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## Future flooding increases unequal exposure risks to relic industrial pollution

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E-mail: [twm9710@nyu.edu](mailto:twm9710@nyu.edu)**Keywords:** environmental inequality, flood risk, legacy pollution, social vulnerability, climate changeSupplementary material for this article is available [online](#)

## Abstract

Climate change is increasing the probability that urban communities with lengthy histories of land-based industrial pollution and ongoing residential segregation will experience more frequent and destructive flooding in the years ahead. This paper investigates where these past, present, and future forces will converge to potentially produce a new type of climate injustice, as the flooding of former, or ‘relic,’ industrial sites threatens to transport sequestered industrial contaminants off site. Merging property-level flood-risk projections from the First Street Foundation with historical data on former hazardous manufacturing facilities in 6 U.S. cities, we identify more than 6000 relic industrial sites with elevated flood risk over the next 30 years. Exploratory spatial analysis reveals that these sites cluster spatially to create identifiable zones of cumulative impact, within which as many as 560 thousand residents and 229 thousand housing units are currently located. Spatial multilevel modeling further indicates that socially vulnerable groups (i.e. racial minorities, those with lower incomes, and those residing in less autonomous housing) are consistently and disproportionately likely to live in these areas. These findings highlight the need to develop new strategic plans to rethink site-based strategies of remediation and to engage residents of historically marginalized communities in planning efforts as government agencies at all levels work to make their cities more resilient and environmentally just in the age of climate change.

## 1. Introduction

This study investigates whether and where climate change is likely to increase residential exposure to hazardous chemicals through the flooding of former, or ‘relic,’ industrial sites. These are sites where toxic contaminants from prior industrial uses are likely to be buried in the soil or suspended in the groundwater, posing significant health risks to humans and other living organisms (Sengul *et al* 2012, Muller *et al* 2018, Wodtke *et al* 2020). Climate change can spread and magnify exposure to these land-based contaminants by increasing the frequency and intensity of local flooding (Masson-Delmotte *et al* 2021, ch 11) that mobilizes those contaminants on-site and spreads them to nearby parcels (Ponting *et al* 2021). These dynamics are especially pertinent in socially

marginalized urban communities, where sites of hazardous industrial production have historically concentrated (Salazar *et al* 2019) and now face increasing flood risks (Buchanan *et al* 2020, EPA 2021, Tate *et al* 2021, Wing *et al* 2022). The result, if confirmed, would be a new kind of climate injustice emerging at the conjunction of past pollution, ongoing social inequities, and future flooding, calling for a new kind of policy thinking and action.

One reason these developments have received little attention to date is that environmental justice research typically measures residential proximity only to known hazards such as waste disposal sites and industrial facilities documented in government databases (Mohai *et al* 2009). While research has used these databases to document many inequitable risks and exposures (Taylor 2014, Muller *et al* 2018,

Banzhaf *et al* 2019), their 1980s starting-point renders associated analyses historically incomplete and thus prone to bias (Downey 2003). One study utilizing more comprehensive manufacturing site data back to the 1950s finds that contemporary government databases miss more than 90% of relic and active sites of hazardous industry operating since World War II (Frickel and Elliott 2018; see also Marlow *et al* 2020).

Meanwhile, cities where these sites disproportionately concentrate remain highly segregated owing to a number of cross-cutting historical forces that include Jim Crow laws, discriminatory redlining practices in real estate markets, and urban renewal. A recent report from the University of California-Berkeley indicates that of the 113 U.S. cities with populations over 200 000, only two are racially integrated (Menendian *et al* 2021)<sup>4</sup>. And, most have grown more rather than less racially segregated since 1990<sup>5</sup>. Similar trends are also occurring along economic lines (Reardon and Bischoff 2011)<sup>6</sup>. As a result, past social inequities linger on in place, threatening to intertwine with rising urban flood risk that the National Academies of Sciences identifies as one of America's leading climate challenges (National Academies of Sciences, Engineering and Medicine 2019; see also Masson-Delmotte *et al* 2021; see Mallakpour and Villarini 2015).

To scope the risks presented by the intersection of urban flooding, residential segregation, and past industrial activities, our analyses combine for the first time address-level data on relic sites of industrial production operating in sectors known to release toxic contaminants to on-site lands with address-level data on future flood risks. We integrate these data for six U.S. urban areas selected to maximize variation in local industrial, social, and flood contexts. The aim is to determine if general patterns emerge, not only in the geographic extent of probable exposures but also in their inequitable distribution across local communities of varying racial, economic, and housing status in ways indicative of a new era and type of environmental injustice.

## 2. Data and methods

The six urban areas we analyze include: the Providence metropolitan area of Rhode Island; Harris County, Texas, which contains most of the city of Houston; Philadelphia County, Pennsylvania; Multnomah County, Oregon, which contains most of the city of Portland; Orleans Parish, Louisiana, which

contains most of the City of New Orleans; and Hennepin County, Minnesota, which contains most of the City of Minneapolis. Like most U.S. urban centers, these six areas have experienced significant industrial development and documented site-based legacy contamination (US EPA, O 2015). Located near coasts or along major rivers, they also illustrate a range of local flood scenarios and patterns of residential segregation.

### 2.1. Relic industrial site data

We collected address-level data on relic industrial sites in sectors that regularly report on-site hazardous waste releases. We used state manufacturing directories<sup>7</sup> covering every 2–5 years from 1953 to 2010, excluding facilities still in operation after 2010 to spotlight relic sites that are no longer visibly active (Frickel and Elliott 2018, Berenbaum *et al* 2019). We exclude addresses containing P.O. boxes to avoid non-industrial headquarter sites. One limitation of focusing on relic sites detected from manufacturing directories is that we do not know the true presence or significance of contamination on respective sites. Furthermore, there may be heterogeneity across cities in toxic risk due to differences in the types of hazardous chemicals left behind and how they were deposited into on-site lands. To minimize this uncertainty, we select only relic sites in industrial sectors identified as having a high probability of historical onsite contamination known harmful to humans (Noonan and Vidich 1992). Those sectors include chemicals and allied products, petroleum and coal products, rubber and plastics products, stone/clay/glass and concrete products, primary metal production, fabricated metal production, machinery and computer products, and transportation equipment manufacturing. In Noonan and Viditch's study, the probability of site contamination in these sectors ranges from 80% to 95%. In Providence only, we also include jewelry manufacturing, which dominated local industry during much of the 20th century, utilizing heavy metals as well as polyvinyl chloride and other organics. The result is an address-level database of 15 419

<sup>4</sup> 'Most to Least Segregated Cities in the US, 2019', <https://belonging.berkeley.edu/most-least-segregated-cities>.

<sup>5</sup> 'Change in Segregation, 1990–2019', <https://belonging.berkeley.edu/change-segregation-1990-2019>.

<sup>6</sup> For data and details, see: Kendra Bischoff and Sean F Reardon. Residential Segregation by Income, 1970–2009. US2010 Project. (October 2013).

<sup>7</sup> Directories of manufacturers are print directories produced regularly since the 1950s by a variety of private publishers and public institutions, typically using data from state business tax records. The consistent intent across all directories is to provide a comprehensive inventory for entities looking for manufacturers to produce their goods. Directories include basic firm information such as location, industrial sector, the products produced, and the number of employees. Print manufacturing directories are often available in local libraries and in the Library of Congress. Researchers also increasingly have access to manufacturing and city directories via digitization projects like the Internet Archive. For example, North Carolina's 1990 manufacturing directory is viewable at <http://archive.org/details/northcarolinaman1990nort>. For a full description of the methods used for extracting data from directories see the semi-automated approaches described in Berenbaum *et al* (2019), Bell *et al* (2020) or alternatively, the manual approach of Frickel and Elliott (2018).

unique sites where hazardous industries operated but are no longer active across the six study areas.

## 2.2. Flood risk projections data

To estimate the future flood risk of relic industrial properties, we use site-specific flood risk projection data from the First Street Foundation (FSF). To produce these projections, FSF uses a combination of 21 global climate models under the middle Intergovernmental Panel on Climate Change (IPCC) RCP 4.5 emissions scenario while considering a range of high (75th percentile) and low (25th percentile) scenarios. They also incorporate a baseline climate period of 1980–2010 and incorporate data on historical flood events (First Street Foundation 2020b). FSF flood modeling methodology was independently reviewed and has since been used by the U.S. Environmental Protection Agency (EPA) in their 2021 report on evaluation of social vulnerability during climate change (EPA 2021). Compared to Federal Emergency Management Agency (FEMA) estimates of property flood risk, the FSF identifies many more properties in the United States at risk (First Street Foundation 2020a).

Using this methodology, FSF calculates a Flood Factor (FF) for each property. The FF is an integer between 1 and 10 that captures the likelihood and severity of flooding by 2050, with 1 representing minimal risk and 10 representing extreme risk (First Street Foundation no date). The number increases as the probability increases or as the depth increases, or both. We identify properties with a value of three or higher as being at an elevated risk of future flooding (i.e. what FSF characterizes as ‘moderate risk’ or greater). At this threshold, a property at ‘moderate risk’ ( $FF \geq 3$ ) has at least a 6%–12% chance of flooding by 2050, or a good chance of flooding to a depth of 6–9 inches by 2050.

## 2.3. Residential socio-demographic data

To measure social inequities in exposure, we use demographic data from the U.S. Census Bureau (US Census Bureau no date). Block counts of population and households as well as land area come from the 2010 decennial census. Block-group racial, economic, and housing compositions come from the American Community Survey 2015–2019 five-year estimates. With those data, we follow the Center for Disease Control and Prevention’s (CDCs) Agency for Toxic Substances and Disease Registry to construct several multi-item measures of social vulnerability (Center for Disease Control 2021). The CDC developed their measure of social vulnerability to incorporate multiple neighborhood characteristics, grouped into key vulnerability themes (see table 1). The first theme captures the socioeconomic status (SES) of a place. The second focuses on racial composition, and the third, housing conditions. Table 1 displays the census variables included in each multi-item theme, or measure.

Following the CDC’s approach, each variable is first converted to a percentile rank relative to other block groups in the same city. Where necessary, ranks are inverted by subtracting their values from one so that *larger values always indicate higher vulnerability* (i.e. a higher SES vulnerability score indicates lower SES; and, a higher housing vulnerability score indicates lower housing quality). Next, the percentile ranks of variables associated with each theme are summed, and that total is given its own percentile rank. The effect of this additive-ranking approach is that each variable for a given theme is given the same weight, and the final theme score then ranges from 0 to 1, with values closer to 1 indicating greater social vulnerability relative to other block groups in the same city. Unlike the CDC, we keep the theme scores distinct to evaluate their unique association with elevated flood risk on relic sites. Consistent with Marino and Faas (2020), we caution against interpreting these scores as essential, immutable traits of the communities they describe. Instead, we conceptualize these metrics as indicating where historical inequities have produced contested sites of struggle for contrasting articulations of risk and visions of local futures. In this way, the scores approximate the status and resources of residents to be engaged *now* in planning for future flooding; they are not a projection of who will be present in those areas when future flooding occurs.

## 2.4. Methods

For each study area, we perform a series of analyses. We begin by merging the binary, address-level indicator of elevated flood risk (yes/no) to each address-level relic industrial site to reveal the number and proportion of such sites at elevated flood risk over coming years. Next, we use kernel-density maps to show where those sites cluster spatially. Then, we identify the number of individuals and households at different scales of nearby exposure risk. We conclude with a series of regression analyses to explore the relationship between social vulnerability and the probability of a block group having at least one relic industrial site at elevated flood risk. Because diagnostics reveal spatial dependence in that probability (see Anselin and Li 2019), all models are estimated using an intrinsic conditionally autoregressive process (Besag *et al* 1991) based on a first-order queen contiguity weights matrix. This specification is a common way of modeling spatial dependence via a spatially structured random effect.

Our statistical analysis then proceeds in three steps. First, we fit a pooled spatial multilevel model to evaluate the average relationship between the probability of a block group containing a flood-prone relic site and respective vulnerability indicators (see Dong and Harris 2015). In addition to the spatial random effect, our spatial multi-level model accounts for city-level covariance as an independent and identically distributed random effect. We then use this model to

**Table 1.** Social vulnerability themes and associated census variables at the level of block groups.

Social vulnerability	Theme 1: Socioeconomic status (SES)	Theme 2: Minority status	Theme 3: Housing status
Census variables	<ul style="list-style-type: none"> <li>• % below the poverty line</li> <li>• % unemployed</li> <li>• % with H.S. degree or less</li> <li>• Median household income</li> </ul>	<ul style="list-style-type: none"> <li>• % non-white</li> <li>• % speak English 'Less than well'</li> </ul>	<ul style="list-style-type: none"> <li>• % housing units in multi-unit structures</li> <li>• % housing units that are mobile homes</li> <li>• % housing units that are crowded</li> <li>• % households without a car</li> <li>• % group quarters</li> </ul>

predict the probability of a block group containing a flood-prone relic site over the full range (0–1) of each measure of social vulnerability. In a second analysis, we fit each study area separately (still controlling for spatial dependence) to evaluate the heterogeneity in our effects across cities (see figure 4(b)). Finally, to assess the cumulative effect of vulnerability across multiple themes, we estimate the probability of block groups containing a flood-prone relic site under two scenarios. In the first scenario, all three themes are set to the 90th percentile (i.e. the most vulnerable populations). In the second scenario, all three themes are set to the 10th percentile (i.e. the most privileged populations). All models are estimated using Integrated Nested Laplace Approximation (Rue *et al* 2009, 2017) via the R programming language (R Core Team 2020).

### 3. Results

#### 3.1. Relic sites of hazardous industry at elevated flood risk

Analysis starts with an assessment of relic sites with an elevated probability of flooding by 2050 (figure 1). In total, we identify 6636 such sites across our six study cities. While the actual pollution on each site is unknown, the sheer number extends beyond known contamination lists such as the EPAs National Priority List. In Houston's Harris County, for example, there are 15 state and federally recognized superfund sites identified by the Government Accountability Office as being at risk of future flooding (GAO 2019). By comparison, results in figure 1 indicate that there are 1985 relic industrial sites at elevated flood risk. Even Minneapolis's Hennepin County, with the lowest count of flood-prone relic sites in our study, has 436. In addition, figure 1 indicates the proportion of relic sites at risk of projected flooding. Here we see that all of the 733 relic sites in New Orleans are at risk, compared with a low of 19% of relic sites in Minneapolis. Supplemental information figures 1 and 3 describe the presence of flood-prone relics in cities using higher probability and impact FF thresholds. Even with these more extreme cutoffs, numerous sites remain at risk, demonstrating that the results are not an artifact of low probability flooding.

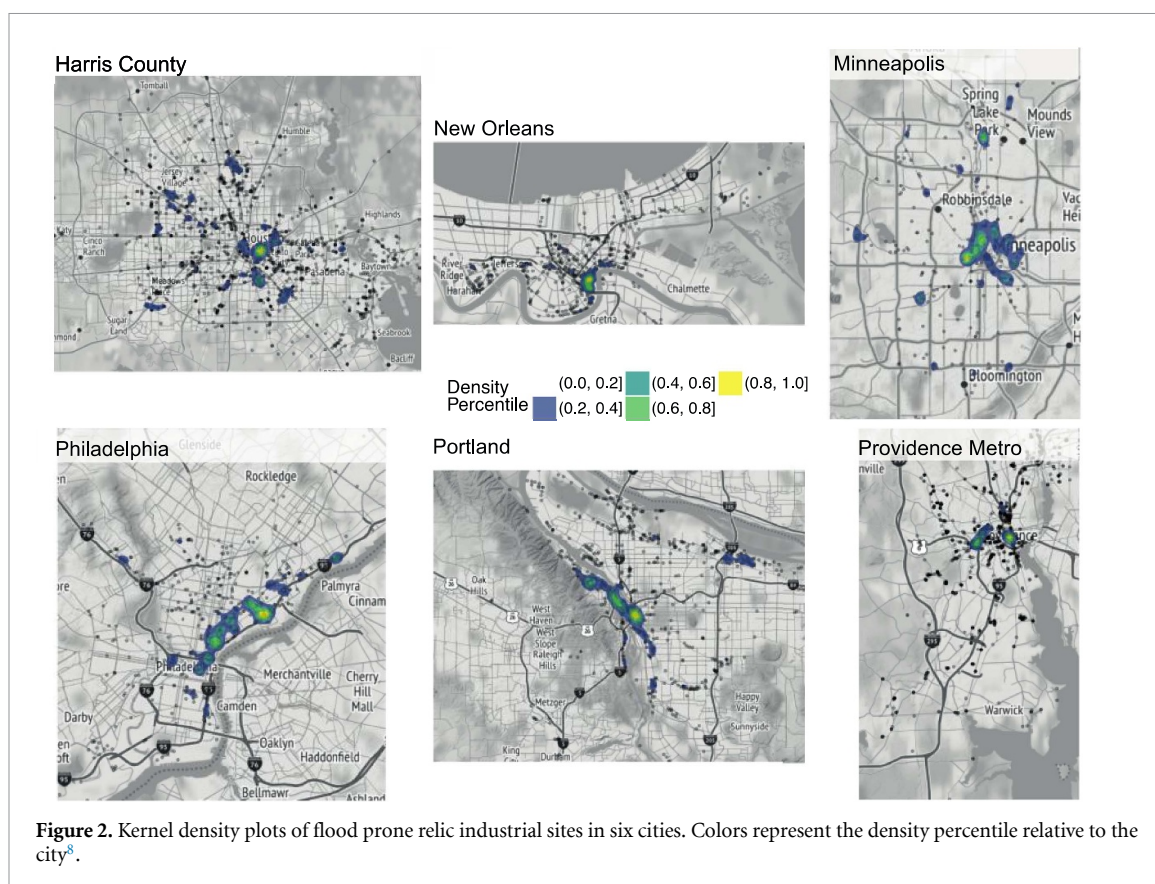
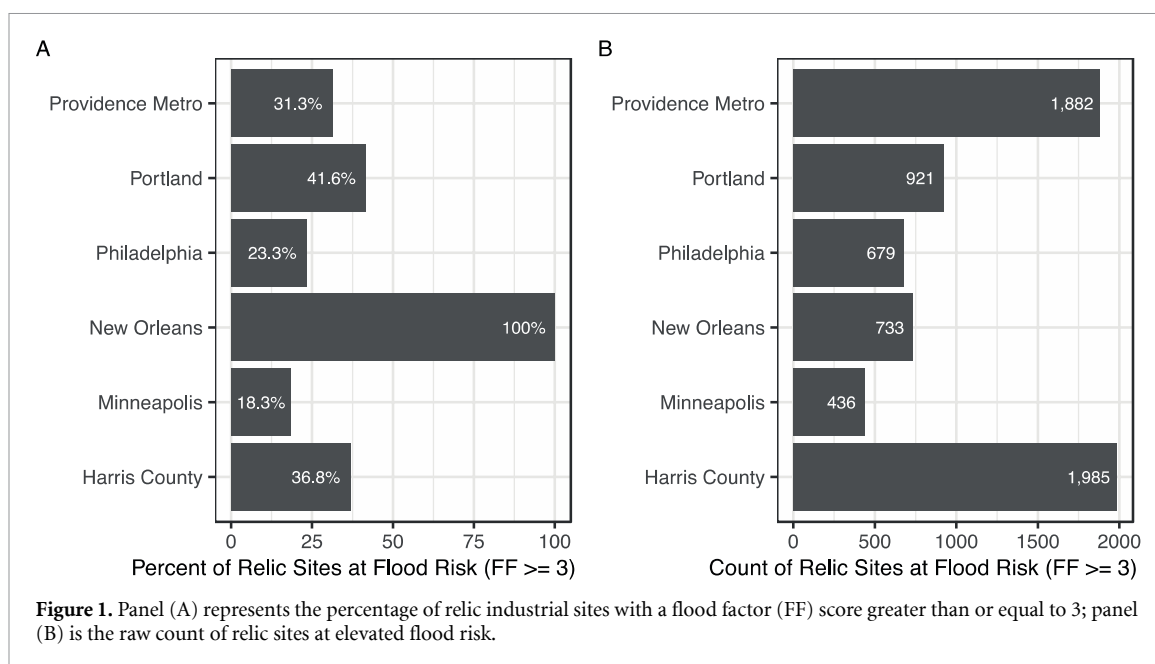
#### 3.2. Zones of elevated exposure risks

As analysis extends to include not just well-documented superfund sites but also the multitude of less-known formerly industrialized sites, understanding of exposure risks changes. Figure 2 illustrates this point using kernel-density maps to show where flood-prone relic sites cluster in each study area. Results indicate that, despite different local histories and hydrological contexts, each city has clearly identifiable zones where large numbers of relic sites face elevated future flood risk from climate change. Moreover and regardless of the city, these zones are consistently located near downtowns where industry once thrived and low-income communities historically settled and established lasting attachments to place.

#### 3.3. Population and housing exposures

In considering human exposures to relic sites of elevated flood risk depicted in figure 2, there is no correct way to count the number of residents and housing units potentially impacted. Different contaminants respond differently to flooding, and local hydrology influences where respective contaminants will spread in varying concentrations (see Martin *et al* 2021). In addition, most residents are not confined to their homes; instead, they walk about their neighborhoods and sometimes, when necessary, wade through local flood waters. As a result, there are multiple, nested scales of exposure risk. The most spatially proximate is at the block level, where a resident's home and one or more relic sites both face elevated flood risk. At this scale, flood waters can create a direct, hydrological plain that transports land-based contaminants from a flooded relic site to the flooded home nearby. Scaling outward on the same block, there may also be homes that do not face elevated flood risk. For them, flooding of a relic site on the same block may not bring contaminants directly to their home, but daily activities on the block could still result in direct exposure as well as indirect exposure to underground plumes that shift and expand as local flood waters saturate local soils. Extending outward, we can also count homes in the surrounding block group, a unit of census geography that can

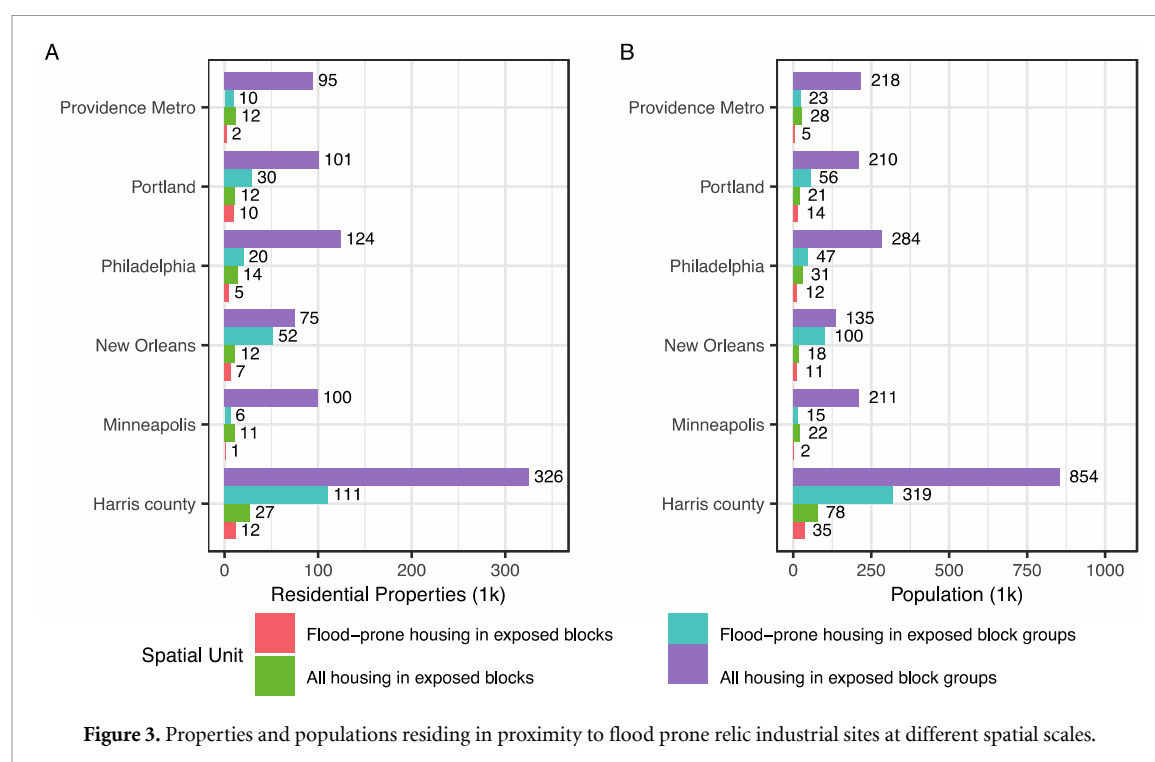




include as few as two to three blocks in densely settled urban areas. Those homes can then be subdivided by whether they also face elevated flood risk (yes or no).

<sup>8</sup> All points in figure 2 indicate relic industrial sites at elevated flood risk. The colored zones do not respect the boundaries of the FEMA-designated flood plain; they are based solely on the location of relic sites at elevated flood risk ( $FF \geq 3$ ).

To count the number of residents and housing units at each of these four, nested scales of exposure risk, we use the same FF cutoff score ( $\geq 3$ ) for residential addresses as for relic industrial sites. Figure 3 shows that even at the smallest geographic scale (flood-prone homes on blocks with flood-prone relic sites), the exposure risks are notable. At the low end, Minneapolis has approximately 2000 residents living in 1000 homes. At the high end, Houston



has approximately 35 000 residents living in 12 000 homes. As analysis scales out to include all homes and residents in block groups with one or more flood-prone relic sites, these numbers increase noticeably. In Minneapolis, they rise to approximately 211 000 residents living in 100 000 homes; and in Houston, they rise to approximately 854 000 residents living in 326 000 homes. Even in New Orleans, with the smallest residential exposure counts in our study, approximately 75 000 people (or 22% of city's current population) live in a block group where a relic industrial site faces elevated flood risk from climate change.

### 3.4. Social inequities in exposure risk

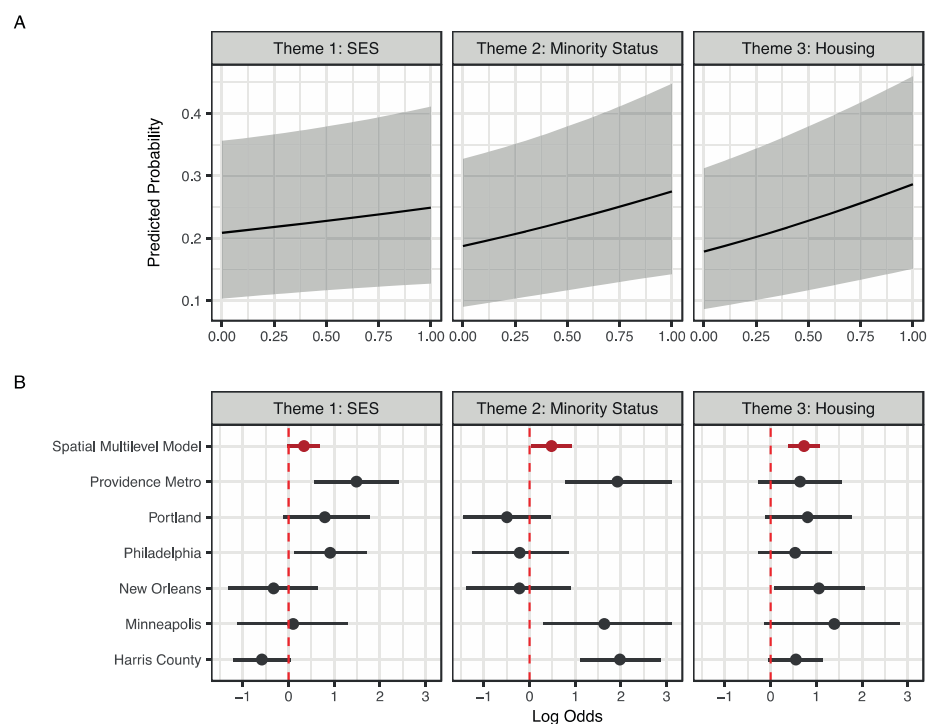
To assess social inequities in exposure risks, we use the spatial modeling procedures described in the section 2.4. The unit of analysis is the block group. The dependent variable is the probability of the block group containing one or more relic sites of elevated flood risk ( $FF \geq 3$ ). With this approach we are estimating exposure risk at the most inclusive geographic scale displayed in figure 3. Our predictors of interest are the three measures, or themes, of social vulnerability described in table 1. For all three measures, higher values indicate higher vulnerability. To start, we enter each measure separately, along with controls for the total population, number of households, and land area in the block group. Then, we enter the three measures simultaneously with the same controls.

Panel (A) of figure 4 graphs the results for each vulnerability measure in our model for all six study areas pooled together, net of controls and accounting for local spatial dependence among block groups. These results reveal a common pattern: all else equal

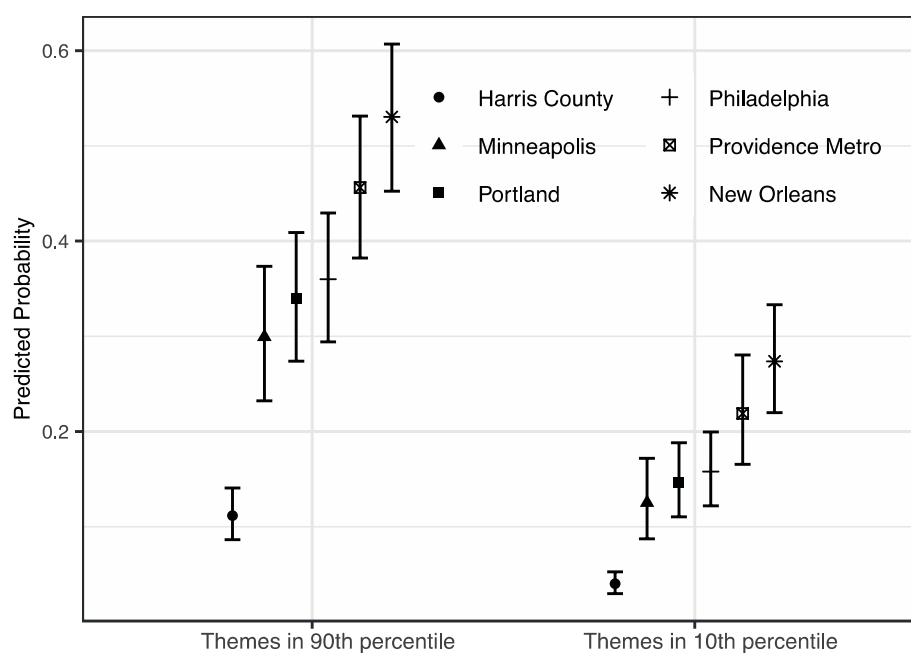
and regardless of the indicator, the more socially vulnerable the block group, the higher its probability of having one or more relic sites at elevated risk of future flooding.

To illuminate city-level variation, Panel (B) displays coefficient plots for respective vulnerability indicators for each city modeled separately. Those appear beneath the estimated coefficient (in red) for the pooled results graphed in Panel (A). Here, each dot represents the estimated log-odds associated with a given vulnerability theme in a given city, net of other themes; the horizontal line indicates the 95% credibility interval. Points above zero indicate that higher vulnerability scores correlate positively with higher probabilities of having a flood-prone relic site in the block group. Overall, these results indicate notable socioeconomic and racial variation across cities along with consistently positive coefficients for housing vulnerability. Analyses using cutoffs for middle-range risk ( $FF \geq 3$  &  $\leq 6$ ), high risk ( $FF > 6$ ), and the presence of five or more flood prone relics indicate substantively similar results to those reported here (presented in supplementary information figure 2).

However, socioeconomic, racial, and housing vulnerabilities rarely exist independently in urban neighborhoods; instead, they tend to overlap. To help visualize this cumulative overlap, figure 5 graphs estimated probabilities when all three indicators of social vulnerability are assigned to their 10th versus 90th percentiles in each city. Here simulated results show particularly high exposure probabilities for the most vulnerable block groups in New Orleans and Providence. They also reveal the range of exposure inequity within each city.



**Figure 4.** Regression models estimating the probability that a block group will contain a flood prone relic site while varying values of each social vulnerability theme. Panel (A) displays the average effect in the spatial multi-level model as predicted probabilities across the range of possible values for the theme (0–1). All other covariates are held at their median values and the random effects (spatial and city) are set to zero. High values of a theme indicate greater social vulnerability. Panel (B) displays the estimated effect sizes in log odds for each social vulnerability theme. The top line is the spatial multilevel model and others correspond to separate city models. Values greater than zero indicate a positive correlation between increasing social vulnerability and the probability of a block-group containing a flood prone relic site.



**Figure 5.** To better understand the cumulative effects of the social vulnerability themes, we predict the probability of a block group containing a flood prone relic site under different extreme scenarios. Results in the left column predict the probability given that a place is in the 90th percentile in all three dimensions of vulnerability (i.e. the most socially vulnerable places). The right column shows the probability given that a place is in the bottom decile of vulnerability (i.e. the least vulnerable places).



## 4. Discussion

Climate change is raising the probability that urban flooding will remobilize and spread hazardous wastes contaminating the soils of potentially thousands of former industrial sites, increasing exposure risks for urban residents generally—a finding suggestive of a new kind of climate injustice for more socially vulnerable communities. Researchers and policymakers alike are beginning to register concern over these developments as witnessed by recent discussions over the Biden Administration's American Jobs Plan, which proposed \$5B to remediate and redevelop 'idle' industrial sites and attend to legacy pollution confronted by low-income communities of color (The White House 2021: 10). Yet, despite growing attention, the scale and scope of the problem and thus potential solutions remain poorly specified, constrained by government databases that overlook the vast majority of relic industrial sites, many of them likely to contain legacy contaminants.

To overcome these limitations, we paired historically comprehensive industrial site data with address-level projections of future flood risk. Results reveal entire zones of flood-prone relic industrial sites, with thousands to hundreds of thousands of residents locally exposed (depending on the scale of analysis). Our analyses further reveal that these at-risk areas tend to be disproportionately inhabited by more socially vulnerable groups (i.e. racial minorities, those with lower-incomes, and/or those living in lower quality housing). The theoretical contributions of these findings are to explicate and document an emergent type of environmental inequality created when past industrialization, ongoing social marginalization, and future flood risk intersect. Specifically, such inequality emerges when legacy contaminants on flood-prone relic industrial sites are remobilized into surrounding residential and public spaces.

A limitation of the present study, however, is that we do not know the extent of contaminants on each relic site, nor do we know how those contaminants will remobilize and spread during future flood events. Yet, the sheer number of flood-prone relic sites does suggest that the cumulative burden will be high, regardless, even if not every site is equally or heavily polluted. It also calls for us to rethink conventional approaches to environmental assessment and intervention.

The broader implication is that current theory, thinking, and action on environmental risk and injustice must catch up to the new era in which we are entering—one where the hidden legacies of industrial pollution and social inequities collide with rising flood risks. Future flooding threatens to inundate already marginalized communities with toxin-laced waters through no fault of their own (GAO 2022). This is not to say that the same people living in these communities today will be the ones ultimately

exposed. Rather, it is to acknowledge that efforts to address these compounding risks must include and engage these communities *now* as we plan for future eventualities (Chan *et al* 2021). In doing so, we must also recognize that current socio-demographics do not make some urban dwellers inherently more vulnerable than others. Instead, we should understand vulnerable neighborhoods as contested sites of struggle, places that have been historically marginalized and where residents' understandings and experiences of risk and mitigation strategies often continue to be ignored. Such community-centered planning, as well as a parallel focus on the broader processes of industrial pollution, social marginalization, and rising urban flood risks, are relevant outside of the U.S. context, too. Thus, our findings could prove useful for climate justice scholars whose research focuses on urban areas worldwide because of the historical location of industry near coasts and waterways (Harlan *et al* 2015, Shi *et al* 2016, Chu and Michael 2019).

## 5. Conclusion

The goal of this study was to illuminate the scale and scope of risk that U.S. cities face from future flooding of relic industrial sites as well as the socially inequitable distribution of that risk across different types of communities. In our six sample cities, we identified more than 6000 relic sites at an elevated risk of flooding by 2050, exposing tens of thousands of people and homes to this under-studied but ascendant type of environmental risk. Using spatial regression models, we also found that block groups with higher measures of social vulnerability have higher predicted probabilities of exposure to flooded relic sites. These results indicate a new kind of climate injustice emerging at the conjunction of past pollution, ongoing social inequities, and future flooding, calling for a new kind of policy thinking, theory, and action.

## Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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