

Deciphering spatial-temporal dynamics of flood exposure in the United States^{☆,☆☆}

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ARTICLE INFO

Keywords:

Flood exposure
Urban-rural disparities
Flood zone
Moran's I
Urban development
United States

ABSTRACT

Extracting baseline information on flood exposure and its temporal evolution is essential to formulate flood risk reduction strategies. At present, comprehensive, long-term spatial-temporal flood exposure research in the United States is lacking. The objective of the study is to evaluate county-wide flood exposure in the US and unravel its spatial-temporal dynamics from 2001 to 2019 to answer three research questions via hypothesis testing. First, how have human settlement areas exposed to flood threats in the US changed over the past two decades? Second, has the occurrence of floods and their resulting damage influenced the growth of developed areas in flood zones? Third, do disparities exist in the sensitivity to flood threats among urban-rural communities? Results show that the overall rate of development in flood zones in the contiguous United States has steadily decreased from 2001 to 2019. The Local Moran's I analysis discovers pockets of emerging, expanding, shrinking, and changing clusters of communities that show a rapid increase or decrease of developed areas within flood zones over time. Most counties that experienced more frequent flooding events demonstrate greater responsiveness to flood hazards by avoiding development in flood zones. Finally, urban communities exhibit a higher exposure and sensitivity to flood hazards compared to rural areas.

1. Introduction

Flooding is one of the most recurrent and costliest natural disasters that has led to significant fatalities and economic losses worldwide (Qiang et al., 2017; Abedin & Khatun, 2019; Hassan et al., 2020; Lyu & Yin, 2023; Sauer et al., 2023). In the United States, floods caused an average of \$8.2 billion of damage each year over the past two decades (Wing et al., 2018; Huang & Wang, 2020). Floods have become more devastating and frequent in recent years, and the trend is projected to continue, posing additional challenges to human communities (Kryva-shyeyu et al., 2016; Hassan et al., 2020; Zhou et al., 2022; Bakhtiari et al., 2023). The (U.S.) Federal Emergency Management Agency (FEMA) projects that, by 2100, rising sea levels and more extreme weather conditions are anticipated to increase the flood-prone areas by up to 45 % in the United States (FEMA, 2013). Therefore, efforts to

assess and reduce flood risk are of great societal significance and have attracted the attention of governments, researchers, and the public.

According to the Intergovernmental Panel on Climate Change (IPCC), flood risk is defined as the product of flood hazard, flood exposure, and vulnerability (IPCC, 2012) and can be minimized by lessening any of the three components (Qiang et al., 2017). A key factor in the risk that is sometimes overlooked is flood exposure, which refers to valued community components such as people, infrastructure, resources, livelihood, etc., located in floodplains (de Moel et al., 2011; Koks et al., 2015; Tate et al., 2021). Evaluating flood exposure is the initial phase toward an improved perception of the overall flood threat and risk mitigation. Monitoring flood exposure increase or decrease in a region can reveal the community's collective decision on flood management, which is frequently a consequence of balancing the flooding risk and the service extended in the flood zone (McGranahan et al.,

[☆] **Funding sources:** This research is supported by the U.S. National Science Foundation under the Human Networks & Data Science Infrastructure Program (Award No.: 2318204 & 2318206). ^{☆☆} **Conflicts of Interest:** The authors declare no conflict of interest.

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<https://doi.org/10.1016/j.scs.2024.105444>

Received 30 October 2023; Received in revised form 10 March 2024; Accepted 14 April 2024

Available online 15 April 2024

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2007; Wheater & Evans, 2009).

Several studies have considered FEMA's designated floodplain to assess flood exposure and its spatial distribution (Blessing et al., 2017; Tate et al., 2021). Comparative county-based and block-group-wise evaluations of population and critical infrastructure exposure to flood and the underlying socio-economic inequalities in the United States have been investigated (Wing et al., 2018; Qiang, 2019a; Qiang, 2019b; Huang & Wang, 2020). Existing literature also examined the relationships between future flood exposure over a 30-year period and social, ecological, and technological vulnerability at different spatial scales in four selected US cities (Sauer et al., 2023). However, those studies mainly emphasized the spatial patterns of flood exposure for selected floodplains. They also largely overlooked the long-term temporal variations of flood exposure. Simultaneously, prior studies rarely examined the potential driving factors, e.g., flood incidents and damage, urban-rural settings, etc., that influence the decision-making of human settlement and development in flood-prone regions. Comprehensive assessments of national-scale flood exposure considering various levels of flood zones and their temporal evolution are essential to decipher the spatial-temporal disparities in flood risk perceptions and inform effective flood risk reduction strategies.

The objective of this investigation is to fill the research gap by evaluating the evolving county-wide flood exposure in the United States from 2001 to 2019. This study defines flood-prone areas by the 100-year and 500-year (also recognized as 1 % and 0.2 % annual probabilities of inundation) flood zones characterized by FEMA. Flood exposure is assessed by the proportion of developed land in the 100-year and 500-year flood zones.

Specifically, we aim to answer three research questions. First, how have human settlement areas (also referred to as developed areas in this investigation) exposed to flood in the contiguous United States changed from 2001 to 2019? Second, did a higher occurrence of floods and greater flood-related damages lead to a slower subsequent development in flood zones? Third, were there any urban-rural disparities in community sensitivity to flood threats? Three associated hypotheses were examined: (1) the rate of expansion of human settlements in flood zones had continuously declined across the contiguous United States from 2001 to 2019; (2) communities experiencing higher flood occurrences and damages were more responsive to floods by avoiding development in flood zones than communities with fewer flood incidents and impacts; (3) urbanized communities were more sensitive to floods with decelerated development in flood zones than rural communities. The study sheds light on the spatial-temporal patterns of flood exposure and reveals community departures from the general trend in the contiguous United States. The research also creates essential baseline information on communities threatened by floods, which is valuable for policy-makers and disaster practitioners to formulate flood mitigation policies and strategies, develop localized adaptation approaches, and allocate resources.

The article is organized as follows. First, we provide a literature review of prior flood exposure studies in Section 2. Section 3 elaborates on the data sources and methodology for data accumulation and administration. The methodology of spatial-temporal and statistical analysis is detailed in Section 4. In Section 5, we highlight the results in light of the hypotheses, and compare the findings with other studies. The implications and limitations, as well as suggestions for future research, are discussed in Section 6. Finally, Section 7 summarizes the conclusions of this work.

2. Literature review

Numerous studies have attempted to evaluate flood extent, exposure, and risk at regional and national scales. Most of the research measures the portion of population or critical infrastructure exposed to flood, as well as their socioeconomic and built-environment characteristics and distribution patterns, to elucidate climatic injustice. For example, in

documenting the unavailability of hydrological data in Afghanistan, Hagen et al. (2010) proposed an economic model that relies on accessible retrospective flood data to generate a national flood extent map for Afghanistan through a 'reverse engineering' approach. Cammerer et al. (2013) applied flood maps from the Austrian flood risk zoning project known as the (natural) Hazard Overview & Risk (assessment) Austria (HORA) in the Alpine Lech Valley in Tyrol, Austria, to assess spatio-temporal dynamics of assets at flood risk caused by land use changes. Using modeled urban growth, they predicted the changing fashion of urban areas exposed to flood zones with 30-year, 100-year, and 200-year flood return periods in the research region. Güneralp et al. (2015) assessed the changing exposure of urban infrastructure to floods because of potential urban expansion and projected that the percentage of worldwide urban territory in high-frequency flood zones would increase from 30 % in 2000 to 40 % in 2030. Jongman et al. (2012) directed a country-based evaluation of economic and population exposure to flood using population density and GDP per capita data since 1970 and forecasted their future trends to 2050.

Extensive flood exposure assessments in the United States have been made. The National Oceanic and Atmospheric Administration (NOAA) established a web application named Coastal Flood Exposure Mapper, which enables users to access flood zones and different socioeconomic levels, such as poverty and population density on the East Coast and the Gulf Coast of the United States (NOAA, 2017). Several studies have evaluated the dynamism of flood exposure, vulnerability, resilience, and risk in the conterminous United States (e.g., Cutter & Finch, 2008; Wing et al., 2018). Such research provides empirical substantiation of the spatial and temporal trends in social vulnerability and suggests that the growth in population and GDP are anticipated to result in significant escalations in future flood exposure. Another research offers a methodology for combined spatiotemporal flood risk assessment, providing hourly variations in risks due to hazard, physical vulnerability, users' exposure, and social vulnerability (Bernardini et al., 2024). Comparative county-based evaluation of population and critical infrastructure exposure to FEMA's 100-year flood zones and the underlying socio-economic inequalities in the United States (Qiang, 2019a; Qiang, 2019b; Huang & Wang, 2020) suggest that economically disadvantaged populations tend to inhabit affordable flood zones rather than other areas, with the southern states exhibiting a particularly high exposure ratio across most critical infrastructure sectors. Future estimations of flood exposure and risk, derived from population, asset data, and high-resolution hazard maps for the contiguous United States, are also accessible, as detailed in Wing et al. (2018). Swain et al. (2020) predicted the population exposure in the United States using a framework combining climate and flood model and measured variations in population susceptibility to flood exposure throughout the contiguous United States. Chang et al. (2021) interlinked a social-ecological-technological systems (SETS) vulnerability framework and developed an urban flood vulnerability index for six US cities to investigate the complexity of urban floods.

Despite the robust literature on flood exposure assessment, three research gaps are identified from the existing studies and necessitate further investigations. First, in previous studies, the use of FEMA data for floodplain coverage did not incorporate several regions with significant populations (Qiang et al., 2017; Huang & Wang, 2020). Consequently, the existing large-scale risk assessments tend to underestimate the actual extent of flood exposure significantly (Wing et al., 2018). Incorporating up-to-date FEMA data is relatively straightforward, as FEMA now regularly updates its floodplain information on a weekly basis. Second, earlier studies on flood exposure focused on populations, properties, and infrastructures in 100-year flood zones but disregarded flood exposure in 500-year floodplains in the United States, which are known to house a significant population and infrastructure. Therefore, it is essential to assess how flood exposure in both the 100-year and 500-year floodplains has evolved over time. Third, previous studies inadequately quantified the impact of possible driving factors of flood zone development, e.g., communities' flood experiences, flood damage,

and urban-rural settings. These factors play a crucial role in shaping development decisions in flood-prone areas, and a more comprehensive analysis is required to understand their impacts accurately.

3. Data collection and preprocessing

This study selects counties as the assessment unit because they are well-recognized administrative divisions and share the same governmental and political functions. The main data sets used in this research are land cover data, FEMA flood maps, historical flood frequencies and damage, and rural-urban classifications. The data sources, formats, and dates are summarized in Table 1. All data sets are freely available from the data providers.

3.1. Land cover data

The land cover data for 2001, 2011, and 2019 were collected from the National Land Cover Database (NLCD), which provides Landsat-derived land use and land cover products at a spatial resolution of 30 m by 30 m. This data set has been consistently updated at 2 to 3-year intervals over the past two decades (Dewitz, 2021; Yang et al., 2022). The NLCD data are represented in raster format and categorize pixels into eight broad categories and 16 subcategories corresponding to Anderson's land cover classification system (Anderson et al. 1976). Among these categories, developed land refers to areas where people reside or work and encompasses four subcategories: high-intensity (HI), low-intensity (LI), medium-intensity (MI), and open space (OS). In this study, all four developed land subcategories were treated equally as human settlement areas. Therefore, the land cover types were reclassified into two distinct categories: developed and non-developed.

3.2. Flood hazard maps

The flood hazard maps utilized in this study were obtained from the National Flood Hazard Layer (NFHL), which is provided by FEMA and accessed from the FEMA Flood Map Service Center (<https://msc.fema.gov/portal>). The NFHL data were collected in March 2021 and are represented as polygons in the shapefile format. NFHL flood zones are categorized into three general types based on the possibility of flood inundation: 100-year, 500-year, and minimal flood zones. The 100-year flood zone has a 1 % chance or more of being deluged by flood in a particular year. The 100-year flood zone is also designated as a high flood hazard zone and known as a Special Flood Hazard Area (SFHA) in the Flood Insurance Rate Map (FIRM) of FEMA. FEMA labels 100-year flood zones as Zone A, Zone AO, Zone AH, Zones A1-A30, Zone AE, Zone A99, Zone AR, Zone AR/AE, Zone AR/AO, Zone AR/A1-A30, Zone AR/A, Zone V, Zone VE, and Zones V1-V30. The 500-year flood zones, also known as moderate flood hazard areas, have a 0.2 % or higher annual chance of being inundated by flood and are labeled as Zone B or Zone X by FEMA. The areas higher than the elevation of the 0.2 % annual chance of flood have minimal flood hazard and are labeled as Zone C (FEMA, 2020). The comprehensive definitions and descriptions of different flood zone categories are available on FEMA's website (www.fema.gov/glossary/flood-zones).

Table 1
Data used in this study.

Data Type	Source	Format	Year
100-year & 500-year Flood Map	FEMA	ESRI Shapefile	2021
Land Cover Data	USGS	Raster (30×30 m)	2001, 2011, 2019
Flood Frequency & Damage	SHELDUS	Spreadsheet (county level)	2001–2019
Urban-Rural Classification	US Census	Spreadsheet (county level)	2010

This study exclusively used effective flood maps, encompassing a total area of 4.5 million km², or 55.2 % of the contiguous United States. When the data were collected, the NFHL did not cover the entire contiguous United States. However, FEMA constantly updates the data by improving new flood maps and modifying current ones. As indicated in Fig. 1a, FEMA's flood hazard map coverage differs from county to county with more available data sets in the eastern part of the United States. Counties with low or no flood map coverage are primarily located in complicated topography and predominantly sparsely populated counties (Qiang et al., 2017). In this investigation, counties with less than one percent flood map coverage were excluded, to ensure the certainty of flood exposure estimation. To overlay FEMA's flood maps with land cover data, the flood hazard polygons were converted into raster layers with a resolution of 30 m by 30 m. The few "no data" polygons in the NFHL data were excluded from this research.

3.3. Flood frequency and damage data

Flood frequency and damage data were acquired from the Spatial Hazard Events and Losses Database for the United States (SHELDUS) (www.cemhs.asu.edu/sheldus/). SHELDUS is a county-level hazard data set for the United States from 1960 to present. The database covers natural hazards such as floods (including coastal floods), hurricanes, heavy rainfall, thunderstorms, and tornadoes. The SHELDUS database includes information on the starting and ending dates of each flood event, the affected county and state, and the direct damage caused by the incident, including property damage, crop losses, injuries, and deaths. Flood frequency (how many times a county was flooded) and the sum of property and crop damage per capita (how much per capita flood-induced economic loss a county suffered) were calculated from 2001 to 2011 and from 2011 to 2019 to represent county-level flood frequencies and impacts over the two periods.

Fig. 1b and 1c illustrate the spatial patterns of cumulative flood frequency and the sum of crop and property damage per capita from 2001 to 2019, derived from the SHELDUS database. Over the nearly 20 years, county-level flood occurrences ranged from 0 to 436, while the maximum cumulative flood damage per capita was \$192,319. Notably, regions experiencing more frequent flood hazards were primarily concentrated in southern California, southern Nevada, and southern Arizona. Additionally, several counties in Mississippi, Iowa, Pennsylvania, New York, and South Carolina exhibited high flood frequencies. In contrast, the majority of counties suffering from high flood damage were located in coastal sections of Texas, Louisiana, and Mississippi.

3.4. Rural-Urban classification

The county-level rural-urban classifications were acquired from the U.S. Census Bureau. According to the Census Bureau, urban areas correspond to densely built territory and include commercial, residential, and other non-residential urban land uses (U.S. Census Bureau, 2022). The Census Bureau defines urban areas by employing specific criteria based on the decennial census and additional data. Rural areas comprise all housing, population, and territory not encompassed within urban areas. The rural-urban county classification used in this study was based on the county population residing in rural areas as of the 2010 Census. The U.S. Census Bureau (2022) classifies counties with less than 50 % of the population residing in rural areas as mostly urban; those with 50–99.9 % in rural areas are classified as mostly rural; and those with 100 % of the population outside of urban areas are classified as completely rural. Of the 3108 counties in the United States, 1247 (40.12 %), 1176 (37.84 %), and 685 (22.04 %) are mostly urban, mostly rural, and completely rural, respectively, as displayed in Fig. 1d.

4. Methodology of analysis

This study evaluates county-wide flood exposure changes in the U.S.

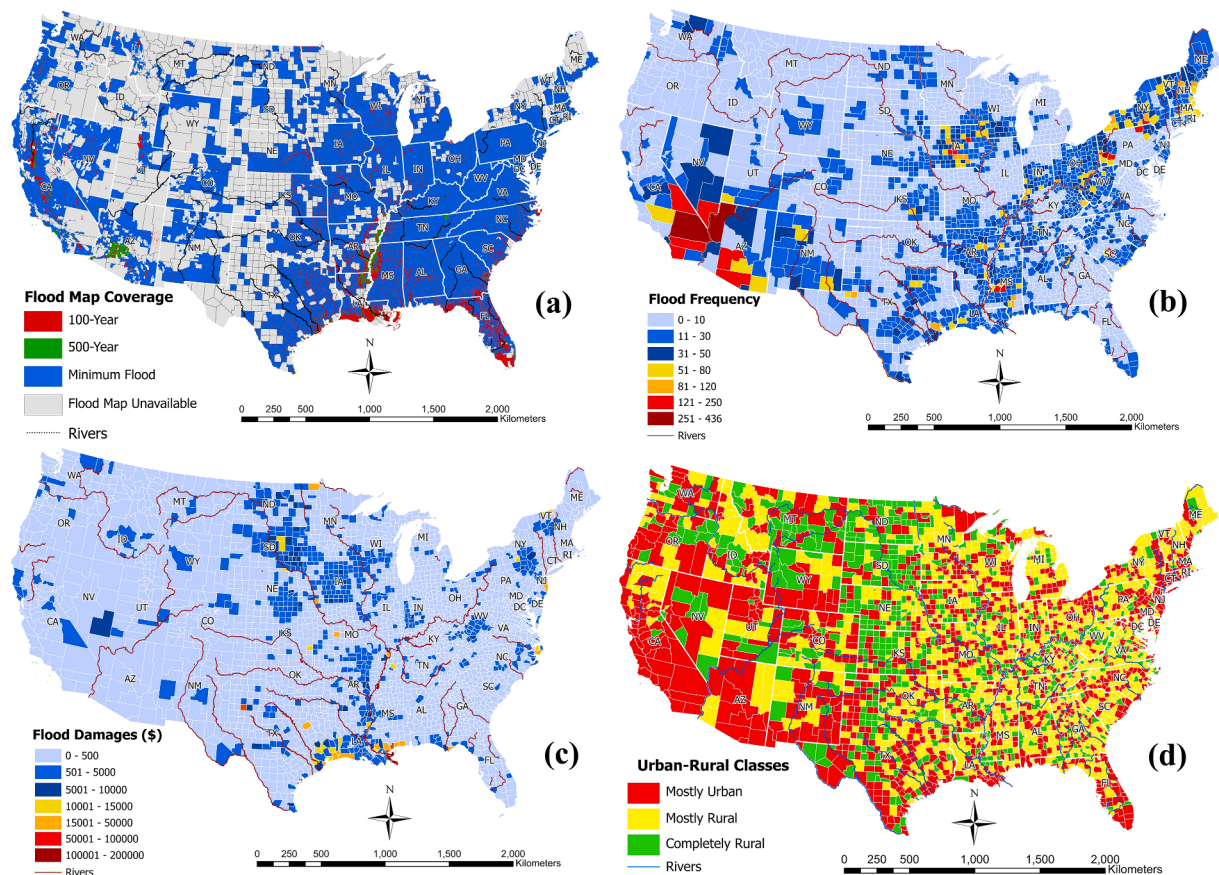


Fig. 1. County-level maps visualizing (a) FEMA flood coverage as of March 2021, (b) flood frequency during the period 2001–2019, (c) the cumulative sum of flood-induced property and crop damage per capita from 2001 to 2019, and (d) rural-urban classification in 2010 across the contiguous United States.

from 2001 to 2019. To achieve the goal, the workflow depicted in Fig. 2 was followed. Specifically, four types of quantities were analyzed, including: (a) exposure of developed land to flood threats, (b) developed land exposure changes over time, (c) impacts of flood frequencies and damage on communities’ development actions in flood zone, and (d) disparities of the urban-rural communities’ sensitivity to flood hazard. The first step calculates the proportion of developed land in flood zones

by year to support the subsequent hypotheses testing. The land cover maps (reclassified into developed and non-developed categories) and the 100-year and 500-year flood zone maps (reclassified into flood zones and non-flood zones) were overlapped to derive the percentages of total land and developed area in flood regions in each county for 2001, 2011, and 2019.

The second step uses the land use and land cover data in 2019 to

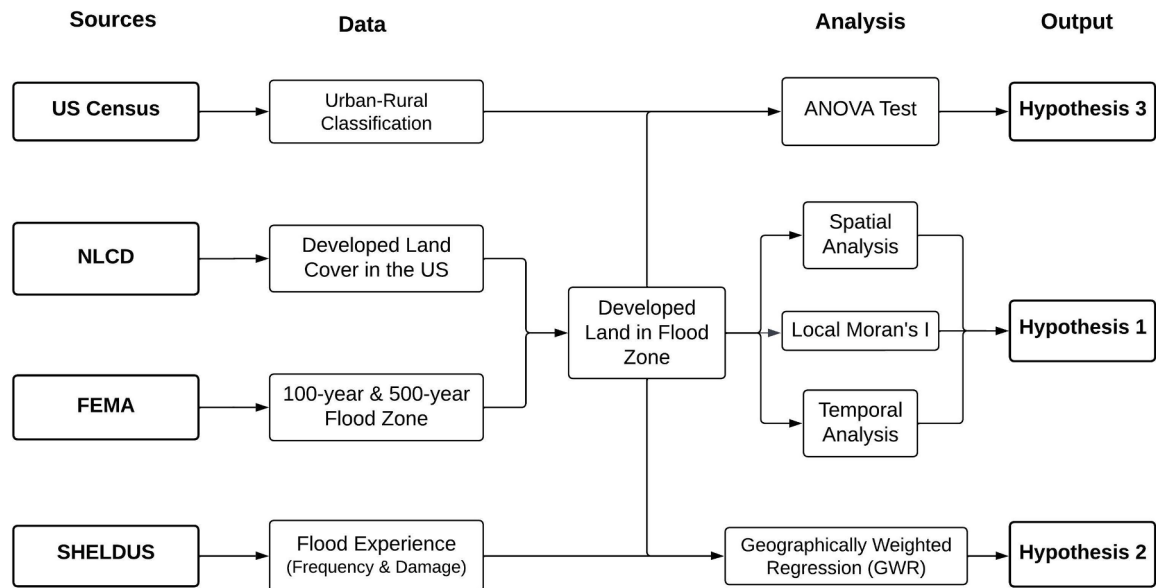


Fig. 2. Workflow of the study.

derive the latest baseline information, delineating the geographical disparities of the difference between the percentages of developed areas and total land lying in flood zones in 2019 (Dv_{2019} and La_{2019}) at the county level. The distinction between Dv_{2019} and La_{2019} , denoted as Df_{2019} , is calculated using Eq. (1), suggesting whether a county has a greater or smaller percentage of developed land in the flood zone than its anticipated value (0), assuming that flood zones are not considered in land development decisions. A positive Df_{2019} value implies that flood areas do not pose significant barriers to urban expansion. This high value further implies that the community is less responsive to flood hazards. On the other hand, a negative Df_{2019} value indicates that flood hazards play a more substantial role in choosing locations for urban advancement. It suggests that the county is more responsive to flood hazards by avoiding development within flood zones and urban expansion occurs more frequently outside of flood zones rather than within them.

$$Df_{2019} = Dv_{2019} - La_{2019} = \frac{\text{Urban in flood zone in 2019}}{\text{Total urban in 2019}} - \frac{\text{Land in flood zone}}{\text{Total land}} \quad (1)$$

The third step evaluates the temporal discrepancies of the percentages of developed regions in flood zones from 2001 to 2011 ($Dv_{2011-2001}$) and from 2011 to 2019 ($Dv_{2019-2011}$) for each county to test Hypothesis One. $Dv_{2019-2011}$ and $Dv_{2011-2001}$ were computed using Eqs. (2) and (3). A positive value of $Dv_{2019-2011}$ or $Dv_{2011-2001}$ in a county denotes an expansion in the percentage of developed areas in flood zones during that particular period and suggests that people in the county turned less responsive to flood threats. Alternatively, negative $Dv_{2019-2011}$ or $Dv_{2011-2001}$ values suggest declines in the proportions of developed areas in flood zones, which means the dwellers were more responsive to avoiding development in flood zones.

$$Dv_{2019-2011} = Dv_{2019} - Dv_{2011} = \frac{\text{Urban in flood zone in 2019}}{\text{Total urban in 2019}} - \frac{\text{Urban in flood zone in 2011}}{\text{Total urban in 2011}} \quad (2)$$

$$Dv_{2011-2001} = Dv_{2011} - Dv_{2001} = \frac{\text{Urban in flood zone in 2011}}{\text{Total urban in 2011}} - \frac{\text{Urban in flood zone in 2001}}{\text{Total urban in 2001}} \quad (3)$$

The fourth step is to further reveal the geographical disparities in flood exposure changes by detecting clusters of counties with high or low flood exposure and how those clusters have evolved over time. This was conducted by estimating the local Moran's I of $Dv_{2019-2011}$ and $Dv_{2011-2001}$ for each county in the United States. A positive local Moran's I value suggests that a particular element is geographically enclosed by similar values to that element, and the result can be considered a portion of a cluster of high or low values (high-high or low-low). A high-high cluster of $Dv_{2019-2011}$ or $Dv_{2011-2001}$ points to a substantial hotspot of counties less responsive to flood threats with more dwelling and urban growth in flood zones than outside of flood zones during the time frame. Contrarily, a low-low cluster implies a hotspot of counties with significantly slower flood zone development than the development in minimal flood threat areas during the period. A negative local Moran's I value implies that the feature is geographically enclosed by features with

different values (high-low or low-high). The z-scores and p-values in local Moran's I reveal whether the evident resemblance (a spatial grouping of any high or low values) or divergence (a spatial outlier) is more prominent than an expected random distribution. This study applied p-values less than 0.05 at a 95 % confidence level.

The fifth analysis examines Hypothesis Two, which states that communities experiencing higher flood occurrences and damages were more responsive to floods by avoiding development in flood zones than communities with fewer flood incidents and impacts. Geographically Weighted Regression (GWR) was used to investigate the relationship between changes in developed land exposure and flood frequencies and damage (Chakraborty et al., 2022; Chen, 2021). GWR is a spatial statistical technique that examines the spatial variation in the relationships between a set of variables. This study defines changes in urban exposure as the response variable and flood frequency and damage as the explanatory variables. By utilizing GWR, we were able to assess whether flood experience was statistically linked to flood zone development and how this relationship varied across different counties over the past two decades. SHELDUS data on flooding frequency and the 2020 adjusted monetary value of flood damage per capita in each decade were collected. The SHELDUS data provide separate values for crop and property damage, which were combined into a unified variable representing overall flood damage. These damage values were normalized by the county's population to ensure cross-county comparisons.

The final analysis assesses disparities in flood sensitivity among urban, suburban, and rural communities to test Hypothesis Three. Counties in the contiguous U.S. were classified as mostly urban, mostly rural, or completely rural. We overlaid these classifications with flood zone maps for three time periods (2001, 2011, and 2019). To determine the significance of the urban-rural classification concerning changes in developed areas within flood zones across the three time periods, we performed an Analysis of Variance (ANOVA) test.

5. Results

5.1. Geographical disparities of flood exposure

Fig. 3a illustrates the proportion of land in flood zones at the county level. For the 2381 counties included in the study out of 3108 counties, the average county-level percentage of land in flood zones is 14 %. Among all the counties, the top ten counties with the highest proportions of land areas in flood zones (91% – 94%) are listed in Table 2. These counties are predominantly located in plain land proximal to either rivers, e.g., the Mississippi River, or the coastline. Conversely, the West Coast generally exhibits a low proportion of land in flood zones, except for a few counties in northern California.

The county-level exposure of developed areas to flood in 2001, 2011, and 2019 is depicted in Fig. 3b-3d. The trend of flood exposure remains consistent from 2001 to 2019, with counties along the Mississippi River, South Coast, and Florida Coast experiencing the highest exposure. The average county-level percentages of developed land in flood zones are

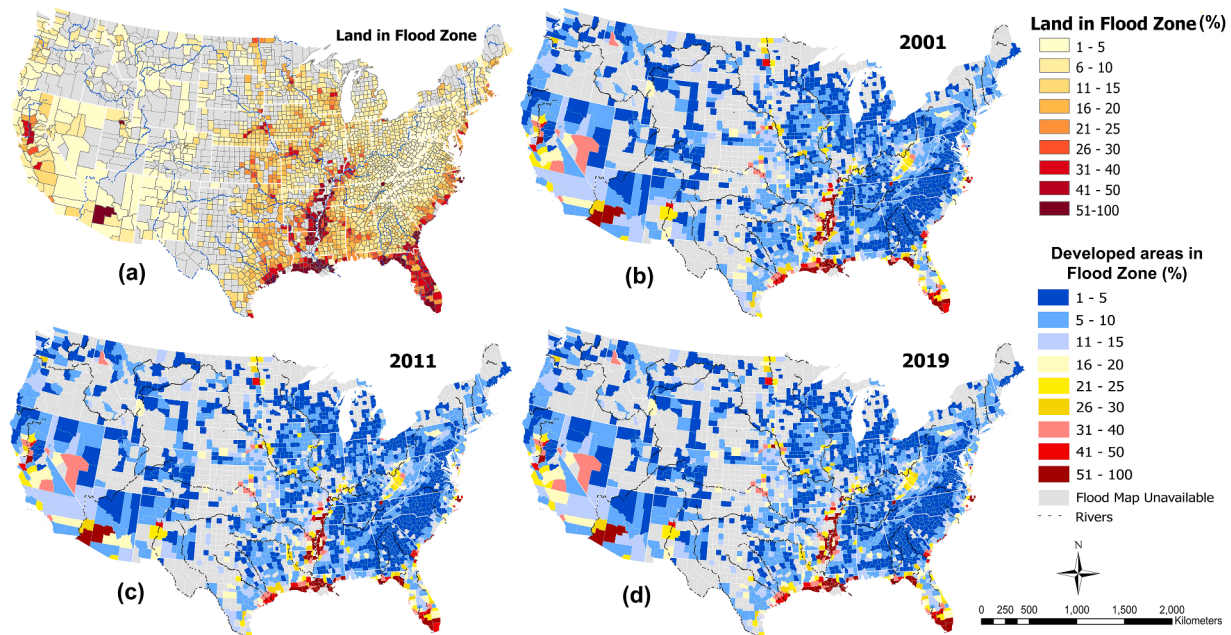


Fig. 3. County-level maps across the contiguous U.S. illustrating the proportions of (a) land in flood zone, (b) developed areas in flood zone in 2001, (c) developed areas in flood zone in 2011, and (d) developed areas in flood zone in 2019.

Table 2

Top ten counties by percentages of land in flood zones and their developed land in flood zones in 2001–2019.

County	State	Land in Flood Zone (%)	Developed Land in Flood Zone (%) in 2001, 2011, 2019
Mississippi	Arkansas	94	99
Crittenden	Arkansas	94	99
Tunica	Mississippi	93	99
Coahoma	Mississippi	93	99
Washington	Mississippi	92	98
Bolivar	Mississippi	92	99
Morehouse	Louisiana	91	98
Campbell	Tennessee	91	97
Madison	Louisiana	91	99
Richland	Louisiana	91	98

10.51 %, 10.49 %, and 10.45 % in 2001, 2011, and 2019, respectively. This finding suggests that the exposure of developed areas to floods in the contiguous United States has slowly declined over time. The spatial distributions of Dv_{2019} and La_{2019} (Fig. 3a and 3d) are alike, with the Pearson correlation between the two patterns being 0.86 ($p < 0.001$), suggesting that counties with a high percentage of land in flood zones tend to have a high percentage of developed area in flood zones and vice versa.

5.2. Discrepancy in the exposure of land and developed land to floods

The difference between the percentages of developed areas and land in flood zones in 2019 (Df_{2019}) is displayed in Fig. 4. Inland counties located in the eastern and western regions of the United States, including those in California, Arizona, Nevada, New Mexico, West Virginia, and Kentucky, recorded higher Df_{2019} values. On the other hand, counties proximal to water bodies (e.g., along the Mississippi River) and the coasts (along the East Coast and Gulf Coast) have lower Df_{2019} values. Notably, the areas near New Orleans, Miami, and San Francisco are the only coastal areas where the difference is positive. A variety of reasons have been proposed to explain the growing development in flood zones in those counties. It may be that the economic or cultural value of these areas outweighs the potential flood risks (Zischg, 2018). Alternatively, it

could indicate a lack of awareness or underestimation of flood risks, inadequate zoning or building codes, or other policy or market failures (Tanoue et al., 2016). As for the consequences, these high Df_{2019} values suggest that these areas may suffer more from flood damage and associated economic and social impacts. In the absence of significant mitigation measures, they could face increasing risks due to climate change and sea level rise. Furthermore, recovery and rebuilding costs after flooding events could place a significant burden on local economies and communities. This situation underscores the importance of effective flood risk management, including floodplain mapping, land use planning, building regulations, and insurance mechanisms in these regions.

5.3. Temporal changes of flood exposure in the U.S.

The changes in the exposure of developed areas within flood zones from 2001 to 2011 ($Dv_{2011-2001}$) and from 2011 to 2019 ($Dv_{2019-2011}$) were evaluated (Fig. 5). During 2001–2011, a consistent decline in the proportion of developed areas exposed to flood zones was observed across most counties in the contiguous United States, with values primarily ranging from -0.010 to 0.000 . Several exceptional counties, however, stood out with higher $Dv_{2011-2001}$ values surpassing 0.01, including Nye and Clark counties in Nevada; Platte and Dodge counties in Nebraska; Morton, Grand Forks, and Cass counties in North Dakota; Jasper and Berkeley counties in South Carolina; Yuma County in Arizona; Wasatch County in Utah; Pottawattamie County in Iowa; Marshall County in Kentucky; Catoosa County in Georgia; and Miami-Dade County in Florida. A similar overarching trend emerged during the 2011–2019 period, with most counties witnessing reduced proportions of developed land within flood zones. Only four counties showed $Dv_{2019-2011}$ values exceeding 0.01, namely Baker and Columbia counties in Florida, Cass County in North Dakota, and Dare County in North Carolina.

In analyzing the shifts in spatial patterns over the last two decades, it is evident that the average changes in the exposure of developed areas within flood zones were notably negative. Specifically, the mean changes were -3.23×10^{-4} for $Dv_{2011-2001}$ and -3.41×10^{-4} for $Dv_{2019-2011}$. The observed negative mean differences substantiate the first hypothesis of a prevailing and uniform trend toward reduced development within flood zones from 2001 to 2019 in the United States.

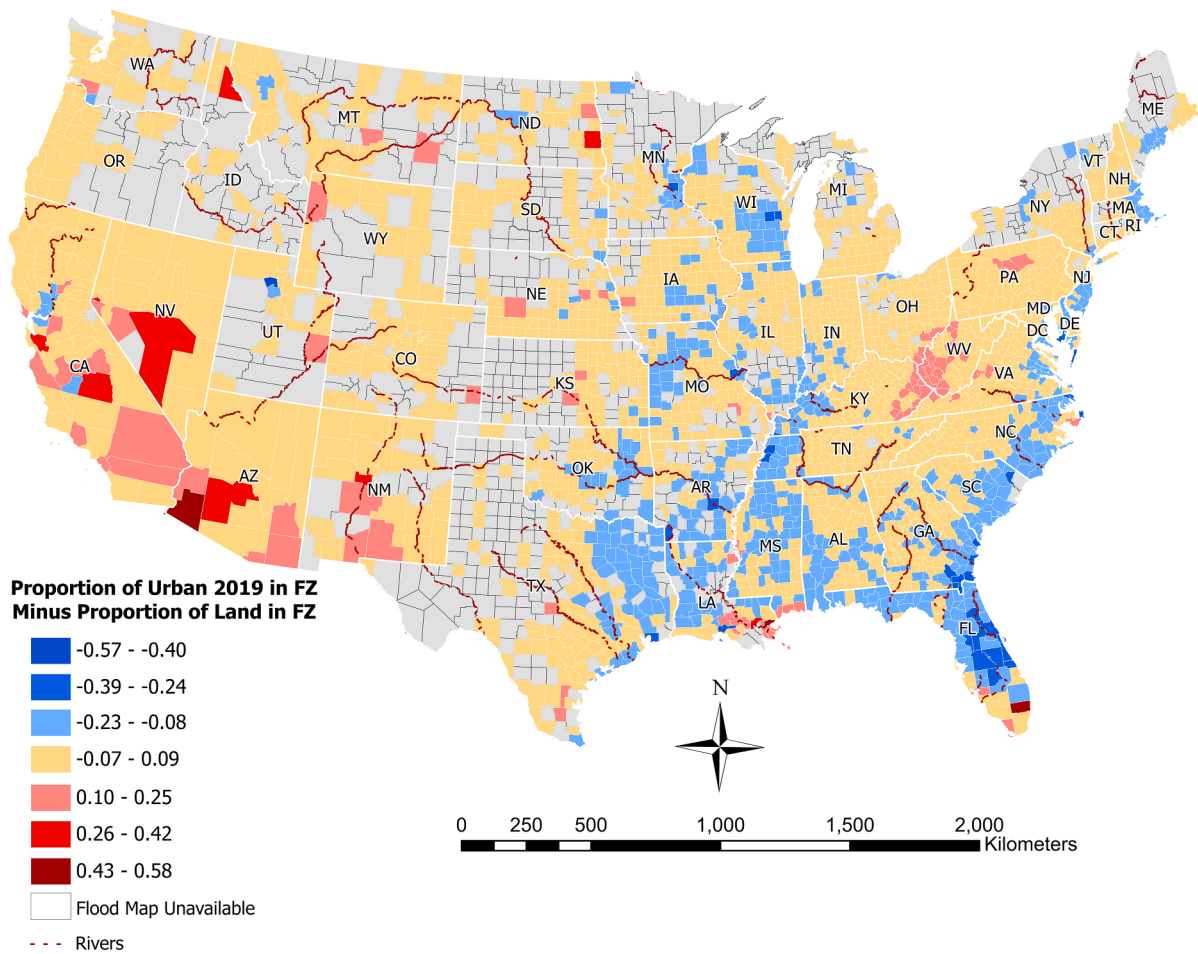


Fig. 4. Difference between the proportion of developed land in flood zones and the proportion of total land in flood zones in 2019.

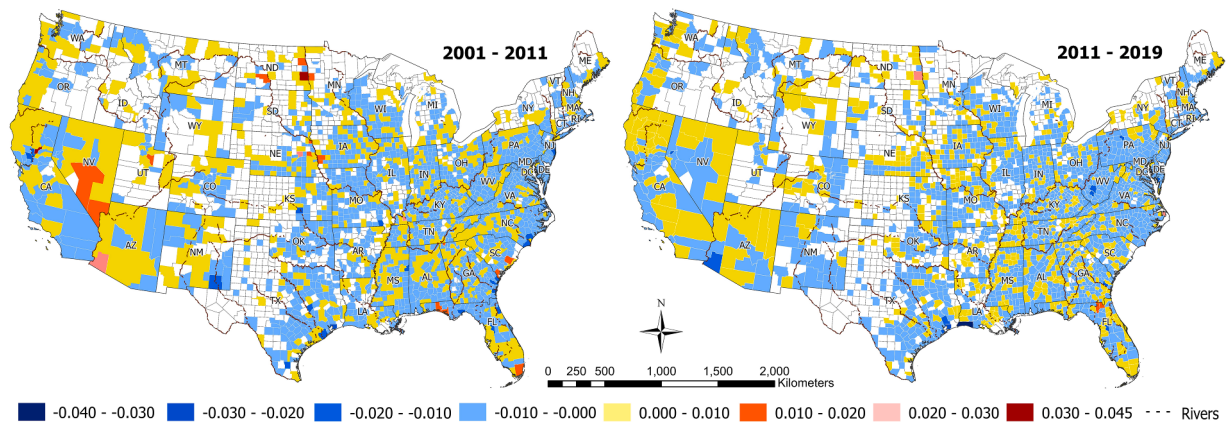


Fig. 5. Changes in proportion of developed areas in flood zones.

The spatial distribution of flood exposure changes over the two periods is uneven, with emerging, expanding, shrinking, changing, and steading clusters of high increase or decrease in flood exposure changes, as pinpointed by the Moran's I analysis. Expanding clusters are high-high or low-low clusters that exhibited an overall increase in size with new counties in the second period (2011–2019) compared to the first period (2001–2011). Changing clusters refer to clusters that experienced a transformation in their characteristics, transitioning from high-high to low-low or vice versa. Shrinking clusters are identified when the overall size of the cluster decreased over the second decade. Emerging clusters

are recognized as newly formed clusters during 2011–2019 that did not exist during 2001–2011. These cluster classifications allow analysis of the dynamic changes in flood exposure patterns over time.

Fig. 6 illustrates the detected clusters during each period. A total of 12 overlapped clusters were detected in both time spans, with an additional two emerging clusters observed in 2011–2019. Among the 12 overlapped clusters, Cluster 1 is in California; Cluster 2 straddles California and Arizona; Clusters 3 and 10 are in Texas; Clusters 4 and 5 are in Florida; Cluster 6 spans Alabama, Georgia, and small parts of adjacent states; Cluster 7 encompasses West Virginia, Ohio, and Pennsylvania;

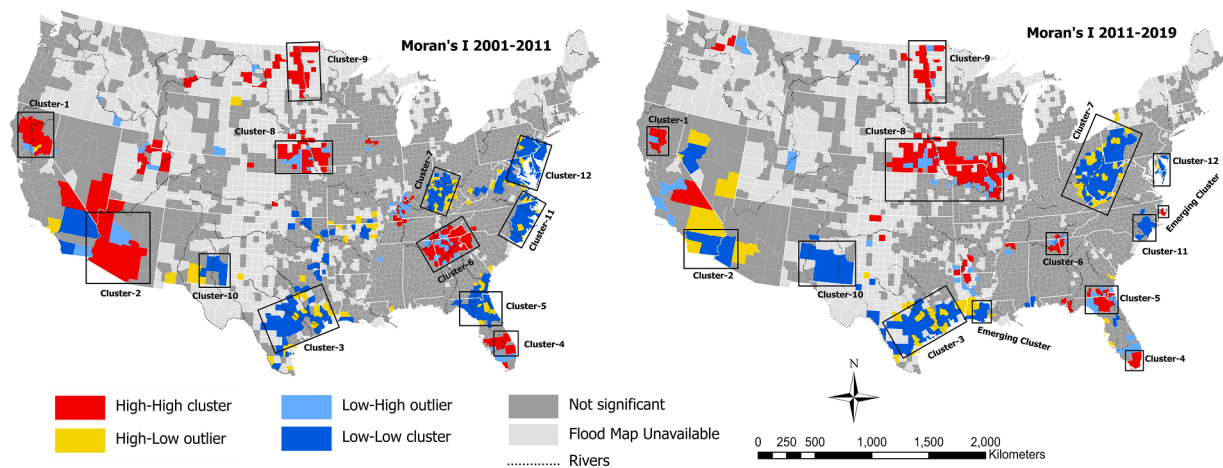


Fig. 6. Clusters of local Moran's I from 2001 to 2011 and 2011 to 2019.

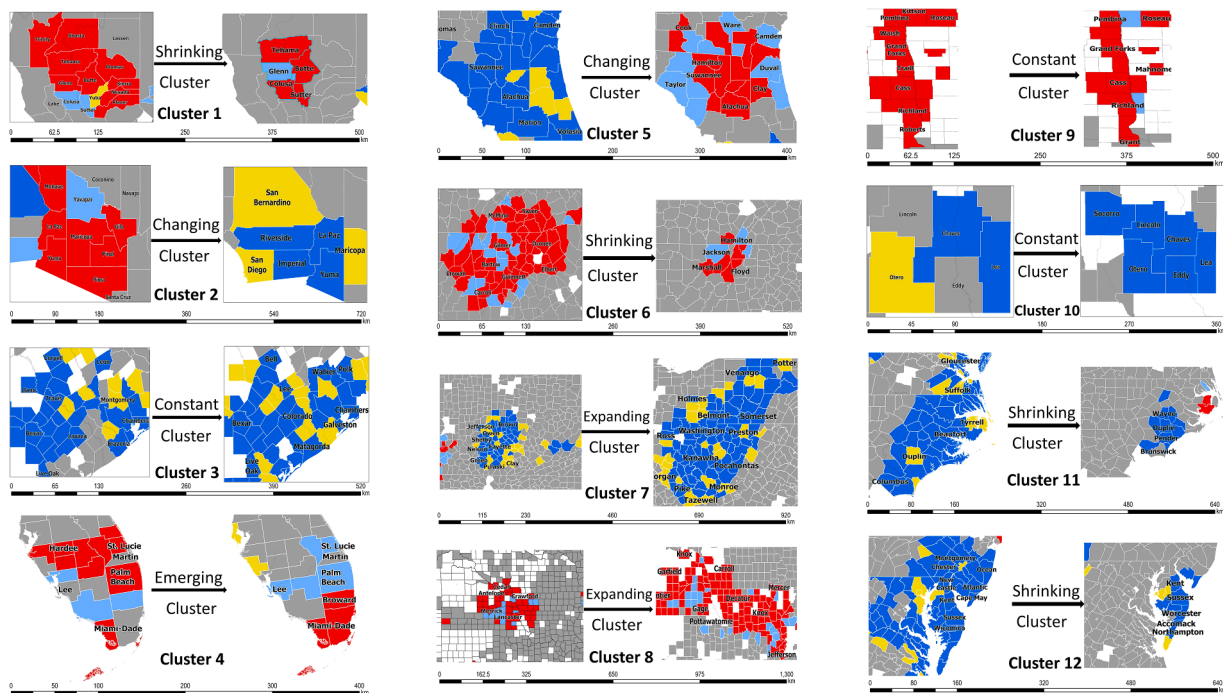


Fig. 7. Changing patterns of the clusters of local Moran's I for both periods.

Cluster 8 spans Nebraska, Iowa, Missouri, and Illinois; Cluster 9 is in North Dakota; Cluster 11 is within North Carolina; and Cluster 12 spans both Maryland and Delaware.

Between 2001 and 2011, six clusters exhibited high-high characteristics while the remaining six demonstrated low-low attributes. The high-high clusters predominantly appeared in inland regions, except for Cluster 4, which was situated on the eastern coast of Florida. Conversely, the low-low clusters were primarily positioned near the west and south coasts. During 2011–2019, a similar pattern emerged, with seven high-high and seven low-low clusters discovered. Among the high-high clusters, four were situated in inland territories, two clusters were in Florida adjacent to the coastline, and one newly emerged along the North Carolina coast. The distribution of low-low clusters remained consistent with the previous period, with one emerging cluster in coastal Louisiana.

Zooming into the 12 clusters and analyzing their evolutions from 2001–2011 and 2011–2019 reveals a comprehensive picture of both transformations and continuities in the context of flood hazard

responsiveness (Fig. 7). Among these 12 clusters, three remained unchanged over the studied timeframe (Clusters 3, 9, and 10), two showed variation (2 and 5), and five were identified as shrinking (1, 4, 6, 11, and 12). Additionally, two clusters expanded (7 and 8), and two clusters emerged during 2011–2019.

Specifically, Cluster 1 in northern California, originally apparent in the 2001–2011 timeframe with 12 counties, became smaller with five counties by 2011–2019. In contrast, Cluster 2 underwent profound transformations, changing its classification from high-high in 2001–2011 to low-low in 2011–2019. These changes suggest that communities in these areas have increased their exposure to flood hazards by expanding the percentage of developed areas in flood zones over the first decade. Cluster 3 maintained its characteristics and pattern unchanged across both intervals. On the other hand, Cluster 4 was identified as a high-high cluster during 2001–2011 but transitioned to a low-high outlier in the subsequent period. Another noteworthy cluster, Cluster 5, exhibited significant changes over time. It shifted from a low-low cluster in 2001–2011 to a high-high cluster in 2011–2019. This

changing pattern suggests that communities in Jacksonville, Florida, and its surrounding areas displayed a reduced responsiveness to flood threats. Clusters 9 and 10 have no discernible transformations detected between the two time periods. In contrast, Clusters 11 and 12 charted a shrinking path. The shrinking trajectory of Clusters 11 and 12 indicates that the communities in these areas have exhibited a degree of adaptability and responsiveness to flood threats. In close proximity to Cluster 11, a high-high cluster emerged in the second decade. It suggests that the communities in this area might have undergone significant transformations in their flood risk management practices.

5.4. Influence of flood experience on flood zone development

In this study, we initially employed Ordinary Least Squares (OLS) regression to examine the relationship between flood experience and flood exposure changes at the national level. The OLS analysis indicates that, on average, the model performed reasonably well (mean residual = 0.0004) in explaining the variation in flood exposure changes. However, the assessment of Moran's I of the residuals revealed the presence of spatial clusters, specifically high-high and low-low clusters. These clusters suggest that there are localized variations in the relationship between flood experience and flood exposure changes that the OLS model might not adequately capture.

Given the evidence of spatial heterogeneity, we subsequently justified the use of Geographically Weighted Regression (GWR) as a more appropriate modeling technique. GWR allows us to account for these localized variations and provides a more comprehensive understanding of how flood experience influences flood exposure changes across different geographic areas. Fig. 8 illustrates the GWR results on the relationship between flood experience, including flood frequency and damage, and flood exposure changes for 2001–2011 and 2011–2019 across the contiguous United States. Fig. 8a and 8b show the local R-squared values of the two GWR models. High positive R-squared values signify robust and consistent associations between flood experience factors and changes in flood exposure, while low positive R-squared values reveal weaker and more heterogeneous relationships. The negative local R-squared values indicate that the GWR model performs poorly in capturing the local relationships between the response variable (flood exposure changes) and the explanatory variables (flood frequency and damage), and those communities should be excluded when interpreting the results (Qiang et al., 2017).

During 2001–2011, high R-squared values (>0.1) are observed in Arizona, New Mexico, North Dakota, Minnesota, and parts of Texas. Conversely, low R-squared values ($0-0.1$) occur in California, Nebraska, Iowa, Wisconsin, Illinois, Missouri, Arkansas, Mississippi, Alabama, Maine, New Hampshire, parts of Michigan, Florida, Nevada, Oregon, Idaho, and Washington. A total of 69 counties scattered in Vermont, Maine, and Michigan show negative R-squared values. In the 2011–2019 timeframe, high R-squared values persist in Arizona, New Mexico, and western Texas, demonstrating the continued significant association between flood experience and flood exposure changes in these regions. Meanwhile, low R-squared values are identified in Arkansas, Mississippi, Alabama, parts of Georgia, Idaho, Nevada, Oregon, California, Florida, South and North Carolina, Michigan, and Wisconsin. Out of 3108 counties, 243 show negative values and appear in states of Montana, Vermont, Maine, New Hampshire, Michigan, Idaho, Georgia, Wisconsin, and Arkansas.

Fig. 8c and 8d display the GWR-derived local coefficients of flood damage per capita in explaining flood exposure changes for each period. A negative coefficient signifies that the community suffering more damage from floods experiences a decline in the development of flood zones over the specified time frame. From 2001 to 2011, flood damage appears to have impeded development in flood-prone areas in Montana, Wyoming, Idaho, parts of New Mexico and Texas, central Florida, southern Arizona, and southern Idaho. Contrarily, a positive relationship is noted in the northwestern and northeastern United States, a cluster of counties in New Mexico, Texas, and Oklahoma, and states surrounding Lake Michigan. From 2011 to 2019, negative correlations are discovered in southern Florida, Utah, parts of Kentucky, Ohio, West Virginia, Colorado, and Wyoming. However, a contrasting trend is evident in states including California, Nevada, Idaho, Oregon,

Table 3

Urban-rural disparities in the percent of developed land in flood zone from 2001 to 2019.

	Mostly Urban	Mostly Rural	Completely Rural
2001	0.096	0.076	0.056
2011	0.096	0.075	0.056
2019	0.095	0.075	0.056
2001–2011	–0.000330	–0.000251	–0.000077
2011–2019	–0.000301	–0.000265	–0.000168

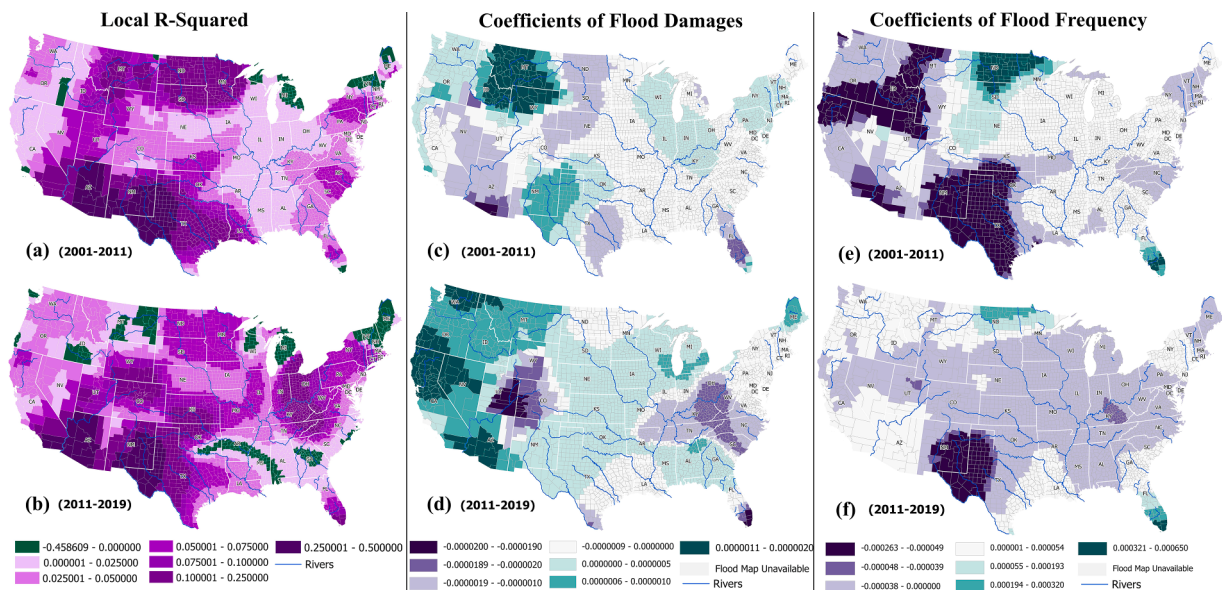


Fig. 8. Map of the local R-squared of GWR of flood frequency, damage with exposure changes (a, b), coefficients of flood damage with exposure changes (c, d), and coefficients of flood frequency with exposure changes (e, f) for 2001–2011 and 2011–2019 in the United States.

Washington, Montana, Arizona, and Maine. This result implies that these regions, having experienced an increased number of flood damage, did not curtail development in flood-prone zones.

Fig. 8e and 8f display the GWR-derived local coefficients of flood frequency in explaining flood exposure changes for each decade. A negative coefficient demonstrates that the community enduring more frequent floods deliberately refrains from developing human settlement areas within flood zones and vice versa. From 2001 to 2011, a negative correlation is evident in states such as Texas, New Mexico, Oklahoma, Montana, Idaho, Utah, Oregon, and California. In contrast, a positive relationship was observed in Florida, North Dakota, and Minnesota, suggesting that these states have experienced a higher number of flooding incidents and have become less responsive to flood threats, resulting in an acceleration in development within flood-prone zones. From 2011 to 2019, the negative correlation was primarily observed in a cluster of counties spanning western Texas and eastern New Mexico, suggesting that these states had continuously become more responsive to flood hazards. Concurrently, the other states that had exhibited a strong negative correlation between flood frequency and changes in flood exposure during 2001–2011 displayed a weakened negative relationship in 2011–2019.

5.5. Urban-Rural disparities in flood sensitivity

The last analysis scrutinizes the differential sensitivity to flood threats and associated development actions among urban, suburban, and rural communities. Table 3 delineates disparities in the percentage of developed land in flood zones for 2001, 2011, and 2019, across Mostly Urban, Mostly Rural, and Completely Rural counties. Mostly Urban counties consistently recorded high mean values (0.095–0.096), followed by Mostly Rural counties (0.075–0.076), whereas completely rural counties exhibited notably lower mean values (0.056). For Mostly Urban areas, the proportion of developed land in flood zones decreased slightly from 0.096 in 2001 and 2011 to 0.095 in 2019. In Mostly Rural areas, a similar trend was observed, with a decrease from 0.076 in 2001 to 0.075 in 2011 and 2019. Completely Rural areas maintained a constant value of 0.056 across the given time frame.

Additionally, the data reveal a marginal declining proportion of developed lands in flood zones in all community classifications, with the steepest decrease observed in Mostly Urban areas from 2001 to 2011 (−0.00033). The ANOVA test results reveal a statistically significant association ($p < 0.001$) between the urban-rural classification and changes of developed land exposure to floods. This evidence indicates that urban communities tend to exhibit higher sensitivity to flood risks and adapt their developmental strategies accordingly, more so than their rural counterparts. This trend underscores the necessity for differentiating strategic planning for urban and rural communities. For instance, more attention could be devoted to rural counties to enhance their efforts to mitigate flood exposure.

6. Discussion

6.1. Significant implications

This study integrates publicly available data from FEMA, NLCD, and SHELUS, to analyze the exposure of human settlement areas to flood threats and their evolving patterns over time. It further delves into comprehending how flood experience affects the responsiveness of communities to flood hazards. Additionally, it underscores discrepancies in development efforts among urban, suburban, and rural communities located in flood-prone regions. The study employs a range of spatial and temporal analysis techniques, including hotspot analysis and GWR, which are reproducible and transferable to assess flood exposure changes and their driving factors in other regions and for other disasters. Compared to previous studies in the United States, this study uses the more recent FEMA 100-year and 500-year flood data and investigates

the changes of developed area exposure over two decades, resulting in a more comprehensive and up-to-date flood exposure assessment.

We commenced our examination of flood exposure changes in the conterminous United States by formulating three hypotheses. The first hypothesis targets the changing pattern of human settlements in flood zones in the United States from 2001 to 2019, questioning whether the flood exposure of developed areas has changed over time. The findings suggest that people in the United States have become more proactive in responding to flood threats by avoiding urban expansion in high and middle-threat flood zones from 2001 to 2019, although different trends exist across various regions of the nation. Counties with a high percentage of land in flood zones also had high proportions of developed areas in flood zones and were more responsive to flood hazards by avoiding human settlement area expansion in 100-year and 500-year flood zones during 2001–2019. Such counties are primarily located along rivers and coasts. Conversely, most inland counties with a low percentage of developed land in flood zones were less responsive to flood threats, except for those located along the Mississippi River. This aligns with findings from Qiang et al. (2017) that inland counties, particularly those in the western mountainous and eastern inland regions, had higher rates of development in flood zones, indicating they were less responsive to flood hazards.

A hotspot analysis was then conducted to identify clusters with emerging, expanding, shrinking, changing, and steadying clusters of high increases or decreases in proportions of development in flood zones from 2001 to 2019. The distribution of clusters of counties with high increase in flood zone development mostly occurred in inland areas, excepting one cluster located in the eastern Florida coast. Several possible reasons for the emergence of high-high clusters on the Florida coast, as well as the conversion of the cluster in North Florida from low-low in 2001–2011 to high-high in 2011–2019, may exist. As Qiang et al. (2017) noted, significant increases in urban development within flood zones were detected in emerging hot spots in the Miami region, indicating exceptions to broader responsiveness trends. Recent natural disasters such as Hurricane Irma in 2017 and Hurricane Michael in 2018 may have played a role in the change due to factors such as post-disaster reconstruction, economic incentives, and changes in land use policies. More research and attention in different clusters are needed to identify the underlying triggers and develop appropriate strategies to reduce flood risk. Effective measures include increasing public awareness (Calloway et al., 2022), improving flood education (Sandink & Binns, 2021), encouraging housing development beyond flood zones (Seifert-Dähnn, 2018), enforcing laws in critical areas, and implementing robust flood alleviation approaches in hotspot areas.

The second hypothesis aims to answer if high flood incidents and destruction interfere with development in flood zones. The findings show that a negative correlation between flood exposure and frequency/damage was only observed in certain counties primarily in Montana, Wyoming, Idaho, New Mexico, Texas, Florida, Arizona, Oregon, Colorado, California, and Idaho states. This result indicates that these communities have become more responsive to floods and have avoided developing in flood zones. On the other hand, counties in some regions mostly in Florida, North Dakota, Minnesota, California, Nevada, Idaho, Oregon, Washington, Montana, Arizona, Maine, New Mexico, Texas, and Oklahoma states exhibit a positive correlation between flood exposure and flood frequency and damage, suggesting that experiencing floods did not influence development in flood zones in these regions. Some flood-prone areas exhibit increased development despite experiencing disasters, which seems to contradict typical post-disaster policy reforms (Birkland, 2006; Crow et al., 2018). However, other empirical studies suggest additional factors may incentivize persisting floodplain development. Burby (2001) pointed the Lax enforcement of floodplain development restrictions can enable the reconstruction of damaged properties. Kousky and Kunreuther (2014) found the NFIP's history of offering discounted premiums to some policyholders enabled continued residential development in high-risk floodplains. Subsidized flood

insurance rates and post-disaster assistance have facilitated rebuilding in hazardous coastal areas despite frequent storm flooding (Burby, 2006). Burby (2006) reviewed land use plans across the U.S. and discovered floodplain development policies were often inadequate or poorly enforced in practice, pointing to gaps in regulations. To further uncover the factors enabling ongoing floodplain development despite flood experiences, future studies could conduct comparative case studies of communities that implemented protective policies versus those that continued risky trajectories after disasters. In-depth interviews with planners, elected officials, developers and residents could provide insights into motivations, perceptions, and decisions driving development. Synthesizing findings across multiple sites through meta-analysis could uncover systematic gaps to address through state or national policies. The findings of this study have significant implications for flood management and disaster risk reduction strategies. More attention should be given to communities with a high exposure to flood and a high development in flood zones. This can be achieved by adopting measures to mitigate the impact of floods, such as land-use planning and zoning, early warning systems, and flood insurance programs. Concurrently, counties with a positive relationship between flood exposure and frequency and damage may require more comprehensive measures to promote flood risk reduction and management.

The third hypothesis evaluates the disparities in the urban-rural communities' sensitivity to flooding hazards. The study revealed that there were disparities in the urban-rural communities' sensitivity to high flood threats. Urban communities displayed a higher exposure to floods compared to rural communities. Meanwhile, urban communities were more sensitive to flood by decelerating development in flood zones. The observed disparities in flood sensitivity between urban and rural communities align with prior research, highlighting the varying impacts of floods across different settings (Bukvic & Harrald, 2019). Previous studies have noted the heightened vulnerability of urban areas to flood hazards due to factors such as population density, land use patterns, the density and imperviousness of the urban landscape, compounded by continuing urbanization, increases rapid surface runoff and hence flood hazard. Urban drainage systems are often overwhelmed, leading to more frequent, deeper, and more widespread pluvial flooding (Douglas et al., 2010). However, limited attention has been paid to the nuanced differences in sensitivity between urban and rural communities and the underlying reasons behind these disparities which necessitate further research. The results of this study provide insights into the differences in flood sensitivity between different community types, which can inform policies and interventions aimed at reducing flood risk and enhancing community resilience.

6.2. Limitations and future research

To identify avenues for future research, it is essential to consider the limitations of this study. First, the flood exposure assessment does not differentiate between the 100-year and 500-year flood zones, but rather considers both flood zones as the same, which may result in an oversimplification of flood exposure levels. Since FEMA flood maps are derived using different hydrological models, the degree of flood exposure can vary from floodplain to floodplain. Future research can improve flood exposure assessments by differentiating between 100-year and 500-year flood zones and using more detailed flood hazard data and hydrological models, leading to a more precise and nuanced understanding of flood exposure levels in various floodplains.

Additionally, this study chooses county as the analysis scale and does not consider the variability of floodplain products in their physical coverage, potentially overlooking variations in flood exposure at finer spatial scales. Researchers could explore using higher-resolution floodplain products or spatially disaggregated flood data, which can provide a more granular and comprehensive view of flood exposure patterns. Meanwhile, the analysis of developed area exposure changes is based solely on developed land expansion and does not consider the level of

urban development within flood zones, which may neglect differences in flood vulnerability and potential damage within these areas. Future research could weigh each developed area differently based on the development levels.

Furthermore, this study does not validate the FEMA flood map with other available flood zone maps in the United States. Areas not covered by the FEMA map may introduce ambiguity in flood exposure assessment. Therefore, it is necessary to consider areas where flood maps are absent and to validate FEMA maps with other available flood zone maps. This validation process will help ensure the accuracy and comprehensiveness of flood exposure assessments, particularly in areas where FEMA's data may be incomplete or outdated. Finally, understanding flood risk involves evaluating the product of three interrelated components: flood hazard, flood exposure, and vulnerability. While this study examined flood exposure at a national level over a 20-year period, a comprehensive understanding of flood risk requires the integration of all three components to provide a better picture of how flood risks vary across different regions.

An important factor that may influence flood exposure dynamics not considered in this study is the presence of structural flood protection measures such as levees, floodwalls, dams, and embankments along rivers and coastlines. These structures are designed to reduce flood risk, but their presence can also induce societal effects that unintentionally increase exposure over time, an occurrence known as the "levee effect" (Ludy & Kondolf, 2012). The installation of levees and similar structures can provide communities with a false sense of security, encouraging further development in floodplains by reinforcing perceptions that an area will remain flood-free (Burby, 2006). As a result, while structural protections aim to lessen flood impacts, they have also been associated with increases in exposure and potential catastrophic losses when rare flood events overtop or damage these protections. To account for the potential influence of structural protections on observed spatiotemporal flood exposure patterns, future work could incorporate the U.S. Army Corps of Engineers National Levee Database which details the locations and characteristics of over 30,000 miles of levees across the U.S. (USACE, 2022). This database could be integrated with FEMA flood maps and development data to delineate protected versus unprotected flood zones and analyze if differences in exposure changes exist between these areas over time.

Investigating whether physical flood defenses have been added over time to protect growing development in high flood exposure counties would constitute an impactful follow-up study, as evidenced by existing literature. Several studies have analyzed the effectiveness of structural flood controls in reducing community exposure and damage in regions other than the United States. For instance, De Moel et al. (2011) developed flood risk maps for Netherlands under different climate and socioeconomic scenarios. Their projections showed that upgraded flood defenses would be economically beneficial by reducing expected losses. Du et al. (2019) assessed the effectiveness of concave green land (CGL) in mitigating flood exposure and enhancing resilience in central Shanghai, China. Their study analyzed a "Sponge City" plan utilizing CGL as a nature-based solution for pluvial flood mitigation. Through modeling different CGL deployment scenarios, they quantified its capacity to reduce runoff and inundation depths, showing its potential to decrease flood hazards and enhance community resilience. Building on empirical research like these studies, further analysis of flood defense expansion and effectiveness for highly exposed U.S. counties would provide valuable insights to guide comprehensive and equitable flood risk management policies.

7. Conclusion

This research evaluates the spatial-temporal dynamics of flood exposure in the contiguous United States from 2001 to 2019 and examines the impacts of flood experience and urban-rural settings on flood exposure changes. First, multi-source data were integrated to assess

county-level flood exposure across the contiguous United States. Second, the proportion of developed land in 100-year and 500-year flood zones for 2001, 2011, and 2019 was calculated to evaluate flood exposure changes over time. Spatial analysis reveals that coastal and riverside counties had higher flood exposure over the past two decades. Third, clusters with increasing or decreasing flood zone development were identified using hotspot analysis. Emerging, expanding, shrinking, changing, and steadying hotspots were detected, indicating geographic disparities in flood responsiveness. Fourth, the relationship between flood experiences and flood zone development was analyzed. Most of the counties with more frequent flooding showed greater responsiveness by avoiding flood zone expansion. Fifth, urban-rural differences in flood sensitivity were examined. Urban counties displayed higher sensitivity with greater reductions in flood zone development compared to rural areas. Finally, key gaps in flood exposure knowledge and methods were identified and future research solutions were proposed.

This research advances understanding of flood risk in several ways. First, it provides valuable insights into the changing patterns of human settlements in flood zones over a 20-year period, shedding light on the responsiveness of communities to flood threats. The identification of hotspots and clusters of development in flood-prone areas offers a better understanding of the spatial patterns of flood exposure, aiding in targeted flood risk management strategies. Furthermore, the analysis of disparities among urban, suburban, and rural communities in flood sensitivity enhances knowledge of how different communities perceive and respond to flood risks, allowing for the development of tailored flood risk management approaches that consider the unique challenges and preferences of each community type. Last, it provides a reproducible methodological framework that can be applied to assess flood exposure in other regions worldwide.

This research holds significant implications for researchers, the public, and policymakers. For researchers, this study offers new insights into the geographical disparities of flood exposure, the temporal changes in flood exposure patterns, and the factors influencing community responsiveness to floods. The public can gain a better understanding of the spatial and temporal aspects of flood exposure, fostering awareness and supporting informed decision-making regarding flood hazards and development and relocation choices. Policymakers can utilize the research to inform evidence-based flood risk management strategies, including floodplain mapping, land use planning, building regulations, and insurance mechanisms. The identification of geographical disparities in flood exposure emphasizes the need for targeted and localized flood risk management strategies, considering the dynamic nature of flood exposure and the influence of flood experience on development decisions.

CRedit authorship contribution statement

Joynal Abedin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Lei Zou:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Mingzheng Yang:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing. **Robert Rohli:** Methodology, Validation, Writing – review & editing. **Debayan Mandal:** Formal analysis, Methodology, Writing – review & editing. **Yi Qiang:** Methodology, Validation, Writing – review & editing. **Humaira Akter:** Formal analysis, Writing – review & editing. **Bing Zhou:** Methodology, Writing – review & editing. **Binbin Lin:** Methodology, Writing – review & editing. **Heng Cai:** Funding acquisition, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We would like to thank the anonymous reviewers and the editors for their valuable feedback and suggestions. We would also like to acknowledge the funding agencies for sponsoring this investigation. This article is based on work supported by three grants. Two are from the U.S. National Science Foundation - Collaborative Research: HNDS-I: Cyber-infrastructure for Human Dynamics and Resilience Research (Award No. 2318206 and 2318204). The other one is from FEMA's 2024 Louisiana State Hazard Mitigation Plan update via Louisiana's Governor's Office of Homeland Security and Emergency Preparedness (GOHSEP) (Federal Award No. PO#2000796343). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies.

References

- Abedin, J., & Khatun, H. (2019). Impacts of flash flood on livelihood and adaptation strategies of the haor inhabitants: A study in Tangar haor of Sunamganj, Bangladesh. *The Dhaka University Journal of Earth and Environmental Sciences*, 8(1), 41–51. <https://doi.org/10.3329/dujees.v8i1.50757>
- Bakhtiar, V., Piadeh, F., Behzadian, K., & Kapelan, Z. (2023). A critical review for the application of cutting-edge digital visualisation technologies for effective urban flood risk management. *Sustainable Cities and Society*, Article 104958.
- Bernardini, G., Ferreira, T. M., Julià, P. B., Eudave, R. R., & Quagliarini, E. (2024). Assessing the spatiotemporal impact of users' exposure and vulnerability to flood risk in urban built environments. *Sustainable Cities and Society*, 100, Article 105043.
- Birkland, T. A. (2006). *Lessons of Disaster: Policy Change After Catastrophic Events*. Georgetown University Press.
- Blessing, R., Sebastian, A., & Brody, S. D. (2017). Flood risk delineation in the United States: How much loss are we capturing? *Natural Hazards Review*, 18(3), Article 04017002.
- Bukvic, A., & Harrold, J. (2019). Rural versus urban perspective on coastal flooding: The insights from the US Mid-Atlantic communities. *Climate Risk Management*, 23, 7–18.
- Burby, R. J. (2001). Flood insurance and floodplain management: The US experience. *Global Environmental Change Part B: Environmental Hazards*, 3(3), 111–122.
- Burby, R. J. (2006). Hurricane Katrina and the paradoxes of government disaster policy: Bringing about wise governmental decisions for hazardous areas. *The Annals of the American Academy of Political and Social Science*, 604(1), 171–191.
- Calloway, E. E., Nugent, N. B., Stern, K. L., Mueller, A., & Yaroch, A. L. (2022). Lessons learned from the 2019 Nebraska floods: Implications for emergency management, mass care, and food security. *International Journal of Environmental Research and Public Health*, 19(18), 11345.
- Cammerer, H., Thieken, A. H., & Verburg, P. H. (2013). Spatio-temporal dynamics in the flood exposure due to land use changes in the Alpine Lech Valley in Tyrol (Austria). *Natural Hazards*, 68(3), 1243–1270.
- Chakraborty, L., Rus, H., Henstra, D., Thistlethwaite, J., Minano, A., & Scott, D. (2022). Exploring spatial heterogeneity and environmental injustices in exposure to flood hazards using geographically weighted regression. *Environmental Research*, 210, Article 112982.
- Chang, H., Pallathadka, A., Sauer, J., Grimm, N. B., Zimmerman, R., Cheng, C., ... Herreros-Cantis, P. (2021). Assessment of urban flood vulnerability using the social-ecological-technological systems framework in six US cities. *Sustainable Cities and Society*, 68, Article 102786.
- Chen, I. H. (2021). New conceptual framework for flood risk assessment in Sheffield, UK. *Geographical Research*, 59(3), 465–482.
- Crow, D. A., Albright, E. A., Ely, T., Koebele, E., & Lawhon, L. (2018). Do disasters lead to learning? Financial policy change in local government. *Review of Policy Research*, 35(4), 564–589.
- Cutter, S. L., & Finch, C. (2008). Temporal and spatial changes in social vulnerability to natural hazards. *Proceedings of the National Academy of Sciences*, 105(7), 2301–2306.
- De Moel, H., Aerts, J. C., & Koomen, E. (2011). Development of flood exposure in the Netherlands during the 20th and 21st centuries. *Global Environmental Change*, 21(2), 620–627.
- Dewitz, J. (2021). *National Land Cover Database (NLCD) 2019 products*. Sioux Falls, SD, USA: US Geological Survey.

- Douglas, I., Garvin, S., Lawson, N., Richards, J., Tippet, J., & White, I. (2010). Urban pluvial flooding: A qualitative case study of cause, effect and nonstructural mitigation. *Journal of Flood Risk Management*, 3(2), 112–125.
- Du, S., Wang, C., Shen, J., Wen, J., Gao, J., Wu, J., ... Xu, H. (2019). Mapping the capacity of concave green land in mitigating urban pluvial floods and its beneficiaries. *Sustainable Cities and Society*, 44, 774–782.
- Federal Emergency Management Agency (FEMA). (2013). *The Impact of Climate Change and Population Growth on the National Flood Insurance Program through 2100*. Washington, DC: FEMA.
- Federal Emergency Management Agency (FEMA) (2020). Flood zones. <http://www.fema.gov/flood-zones> (last accessed 30 January 2022).
- Güneralp, B., Güneralp, İ., & Liu, Y. (2015). Changing global patterns of urban exposure to flood and drought hazards. *Global Environmental Change*, 31, 217–225.
- Hagen, E., Shroder, J. F., Jr, Lu, X. X., & Teufert, J. F. (2010). Reverse engineered flood hazard mapping in Afghanistan: A parsimonious flood map model for developing countries. *Quaternary International*, 226(1–2), 82–91.
- Hassan, M. M., Ash, K., Abedin, J., Paul, B. K., & Southworth, J. (2020). A quantitative framework for analyzing spatial dynamics of flood events: A case study of super cyclone Amphan. *Remote Sensing*, 12(20), 3454.
- Huang, X., & Wang, C. (2020). Estimates of exposure to the 100-year floods in the conterminous United States using national building footprints. *International Journal of Disaster Risk Reduction*, 50, Article 101731.
- Intergovernmental Panel on Climate Change (IPCC). (2012). *Managing the risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special report of the Intergovernmental Panel on Climate Change*. London: Cambridge University Press.
- Jongman, B., Ward, P. J., & Aerts, J. C. (2012). Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change*, 22(4), 823–835.
- Koks, E. E., Jongman, B., Husby, T. G., & Botzen, W. J. (2015). Combining hazard, exposure and social vulnerability to provide lessons for flood risk management. *Environmental Science & Policy*, 47, 42–52.
- Kousky, C., & Kunreuther, H. (2014). Addressing affordability in the national flood insurance program. *Journal of Extreme Events*, 1(01), Article 1450001.
- Kryvasheyev, Y., Chen, H., Obradovich, N., Moro, E., Van Hentenryck, P., Fowler, J., & Cebrian, M. (2016). Rapid assessment of disaster damage using social media activity. *Science Advances*, 2(3), Article e1500779.
- Ludy, J., & Kondolf, G. M. (2012). Flood risk perception in lands “protected” by 100-year levees. *Natural Hazards*, 61, 829–842.
- Lyu, H. M., & Yin, Z. Y. (2023). Flood susceptibility prediction using tree-based machine learning models in the GBA. *Sustainable Cities and Society*, Article 104744.
- McGranahan, G., Balk, D., & Anderson, B. (2007). The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, 19(1), 17–37.
- National Oceanic and Atmospheric Administration (NOAA) (2017). Coastal flood exposure mapper. <https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html>.
- Qiang, Y. (2019a). Disparities of the population exposed to flood hazards in the United States. *Journal of Environmental Management*, 232, 295–304.
- Qiang, Y. (2019b). Flood exposure of critical infrastructures in the United States. *International Journal of Disaster Risk Reduction*, 39, Article 101240.
- Qiang, Y., Lam, N. S., Cai, H., & Zou, L. (2017). Changes in exposure to flood hazards in the United States. *Annals of the American Association of Geographers*, 107(6), 1332–1350.
- Sandink, D., & Binns, A. D. (2021). Reducing urban flood risk through building-and lot-scale flood mitigation approaches: Challenges and opportunities. *Frontiers in Water*, 3, Article 689202.
- Sauer, J., Pallathadka, A., Ajibade, I., Berbés-Blázquez, M., Chang, H., Cook, E. M., ... Post, G. C. (2023). Relating social, ecological, and technological vulnerability to future flood exposure at two spatial scales in four US cities. *Sustainable Cities and Society*, 99, Article 104880.
- Seifert-Dähnn, I. (2018). Insurance engagement in flood risk reduction—examples from household and business insurance in developed countries. *Natural Hazards and Earth System Sciences*, 18(9), 2409–2429.
- Swain, D., Wing, O. E., Bates, P. D., Done, J., Johnson, K., & Cameron, D. (2020). Increased flood exposure due to climate change and population growth in the United States. *Earth's Future*, 8(11), Article e2020EF001778.
- Tanoue, M., Hirabayashi, Y., & Ikeuchi, H. (2016). Global-scale river flood vulnerability in the last 50 years. *Scientific Reports*, 6(1), 36021.
- Tate, E., Rahman, M. A., Emrich, C. T., & Sampson, C. C. (2021). Flood exposure and social vulnerability in the United States. *Natural Hazards*, 106(1), 435–457.
- U.S. Census Bureau. (n.d.). 2010 Census urban and rural classification. U.S. department of commerce. Retrieved November 15, 2022, from <https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural/2010-urban-rural.html>.
- USACE, 2022. National Levee Database. U.S. Army Corps of Engineers. Available at: <https://levees.sec.usace.army.mil/> [Accessed February 13, 2024].
- Wheater, H., & Evans, E. (2009). Land use, water management and future flood risk. *Land Use Policy*, 26, S251–S264.
- Wing, O. E., Bates, P. D., Smith, A. M., Sampson, C. C., Johnson, K. A., Fargione, J., & Morefield, P. (2018). Estimates of present and future flood risk in the conterminous United States. *Environmental Research Letters*, 13(3), Article 034023.
- Yang, M., Zou, L., Cai, H., Qiang, Y., Lin, B., Zhou, B., & Mandal, D. (2022). Spatial-temporal land loss modeling and simulation in a vulnerable coast: A case study in coastal Louisiana. *Remote Sensing*, 14(4), 896.
- Zhou, B., Zou, L., Mostafavi, A., Lin, B., Yang, M., Gharaibeh, N., & Mandal, D. (2022). VictimFinder: Harvesting rescue requests in disaster response from social media with BERT. *Computers, Environment and Urban Systems*, 95, Article 101824.
- Zischg, A. P. (2018). Floodplains and complex adaptive systems—Perspectives on connecting the dots in flood risk assessment with coupled component models. *Systems*, 6(2), 9.