Changes in Exposure to Flood Hazards in the United States

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This article conducts a national, county-based assessment of the changes in population and urban areas in high-risk flood zones from 2001 to 2011 in the contiguous United States. The U.S. Federal Emergency Management Agency's (FEMA) 100-year flood maps, land cover data, and census data were used to extract the proportion of developed (urban) land in flood zones by county at the two time points, and indexes of difference were calculated. Local Moran's *I* statistic was applied to identify hot spots of increase in urban area in flood zones, and geographically weighted regression was used to estimate the population in flood zones from the land cover data. Results show that in 2011, an estimate of about 25.3 million people (8.3 percent of the total population) lived in high-risk flood zones. Nationally, the ratio of urban development in flood zones is less than the ratio of land in flood zones, implying that Americans were responsive to flood hazards by avoiding development in flood zones. This trend varied from place to place, however, with coastal counties having less urban development in flood zones than the inland counties. Furthermore, the contrast between coastal and inland counties increased between 2001 and 2011. Finally, several exceptions from the trend (hot spots) were detected, most notably in New York City and Miami, where significant increases in urban development in flood zones were found. This assessment provides important baseline information on the spatial patterns of flood exposure and their changes from 2001 to 2011. The study pinpoints regions that might need further investigations and better policy to reduce the overall flood risks. *Key Words: climate change, flood exposure, flood zone, natural hazard, urban development*.

本文从事美国大陆在 2001 年至 2011 年间，以全国郡县为基础的高风险洪泛区的人口与城市面积变迁评估。本文运用美国联邦紧急事务管理署 (FEMA) 的百年洪泛图、土地覆盖数据和人口统计数据，以取得各郡县在两个时期的洪泛区中已发展的(城市)土地比例，并计算差异指数。本文应用地方莫兰指数 (Moran's I) 统计，指认洪泛区中城市面积增加的热点，并运用地理加权迴归，评估土地覆盖数据的洪泛区中的人口。研究结果显示，在 2011 年，大约有两千五百三十万的人口 (约总人口的百分之八点三) 居住于高风险的洪泛区。全国而言，洪泛区的城市发展比率，较洪泛区中的土地比率为少，意味着美国人以避免在洪泛区发展来回应洪灾。此一趋势在各地却有所不同，其中沿海郡县在洪泛区的城市发展较内陆郡县为少。此外，在2001年与2011年间，沿海与内陆郡县的对照有所增加。最后，本文发现该趋势(热点)的若干例外，尤其多半在纽约市与迈阿密，发现洪泛区的城市发展有显着的增加。此一评估对2001年至2011年的洪泛曝险之空间模式及其改变提供了重要的基础信息。本研究准确定位出有可能需要进一步调查和更佳的政策以降低总体洪泛风险的区域。 *关键词： 气候变迁，洪灾曝险，洪泛区，自然灾害，城市发展。*

Este artículo efectúa una evaluación nacional a nivel de condado de los cambios en población y áreas urbanas en zonas de alto riesgo de inundación en los Estados Unidos contiguos, de 2001 a 2011. Los mapas de inundaciones, datos sobre cobertura del suelo y datos censales de 100 años de la Agencia Federal para el Manejo de Emergencias de los EE.UU. (FEMA) se usaron para extraer la proporción de tierra desarrollada (urbana) en zonas de inundación por condado en los dos puntos del tiempo, y se calcularon índices de diferencia. Se aplicó la estadística local de Moran I para identificar puntos calientes de incremento de área urbana en zonas inundables, y se usó la regresión geográficamente ponderada para calcular la población en áreas inundables a partir de los datos de cobertura del suelo. Los resultados muestran que en 2011 vivía un estimativo de alrededor de 25.3 millones de personas (8.3 por ciento de la población total) en zonas de alto riesgo de inundación. A escala nacional, la ratio del desarrollo urbano en zonas inundables es menor que la ratio de tierra en zonas inundables, lo cual implica que los americanos fueron receptivos a los riesgos de inundación, evitando el desarrollo en áreas inundables. Sin embargo, esta tendencia varía de un lugar a otro, de modo que los condados litorales tienen menor desarrollo urbano en zonas inundables que sus contrapartes del interior. Aun más, el contraste entre

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condados litorales e interiores se incrementó entre 2001 y 2011. Por último, se detectaron varias excepciones de la tendencia (puntos calientes), más notablemente en la Ciudad de Nueva York y en Miami, donde se hallaron incrementos significativos de desarrollo urbano en áreas inundables. Esta evaluación provee importante información de referencia sobre los patrones espaciales de exposición a las inundaciones, y sobre sus cambios entre 2001 y 2011. El estudio ubica regiones que podrían necesitar más investigaciones y mejores políticas para reducir los riesgos totales por inundaciones. *Palabras clave: cambio climático, exposición a la inundación, zona inundable, amenazas naturales, desarrollo urbano.*

Worldwide, floods are the most common natural disaster and the leading cause of natural disaster fatalities (Schipper and Pelling 2006). With increasing population pressure and resource needs, the threat of flood disasters is greatly amplified by deforestation (Bradshaw et al. 2007), urbanization (Nirupama and Simonovic 2006), alteration of the natural landscape (Nicholls and Small 2002), and climate change (Milly et al. 2002). In the United States, a report from the Federal Emergency Management Agency (FEMA) estimates that rising seas and increasingly severe weather are expected to increase the areas at risk of floods by up to 45 percent by 2100 (FEMA 2013). With the increasing threat of floods, it is important to develop baseline information on flood hazard and how it could affect people and communities. Several key questions are put forth: how much urban area and how many people are exposed to potential flood hazards in the United States, where they are, and whether the exposure has increased or decreased over time. Answers to these key questions will inform the development of better flood mitigation and adaptation strategies.

The objective of this study is to conduct a nationwide county-based assessment of flood exposure and its spatial and temporal changes in the contiguous United States. This assessment will reveal the general trend as well as departures from that trend so that the findings can help decision makers design corresponding mitigation strategies to reduce flood exposure. Recognizing that there are disagreements and confusion of terminology across the broad field of hazard, risk, and vulnerability, this article adopts the definitions used by the Intergovernmental Panel on Climate Change (IPCC) and the insurance industry and defines the terms as follows (IPCC 2012; Kobayashi and Porter 2012; Koks et al. 2015). The *flood hazard* in a locality refers to the likelihood of a flood event, *exposure* is the number of population and assets in the locality, and *vulnerability* is the capacity of the people to deal with the event. *Flood risk* is the product of all these three elements:

$$\text{Flood Risk} = \text{Flood Hazard} \times \text{Exposure} \times \text{Vulnerability}.$$

From a management perspective, flood risk can be decreased by reducing any of the three elements. Flood hazards can be reduced by structural measures such as building dams and levees. Exposure to flood hazards can be best managed by land use controls and population resettlement. Vulnerability of people and assets to flood hazards can be modified by nonstructural measures such as raising the house structure and developing better flood forecasting. In addition to these four terms, resilience is increasingly used in the literature. *Resilience* is defined as the ability of a community to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events (Cutter et al. 2013; Lam, Pace et al. 2009, Lam, Qiang et al. 2015). Thus, the concept is closely related to vulnerability and is often considered the opposite of vulnerability (Adger et al. 2005; Lam et al. 2016).

In this article, flood hazard in a county is denoted by the 100-year (also known as 1 percent chance of flood per year) flood zone maps defined by FEMA, and high-risk flood zones in this article refer to areas that have equal or more than a 1 percent chance of flooding in any given year. Flood exposure is evaluated using two quantities: amount of urban (developed) land and number of population located in the high-risk flood zones. Analyzing exposure to flood hazards is the first step toward a better understanding of the overall flood risk. An increase or decrease in flood exposure in a locality can reflect the community's cumulative decision, which is often a result of balancing between the risk of flooding and the utility offered in the flood zone (McGranahan, Balk, and Anderson 2007; Wheater and Evans 2009). For ease of discussion, we use the term *responsiveness* to flood hazards in this article to represent the degree to which people are aware of, attach importance to (as a trade-off decision between flood risk and other amenities), adapt to potential flood hazards, and consideration of other political or institutional factors. In other words, an increase in exposure (people or developed areas) to flood hazards in a county is referred to as less responsive of the county to flood hazards, which could mean a combination of the four scenarios. An evaluation of the spatiotemporal variation of flood exposure at the national level can help reveal the dominant trend, the deviations from the trend, and their changes over time. The findings from this national, county-based assessment will provide basic benchmark information on the level of responsiveness in different communities and offer valuable insights into the underlying factors that cause the differences.

Related Work

Although much work has been conducted on flood exposure in different areas, a national-scale assessment of flood exposure is currently lacking. In developing countries, due to the lack of well-established flood mapping methodologies (Osti, Tanaka, and Tokioka 2008) and high-quality terrain data (Di Baldassarre and Uhlenbrook 2012), the majority of literature has been focused on estimating the extent of potential flood hazard, and assessment of flood exposure is rather limited. For instance, Brouwer et al. (2009) evaluated the willingness to pay (WTP) to varying flood exposure levels in a flood-prone delta in Bangladesh. In their study, flood exposure is simply measured as the distance people live from the river, based on the assumption that flood probability is linearly related to the proximity to the river. This assumption only holds in low-lying flat areas, though. More hydrological and hydraulic considerations are needed for mountainous areas with more complex topography. Hagen et al. (2010) recognized the shortage of hydrological data in Afghanistan and introduced a rudimentary inundation model to estimate potential flood hazard using observed past floods. Their approach was to extrapolate the data of several local flooding events to the national scale, assuming the same hydrologic conditions and constant recurrence period of such events in the whole country. It is useful for flood hazard assessment in small countries with limited flood and hydrological data, but the inaccuracy can propagate significantly when applied to a larger area.

Developed countries generally have more established techniques and complete data archives for flood zone mapping. In Europe, due to the lack of standardized nomenclature and agreed practices, decision makers, governments, and the public are confronted with a variety of approaches to flood mapping, which hampered the comparison of flood risk among countries and analysis of general trends at a larger scale (Merz, Thieken, and Gocht 2007). For instance, Cammerer, Thieken, and Verburg (2013) used flood maps from Austrian Flood Risk Zoning Project (HORA) to estimate spatiotemporal dynamics of flood exposure in the Alpine Lech Valley in Tyrol, Austria. Using simulated land cover changes (particularly urban growth), the researchers projected the changing trend of urban areas exposed to flood zones with different flood recurrence intervals (30, 100, and 200 years) in the study area. In The Netherlands, there is theoretically no flood zone under the same standards of flood recurrence intervals, as the majority of flood-prone areas have already been protected by embankments. Instead, Jongman et al. (2014) used the flood extents in several historical flooding events as benchmarks to classify the territory of The Netherlands into five categories: (1) outer dike, (2) 1953 flooded, (3) 1993/1995 flooded, (4) protected flood-prone, and (5) non-flood-prone. Then, the flood zones are overlapped with individual properties acquired from a government building registry to analyze the spatiotemporal changes of flood exposure in The Netherlands.

In the United States, flood exposure studies have been limited to mostly local areas (Suarez et al. 2005; Johnson, Fischbach, and Ortiz 2013). There are several compelling initiatives on large-scale flood exposure assessment, however. The Coastal Flood Exposure Mapper is a Web application developed by the National Oceanic and Atmospheric Administration (NOAA) that allows public users to visualize flood zones and socioeconomic layers (e.g., population density, poverty) in the East Coast and the Gulf Coast of the United States (NOAA 2017). At the global scale, Jongman, Ward, and Aerts (2012) conducted country-based assessment of urban and population exposure to flood hazards by combining multiple flood databases. Using the World Bank's population and gross domestic product data, the researchers analyzed the economic and population exposures to flood hazards since 1970 and projected the future trend to 2050. Due to limitations of data availability, quality, and resolution, however, their study was conducted at the country or food production unit level where spatial variation at finer resolutions is hard to capture.

With the increasing threat of floods worldwide, it is important to develop better baseline information on flood hazard, flood exposure, and flood vulnerability. A county-based assessment of flood exposure and its spatiotemporal changes in the contiguous United States, as conducted in this article, should contribute by providing much-needed baseline information as well as methodology that can be applied in many other study areas.

Data

The major data sets used in this study are (1) land cover data, which represent urban (i.e., developed) land distribution; (2) FEMA flood hazard maps, which reflect the distribution of potential flood hazards; and (3) census data, which include county population and county boundary. All data sets used in this study are freely accessible from the Web sites of the data providers.

Urban Area Data

The 2001 and 2011 land cover data used in this study were acquired from the National Land Cover Database (NLCD). The NLCD is designed to provide five-year cyclical updates of the U.S. land cover changes using the 30-m resolution Landsat Thematic Mapper (TM) images. The 2011 NLCD currently provides a decade of consistently produced land surface classification for the United States at three time stamps: 2001, 2006, and 2011 (Homer et al. 2007). The NLCD land cover data are represented in raster format and classified into eight general types and sixteen subtypes of land cover according to the Anderson Land Cover Classification System (Anderson et al. 1976). Developed (urban) land is one of the eight general types, which is further classified into four subtypes, including high-intensity, medium-intensity, and low-intensity developed land and open space. In this article, the general land cover types were reclassified as either urban or nonurban, and the amount of urban growth was compared from 2001 to 2011. Afterward, the population at each urban pixel was interpolated using the four subtypes of developed land and geographically weighted regression (GWR).

Flood Hazard Maps

The flood hazard maps used in this study were acquired from the National Flood Hazard Layer (NFHL) provided by FEMA (2015a). The NFHL is the digital version of FEMA's flood maps, which is a national standard used by FEMA and all federal agencies for the purposes of requiring and rating the purchase of flood insurance and regulating new development. The flood mapping process essentially includes the following steps: (1) estimating design flow (e.g., 100/50-year return period flow) using a hydrologic model and precipitation input; (2) estimating water surface elevation using a hydraulic model and design flow estimated in Step 1; and (3) contracting digital elevation model with the estimated water surface to identify inundated areas as flood zones (FEMA 2001).

The NFHL is stored in the ESRI shapefile format and can be accessed from the Web site of FEMA Map Service Center (MSC). So far, the NFHL has not covered the contiguous United States completely, but it is continuously updated by adding new flood maps and revising existing flood maps. The NFHL includes effective and preliminary flood maps. The former type is official and can be used to rate flood insurance policies or enforce development standards for new properties, whereas the latter type is not final but is the best information available at the current time. To obtain more complete coverage of the entire contiguous United States, both the effective and preliminary flood maps in the NFHL were used in this study. The flood maps used in this study were last accessed on 28 September 2015. The total area covered by these flood maps is 4.9 million km^2, which is 63.1 percent of the area of the contiguous United States (Figure 1).

The primary features of the flood maps are flood zones, which are geographic areas defined by FEMA according to the chance of flood inundation and type of flooding. Flood zones in the NFHL are classified into three general categories. First, high flood risk zones are defined as areas that have equal or more than 1 percent chance of being inundated by flood in any given year (FEMA 2015b). The 1 percent chance flood is also called the base flood or 100-year flood. High flood risk zone is also referred to as Special Flood Hazard Area (SFHA) in

FEMA's National Flood Insurance Program (NFIP), where floodplain management regulations must be enforced and the area where mandatory purchase of flood insurance applies (FEMA 1986). In the NFHL data sets, the high flood risk zones are labeled as zones starting with the letter A or V, which includes A, AO, AH, AR, A1–A30, AE, A99, V, VE, and V1–V30. Second, moderate–low flood risk zones are defined as areas that have less than 1 percent annual flood chance, which are labeled as Zone B, X, and C. Third, Zone D represents undetermined flood zones where no analysis of flood hazard has been conducted and flood chance is possible but undetermined. A detailed explanation and definition of the different zones can be found on FEMA's Web site. The available flood maps in the contiguous United States include 11.7 percent high flood risk zones, 72.7 percent moderate–low flood risk zones, and 15.5 percent undetermined flood risk zones. In the remainder of this study, high flood risk zones will be denoted as flood zones and moderate–low flood risk zones will be referred to as nonflood zones.

Census and Other Data

The U.S. county boundary shapefile and the 2010 population by county were acquired from the U.S. Census Bureau. The county boundary was used to aggregate flood zone distribution and develop flood exposure by county. Counties were chosen as the unit of analysis because counties are well-established administrative units that share similar political and governmental functions. Results aggregated in county units can be easily related to a host of social, economic, health, and physical data that are available at the county level. The 2010 county population were downscaled into population by urban pixels in 2011 to estimate the population exposed to flood zones. Additionally, a constraint layer is created to represent areas that are prohibited for urban development, which are excluded from the total land and urban areas in the following calculation. These undevelopable areas include water bodies (from the U.S. Geological Survey's [USGS] NLCD), military sites (U.S. Census), wildlife refuge (U.S. Fish and Wildlife Service), federal land (USGS), and national parks (National Park Service).

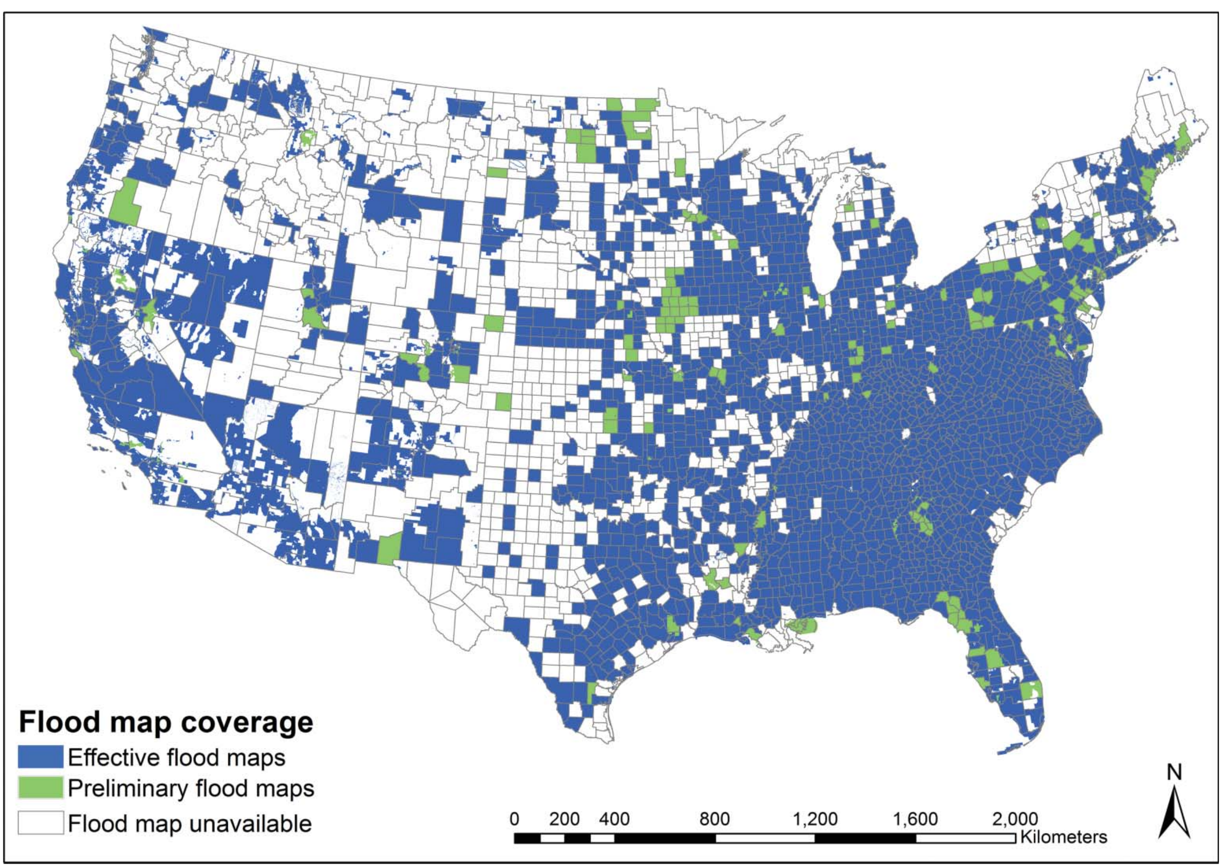

Figure 1. The flood map coverage in the contiguous United States (as of September 2015). (Color figure available online.)

Methods

Data Processing

FEMA's flood maps only have partial coverage for the territory of the United States and the coverage varies from county to county. Of the flood maps used in this study (accessed September 2015), 55.0 percent of the counties in the contiguous United States have complete flood map coverage (coverage > 99.9 percent), whereas 22.7 percent have no flood map available (coverage < 0.1 percent). Figure 2 shows that counties in the eastern part of the United States have more complete flood map coverage than counties in the west, whereas counties with no flood map are mostly distributed in rural areas in the Mountain States. The incomplete flood map coverage can be caused by local conflicts of flood zone delineation (Linskey 2013). In the midwestern and western counties, however, incomplete flood map coverage is usually due to low population density. In these counties, flood maps are more likely to be available in areas where human settlements are located, because the purpose of the flood maps is to rate flood insurance policies for human properties in developed areas and creating flood maps for uninhabited areas is not necessary. To minimize uncertainty of flood exposure estimation in counties with very low coverage of flood maps, only those counties with at least 10 percent of the area covered by flood maps were used in this study, which resulted in 2,234 qualified counties out of the 3,109 (71.9 percent) counties in the contiguous United States.

To integrate with the urban land cover data, the NFHL was converted into a raster map using the same pixel size as that of the urban raster layers (30×30 m^2). The value of each pixel is the flood zone category to which the cell belongs. Due to unanalyzed flood possibility, the undetermined flood risk zones (Zone D) were treated as nondata area and excluded in this study. The remaining flood zones were converted into a binary raster, which includes only flood zones (valued as 1) and nonflood zones (valued as 0).

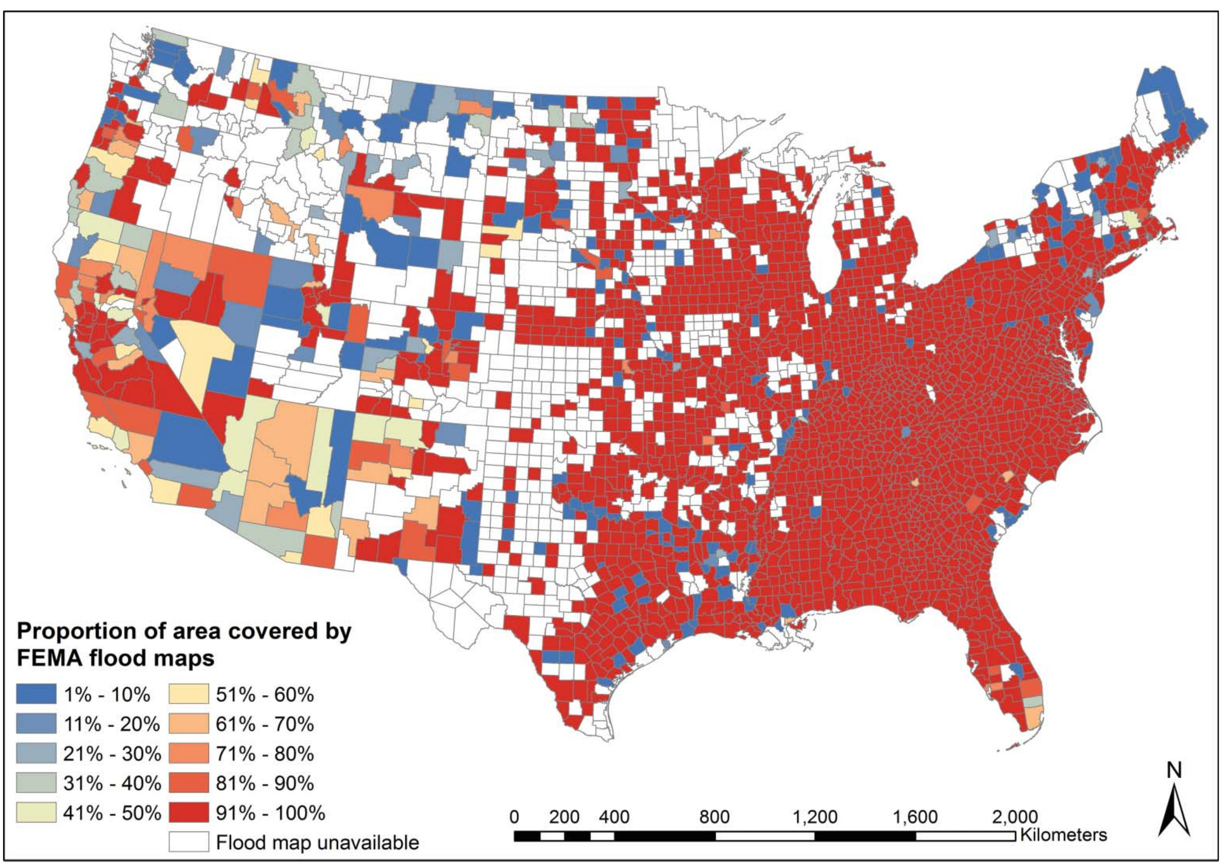

Figure 2. Proportion of area covered by the Federal Emergency Management Agency flood maps by county. FEMA = Federal Emergency Management Agency. (Color figure available online.)

Data Analysis

Land cover maps in 2001 and 2011 and the 100-year-flood zone map were overlaid to derive the proportion of total land and urban (developed) land areas in flood zones in each county in both years. To address the questions of how many people (and urban development) in the United States are exposed to potential flood hazards, where they are, and whether flood exposure has increased over time, five analyses were conducted.

First, for each county in 2011, the proportion of urban areas in flood zones (U_{2011}) was compared with the proportion of land in flood zones in 2011 (L_{2011}). The difference between these two quantities, D_{2011}, would indicate whether the county has a higher or lower proportion of urban land in a flood zone than its expected value, which is zero (Equation 1). The expected value of zero serves as a null hypothesis that urban development is random, regardless of whether the location is in a flood zone or not. A positive deviation from the expected value of zero (positive D_{2011}) would imply that flood zones do not present as barriers of urban development; other factors such as job opportunities or lower housing costs in the flood zones might be more important. On the other hand, a negative D_{2011} value could suggest that flood hazards play a more dominant role in selecting locations for urban development. Thus, a comparison of D_{2011} among different counties can reveal how the dominance of the flood hazard factor, or responsiveness, varies across the space. The difference index (D_{2011}) among counties will provide a quantitative measure and an overview of which counties are more exposed to flood hazards.

$$\begin{aligned} D_{2011} &= U_{2011} - L_{2011} \\ &= \frac{\text{Urban in flood zones in 2011}}{\text{Total urban in 2011}} \\ &\quad - \frac{\text{Land in flood zones}}{\text{Total land}}. \end{aligned} \tag{1}$$

Second, for each county, $U_{2011\text{-}2001}$, the difference between the proportion of urban areas in flood zones in 2001 and 2011, was compared to examine the temporal trend (Equation 2). A high value of $U_{2011\text{-}2001}$ in a county represents an increase in proportion of urban area in flood zones from 2001 to 2011, which implies that people in the county became less responsive to flood hazards during the period. Conversely, a low $U_{2011\text{-}2001}$ value indicates a decrease in proportion of urban area in flood zones in 2011, implying that the county became more responsive to flood hazards by avoiding development in flood zones.

$$\begin{aligned} U_{2011\text{-}2001} &= U_{2011} - U_{2001} \\ &= \frac{\text{Urban in flood zones in 2011}}{\text{Total urban in 2011}} \\ &\quad - \frac{\text{Urban in flood zones in 2001}}{\text{Total urban in 2001}}. \end{aligned} \tag{2}$$

Third, to detect clusters that have significantly high difference ($U_{2011\text{-}2001}$) values, local Moran's I was computed for each county. Local Moran's I is commonly used to evaluate the existence of clusters in the spatial arrangement of a given variable (Anselin 1995). A positive value for local Moran's I indicates that the feature is surrounded by features with similar values, which can be viewed as a part of a cluster. A negative value of I indicates that the feature is surrounded by features with dissimilar values. The local Moran's I index can only be interpreted within the context of the computed z score or p value. In this study, the significance level of $p < 0.05$ was used to detect clusters. A high–high cluster of $U_{2011\text{-}2001}$ indicates a significant hot spot of counties that were less responsive to flood hazards by continuing to have more urban development in flood zones. A low–low cluster would indicate the reverse.

Fourth, to estimate the number of people exposed to flood zones in each county, GWR was used to derive the function between population (dependent variable) and type of urban pixels (independent variables) in each county (Equation 3). Specifically, the four subtypes of urban pixels were high-intensity (HI), medium-intensity (MED), and low-intensity (LOW) developed land and open space (OS). Due to uneven population density across the United States, using a global model to fit Equation 3 will lead to bias in local areas. Compared with the ordinal least square (OLS) regression and spatial autoregression models, GWR can better handle local spatial autocorrelation and nonstationary, and it usually leads to a higher fit in modeling variables with strong local variation (Brunsdon, Fotheringham, and Charlton 1996). In this study, GWR increases the overall R^2 from 0.915 when using OLS to 0.991.

$$\begin{aligned} \text{Population} &= a_1 * \text{OS} + a_2 * \text{LOW} + a_3 * \text{MED} \\ &\quad + a_4 * \text{HI} + \varepsilon \end{aligned} \tag{3}$$

Using GWR, every county was assigned a specific set of coefficients (a_1, a_2, a_3, and a_4), which represent the local relationship between population and the four types of urban pixels. ε is the residual.

These local coefficients were then used to estimate the population in and out of flood zones in each county.

Similar to the second analysis, the fifth analysis is to compare the proportion of population in flood zones (P_{2010}) with the proportion of land in flood zones. The difference is computed as follows:

$$D'_{2011} = P_{2010} - L_{2011}$$

$$= \frac{\text{Population in flood zones}}{\text{Total population}}$$

$$- \frac{\text{Land in flood zones}}{\text{Total land}}. \tag{4}$$

The difference (D'_{2011}) takes into account the spatial variation of population density. This analysis will provide a better picture of how many people are exposed, where they are, and how responsive they are to flood hazards by avoiding development in flood zones.

Results

Results from the previous five analyses are organized as follows. The first section presents the results of the first analysis, which answers the question of how much urban development is exposed to flood hazards and where it is. Results of the second and third analyses, described in the second section, address the question of whether flood exposure has increased over time. Results of the fourth and fifth analyses, elaborated in the third section, answered the question of how many people, instead of urban development, are exposed to flood hazards and the changes over time.

The Spatial Pattern

Figures 3 and 4 show the results of the first analysis. As expected, high proportion of land in flood zones (L_{2011}) are concentrated in flat areas near water bodies and the coast, such as coastal Louisiana, western Florida (near Tallahassee), southern Florida (Miami-Naples), and the Carolina coast. In contrast, the West Coast generally has a lower proportion of land in flood

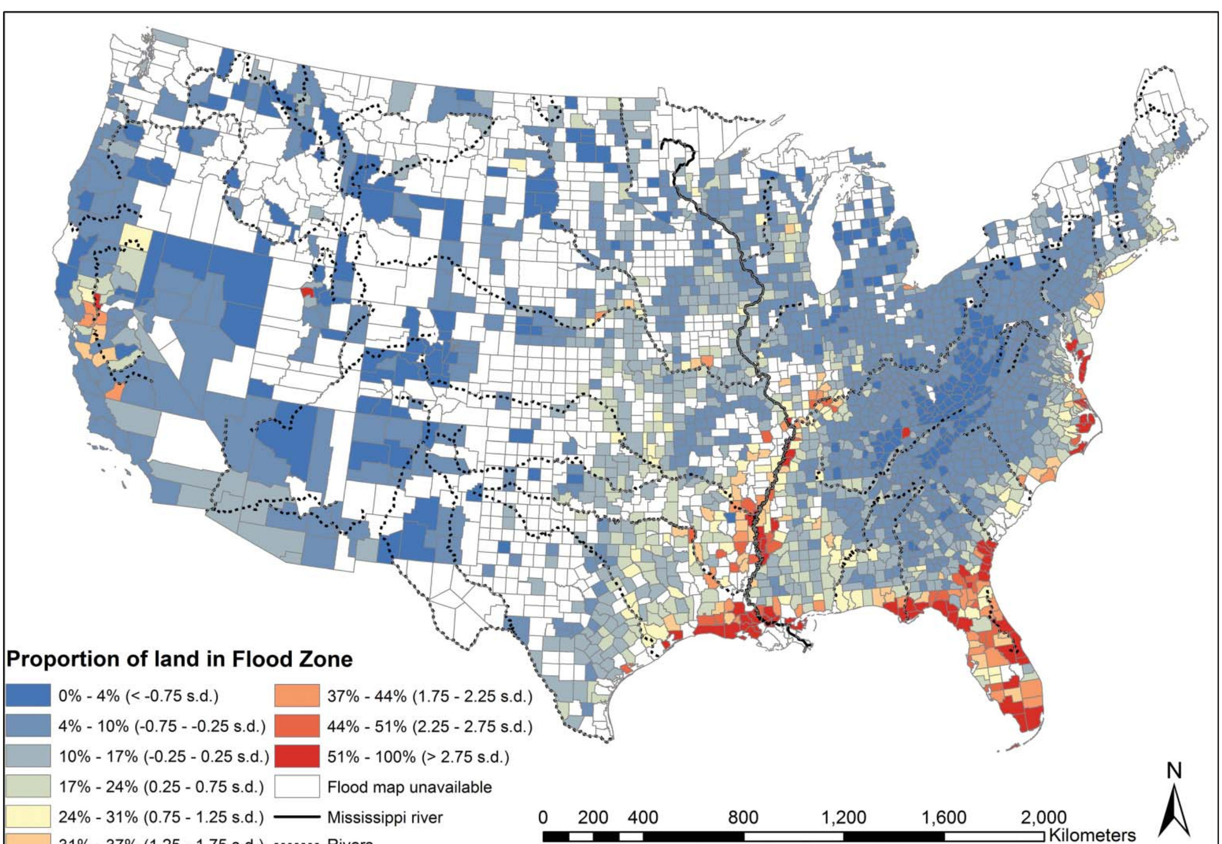

Figure 3. Proportion of land in flood zones (L_{2011}) by county in 2011. (Color figure available online.)

zones than the other coasts, except for a few counties near Sacramento in northern California. The mean value of the proportion of land in flood zones for the 2,234 studied counties was 0.129, compared with 0.084, the mean value of the proportion of urban land in flood zones in 2011. The spatial distributions of U_{2011} and L_{2011} are very similar, with the correlation between the two map patterns being 0.78 ($p < 0.001$; Figures 3 and 4), which indicates that a county that has a high proportion of land in flood zones usually has a high proportion of urban land in flood zones and vice versa.

If we assume that communities are not concerned with the distribution of flood zones, then the proportion of urban land in flood zones is expected to be equal to the proportion of total land in flood zones (the null hypothesis: $U_{2011} = L_{2011}$). Hence, when D_{2011} (Equation 1) is positive, it can be interpreted as more urban development in flood zones than expected, further suggesting that the community is less responsive to flood hazards than other factors by adding more urban development in flood zones. Conversely, if the D_{2011} value is low or negative, the county is more responsive to flood hazards and avoids development in flood zones. A t test between the two mean values (U_{2011} and L_{2011}; 0.084 vs. 0.129) finds that they are significantly different ($p < 0.001$). Hence, in general, urban development in the contiguous United States tends to be greater outside flood zones than in them.

A close examination of the spatial pattern of the difference between the proportion of land in flood zones and the proportion of urban land in flood zones (D_{2011}), however, reveals two important trends (Figure 5). First, counties near water bodies and the coasts, such as those along the Gulf Coast, East Coast, and the middle-lower Mississippi River, have lower D_{2011} values, indicating that they were more responsive to flood hazards by avoiding development in flood zones. In contrast, counties in the western mountainous region and the eastern inland region had higher D_{2011} values, implying that flood hazard is less important compared with other factors for selecting locations for urban development. The three-dimensional view in Figure 6 (the z-axis represents elevation) gives an additional perspective. For example, it shows that the eastern cluster is located along the western hillside

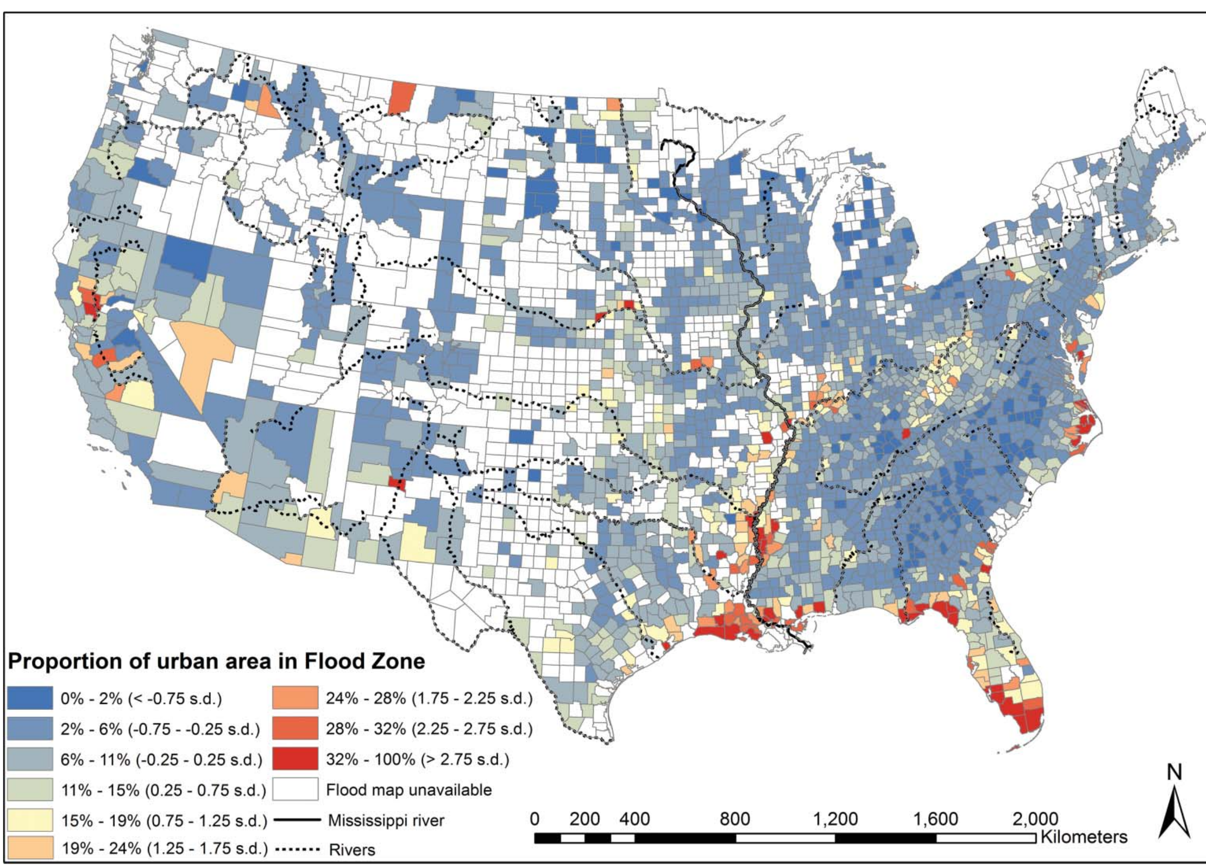

Figure 4. Proportion of urban in flood zones (U_{2011}) by county in 2011. (Color figure available online.)

of the Appalachian Mountains. The second trend, which is closely related to the first one, is that counties that already had high proportions of total land and urban land in flood zones, such as coastal counties, were generally more responsive to flood hazards by avoiding more development in flood zones. On the contrary, counties that have lower proportions of total land and urban land, such as inland counties, were less responsive. This second trend implies that more attention might be needed in these inland counties in reducing exposure to flood hazards.

The Temporal Change

Results from the second analysis, an evaluation of the changes in the proportion of urban areas in flood zones between 2001 and 2011 ($U_{2011\text{-}2001}$; Equation 2), show that the mean difference of the 2,234 studied counties was -2.8×10^{-4}, which is significantly lower than 0 ($p < 0.001$). This finding indicates that at the national scale the proportion of urban area in flood zones decreased between 2001 and 2011, suggesting that the tendency of developing urban areas outside the flood zones has intensified during the decade. This national trend of more development occurring outside flood zones implies that U.S. communities have become more responsive to flood hazards by decreasing development in flood zones.

The spatial distribution of $U_{2011\text{-}2001}$ is not even, however; it shows pockets of high increase in urban land in flood zones (Figure 7). To pinpoint regions that might need attention, we applied the local Moran's *I* analysis to detect significant clusters of high increase. The results from this third analysis show that most low–low clusters are distributed along the coast, especially the East Coast, Houston, and San Francisco regions. On the other hand, most high–high clusters are distributed in inland areas, except the two high–high clusters in New York City and the Miami region (red color in Figure 8 and Figure 9). This result further illustrates that inland communities generally were less responsive to flood hazards during the ten-year period, compared with

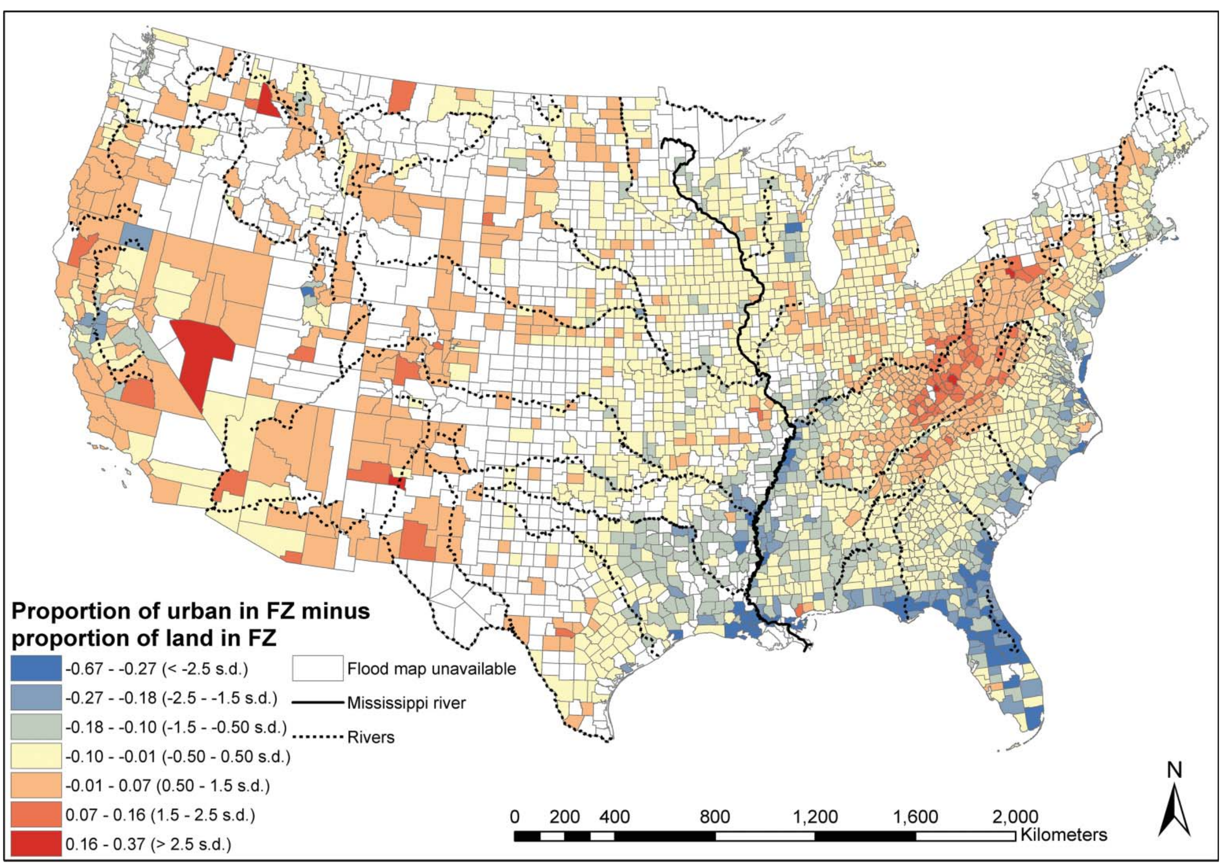

Figure 5. The difference between the proportion of urban land in flood zones and the proportion of total land in flood zones in 2011 (D_{2011}). FZ = flood zone. (Color figure available online.)

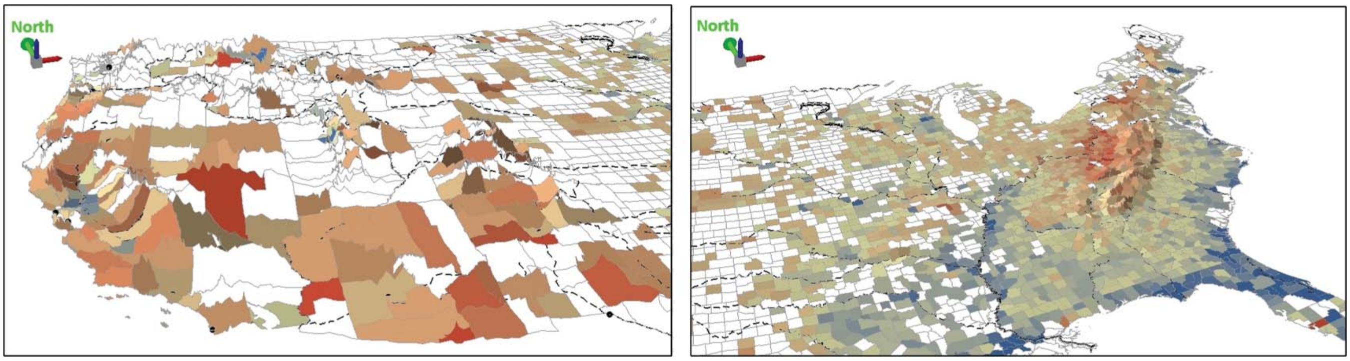

Figure 6. The three-dimensional view of Figure 5 (D_{2011}) with elevation as the z-axis. Left: The Western region. Right: The Eastern region. (Color figure available online.)

coastal communities, which became more responsive by avoiding new urban development in flood zones. The exceptions found in New York City and Miami are worth noting. Unlike other coastal areas, these two large metropolitan areas along the coast have increased their exposure by increasing the proportions of urban areas in flood zones in recent years.

Population Exposure to Flood Hazards

Our fourth analysis was to use GWR to estimate the population in flood zones in 2010 from the four types of urban pixels (Equation 3). For each county, a specific set of coefficients (a_1, a_2, a_3, and a_4) was derived. Theoretically, all coefficients should be positive or at least equal to zero because population cannot be

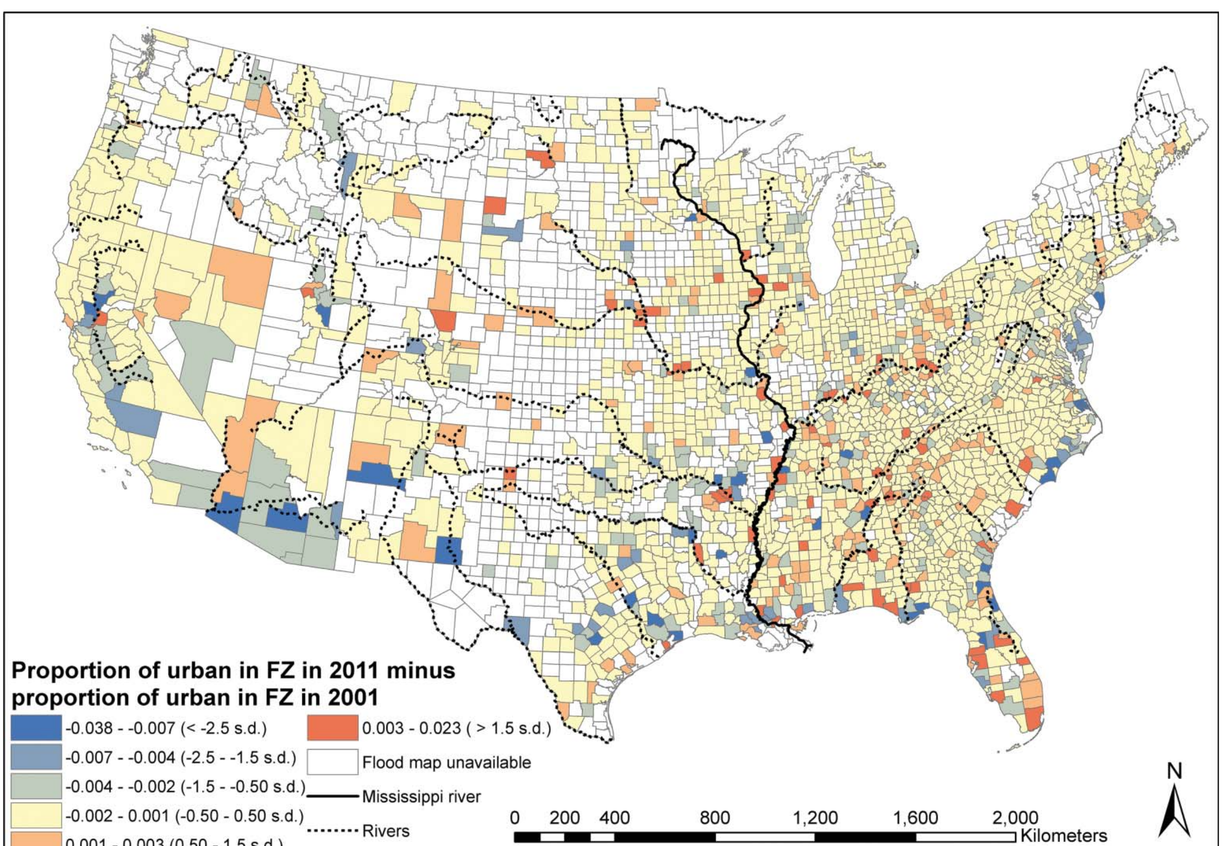

Figure 7. Difference between the proportion of urban area in flood zones in 2011 and the proportion of urban area in flood zones in 2001 (denoted as $U_{2011\text{-}2001}$). FZ = flood zone. (Color figure available online.)

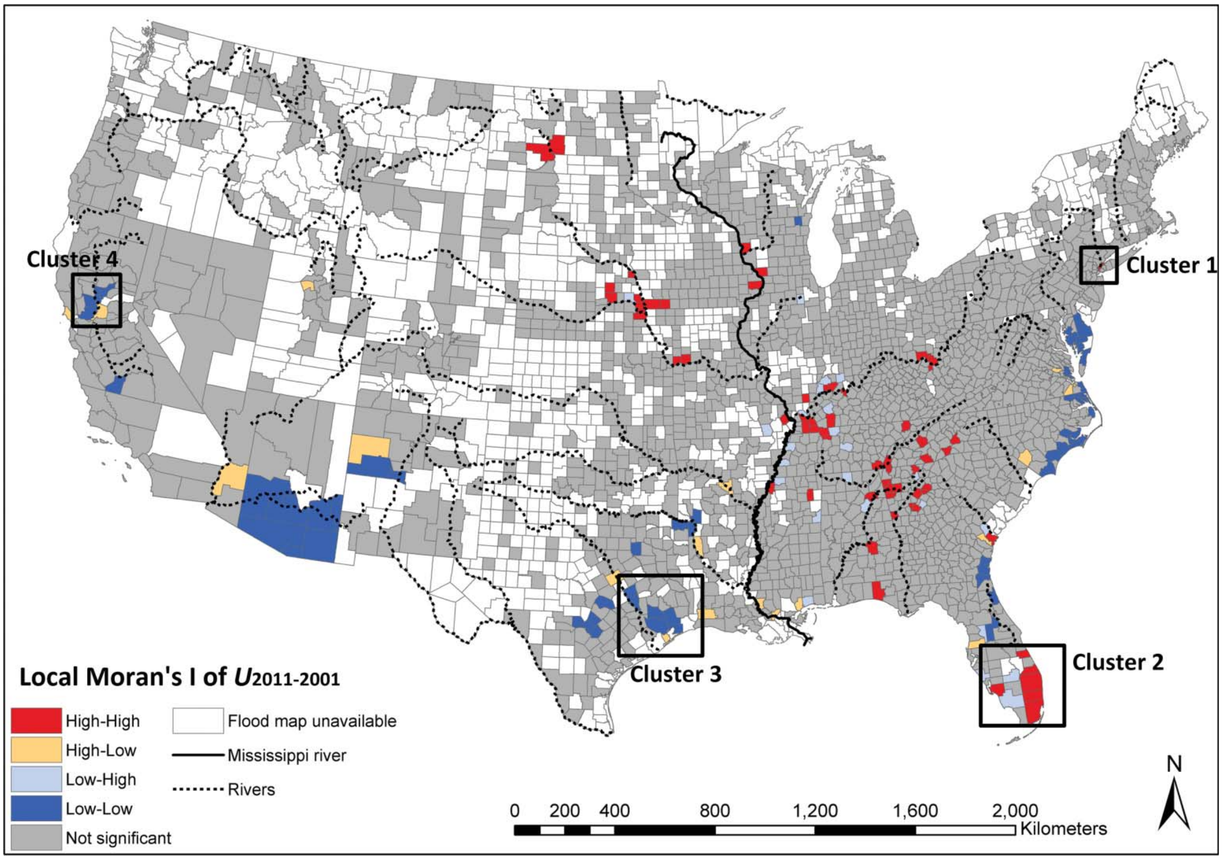

Figure 8. Clusters of local Moran's I of $U_{2011\text{-}2001}$. (Color figure available online.)

negative. Due to collinearity among the independent variables, however, the coefficients derived by GWR are negative in some counties. The result shows that forty-one counties had a negative population either in or out of flood zones. These counties were not included in this analysis. The average proportion of population (P_{2010}) in flood zones in the remaining 2,193 counties was 0.083, which is very close to the average proportion of urban land (U_{2011}: 0.084) derived in the previous section. Similar to the case of urban land, the proportion of population in flood zones is significantly lower than the proportion of total land in flood zones, which confirms that nationally, Americans were responsive to flood hazards and tend to reside or work outside of flood zones. By extrapolating P_{2010} to the total population in the contiguous United States in 2010, which was 306.5 million, we can estimate that 25.3 million (306.5 million × 0.083) people resided in flood zones. Figure 10 illustrates the spatial distribution of P_{2010} and Table 1 lists the top ten counties ranked by P_{2010}.

For our fifth analysis, we calculated the difference (D'_{2011}, Equation 4) between the proportion of population in flood zones (P_{2010}) and the proportion of land in flood zones (L_{2011}). The resultant map (Figure 11) resembles the spatial pattern of D_{2011} (Figure 5) but with less contrast, because D'_{2011} values take into account the varying population density values in different regions. Clusters of high D'_{2011} values can be easily observed, and they are mostly located in inland counties in the Northeast, Appalachia, and the Southwest, whereas coastal counties and counties along the Mississippi River generally had low D'_{2011} values. This further illustrates that inland counties were less responsive to flood hazards than coastal counties, resulting in a higher proportion of population exposure than expected. The top ten and bottom ten counties ranked by the responsiveness to flood hazards (D'_{2011}) are listed in Table 2, which shows that the counties most responsive to 100-year flood threats are in Florida and Louisiana.

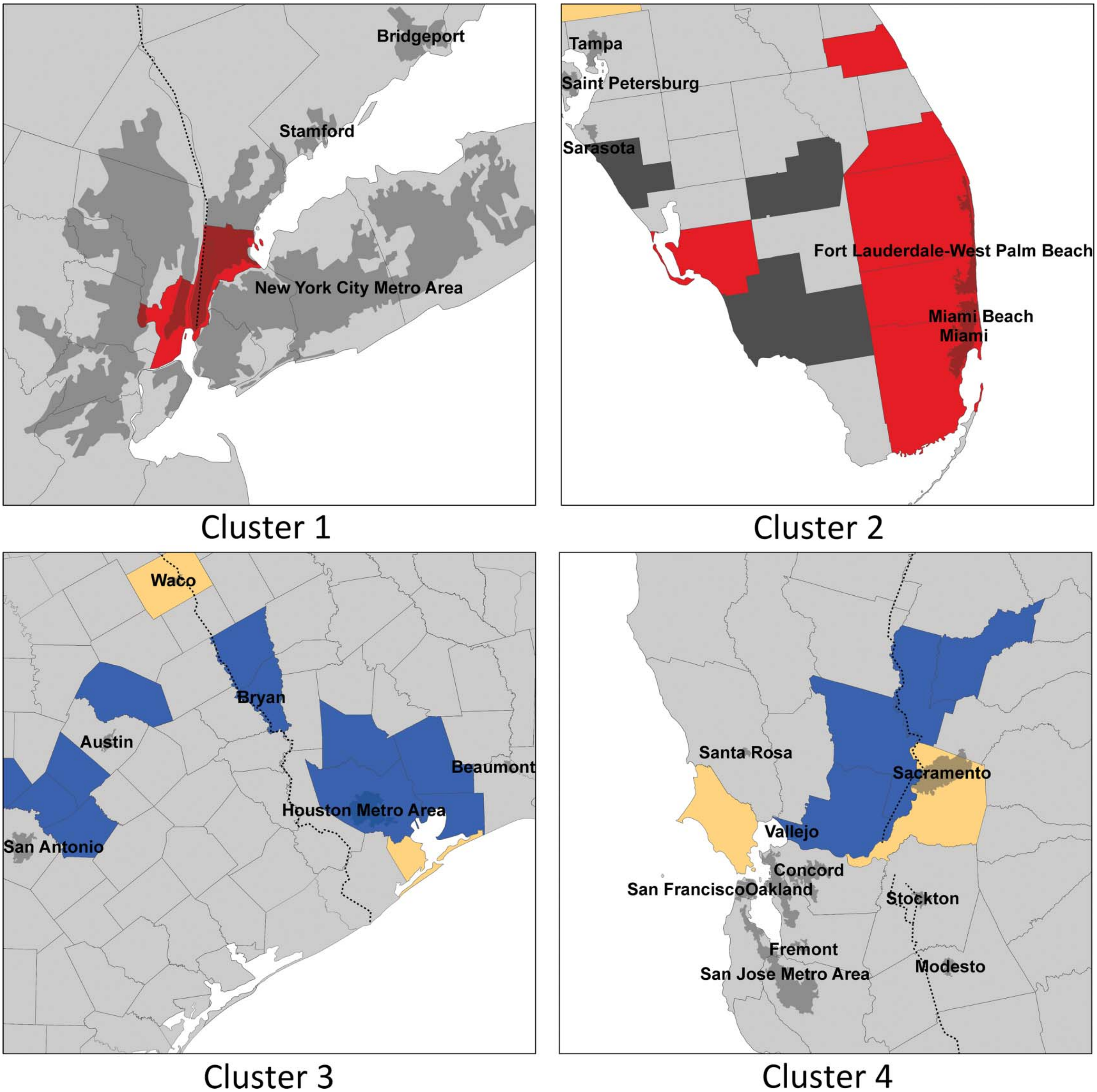

Figure 9. Zoomed-in views of the clusters marked in Figure 8. (Color figure available online.)

Discussion

This study provides a national, county-based assessment of the changing patterns of population and urban exposure to flood hazards in the contiguous United States. The study demonstrates that by integrating several publicly available databases it is possible to identify major trends and patterns of population and urban exposure to flood hazards over time. The several indexes computed from the equations and the spatial analytical methods, including the hot spot analysis and the GWR methods, are straightforward and can be easily applied to other regions or countries to assess and monitor exposure to floods or other natural hazards.

The FEMA flood maps are delineated using a standardized process and a number of parameters including

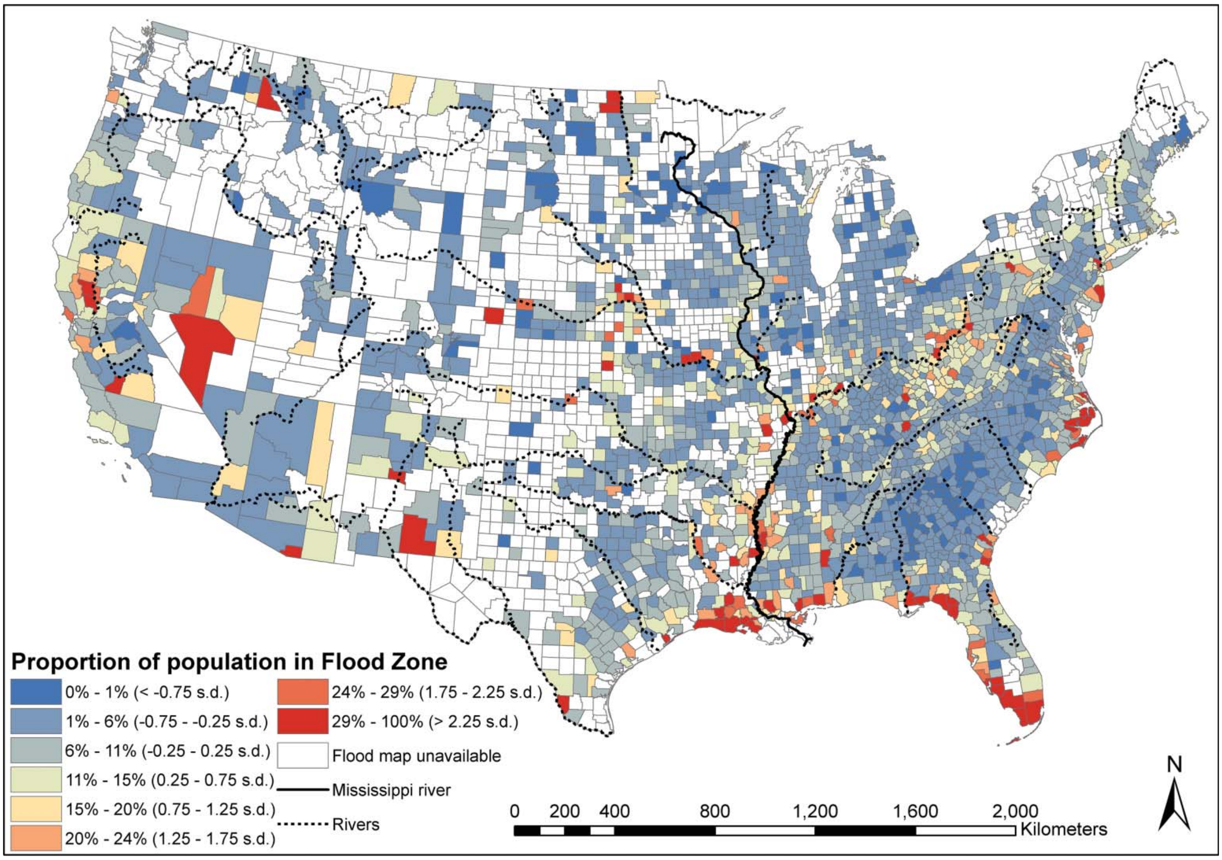

Figure 10. Proportion of population in flood zones in 2010. (Color figure available online.)

terrain elevation, design flow (100-year return period flow), and water surface elevations. Data accuracy, parameters used in the models, and lack of updates are all potential sources of uncertainty at local scales. A comprehensive review of uncertainties in FEMA flood maps can be found in Merwade et al. (2008).

Table 1. The top 10 ranked counties by proportion of population in flood zones

County	State	Population in flood zones	% of population in flood zones
Cameron	Louisiana	6,401	93.60
Monroe	Florida	66,804	91.40
Galveston	Texas	241,204	82.80
Franklin City	Virginia	6,891	80.30
Hyde	North Carolina	4,538	78.10
Issaquena	Mississippi	1,064	75.70
Campbell	Tennessee	30,659	75.30
Tyrrell	North Carolina	3,305	75.00
Ocean	New Jersey	421,470	73.10
Dare	North Carolina	23,405	69.00

Although FEMA flood maps can be inaccurate for some local areas, given that there is no systematic error or discrepancy reported in the mapping process and the entire product, patterns identified in a nationwide study should be able to reflect the general trends at larger spatial scales. Moreover, because this study is confined to a short time period of ten years, it is expected that amendments to the flood zone boundaries in the form of approved letters of map amendment will be relatively few, especially because these amendments often involve only a single lot or a portion of a lot (FEMA 2015b). Hence, it is reasonable to assume that the changes of flood maps will have a very minor influence on these results. For longer term exposure assessment, the uncertainty of flood maps can be amplified by climate change, land subsidence, and new hydrological projects (levees and dams). A more comprehensive survey of flood map accuracy in future studies will be needed.

The results from this study reveal several important national trends that have not been documented or quantified before. This study indicates a general trend that U.S. communities (counties)

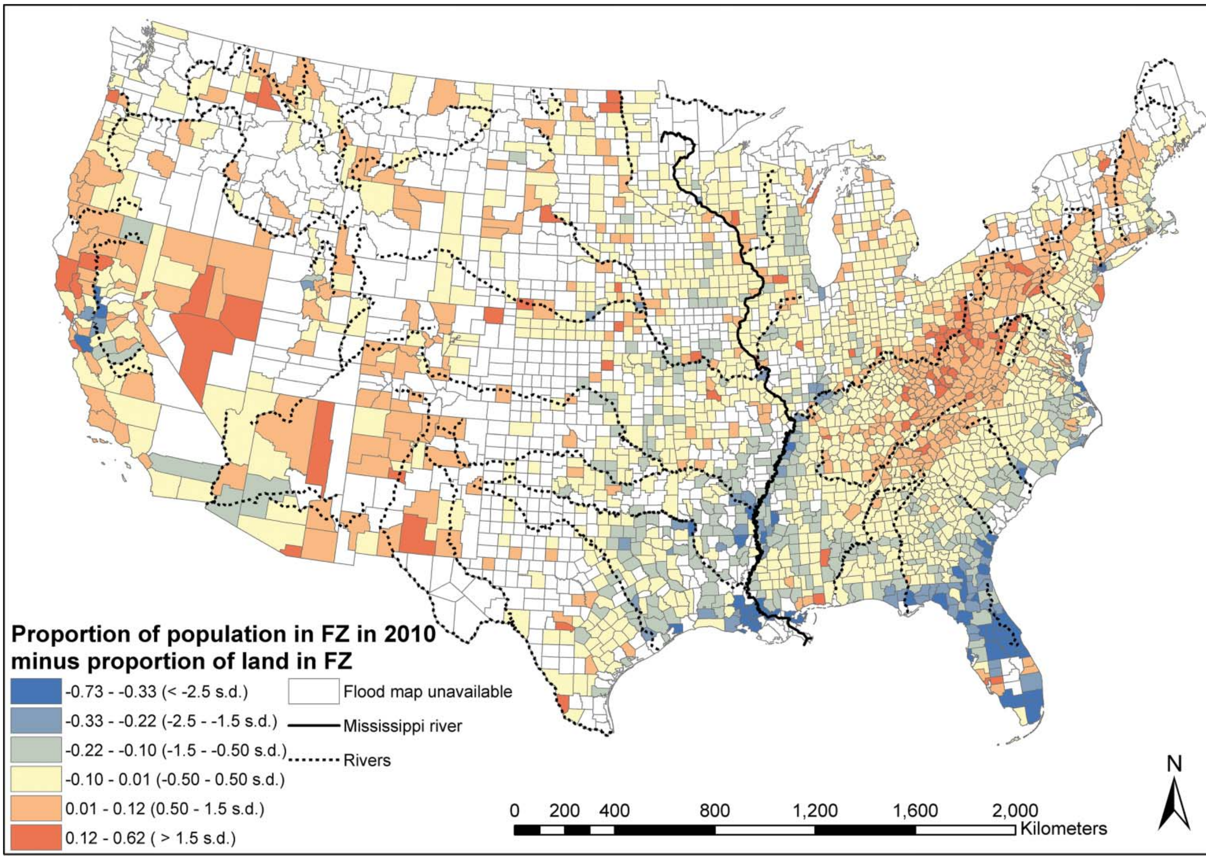

Figure 11. The difference between proportion of population in flood zones and proportion of area in flood zones in 2010. FZ = flood zone. (Color figure available online.)

have become more responsive to flood hazards by avoiding urban development in high-risk flood zones during between 2000 and 2011. At the same time, the study reveals that there were significant departures from this general trend in different parts of the country. Specifically, counties that had a high proportion of land areas in flood zones, including most coastal and riverside counties, were

Table 2. The top 10 and bottom 10 counties ranked by the difference between proportion of population in flood zones and proportion of land in flood zones (D'_{2010})

Top 10 counties ranked by human responsiveness to flood risk (D'_{2010})			Bottom 10 counties ranked by human responsiveness to flood risk (D'_{2010})		
County	State	Difference between % of population in FZ and % of land in FZ	County	State	Difference between % of population in FZ and % of land in FZ
St. Bernard Parish	Louisiana	−0.73	Jackson	Kentucky	0.62
New York	New York	−0.72	Ocean	New Jersey	0.50
St. John the Baptist Parish	Louisiana	−0.68	Calhoun	Illinois	0.47
Iberville Parish	Louisiana	−0.66	Campbell	Tennessee	0.42
St. Martin Parish	Louisiana	−0.62	Valencia	New Mexico	0.42
Indian River	Florida	−0.60	Logan	Colorado	0.40
St. James Parish	Louisiana	−0.59	Stanton	Nebraska	0.36
Orleans Parish	Louisiana	−0.57	Wetzel	West Virginia	0.35
Brevard	Florida	−0.56	Otero	New Mexico	0.33
Miami–Dade	Florida	−0.54	Shoshone	Idaho	0.31

Note: FZ = flood zone.

found to be more responsive to flood risk and avoided new urban development in flood-prone areas, whereas counties with a low proportion of land in flood zones, including most inland communities, were less responsive to flood risk and did not avoid flood zones for urban development. The hot spot analysis pinpoints several clusters of high increases in proportion of urban development during 2001 to 2011, most notably the New York City and Miami regions. Further studies are needed to uncover the underlying factors for these clusters. Moreover, it is noted that this analysis is based on 2001 and 2011 land cover data, the time span of which predates Hurricane Sandy (2012) and Texas and Louisiana inland floods (2016). It would be useful to investigate the trend after these flooding events when new land cover data become available to monitor how the pattern of flood exposure changes.

There are major policy implications of the findings. As already mentioned throughout the article, people and urban development in flood zones could be a result of four scenarios: lack of awareness of the risk (awareness), being able to adapt to the risk by reducing the negative impacts (vulnerability), a trade-off decision between flood risk and other amenities (trade-offs), and other factors such as political and institutional factors. Additionally, there are many other factors that could lead to these local variations, and a thorough interpretation of the various local factors would be impossible. In this article, we use the term responsiveness to generalize the combination of these factors. This study pinpoints regions of concern and shows that more in-depth analyses of these regions will be needed to identify the underlying factors and devise local strategies to reduce the overall flood risk. For example, our findings might point to the need for policies designed for more awareness, better education, adjustment of insurance rates, better land use zoning, and better adaptation to flood events. This is especially needed for the inland counties, which were found to be generally less responsive to flood hazards than coastal regions. In some cases, complete relocation of the entire community might be necessary to reduce the exposure, such as the well-known relocation of the Isle de Jean Charles Native American community in coastal Louisiana, residents of which have been dubbed the first American "climate refugees" (Davenport and Robertson 2016).

Flood risk, as defined in many studies and used in this study, includes three elements—hazard, exposure, and vulnerability. This article provides a national assessment of flood exposure only, and the overall flood risk in each community will be changed depending on the vulnerability of the community, such as whether different mitigation strategies have been implemented. Thus, a comprehensive assessment of the overall flood risk should also include validated measures of vulnerability or resilience for each community. There are various approaches to assessing social vulnerability and resilience, and each has its own advantages and disadvantages (see, e.g., Cutter and Finch 2008; Peduzzi et al. 2009; Cutter, Burton, and Emrich 2010; Tate 2012; Ostadtaghizadeh et al. 2015; Cai et al. 2016; Lam et al. 2016; Qiang and Lam 2016). These vulnerability or resilience measures could be included in future assessments to provide a better picture of how different regions' flood risks vary despite their high exposure. In addition, the variable of flood hazard could be modified to include frequency of actual events or models to take into account the climate change scenarios (Alfieri et al. 2015) to validate and simulate future flood risks. These are all worthwhile future studies. In sum, the findings from this study provide basic benchmark information and a national snapshot of people and urban exposure to flood hazards. Future studies and policies could use these findings to generate detailed local or regional analyses.

Conclusion

This study integrated FEMA flood maps, land cover data, and census data to analyze changes in flood exposure by county in the contiguous United States from 2001 to 2011. The study seeks to answer several key questions: How many people and urban areas are exposed to flood hazards? Where are they? Has flood exposure increased or decreased over time? The findings from the study include the following. First, approximately 25.3 million people, or 8.4 percent of urban land, were located in high-risk flood zones (100-year flood) in 2011. As expected, areas with a high proportion of land located in high-risk flood zones are concentrated in low-lying regions near the coast, rivers, and water bodies. These are areas that need to have appropriate strategies to cope with flood hazards. Second, this article reveals that nationally, Americans have become more responsive to flood hazards by avoiding new development in high-risk flood zones between 2001 and 2011. There are significant departures from this general trend in different parts of the country, however. Third, through comparing the spatial distributions of flood zones and urban development, this article found that communities that already had a high proportion of land areas in flood zones, including most coastal and riverside counties, were more responsive to flood hazards and tended to avoid urban development in flood-prone areas. Conversely, communities with a low proportion of land in flood zones, including most inland counties, were less responsive to flood hazards and did not avoid flood zones for urban development. Fourth, this contrast between coastal and inland counties increased between 2001 and 2011. This is an alarming trend, which might point to the need for more attention to these inland regions, such as promoting more awareness, better education and communication of risk, better affordable housing in nonflood zones, or better flood mitigation strategies. Finally, several exceptions to the trend (hot spots) were detected, including New York City and Miami, where significant increases in urban development in flood zones were found. The findings from this article point to the need for more in-depth analyses of different regions to identify the underlying factors and devise appropriate local strategies to reduce the overall flood risk.

Analyzing flood exposure and its temporal trend is the first step toward understanding flood risk, flood hazard, and flood vulnerability. This study produces a national assessment of flood exposure at the county level. The findings provide basic benchmark information on flood exposure in the United States. The results pinpoint areas that need further investigation and policies to cope with the potential effects of increased exposure. Methodologically, the study demonstrates that the integration of the three publicly available databases could provide a snapshot of the spatial and temporal relationships between hazard distribution and human responses. The same methodology can be applied worldwide to assess the overall trend as well as to identify hot spots that need further attention.

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