used a case study to address this difficulty, as it has a lead mining district with several tailings dams that have disseminated lead via wind and rain erosion [8], [9], [10], [11]. Exposure to lead has serious health effects, especially for children who are the population of focus for this study. According to the Centers for Disease Control and Prevention (CDC), children under the age of six are at the greatest risk for health problems if exposed to lead [12]. Acknowledging this fact and that rural communities, like the ones in Southeast Missouri, tend to have limited access to healthcare resources, this study investigated a potential health impact of tailings dam failures. These failures in particular being defined by the tailings dams' inability to entirely contain the waste they were built to hold (i.e. lead mining waste).

MATERIALS & METHODS

Study Area

Southeast Missouri has a lead mining district that contains several tailings dams. This region is on the EPA's National Priorities List (NPL), which is used to guide the EPA in investigating sites in the U.S. that egregiously release hazardous pollutants. According to the EPA, wind and rainfall have eroded these dams over time, leading to leakage that has contaminated surface water and soil throughout the region, especially in Washington County where it has the most known tailings dams as shown in **Fig. 2.** [8], [9], [10], [11], [13]. Due to the relatively immense number of tailings located there, Washington County was the specific area of focus for this study.

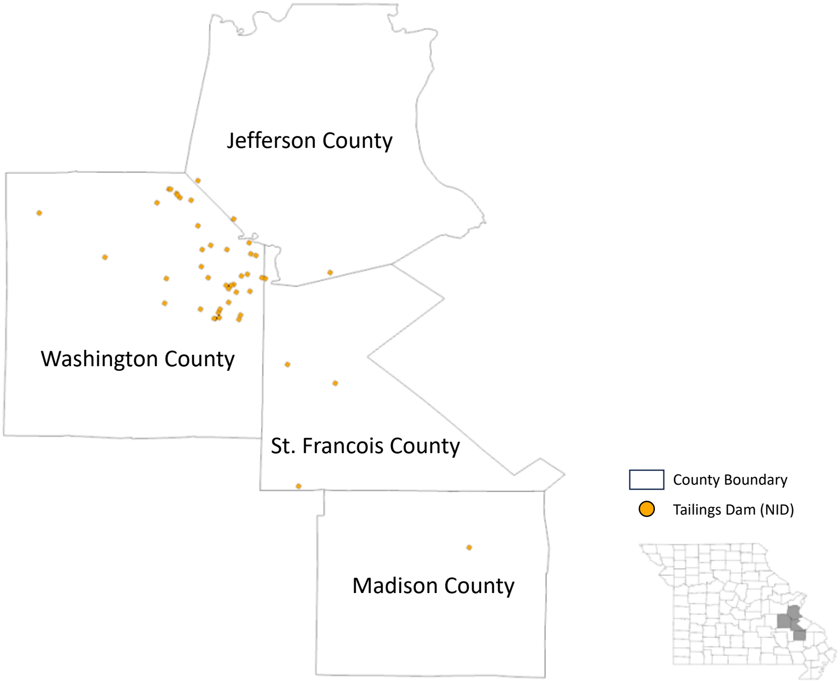


Fig. 2. Southeast Missouri Counties on EPA's NPL list and locations of tailings dams [Sources: U.S. Environmental Protection Agency and U.S. Army Corps of Engineers]

Blood Lead Level Data

Before assessing the level of contamination that has resulted from the tailings dams in Washington County, it is imperative to consider the current healthcare landscape with regards to lead poisoning and exposure. Missouri's Environmental Public Health Tracking (EPHT) program is within its Missouri Department of Health and Senior Services (MDHSS) and has a database containing blood lead level test results for the state by county from 2000 to 2019 [14]. Since children under the age of six is the population of focus for this study, the Test Outcome and Confirmed Test datasets were retrieved for children under six years old for all available years. Blood Lead Level Annual Report data from 2014 through 2018 was also obtained from MDHSS. These reports tracked the progress of Missouri's Childhood Lead Poisoning Prevention Program and summarized child testing data for each county [15]. The EPHT and MDHSS datasets were chosen particularly for Washington County and St. Louis City so that the number of elevated blood lead level tests (**Table 1**), confirmed tests (**Table 2**), and tests per year (**Fig. 4.**) could be compared between a rural area (Washington County) impacted by an atypical source of lead (tailings dams) and an urban area (St. Louis) with better known sources of lead (i.e. paint, drinking water). Specifically, these comparisons helped determine if potential healthcare inequity could be happening between Washington County and St. Louis. The MDHSS requires Washington County and St. Louis to conduct annual blood lead testing for every child under six years-old living there [16], [17]. If St. Louis had proportionately less elevated blood tests, more confirmed tests, and more tests per year, then it is possible that healthcare systems in Washington County are not as well-equipped to address and prevent lead exposure and poisoning.

Residential Lead Sample Data

In March 2023, residential lead soil samples were received for Washington County via the Freedom of Information Act from EPA Region 7, which serves Missouri. Each sample has a property ID, geographical coordinates, and soil test results associated with it. The unit in which the test results are reported vary, but all measure the lead composition of the soil sample. Each sample also has a status of either "Remediated" or "Sampled" to indicate which residential site has had their soil remediated for lead or solely sampled at the time the data was received.

The lead soil sample dataset was cleaned using R to extract and categorize relevant entries for the study. Negative entries along with entries that had errors in the units used were removed. Also removed were entries that did not explicitly use common units used in technical environmental reports involving soil – these units being parts per million (PPM) and its one-to-one equivalent mg/kg [18]. It was unknown why several residences had multiple sample entries that varied greatly in value while other residences did not. To be conservative, the entry with the highest value was taken for each unique geographical coordinate, thus each residence. Next, the samples were categorized by status (i.e. Remediated and Sampled). "Sampled" samples were further categorized by their result values. Prior to January 2024, the EPA defined soil lead concentrations above 400 PPM as hazardous for residential and high-use child areas

[19], [20]. As of January 2024, that limit has been reduced to 200 PPM. California's Office of Environmental Health Hazard Assessment set its own threshold of 80 PPM in 2017 to account for more potential lead exposure [21]. Since this study was conducted before January 2024, the result values were subcategorized by values greater than 400 PPM and values greater than 80 PPM. These subcategories helped decipher the severity levels of lead contamination in Washington County since California's threshold is 5 times less than the original EPA limit and creates another level of exposure to consider for the study area. As shown in **Fig. 5.**, heat maps were subsequently created in ArcGIS Pro to show the distribution of all samples (after being cleaned), remediated samples, samples over 80 PPM, and samples over 400 PPM.

According to Region 7, residential properties are defined as residential yards, public use areas, and high-use child areas (e.g. child care facilities, public parks, playgrounds) [13]. However, the dataset does not indicate the type of area for each entry. The indication of high-use child areas would have helped determine where children are most concentrated. As a more targeted alternative to see where children under six years-old are located, Washington County's 2021-2022 school district boundaries (**Fig. 3.**) were used in ArcGIS Pro along with the coordinates of their public and private schools [22], [23]. The National Center for Education Statistics (NCES) also has a database that contains estimates on the number of children by grade for public and private schools throughout the country [24]. Using county zip codes obtained from the Missouri Department of Insurance, the number of pre-kindergarteners, kindergarteners, and first-graders enrolled in the schools where counted for each district. Finally, **Table 3** was created in order to compare the number of lead samples per PPM category, students, and tailings dams between the school districts.

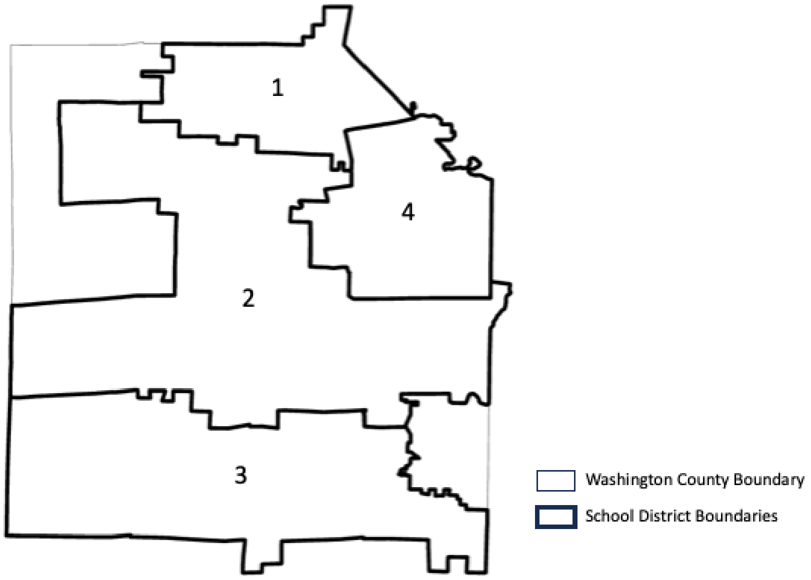


Fig. 3. Washington County school districts numbered
[Source: National Center for Education Statistics]

RESULTS

Disclaimer

In 2012, the CDC stopped using the term "elevated blood lead levels" to identify children with higher levels of lead in their blood [25]. No amount of lead is safe, especially since relatively lower levels of lead in the blood have shown cognitive effects as well [25]. With this in mind, the CDC is now using a blood lead reference value (BLRV) to determine which children have the highest blood lead levels compared to most children. However, it seems that Missouri did not take this change into account when recording its 2012-2019 EPHT datasets. The data can be explicitly organized by elevated and not elevated. In addition to the terminology change, the CDC decreased the BLRV from 5 µg/dL to 3.5 µg/dL in 2021. The EPHT datasets were recorded before this change, so the number/percent of children that tested above CDC's new recommended BLRV could not be reflected in the following results. To appropriately incorporate both the CDC's recommendation and Missouri's use of elevated/not elevated for the EPHT data, the phrase "recommended threshold" was used when referencing children who tested above the BLRV of 5 µg/dL.

Blood Lead Levels

Table 1 shows that compared to St. Louis, Washington County had a disproportionate number of children with blood lead levels testing above the CDC's recommended threshold. From 2000 to 2019, the percentage of children testing above the threshold in Washington County was about 20% higher than all of Missouri, while St. Louis was 10% higher. Even with Washington County having a smaller test population than St. Louis, Washington County still had about 10% more children testing above the threshold than St. Louis.

Table 1. Blood lead level test outcomes for children < 6 years-old (2000-2019)

Location	Total Children Tested	No. Children Tested "Not Elevated"	No. Children Tested "Elevated"	% Children Tested "Elevated"
St. Louis City	243,797	185,700	58,097	23.83
Washington	6,683	4,404	2,279	34.10
Missouri	1,646,716	1,427,856	218,860	13.29

Source: Missouri's Environmental Public Health Tracking (EPHT) program

Table 2 reveals that Washington County had disproportionately more unconfirmed tests than St. Louis and all of Missouri. A confirmed blood lead level test is one where a venous sample, verses a capillary sample, is taken [26]. If a capillary sample is initially taken and the results are equal to or greater than the CDC's recommended threshold, a venous sample needs to be taken to confirm the results. Washington County had the highest percentage of unconfirmed tests. This was about 15% more than all of Missouri and 45% more than St. Louis, both of which also had considerably larger testing populations.

Table 2. Confirmed & unconfirmed blood lead level tests for children < 6 years-old (2000-2019)

Location	No. Children Tested	No. Tests Confirmed	No. Tests Unconfirmed	% Tests Unconfirmed
St. Louis City	243,797	182,313	61,484	25.22
Washington	6,683	1,974	4,709	70.46
Missouri	1,646,716	723,683	923,033	56.05

Source: Missouri's Environmental Public Health Tracking (EPHT) program

Fig. 4. shows 2014-2018 testing rates (i.e. percent of children under six years old tested) for the state of Missouri (red), St. Louis (green), and Washington County (blue). Throughout the years, Washington maintained 30% to 40% lower test rates than St. Louis and about 10% lower rates than all of Missouri. Overall, Washington County tested around 10% of its population under six years-old every year, while St. Louis tested between 40% and 55%.

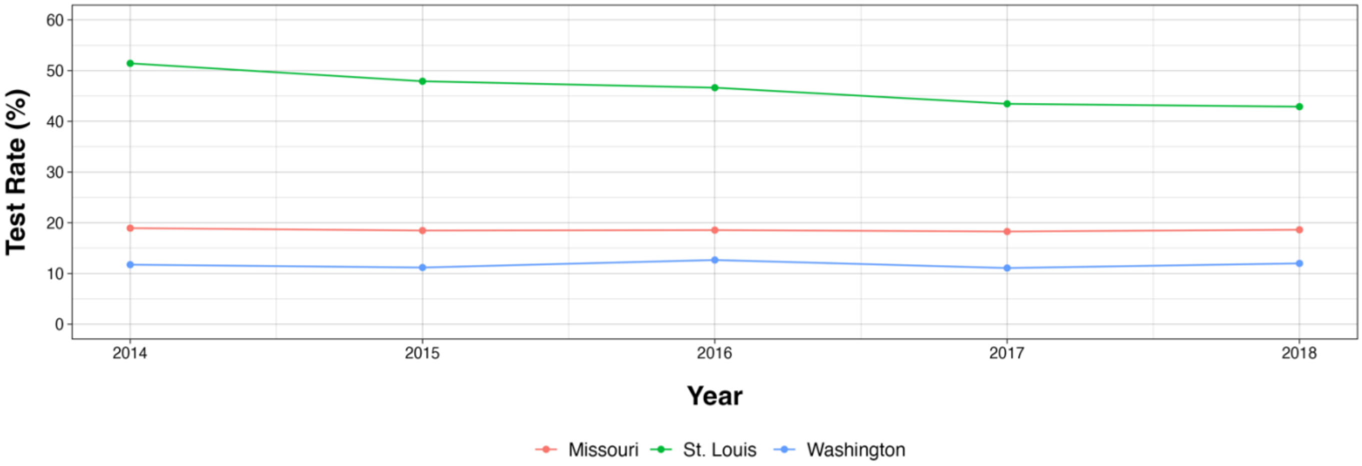


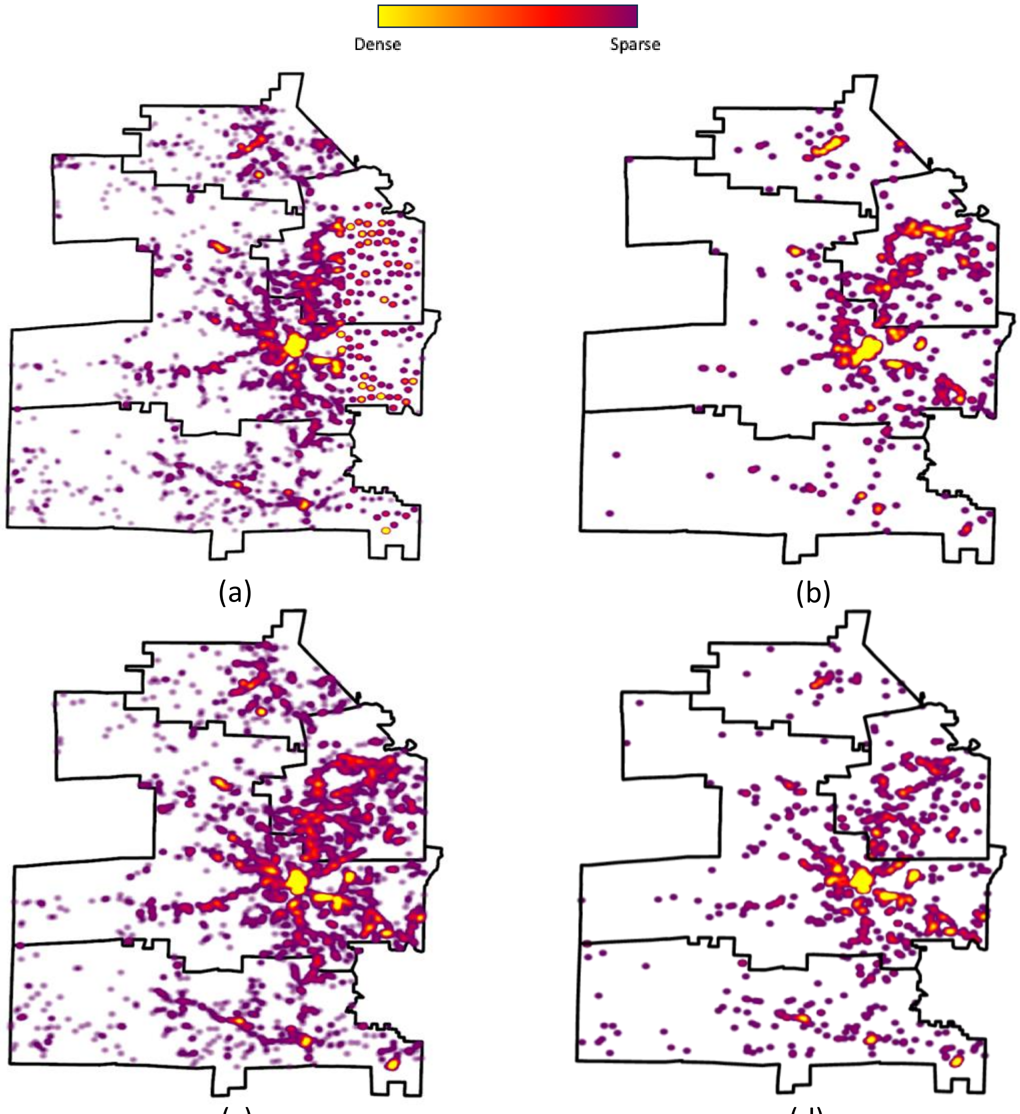
Fig. 4. Blood lead level testing rates for children less than 6 years-old (2014-2018)
[Source: Missouri Department of Health & Senior Services]

Soil Lead Samples

Fig. 5. shows the distribution of the soil lead samples throughout the school districts in 4 categories – (a) all, (b) remediated, (c) over 80 PPM, and (d) over 400 PPM. Districts 2 and 4 had

the highest density of samples. These districts also had the highest density of remediated samples. However, they also had significantly more samples over California's threshold of 80 PPM. The number of samples over 400 PPM was less dense for each district compared to samples over 80 PPM, but they were still more dense in districts 2 and 4.

Fig. 6. shows the locations of tailings dams, elementary schools, and daycares throughout the four districts. When comparing this figure with the figures in **Fig. 5.**, there seemed to be high densities of remediated samples near schools and daycares. However, there were still many tailings dams surrounding them as well as high densities of samples over 80 PPM and 400 PPM.



(a) (b)

(c) (d)

Fig. 5. Lead soil sample distributions in school districts. (a) all samples, (b) remediated samples, (c) samples over 80 PPM, and (d) samples over 400 PPM
[Source: U.S. Environmental Protection Agency Region 7]

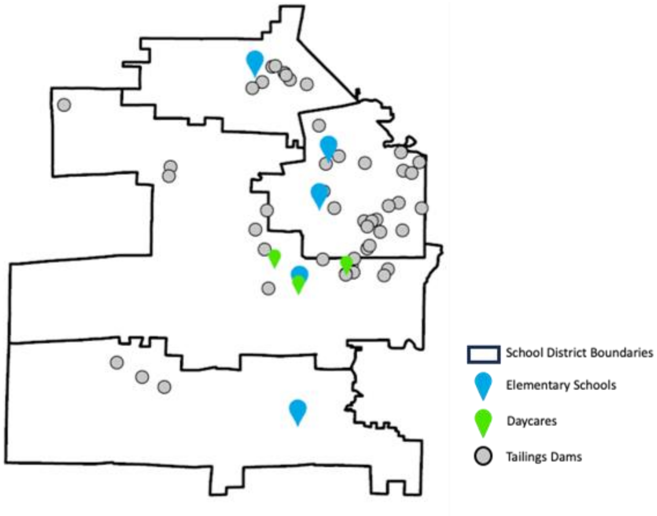


Fig. 6. Locations of tailings dams, elementary schools, and daycares in each school district [Sources: U.S. Army Corps of Engineers, Missouri Department of Health & Senior Services, Missouri Department of Elementary & Secondary Education]

Table 3 contains comparisons made between each school district regarding the number of students enrolled in pre-kindergarten through first grade, the number of tailings dams, and the number of remediated, over 80 PPM, and over 400 PPM samples. Daycares were not included in the student count because children could be attending both school and daycare. The Missouri Department of Elementary and Secondary Education (MDESE) also does not report a breakdown of age groups for licensed daycares in their childcare center database [27]. This prevented the number of children under six years-old in daycares from being deciphered. “No. Samples Not Remediated” equates to the number of all samples taken minus the number of samples remediated. “No. Lead Samples < 80 PPM” and “No. Samples < 400 PPM” are the number of samples not remediated minus the number of lead samples over 80 PPM and 400 PPM, respectively. About 18% of the 6561 samples (i.e. residential properties) were remediated. Around 91% of non-remediated properties had a soil sample over 80 PPM, which was about 64% difference from the percentage of properties with samples over 400 PPM (27%). Districts 2 and 4 had the highest number of enrolled students, samples taken, samples not remediated, samples over 80 PPM, and samples over 400 PPM. These two districts also had the most lead samples over 80 PPM and over 400 PPM, which is supported by the density maps in **Fig. 5.** In addition, they had 90% of their samples over 80 PPM as well as the highest percentage of remediated samples and the highest number of tailings dams.

Table 3. School district comparisons

District	No. Children in Pre-K, KG, & 1st Grade	No. Tailings Dams	All Samples Taken	No. Samples Remediated	% Samples Remediated	No. Samples Not Remediated	No. Samples > 80 PPM	No. Samples < 80 PPM	% Samples > 80 PPM	No. Samples > 400 PPM	No. Samples < 400 PPM	% Samples > 400 PPM
1	14	8	552	97	17.57	455	363	92	79.78	45	410	9.89
2	312	15	3592	675	18.79	2917	2714	203	93.04	945	1972	32.40
3	74	3	866	69	7.97	797	659	138	82.69	193	604	24.22
4	176	21	1551	328	21.15	1223	1174	49	95.99	271	952	22.16
Total	576	47	6561	1169		5392	4910	482		1454	3938	

DISCUSSION

Blood Lead Levels

The blood lead level test outcomes (**Table 1**) revealed that a disproportionate number of children tested above the CDC threshold in Washington County compared to St. Louis and all of Missouri. This could be because Washington County children live within the lead mining district and in close proximity to a large portion of the district's tailings dams. The disproportionality and level of exposure underscores the importance of Missouri's requirement that children under six years of age in Washington County be tested annually. However, as **Fig. 4.** demonstrates, Washington County was continuously testing children at about a 10% rate, which is alarmingly low considering the high level of exposure to lead in the county. This observation is reinforced by the CDC's claim that blood lead levels in Missouri are higher than the national average, but testing rates are low in the state's high-risk areas, which include Washington County [17], [28].

Low test rates could support the county's considerably high unconfirmed test percentages. As mentioned before, a confirmed test indicates that a venous blood sample is taken to validate the results from a capillary sample. Since the county had a high percentage of unconfirmed tests, it can be implied that capillary samples are often not being followed up by venous testing in the county. This could stem from lack of resources for or knowledge about retrieving venous samples, as a barrier for Missouri testing is gaps in healthcare provider knowledge about testing requirements [28]. Lack of resources and knowledge can also be assumed from St. Louis significantly exceeding Washington County in testing rates and the percentage of confirmed tests. Cities tend to have more healthcare resources than rural communities which could explain this disparity. Other reasons why venous testing could be low are challenges associated with following up after a capillary test. Parents could be missing venous testing appointments, as it is a common challenge in rural areas to have the resources necessary to get to healthcare facilities [29], [30], [31].

Overall, the disparities in blood lead level testing between Washington County and St. Louis is evidence of not only healthcare injustice but also environmental injustice. Both locations are high-risk areas for lead exposure. However, the rural location (i.e. Washington County) has just as much, if not more, exposure to environmental sources of lead but is lacking in testing its most vulnerable population for lead poisoning. As explained above, this could be because of limited access to and knowledge about testing requirements for both healthcare providers and the patients they serve, further emphasizing the gap in healthcare resources between rural and urban communities.

Soil Lead Samples

Although Districts 2 and 4 had the most remediated properties and properties sampled, the exposure to lead is still alarming. These districts had the most enrolled students in the targeted age group (i.e. under six years-old) while also having the most tailings dams and samples over 80 PPM and 400 PPM. Regardless of the district in question, it is also still concerning that most samples were over California's 80 PPM threshold compared to the EPA's 400 PPM threshold. This can indicate that the most vulnerable population to lead poisoning lives within communities where lead is conservatively considered hazardous.

The low percentage of properties that have been remediated is also a cause for concern, as this could slow progress of preventing lead exposure. This low percentage could mostly be a result from many Washington County residents refusing sampling and remediation of their properties [8], [9], [10], [11]. EPA Region 7 does not state a reasoning behind these refusals. However, one reason for them could be mistrust in government, a sentiment rightfully prominent in rural communities due to their historical exclusion from government healthcare and financial opportunities [32], [33]. Along with limited healthcare resources, this mistrust potentially adds another barrier to effectively eradicating lead exposure and poisoning in the region.

Limitations

The primary limitation of this study is its inability to precisely quantify the number of children under the age of six at risk of lead exposure/poisoning in Washington County. The only appropriate counts that were publicly available and within the targeted age group were for public and private schools. This excludes children too young for elementary school, children in daycares, children supervised by friends or family after or during school hours, unenrolled students, or homeschooled children. Each of these possibilities make it difficult to pinpoint where children under six years-old are located, thus challenging to assess their level of exposure. The low child blood lead level test rates in Washington County also makes assessing exposure and poisoning challenging, as more testing could help identify hazardous lead areas that could be remediated and prevent other children from getting exposed. Overall, knowing more about which children are at risk would have better helped solidify the connection of lead exposure to tailings dams.

Policy Suggestions

In September 2022, EPA Region 7 claimed that Washington County had the most samples in the lead mining district, but less than half of the residential properties that qualify for remediation have been remediated there [13]. One possible solution to this issue is providing Region 7 with more funds to remediate more frequently and efficiently, either through hiring more personnel or obtaining more testing equipment/resources. Funds could also help with increasing awareness to the public in a way that is effectively perceived as urgent and trustworthy. This could hopefully assist residents in seeing the area's lead exposure as a major risk to their health and that remediating their property's soil is a step towards combating that risk. More effective awareness could also make residents feel more encouraged to seek treatments and testing for lead poisoning. However, this is more likely to happen if more resources/funding are provided to better educate healthcare providers and equip them with the tools necessary to address lead exposure/poisoning effectively. The likelihood could also increase from making testing more accessible and affordable for residents.

A more direct and permanent solution to alleviate lead exposure in Washington County is to start gradually removing the tailings dams. Although costly and taking several years to complete, Brazil has been eliminating tailings dams since 2019 with the expectation of removing almost all of them by 2035 [34], [35]. This was a result of the 2019 Córrego do Feijão tailings dam failure in Brumadinho, which killed 270 people. According to the National Inventory of Dams, the majority of the tailings dams in Washington County are in satisfactory condition, implying that failure is not likely [4]. However, this study focuses on the seepage and spread of tailings (i.e. lead mine waste), which could be considered a form of failure since the product that these dams hold is not entirely being contained like it should. Overall, the removal of tailings would help prevent further spread of and exposure to lead, as the EPA has documented that wind and rain erosion of the tailings dams have made them primary culprits.

CONCLUSION

While unpacking a unique intersection between environmental and healthcare injustice, this study used dam, education, and health data to assess and connect two aspects that are overlooked in the U.S. – rural healthcare access and tailings dams failures. Specifically, child blood lead level test data was analyzed to bring insight on potential healthcare barriers of addressing lead poisoning and exposure in Washington County, Missouri. Data on tailings dam locations, soil lead samples, and school districts were spatially analyzed together to help identify where lead exposure could be most risky for children in the county. Findings revealed evidence that Washington County is underperforming in blood lead level testing for children compared to its urban counterpart, St. Louis. This is possibly due to less resources for healthcare providers and residents to initiate and maintain appropriate testing requirements. Findings also showed that hazardous levels of lead and several tailings dams are mostly present in school districts that enroll the most children under six years-old in the county. This further demonstrated the urgency for better testing outcomes and soil remediation rates, both of which could alleviate lead exposure and thus improve health outcomes for the region.

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CONCLUSION

Viewing social impact through an innovative lens, the studies in this dissertation used atypical methods to uncover overlooked issues surrounding dam regulation and failures. These studies also in turn provided potential evidence for racial and/or income inequities that could arise from dam failures. The first study used a novel method to quantify possible inequities in FEMA claim payouts after a severe rainfall and dam incident event. Specifically, there was evidence that when flooding impact was similar between census tracts, the majority of census tract comparisons revealed potential race and/or income inequity. The second study showed that under certain plausible assumptions, the flood risks within a low-income Black community could have severely increased if a dam upstream failed under extreme rainfall conditions. Findings presented that over 100 more buildings could be impacted by the area's floodplain which could further exacerbate the social barriers the community probably already face. Finally, the last study demonstrated a connection between a rural healthcare challenge and tailings dams in Southeast Missouri. It was found that low blood lead level testing, extreme exposure to lead from tailings dams, and low remediation rates of lead in soil pose strong potential indicators of healthcare and environmental injustices for the region. Overall, this dissertation serves as a catalyst to bring concepts from environmental justice to the civil engineering field through the consideration of more social and policy implications of dams, especially since these three studies underscore that lack of appropriate dam regulation could diminish the safety of marginalized communities.