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ORIGINAL PAPER

Uneven experiences of urban flooding: examining the 2010 Nashville flood

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Abstract

Intense precipitation events are projected to rise across the southeast USA. The field of meteorology has expanded knowledge of urban precipitation, yet the uneven impacts of precipitation and flooding on specific communities, particularly in the USA, have received less attention. This paper addresses this gap. Using the 2010 Nashville Davidson County Tennessee flood event, the differential community impacts of flooding and their spatial variations are analyzed. Guided by social vulnerability and hazards methodologies, census block data from the 2012 American Community Survey, ArcGIS imagery and redlining maps are used to develop a social variability index using principal components analysis. Components were overlaid on all 98 Nashville census tracts for Davidson County to reveal that flood impacts were inequitably distributed with socioeconomically and racially marginalized households the most severely impacted from flooding. The consequence is that historical processes of segregation and marginalization continue to shape uneven flood impacts in Nashville. Examining the ways vulnerable populations experience severe precipitation events is needed particularly as extreme events are expected to intensify in the future.

Keywords Urban precipitation · Flooding · Social vulnerability · Marginalization

1 Introduction

Floods are among the most frequent and devastating type of natural disaster worldwide (Carter et al. 2018). Increases in precipitation intensity, precipitation frequency, and changing atmospheric conditions are projected to increase levels of flooding in the twenty-first century (Carter et al. 2018; Easterling et al. 2017; Kunkel et al. 2012; Singh and Borah 2013). Urban environments are particularly vulnerable to extreme precipitation and

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associated flooding due to high concentrations of people, infrastructure, and impervious surfaces altering runoff responses (Taisuke et al. 2009). In the southeastern USA, metropolitan areas have already seen a nearly 40% increase in precipitation during the twentieth century, challenging infrastructure, economic stability, and human activities (Bishop et al. 2019; Serre and Heinzlef 2018). These trends are likely to persist as climate disruptions continue (Trenberth 2011; Wu 2015; Wuebbles et al. 2014).

Over the last century, scholars have increasingly examined the effects of predicted and observed climate change impacts for populations and environments in urban areas. Drawing on the urban heat island effect (UHI), numerous studies document how cities can have notable impacts on the local and regional climate (Debbage and Shepherd 2019; McLeod et al. 2017). By demonstrating how processes of urbanization alter land use and urban microclimates, scholars reveal that urban areas not only experience higher temperatures compared to their rural counterparts (typically by around 1–3 °C) (Santamouris 2015; Sailor 2014), but are at greater risk of flooding due to poor infiltration and increase in artificial surfaces due to urbanization (Zhao et al. 2017; Seto and Kaufmann 2009). These urban processes in turn create hazards for human lives, transportation, housing and infrastructure stability, especially for highly urbanized and populated cities (Chan et al. 2018).

Building on this work, recent literature demonstrates the ways that urbanization also creates feedback effects for precipitation patterns. Studies confirm that convergence and divergence patterns located at the interface between urban and rural environments, along with increased surface roughness within urban environments, both enhance surface convergence and increase the rate and intensity of precipitation in and downwind of urban environments (Shem and Shepherd 2009; Debbage and Shepherd 2019; Ashley et al. 2012; Thielen et al. 2000). Other studies demonstrate how differential thermal properties of cities produce unstable atmospheric conditions through the creation, enhancement, and/or displacement of mesoscale circulations, all of which modify rainfall patterns with implications for human populations (Shepherd and Burian 2003). A recent meta-analysis of 489 studies on the impacts of urbanization on rainfall supports these trends, highlighting how urbanization modifies rainfall such that mean precipitation is enhanced by 18% downwind of a city and 16% over the city (Liu and Niyogi 2019). These dynamics are particularly concerning for urban centers of the southeastern USA, where intense precipitation associated with frontal systems and flood frequency have increased significantly since the beginning of the millennia (Bishop et al. 2019; Mallakpour and Villarini 2015).

2 Uneven impacts of environmental change

As climate variations unfold globally, literature consistently demonstrates how exposures, sensitivity and adaptive capacity to environmental hazards are unevenly distributed across socioeconomic and racial lines (Chakraborty et al. 2014; Walker 2012). Drawing on concepts of justice, vulnerability, and inequality, scholars of both environmental justice and vulnerability studies employ a range of frameworks to theorize how environmental vulnerability, shaped in part by human exposures to a hazard and partly by people's social vulnerability, is situated within multilayered social, economic, and political aspects of resource use and management in urban areas (Turner et al. 2003; Polsky et al. 2007; Cutter et al. 2009). Understanding how "characteristics of a person or a group and their situation influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard" (Wisner et al. 2004; 11) facilitates an understanding of complex socio-spatial patterns of exposure to various hazard types, while simultaneously illuminating the (in) capacities that enable people to mitigate environmental risks (Collins et al. 2018).

By investigating whether and how socially disadvantaged groups are disproportionately exposed to environmental health hazards, numerous studies draw on concepts of environmental justice (EJ) to demonstrate how racial/ethnic minorities, people of low socioeconomic status, and other socially disadvantaged groups experience disparate residential exposure to environmental hazards, such as noxious pollution, hurricanes, and earthquakes (Collins et al. 2017; Grineski et al. 2015, 2017; Collins et al. 2018; Walker 2012; Zhao et al. 2018). Mitchell and Chakraborty (2018), for instance, analyzed social differences in the spatial distribution of urban heat exposure across twenty of the largest metropolitan statistical areas in the USA and revealed that not only is urban heat unevenly distributed socially, with people of low household income, education level, and renter status consistently and significantly impacted by greater urban heat exposure, but that urban heat is also unevenly distributed spatially, with specific neighborhoods at greater risk. By interrogating the segregated structures of cities, Mitchell and Chakraborty (2018) demonstrates that socially and technically constructed urban environments present differential heat exposure for neighborhoods that result in landscapes of thermal inequity.

Other studies too consistently demonstrate how stratification of disadvantaged residents into segregated neighborhoods presents uneven environmental exposures leading to inequity; people with the least socioeconomic means and power to adapt to or mitigate their risk are often the most exposed to environmental harms (Lopez 2002; Morello-Frosch et al. 2002; Morello-Frosch and Jesdale 2006; Morello-Frosch and Lopez 2006). This is particularly true in the USA where racial, ethnic, and economic segregation has played a crucial role in establishing the life constraints and environmental exposures of minorities and individuals of lower socioeconomic status (Mitchell 2019). At the core of this research is the realization that environmental exposures are often contingent on the relative economic and political power of groups in society and their location within neighborhoods of social disadvantage (Mitchell 2019).

While this growing body of literature demonstrates the inequitable impacts of changing climatic conditions for socially vulnerable populations, scholars are only beginning to examine the differential impacts of urban flooding, especially from extreme precipitation events" (see: Lynn 2017; Collins et al. 2018, 2019). Some studies reveal socially marginalized people have reduced capacity to mitigate flood hazards at home pre-event, evacuate in response to floods, and/or return home following flood-induced disruptions (Collins 2009, 2010), while others demonstrate how marginalized populations have reduced ability to access social protection resources necessary to reduce the impacts of flooding (i.e., flood insurance, pre-flood hazard mitigation infrastructure, emergency response information, post-disaster assistance) (Maldonado et al. 2016a; Mustafa 2005). Qiang (2019) for instance assessed critical infrastructure flood exposure across the USA, revealing that while around 21.8 million people are exposed to the FEMA 100-year floodplain, inland communities are less responsive to flood hazards than coastal regions, with those of lower socioeconomic position more likely to reside in inland floodplain regions. Equally, studies underscore how socially vulnerable groups experience the most adverse consequences of flood disaster in terms of morbidity and mortality, reflecting both their increased exposure to flooding and their reduced access to protective resources (Collins et al. 2013a, b; Zahran et al. 2008).

While these studies bring critical attention to the equity implications of urban flooding, more attention to the linkages between flood exposure and social disparities along with the unequal consequences of climate-induced disasters is needed in order to effectively inform planning, adaptation, and mitigation strategies (Emanuel 2017; Forzieri et al. 2016). As Collins et al. (2019, p. 8) contends "more research is needed that assesses linkages between the types of disparities in flood exposure with salient post-event social and health outcomes in order to advance knowledge of the EJ implications of major flood events." This is critical since tropical cyclones are likely to contribute to flooding events. Since storms which intensify by 60 kt in the 24 h just before landfall are projected to occur every 5–10 years by the end of this century, compared to an average of once per century in the climate of the late twentieth century, it is important to unpack the ways historical dimensions interact with storm variations to produce dimensions of inequity (Emanuel 2017; Forzieri et al. 2016; Smiley 2020). Moreover, forecasts that indicate 24-h pre-landfall intensifications of 100 kt may occur as frequently as once per century, which were essentially nonexistent in the late twentieth-century climate, highlighting the urgent need to examine how populations differentially experience flood risks and associated impacts (Emanuel 2017; Forzieri et al. 2016; Flores et al. 2020). The aim of this paper is to examine the relationships between flood exposure and social disparities in the 2010 Nashville Tennessee flood. Although commentaries suggest that marginalized populations, such as the elderly, disabled, uninsured, racialized, and poorest people, were most heavily impacted by the 2010 flood (Spencer 2010; Wilcox 2020; Renkl 2020; Wilemon 2015), the social vulnerability of populations at the neighborhood scale is understudied, potentially contributing to narrow assertions of flood impacts. Thus, we use the 2010 flood event as a window through which to examine how legacies of segregation in Nashville interact with current disparities to shape the social vulnerabilities to flood events and inform mitigation and adaptation strategies in the context of current and future climate shocks.

3 Study context: Nashville Tennessee

As the capital of Tennessee, Nashville is the largest city in the state, with a population of approximately 670,000 people in 2020 (World Pop Review 2020). Growing at a rate of ~ 0.31% annually (World Pop Review 2020), the city is demographically diverse, with approximately 55% White, not Hispanic or Latino, 27.9% black or African American, ~ 10.4% Hispanic or Latino, ~ 3.6% Asian, ~ 2.5% two or more races, ~ 0.2% American Indian and Alaskan native, and 0.1% Native Hawaiian or Other Pacific Islander (World Pop Review 2020; US Census Bureau 2019). The city is located within Davidson County and positioned on the Cumberland River Basin, the second largest tributary of the Ohio River (Benke and Cushing 2005; USACE 2010). The Cumberland River is approximately 1120 km long, with a mean daily discharge of ~ 1055 m^3/s, with seasonal rainfall producing the highest discharge from November to mid-May (Benke and Cushing 2005; USACE 2010).

On May 1–3, 2010, record breaking rainfall led to severe flash flooding and river basin flooding, particularly along the Cumberland River, with severe impacts for Nashville (Yoon and Beighley 2015). Preceded by drier than normal conditions, a low-pressure system positioned over the western USA paired with a high-pressure system over the eastern USA produced an atmospheric river, leading to severe rainstorms and flooding across Tennessee (Moore et al. 2012; National Weather Service 2011). The moisture from the atmospheric river interacted with a stationary front, resulting in severe thunderstorms and record flooding across Tennessee and Kentucky.

While the Nashville National Weather Service (NWS) Weather Forecasting Office (WFO) issued widespread flood warnings on May 1, 2010, the Nashville Army Corps of Engineers officials were concerned that the Old Hickory Dam would break under rising water (US Army Corps 2010). Rainfall measurements from the Nashville International Airport (KNBA) totaled 13.57 inches in 36 h, breaking the 139-year record by a factor of two (Yoon and Beighley 2015). On May 2, 2010, the Nashville Army Corps of Engineers ordered the release of approximately 5.4 billion gallons of water into the Cumberland River, spilling over the banks of the river and into Nashville city. During normal operations, the dam released 24,000 cubic feet of water. Yet, the decision to release the dam resulted in the discharge of approximately 24,000 cubic feet of water per second, impacting the Nashville population downstream (Keim et al. 2018). Water rose from its 4-foot peak in 1975 to approximately 51.68 feet, damaging or destroying approximately 11,000 properties, displacing over 10,000 people, and resulting in 11 casualties in Nashville (National Weather Service 2011; US Army Corps 2010). Even still, the flood created more than two billion dollars in private property damage and one hundred twenty million dollars in public infrastructure damage (US Army Corps 2010). While the entire population of Nashville experienced devastating impacts from the flood, reports suggest historical trends of segregation created disproportionate flood impacts for particular demographic groups (Erickson 2012).

The city of Nashville has a long history of segregation, dating back to the Civil War (Logan and Martinez 2018). Processes of de facto and de jure segregation, following by redlining in the 1930s, were routinely used to deny minority residents access to equal loans, housing, and educational opportunities (Metro Human Relations Commission 2020). Particularly important to the development of these patterns were the Federal Housing Administration (FHA) and the Home Owners' Loan Corporation (HOLC) graded classificatory scheme that was based on the perceived risk of default (Wachter 2019). By assessing one's occupation, residence, annual income, nationality, percentage of "negro families," and percentage of families on relief, the FHA and HOLC assigned security grades to neighborhoods, designating which population could reside in specific locations (Grove et al. 2018, pp. 138–139). Grade A was considered locations of minimal risk for mortgage lenders, whereas Grade D was considered hazardous. Neighborhoods in more affluent suburban areas, such as Green Hills and Belle Meade, housed predominantly white middle class families, while neighborhoods east, north, and southeast of downtown were considered "hazardous" and accommodated largely racialized minority populations (e.g. 48% of the city) (Aycock 2020).

Not only did "hazardous" locations spatially restrict access to key amenities, but they were also commonly located in environmentally hazardous neighborhoods. For instance, historically black neighborhoods, such as Black Bottom, located in South Nashville, and Black Center, located west of the Capitol Building (Fig. 1), were known for their frequent flooding and devastating impacts for marginalized populations (Kreyling 2005). By attaching racial connotations to space, political actors legitimized having marginalized people disproportionately bear the burden of environmental risks (Teelucksingh 2003). As Logan and Martinez (2018) reveal, segregation in Nashville increased as the scale decreased, compounding neighborhood social and economic inequalities.

These spatial ideologies not only informed residential development, but further privileged suburban space in education policy. Since the placement of schools often shape local housing markets, public officials adopted policies of site selection and gerrymandering attendance zones to reinforce and deepen residential segregation (Erickson 2012). Such pro-suburban education policies, housing strategies, and transit tactics helped to deepen

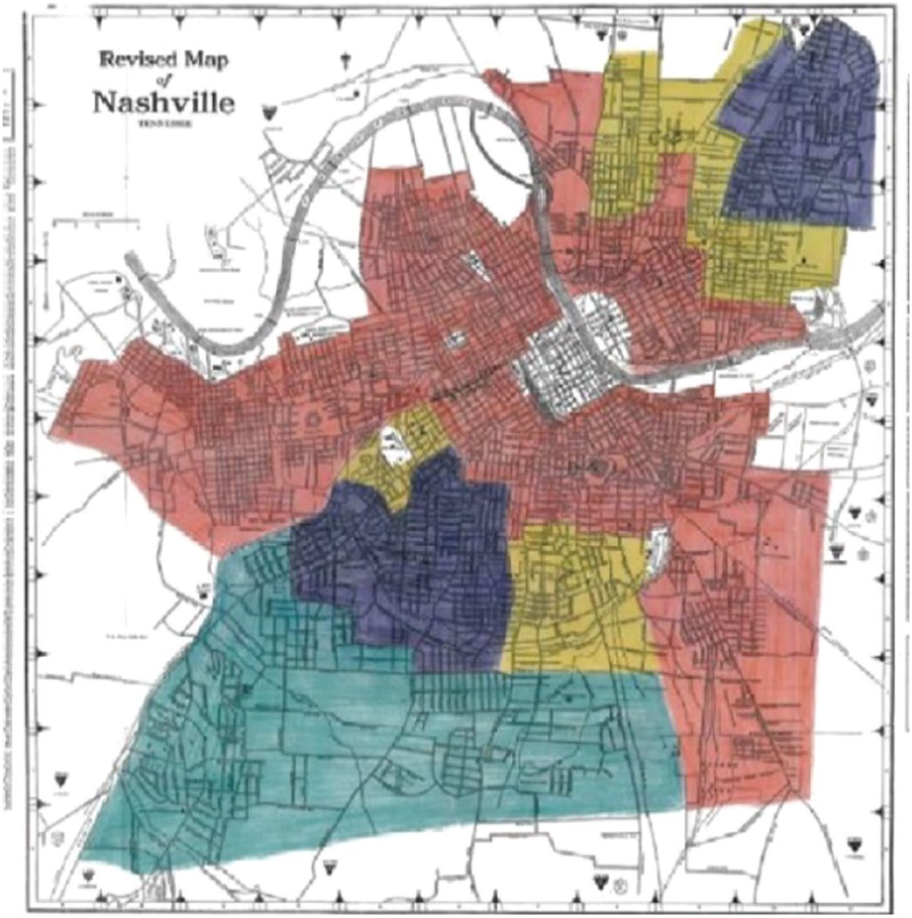

Fig. 1 Redlining map of Nashville. *Note*: Green (Best—A First Grade)—Green areas were considered to be in high demand, and these neighborhoods were almost entirely white. Blue (Still Desirable—B Second Grade)—Blue areas were less desirable because these neighborhoods were not exclusively white; however, they were still desirable because they were at low risk of "infiltration" by non-white groups. Yellow (Definitely Declining—C Third Grade—Most yellow areas bordered black neighborhoods. These areas were considered risky due to the perceived threat of foreign-born or "lower-grade populations" moving in. Red (Hazardous—D Fourth Grade)—"Hazardous" neighborhoods were mostly populated by black residents and these areas were ineligible for FHA backing

patterns of inequality, even in consolidated metropolitan areas that linked city, suburban, and rural areas under a single government (Erickson 2012; Raymond and Menifield 2011). The effect of these various policies, laws, and practices has been to segregate minority populations, institutionalizing a racially based legacy of disinvestment characterized by limited access to credit, most excessive subprime lending loans, high rates of foreclosure and environmental risk (Greer et al. 2014). According to the 2018 Census, 43% of black families in Nashville own their home compared to 72% of white families in former Grade A districts, increasing 35.1% from 1980 (US Census 2018). Even still, residents in former Grade A districts have 131% more home equity than a homeowner in a former redlined district (Dylan

Aycock 2020). These legacies of segregation and the ways they interact with current disparities in Nashville provide the foundation for our social vulnerability assessments.

4 Social vulnerability indicator identification

Developing vulnerability indicators is fundamental to our approach of assessing physical and social vulnerability, as well as operationally representing the concept of vulnerability. This study applies the analytic framework developed by Wang and Yarnal (2012), which integrates the hazard of place model of vulnerability (Cutter 1996) and the three dimensions of vulnerability (Polsky et al. 2007), in order to assess risk exposure, sensitivity, and adaptive capacity. We draw on this framework to examine the vulnerability of households to riverine flooding within the urban context of Nashville.

4.1 Data and methods

Physical vulnerability was assessed using flood imagery retrieved from the Metropolitan Government of Nashville, City of Nashville Map Office & Davidson County, Tennessee's ArcGIS REST Services Directory.[1] The imagery was collected with the Leica ADS40 digital sensor and processes with Leica GPro software. The data were obtained May 3, 2010, and correspond with the National Map Accuracy Standard for 1" = 200' scale mapping products. Redlining maps were obtained from the University of Richmond's Digital Scholarship Lab's page, *Mapping Inequality*,[2] where scans, geo-rectified images, shape files, and GeoJSON files are available for Nashville's HOLC maps from the late 1930s.

Social vulnerability indices are often used to determine the social dimensions of natural hazards vulnerability (Tate 2012). Numerous studies have compared indicator approaches (e.g., Birkmann 2007; Eriksen and Kelly 2007; Hinkel 2011; Tate 2012; Wiréhn et al. 2015) to assess the socioeconomic and demographic factors that unevenly shape household and community adaptation and mitigation strategies to natural disasters. Social vulnerability indices commonly use principal components analysis (PCA) to reduce a large set of indicators to a small set of uncorrelated principal components (e.g., Cutter et al. 2003; Rygel et al. 2006; Tate 2012; Wood et al. 2010). As such, principal components analysis was used in this study to assess which demographic groups from the 2012 ACS to include in the analysis (Naik 2017).

These data were downloaded for the census tracks comprising downtown Nashville and surrounding areas flooded by the Cumberland River in 2010 representing all of Davidson Country. All variables with missing data were removed. We identified 48 proxy variables in the 2012 Survey that represent social vulnerability indicators deemed important in the literature. Variables including race, sex, disability and economic status were selected for analysis. A full list of variables is provided in "Appendix 1." Note that most variables are extracted from the census data at the household level (e.g., household structure and household by race/ethnicity), but some are individual level variables (e.g., age, sex, race/ethnicity). The selection of cross-level variables helps facilitate our understanding of how different factors interact to shape social vulnerability to natural hazards.

[1] https://maps.nashville.gov/arcgis/rest/services/Imagery/May2010_FloodImagery_WGS84/MapServer.

[2] https://dsl.richmond.edu/panorama/redlining/#loc=12/36.145/-86.847&city=nashville-tn&text=downloads.

These variables were then used in a rotated principal component analysis, using Varimax rotation and retaining components with eigenvalues greater than 1.0 (Guttman 1954; Kaiser 1960). Doing so reduced the number of indicators to a smaller set of uncorrelated principal components to create a social vulnerability index (Hung et al. 2016; Cutter et al. 2003; Tate 2012). The eigenvalues in decreasing order were plotted to identify the scree, i.e., the portion of the graph where the slope of decreasing eigenvalues approaches zero (Cattell 1966). Component scores generated through regression analysis were divided by standard deviation (see “Appendix 2” for PCA results). The PCA detected the main household groups and sociodemographic characteristics of vulnerability in Nashville, while GIS in ArcGIS 9.2 demonstrated their spatial distribution of these groups (Naik 2017). The final step of the analysis involved overlaying the results from the PCA on the 98 census tracts in the Nashville urban core and Davidson County area that fell within the flood plain of the Cumberland River in order to identify the populations most at risk of flooding.

5 Results

5.1 Physical vulnerability: risk exposure

The results reveal that areas adjacent to the Cumberland River and areas that parallel the coastline were exposed to flooding in 2010 (Fig. 2). Equally, Fig. 2 demonstrates that other

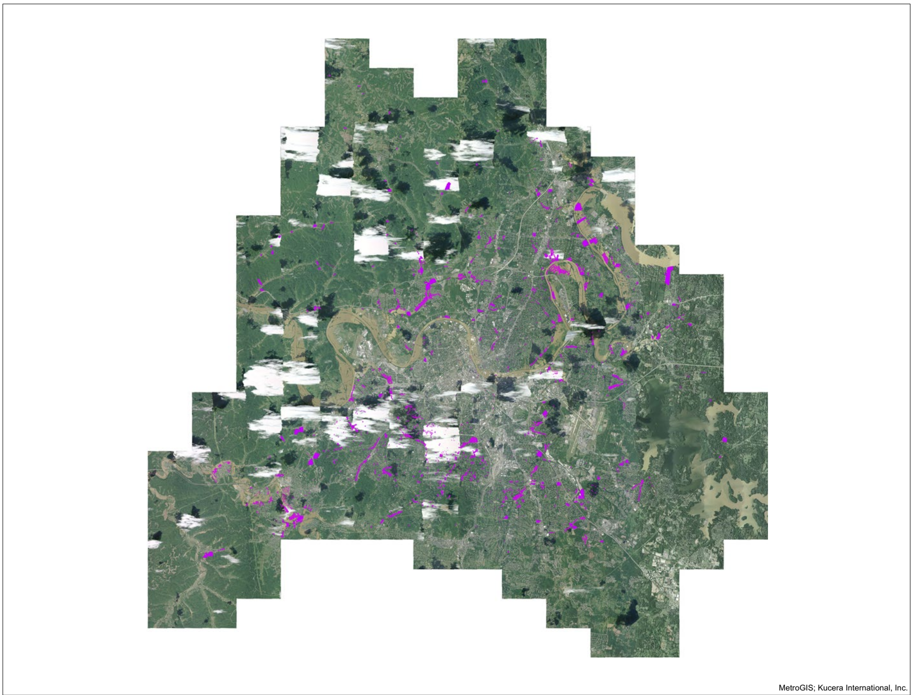

Fig. 2 Flooding in Nashville 2010. *Note*: Purple areas indicate flood impacted areas of Davidson County

large areas located in southern Davidson County, along the northeastern and northwestern blocks of the county, bordering the river were exposed to flooding. Although major flood events are relatively rare in the life of an individual, family, or household, they can produce flooding that threaten areas far inland, as indicated in the 2010 Nashville city flood case.

5.2 Vulnerable households in Nashville, Davidson County

The PCA extracted 10 components with eigenvalues greater than 1.0 that explain a total of 81% in the variance in social vulnerability of household populations in Nashville, Davidson County (Table 1) (see "Appendix 1"). Component 1 (C1) explains approximately 0.277% of the variance, component 2 (C2) explains approximately 0.138%, component 3 (C3) explains 0.09413%, component 4 (C4) explains 0.075, component 5 (C5) explains 0.056, component 6 (C6) explains 0.051, component 7 (C7) explains 0.036, component 8 (C8) explains 0.0346, component 9 (C9) explains 0.033, and component 10 (C10) explains 0.027. Examination of the rotated component loadings suggest the following component names comprise the social vulnerability index: (C1), White alone; (C2), Below poverty line with a disability, in labor force; (C3), Hispanic or Latino; (C4), Two races (not Hispanic or Latino); (C5), Hispanic or Latino, two or more races; (C6), Not Hispanic or Latino, two or more races; (C7), Hispanic or Latino, black or African American alone; (C8), At or above the poverty level in the past 12 months, with a disability, in the labor or armed forces; (C9), Hispanic or Latino, Native Hawaiian, Other Pacific Islander alone; (C10), Renter occupied. Those variables with the largest absolute loadings (greater than or equal to 1 and − 1) are identified as the main corresponding factor. The components and their general relationships to flood vulnerability are briefly described in the following sections.

Four of the components including households who identify as White alone (C1), Two or more races (not Hispanic or Latino) (C6), Hispanic or Latino, black or African American alone (C7), and renter occupied households (C10) have a standard deviation between 1.11 and 3.54 below the mean and contribute to 0.27% of the total variance. While studies commonly indicate that white populations are less vulnerable to the impacts of flooding (Satterfield et al. 2004; Clark et al. 2014), our PCA result is likely indicative of the 2010

Table 1 Social vulnerability variables

Component	Household characteristics
C1	White alone
C2	Income in the past 12 months below poverty level, with a disability, in labor force
C3	Hispanic or Latino
C4	Not Hispanic or Latino, two or more races, excluding some other race, and three or more races
C5	Hispanic or Latino, two or more races
C6	Not Hispanic or Latino, two or more races
C7	Hispanic or Latino, black or African American alone
C8	Income in the past 12 months at or above poverty level, with a disability, in labor force, in Armed Forces
C9	Hispanic or Latino, Native Hawaiian and Other Pacific Islander alone
C10	Renter occupied

population composition in Nashville where the white population comprised 75% of the total population (Capehart and Lindeman 2013). Given this large percentage, it is probable that the absolute number of white households located within the county positioned this population as socially vulnerable to flooding.

Households classified as two or more races, non-Hispanic or Latino (C46) contribute to 0.69% of the total variance and is positively associated with flooding. Two or more races include households who identify as Asian, Indian, Chinese, Filipino, Japanese, Korean, and Vietnamese. Compared to the white demographic in 2012, households who classify as two or more races have a low median household income (i.e. $36,000 vs. 48,000), low per capita income by race (i.e. $18,400 vs. $37,700) and marginal home ownership rates (i.e. 44.5% vs. 61%), likely contributing to the social vulnerability of this demographic group (Nashville Gov. 2016).

Hispanic or Latino, black or African American alone (C7), represents 0.72% of the total variance. Previous studies demonstrate that African Americans are more likely to experience physical hardships and trauma during and after a disaster due to low socioeconomic position and limited financial savings needed to relocate or mitigate flood damage (Perilla et al. 2002; Benevolenza and DeRigne 2019). These socioeconomic factors are characteristic of the population in Nashville. In 2010, the per capita income for the black or African American population in Davidson County was approximately $13,500 less than the white population, increasing further to approximately $18,000 in 2015 (Nashville Gov. 2016). Likewise, compared to the white population in 2010, the black and African American population earned only 57% of their total income (Nashville Gov. 2016). While the median household income for the black or African American population increased from approximately $31,000 to $35,000 between 2010 and 2016, their household income increased only 34% relative to the white population (Nashville Gov. 2016). Historical processes of marginalization, segregation, and uneven access to social services likely contribute to the social vulnerability of this demographic group (Erickson 2012; Raymond and Menifield 2011).

Renter occupied households (C10) contribute to 0.82% of the total variance and are positively associated with flooding. Studies demonstrate that property ownership strongly influences the level of control a resident has over the adoption of protective measures and access to postdisaster assistance, leading to differences in flood susceptibility among home owners and renters. Compared to property owners, renters are associated with higher water inundation levels (Brouwer et al. 2007), more adverse health impacts (Whittle et al. 2010; Tunstall et al. 2006), lower economic loss (Adeola 2009) and higher rates of displacement and job loss following flooding (Elliott and Pais 2006). Although disproportionate impacts of flooding are often associated with the low social status of renters, the causal relationship between tenure and social vulnerabilities is fluid (Steinführer 2007). These factors likely contributed to the social vulnerability of renter households during the 2010 Nashville flood.

Seven of the 10 PCA results including income below poverty level in the past 12 months, with a disability, in labor force (C2), income at or above the poverty level in the past 12 months, with a disability, in the labor or armed forces (C8), Hispanic or Latino (C3), Hispanic or Latino, two or more races (C5), and Hispanic or Latino, Native Hawaiian, Other Pacific Islander alone (C9) and Two races or more races, excluding some other race and three or more races (C4) reported a standard deviation of 1.22–3.54 below the mean. Households below the poverty line with a disability, in the labor force (C2) as well as households with an income in the past 12 months at or above the poverty level, with a disability, in the labor force or armed forces (C8) contributes 0.41% and 0.76% of the total variance, respectively. Disability captures any sensory, physical, mental, self-care, go-outside-home, and employment disability. This result indicates that although these households face several social vulnerabilities, potentially through employment, social security, and/or veterans benefit pathways.

Hispanic or Latino households (C3) contributes 0.41% of the total variance. While it is important to recognize the vast heterogeneity within Hispanic and Latino demographic groups (e.g. foreign born, US born, cultural distinctions, historical variations) (see: Maldonado et al. 2016b) for the purposes of this analysis, we combined Hispanic and/or Latino foreign and US-born populations. Although studies on race/ethnicity and flood exposure have found that minorities may be disproportionately exposed to climate events in some contexts (Highfield et al. 2014; Montgomery 2014; Peacock et al. 2015), our analysis reveals that few Hispanic or Latino households in Davidson County experienced flooding, despite low-income status, possibly due to strong social networks to mitigate the challenges associated with flooding, or due to their low population size within the county (Nashville Gov. 2016).

Households who classify as Hispanic or Latino, two or more races (C5) and households who classify as not Hispanic or Latino, two or more races, excluding some other race, and three or more races (C4) contribute to 0.64 and 0.58% of the total variance, respectively. Households who classify as Hispanic or Latino, Native Hawaiian, and Other Pacific Islander alone (C9) contribute to 0.79% total variance. The small proportion of these households in Nashville in 2010 (e.g., 2.3% respectively) likely contributed to the lower impact to flooding among these groups in the study region.

5.3 Spatial variations of social vulnerability

To inform the interpretation and spatial variations in social vulnerability among the populations of Nashville, we first mapped the number of flood damaged properties per census tract (Fig. 3).

Next, we visualized 5 of the social vulnerability indices based on the component scores for each census block group. We focus on the social vulnerability of demographic groups to flooding in relation to the 100-year flood plain (Fig. 4). Specifically, we visualize the social vulnerability of the white households (C1), Hispanic or Latino households (C3), Hispanic or Latino, black or African American households (C7), and renter occupied households (C10), along with households with income in the past 12 months below the poverty level, with a disability and in the labor force (C2) (Figs. 5, 6, 7, 8, 9). The gradated colors represent the proportion of the specific population impacted by the flood, and the number in each census tract represents the number of flood damaged properties per census tract. Mapping social vulnerability in relative terms by individual component highlights the ways particular populations in Nashville are socially vulnerable along with the places that require priority focus for vulnerability reduction actions.

Figure 4 demonstrates spatial variations in social vulnerability throughout Nashville. As indicated in Fig. 5, a large portion of the white population (C1) is dominated by vulnerable block groups (beyond 3.5 standard deviation) as depicted by the dark purple census tracts along the southern and western census tracts in suburban areas of the city (Fig. 4). As indicated in Fig. 5, although white households experienced flooding, they are situated in tracts with few flood damaged properties per population group and geographically positioned away from the Cumberland River. Moreover, analyzing the white flood-damaged properties in relation to the 100-year flood plane demonstrates that the white population

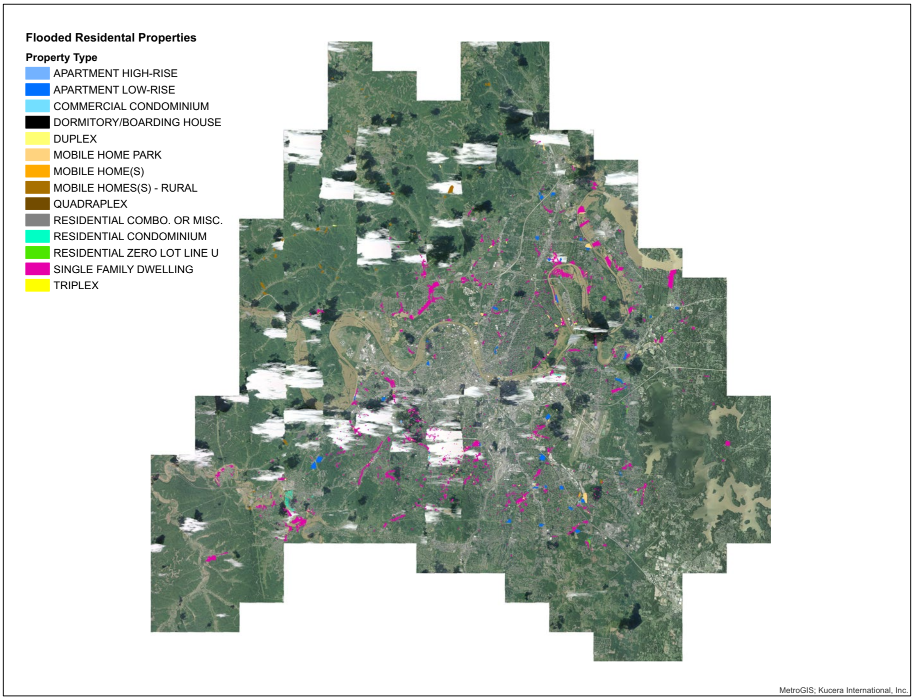

Fig. 3 Number of flood damaged properties, by residential unit type, in Nashville and surrounding Davidson County 2010

who were historically green lined, faired better during the flood than historically redlined districts. Equally, the white population who were impacted by the flood in the southwest census tracts (e.g., condominium residential units), were built later than the 1930s and not associated with historical processes of redlining.

In contrast, Latino and Hispanic households (C3) reside in census tracts scattered throughout central and eastern Nashville, Davidson County near the Cumberland River (Fig. 6). These block groups are highly vulnerable to flooding as indicated by the dark purple census tracts, demonstrating high rates of flood damaged properties per block tract, ranging from 50 to 350 affected units. Analyzing flooded Latino and Hispanic households through a historical lens further demonstrates that these households not only correspond to the 100-year historic flood plane, but are also positioned within segregated "declining" and "hazardous" neighborhoods. The spatiality of social vulnerability changes further when examining Hispanic or Latino, black or African American households. Whereas the majority of the Hispanic or Latino households were centered in pockets northeast and southeast of the Cumberland River, the inclusion of black or African American households in this component (C7) alters the geographic variations of social vulnerability to flooding in Nashville. As Fig. 7 reveals, these households are located primarily in the eastern half of Davidson County and express high vulnerability to flooding, with these households located in tracts with the most flood-damaged properties in Nashville (e.g., ranging from 50 to 850+ flood-damaged properties), corresponding to the 100-year flood plane. The geography of vulnerability to flooding for this demographic group is not only symptomatic of

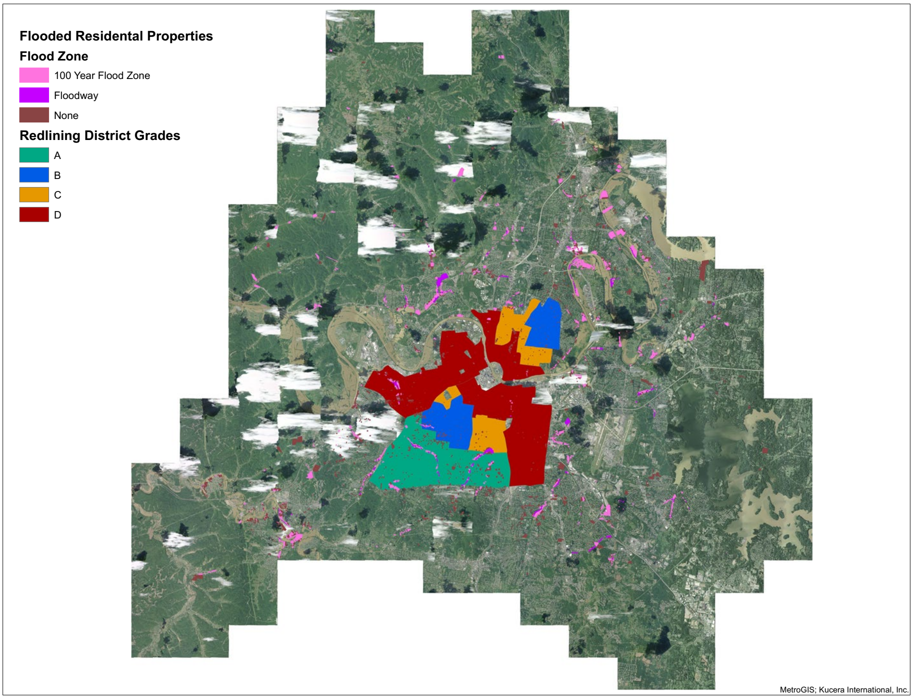

Fig. 4 Vulnerability of flood damaged properties in relation to the 100-year flood plain

their close geographic proximity to the Cumberland River but also corresponds to patterns of historically redlined districts, demonstrating a continuation of segregation and risk.

As for C2, households with income in the past 12 months below the poverty line, with a disability and in the labor force, the most vulnerable block groups (2.52 standard deviation) reside within the center of Nashville, in close proximity to the Cumberland River. As Fig. 8 reveals, the geographical location of these vulnerable areas corresponds with a large number of Section 8-subsidized apartments located in downtown Nashville that house a large number of poor and disabled citizens (Cole 2013). These dynamics, combined with the fact that this demographic is centered directed within the 100-year flood plane, likely exacerbate this populations' vulnerability to flooding.

When considering the vulnerability of renter occupied households, the most vulnerable block groups (1.11 standard deviation) are located within central Nashville and situated within close proximity to the shoreline of the Cumberland River. As Fig. 9 demonstrates, renting households were particularly impacted by the flood given the relative high number of flood-damaged properties in these block tracts. Given that 49% and 23% of Davidson country are cost burdened and severely cost burdened and pay over 30% and 50% of their income on housing, respectively, it is likely that this demographic could not afford to implement housing flood mitigation strategies during the 2010 flood (Nashville Gov. 2016). The positionality of renter households within the 100-year flood plane further demonstrates how compounding vulnerabilities intersect to undermine possibilities for health in the context of precipitation change.

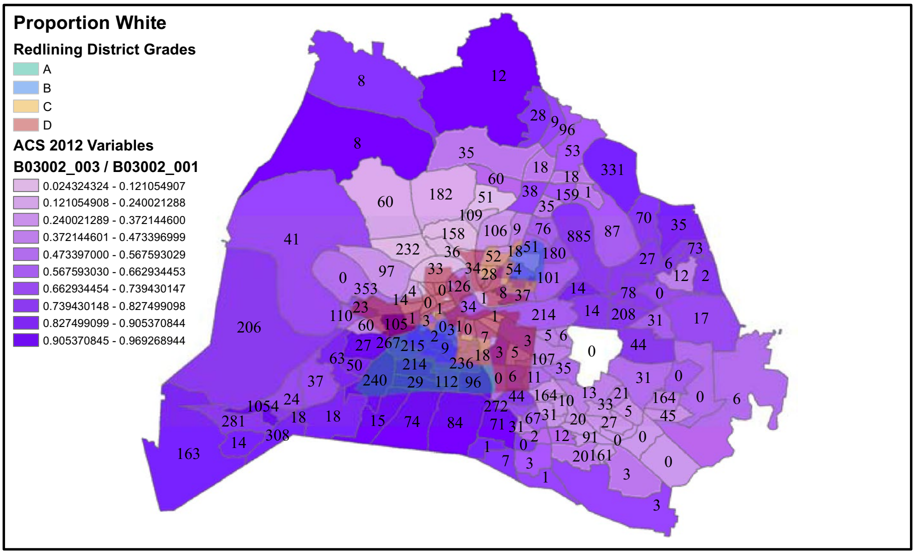

Fig. 5 Proportion of white population

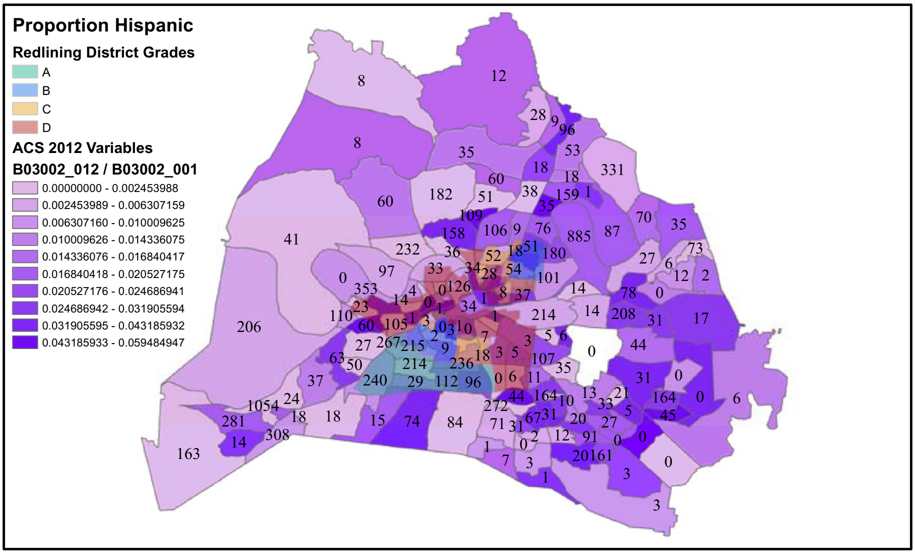

Fig. 6 Proportion of Hispanic and Latino

6 Conclusion

Extreme precipitation events are expected to intensify in the coming decades and have disproportionate impacts within population groups. Using Nashville, Davidson County, Tennessee as an example, the study demonstrates how social disparities intersect with changing

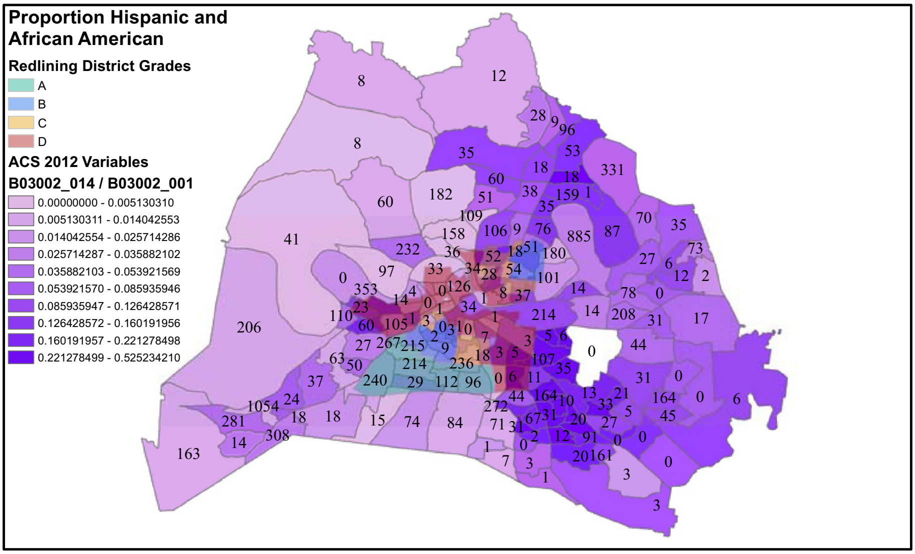

Fig. 7 Proportion of Hispanic and African American

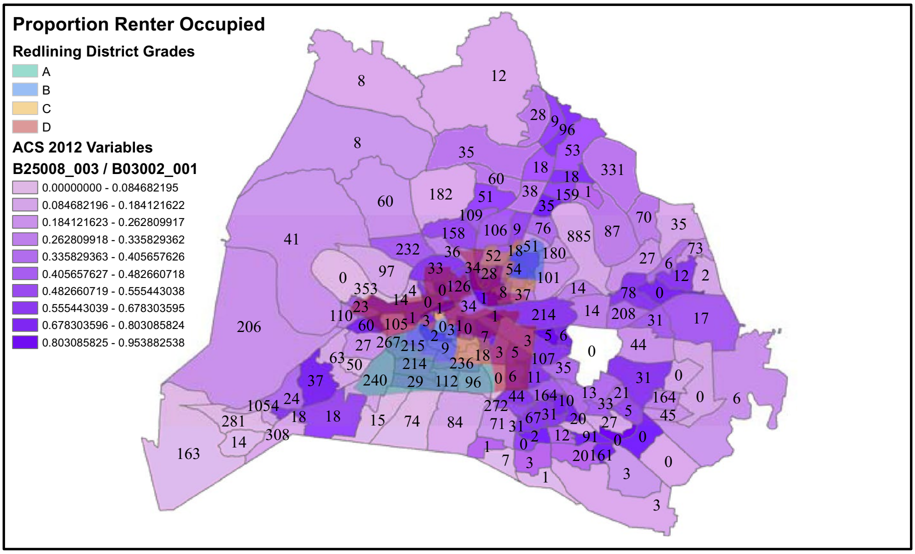

Fig. 8 Proportion of renter occupied

physical environmental systems to produce differential vulnerabilities to flood events. By illustrating the intersections of flood risk and social vulnerability associated with differential household compositions (Figs. 4, 5, 6, 7, 8), the results reveal how socially and technically constructed urban environments present differential flood exposure for neighborhoods that may reduce or exacerbate pre-existing disparities. These constructed environments in

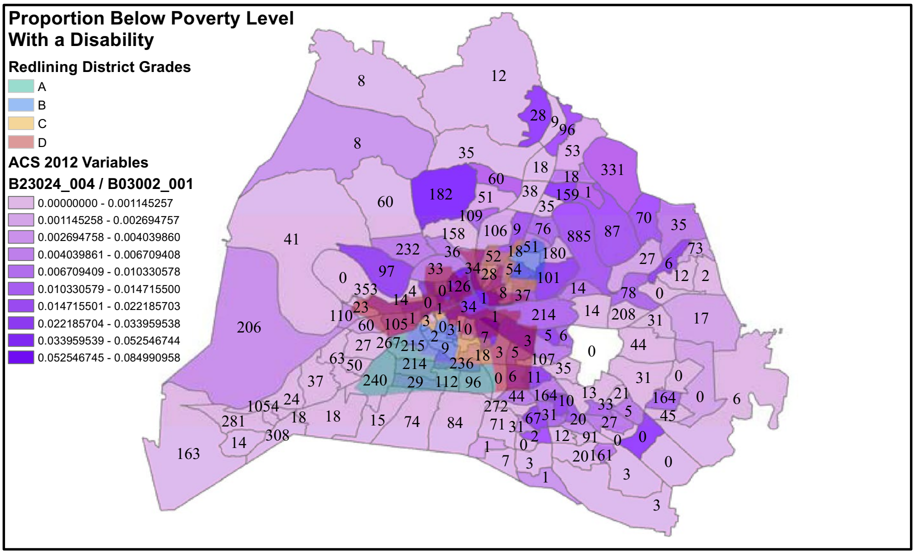

Fig. 9 Proportion below poverty line with a disability in the labor force

turn shape various degrees of physical and social vulnerabilities to risks that result in landscapes of flood inequity.

Synthesizing physical and social vulnerably demonstrate that populations in Nashville, Tennessee, are not equally vulnerable to flood hazards. As the findings reveal, flood exposure in the 2010 Nashville flood was not only dependent on the relative socioeconomic position of households, but further shaped and informed by historical processes of marginalization and segregation. The results of our social vulnerability index underscore the value of examining different forms of social inequities in order to assess how disparities connect to major flood events. As the findings demonstrate, the impacts of flooding on populations are contingent on a set of interlocking factors, some of which are associated with physical geographic location and exposure, while others are tied to the sensitivity and adaptive capacity of individuals living in the area.

Developing a social vulnerability index provided the capacity to unpack the degree and composition of social vulnerability among the population in Nashville, Tennessee. The aforementioned results demonstrate that variations of vulnerability among the population are primarily attributable to differences in financial capital, living arrangements, and historical and contemporary forms of racial segregation. The populations of highest social vulnerability are overwhelmingly situated within the city center, contiguous to the Cumberland River, and correspond to black and African American households, renting households, households below the poverty line, households with a disability, as well as historically redlined neighborhoods, revealing how historical process of marginalization continues to rework inequities in discriminatory ways. When Figs. 5, 6, 7, 8, and 9 are assessed together, the results demonstrate how social vulnerabilities are layered across the city, compounding degrees and geographies of vulnerability. Since flood hazards present a considerable and growing physical risk to a large proportion of the midwestern USA (Bishop et al. 2019; Serre and Heinzlef 2018), attention to marginalized populations such as racial/ethnic groups, disabled individuals, renters, and households below poverty line is urgently needed in order to effectively inform planning, adaptation, and mitigation strategies (Emmanuel 2017). Future mitigation strategies that guide development away from high-risk area and are cognizant of the ways historical dynamics structure contemporary inequities are critical to alleviate future flood exposure (Shepherd et al. 2020).

Moreover, by coupling physical vulnerability with social vulnerability, we found that segments of the population in Nashville Davidson County are most exposed to flood hazards and thereby most physically vulnerable are also most socially vulnerable (e.g., black and African American, renters, households below the poverty line with a disability). In general, the inhabitants of the urban core have a high social vulnerability due to limited financial and physical capital, racial inequities and a high physical vulnerability due to their proximity to the Cumberland River. In contrast, the white population at significant distance from the Cumberland River were far less physically and socially vulnerable to the 2010 flood event due to their geographic proximity and higher socioeconomic position in the district. That said, this demographic group was still socially sensitive to the flood hazards and was unable to mitigate all deleterious effects of the flood. We suggest that more attention be directed to variations in population composition when assessing vulnerability, especially since populations often suffer unevenly and may have few resources to respond to flood events (Collins et al. 2019).

While this analysis provides a comprehensive assessment of vulnerability to flooding, the framework and methodology used in this paper is unable to address all aspects of population vulnerability to flooding events. Although the numerical metrics and measures of vulnerability provide some insight into the physical and social vulnerability of the population in Nashville, vulnerability to flooding is dynamic, shaped by geophysical and socially mediated factors operating across multiple physical and social scales (Polsky et al. 2007; Cutter et al. 2009). Thus, more consideration to the dynamic vulnerabilities of populations to flood risks, engaging mixed method quantitative and qualitative data will help to capture a richer, more nuanced understanding of flood vulnerability in the context of current and emerging climate aberrations.

As indicated in this study, populations are mixed in needs, capabilities, and vulnerability to flooding; therefore, flood vulnerability reduction policies should be tailored to the patterns of vulnerability of populations, cognizant of historical legacies, and contemporary realities of a place. In light of future flood projections, it is imperative to have a well-designed plan for responding to extreme precipitation and flood events that are updated annually with the changing characteristics and dynamics of place. In short, the USA will experience more pronounced and severe precipitation and flood events in the next decade, and the changing demographic composition and growing racial divisions in the USA pose a challenge for emergency response and mitigation strategies. Knowledge of where vulnerable populations are located within communities, and the nature of their vulnerability is an important step toward effective flood management.

Appendix 1: Variable list

Name	Label
B01001_002	Estimate!!Total!!Male
B01001_026	Estimate!!Total!!Female
B03002_002	Estimate!!Total!!Not Hispanic or Latino
B03002_003	Estimate!!Total!!Not Hispanic or Latino!!White alone
B03002_004	Estimate!!Total!!Not Hispanic or Latino!!Black or African American alone
B03002_005	Estimate!!Total!!Not Hispanic or Latino!!American Indian and Alaska Native alone
B03002_006	Estimate!!Total!!Not Hispanic or Latino!!Asian alone
B03002_008	Estimate!!Total!!Not Hispanic or Latino!!Some other race alone
B03002_009	Estimate!!Total!!Not Hispanic or Latino!!Two or more races
B03002_010	Estimate!!Total!!Not Hispanic or Latino!!Two or more races!!Two races including Some other race
B03002_011	Estimate!!Total!!Not Hispanic or Latino!!Two or more races!!Two races excluding Some other race, and three or more races
B03002_012	Estimate!!Total!!Hispanic or Latino
B03002_013	Estimate!!Total!!Hispanic or Latino!!White alone
B03002_014	Estimate!!Total!!Hispanic or Latino!!Black or African American alone
B03002_015	Estimate!!Total!!Hispanic or Latino!!American Indian and Alaska Native alone
B03002_016	Estimate!!Total!!Hispanic or Latino!!Asian alone
B03002_017	Estimate!!Total!!Hispanic or Latino!!Native Hawaiian and Other Pacific Islander alone
B03002_018	Estimate!!Total!!Hispanic or Latino!!Some other race alone
B03002_019	Estimate!!Total!!Hispanic or Latino!!Two or more races
B03002_020	Estimate!!Total!!Hispanic or Latino!!Two or more races!!Two races including Some other race
B03002_021	Estimate!!Total!!Hispanic or Latino!!Two or more races!!Two races excluding Some other race, and three or more races
B03003_003	Estimate!!Total!!Hispanic or Latino
B19013_001	Estimate!!Median household income in the past 12 months (in 2012 inflation-adjusted dollars)
B23024_001	Estimate!!Total
B23024_002	Estimate!!Total!!Income in the past 12 months below poverty level
B23024_003	Estimate!!Total!!Income in the past 12 months below poverty level!!With a disability
B23024_004	Estimate!!Total!!Income in the past 12 months below poverty level!!With a disability!!In labor force
B23024_006	Estimate!!Total!!Income in the past 12 months below poverty level!!With a disability!!In labor force!!Civilian
B23024_007	Estimate!!Total!!Income in the past 12 months below poverty level!!With a disability!!In labor force!!Civilian!!Employed
B23024_008	Estimate!!Total!!Income in the past 12 months below poverty level!!With a disability!!In labor force!!Civilian!!Unemployed
B23024_009	Estimate!!Total!!Income in the past 12 months below poverty level!!With a disability!!Not in labor force
B23024_018	Estimate!!Total!!Income in the past 12 months at or above poverty level!!With a disability
B23024_019	Estimate!!Total!!Income in the past 12 months at or above poverty level!!With a disability!!In labor force

Name	Label
B23024_021	Estimate!!Total!!Income in the past 12 months at or above poverty level!!With a disability!!In labor force!!Civilian
B23024_022	Estimate!!Total!!Income in the past 12 months at or above poverty level!!With a disability!!In labor force!!Civilian!!Employed
B23024_023	Estimate!!Total!!Income in the past 12 months at or above poverty level!!With a disability!!In labor force!!Civilian!!Unemployed
B23024_024	Estimate!!Total!!Income in the past 12 months at or above poverty level!!With a disability!!Not in labor force
B23025_001	Estimate!!Total
B23025_002	Estimate!!Total!!In labor force
B23025_003	Estimate!!Total!!In labor force!!Civilian labor force
B23025_004	Estimate!!Total!!In labor force!!Civilian labor force!!Employed
B23025_005	Estimate!!Total!!In labor force!!Civilian labor force!!Unemployed
B23025_006	Estimate!!Total!!In labor force!!Armed Forces
B23025_007	Estimate!!Total!!Not in labor force
B25008_002	Estimate!!Total!!Owner occupied
B25008_003	Estimate!!Total!!Renter occupied
B25037_001	Estimate!!Median year structure built!!Total
B25037_002	Estimate!!Median year structure built!!Owner occupied

Appendix 2: PCA results

Principal component	Eigenvalue	Variance	Cumulative variance
1	12.52399	27.22607	27.22607
2	6.372886	13.8541	41.08017
3	4.329791	9.41259	50.49276
4	3.454636	7.510079	58.00284
5	2.592146	5.6351	63.63794
6	2.343152	5.093808	68.73175
7	1.674747	3.640755	72.3725
8	1.589606	3.455665	75.82817
9	1.502506	3.266318	79.09449
10	1.235214	2.685248	81.77973
11	1.148833	2.497463	84.2772
12	1.0792	2.346088	86.62328
13	0.852742	1.853786	88.47707
14	0.794241	1.72661	90.20368
15	0.772875	1.680162	91.88384
16	0.685711	1.490676	93.37452
17	0.537324	1.168095	94.54261
18	0.502264	1.091878	95.63449
19	0.40581	0.882195	96.51669
20	0.379405	0.824793	97.34148

Principal component	Eigenvalue	Variance	Cumulative variance
21	0.315012	0.68481	98.02629
22	0.255458	0.555343	98.58163
23	0.192511	0.418501	99.00013
24	0.149977	0.326038	99.32617
25	0.091905	0.199793	99.52596
26	0.080002	0.173917	99.69988
27	0.050591	0.10998	99.80986
28	0.047568	0.103408	99.91327
29	0.028709	0.06241	99.97568
30	0.009323	0.020268	99.99595
31	0.001864	0.004052	100
32	6.14E−31	1.33E−30	100
33	1.00E−31	2.18E−31	100
34	1.00E−31	2.18E−31	100
35	1.00E−31	2.18E−31	100
36	1.00E−31	2.18E−31	100
37	1.00E−31	2.18E−31	100
38	1.00E−31	2.18E−31	100
39	1.00E−31	2.18E−31	100
40	1.00E−31	2.18E−31	100
41	1.00E−31	2.18E−31	100
42	1.00E−31	2.18E−31	100
43	1.00E−31	2.18E−31	100
44	1.00E−31	2.18E−31	100
45	1.00E−31	2.18E−31	100
46	1.00E−31	2.18E−31	100

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Author contributions GL designed the project, reviewed the literature, analyzed the results and helped write the manuscript, AR helped manage the project, assist with data analysis and manuscript writing, BK supervised the project components and provided input in the research design and writing, and MH conducted the data analysis.

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