



# Exposure to Hurricane Harvey flooding for subsidized housing residents of Harris County, Texas

Jayajit Chakraborty<sup>1</sup> · Ashley A. McAfee<sup>1</sup> · Timothy W. Collins<sup>2</sup> · Sara E. Grineski<sup>3</sup>

Received: 29 May 2020 / Accepted: 13 January 2021 / Published online: 2 February 2021  
© The Author(s), under exclusive licence to Springer Nature B.V. part of Springer Nature 2021

## Abstract

This article contributes to research on social vulnerability to natural hazards by analyzing the relationship between spatial patterns of flooding caused by Hurricane Harvey and subsidized rental housing residents. Our study area is Harris County, the most populous county in Texas, which includes the city of Houston and was severely impacted by Harvey-induced flooding. We sought to determine whether: (1) federally subsidized housing units and residents were disproportionately located in areas with greater flood extent and (2) areal extent of flooding around subsidized housing developments was greater for developments where higher proportions of socially vulnerable households reside. We integrated information from the US Federal Emergency Management Agency's Harvey flood depths grid with US Department of Housing and Urban Development data on relevant rental assistance programs. Results from multivariable generalized estimating equations indicated significantly higher percentages of subsidized housing units and residents in neighborhoods with greater flood extent, after accounting for pertinent spatial and social factors. We also found subsidized housing developments with more extensive flooding nearby to contain significantly higher percentages of extremely low income, female-headed and older (62+ years) households. Findings have important implications for future research and policy, since these socio-spatial inequalities are likely to be reproduced through climate change-related disasters projected to affect many cities within and outside Texas.

**Keywords** Disaster · Social vulnerability · Subsidized housing · Hurricane Harvey · Houston

---

✉ Jayajit Chakraborty  
jchakraborty@utep.edu

<sup>1</sup> Department of Sociology and Anthropology, University of Texas at El Paso, 500 West University Avenue, El Paso, TX 79968, USA

<sup>2</sup> Department of Geography, University of Utah, 260 Central Campus Dr., Rm. 4625, Salt Lake City, UT 84112, USA

<sup>3</sup> Department of Sociology, University of Utah, 380 S 1530 E, Rm. 301, Salt Lake City, UT 84112, USA

## 1 Introduction

Hurricane Harvey made landfall on the Texas Gulf Coast as a category 4 storm in August 2017 and caused catastrophic flooding across the Greater Houston metropolitan statistical area (MSA). More than 156,000 homes were damaged and at least 70 people died (Emanuel 2017). Total damages were estimated to be about \$125 billion, making it the second-costliest disaster in US history (Blake and Zelinsky 2018). Although the media referred to Hurricane Harvey as an ‘equal opportunity’ disaster (e.g., Grabar 2017; Linderman 2017), recent research indicates that socially vulnerable groups experienced unequal exposure to Harvey-induced flooding in the Greater Houston MSA. Specifically, the areal extent of flooding was significantly greater in neighborhoods with higher percentages of non-Hispanic Black and lower socioeconomic status residents (Chakraborty et al. 2019a) and people with disabilities (Chakraborty et al. 2019b), after controlling for relevant factors. In one of the few household-level studies of Harvey flood exposure based on primary survey data, Collins et al. (2019) found the areal extent of flooding within 100 m of residents’ home sites to be significantly greater for racial/ethnic minority and lower socioeconomic status households.

Research on social vulnerability to hazards has drawn attention to higher risk exposures and subsequent differential impacts associated with flood events for people with the lowest capacities to prepare, respond and recover from such events (Wisner et al. 2004). Race/ethnicity, income, gender and age (Cutter et al. 2003; Walker 2012; Rufat et al. 2015) as well as housing tenure and type (Lee and Van Zandt 2019; Mehta et al. 2020) have been found to be strongly associated with unequal flood vulnerability across multiple disaster stages, from pre-disaster flood risk to post-disaster outcomes. Residents of federally subsidized housing represent a particularly vulnerable subgroup that is adversely and disproportionately impacted by natural disasters. By definition, federal housing assistance in the USA is only available to households with significantly lower incomes with respect to those living in the same urban area. Subsidized rental housing is often characterized by higher proportions of minorities and households in poverty compared to the general population within a given jurisdiction (Hamideh and Rongerude 2018). These housing developments are also inhabited by other vulnerable populations such as elderly residents, people with preexisting health conditions and others with limited resources or capacity for evacuation.

Although a limited number of hazard vulnerability studies have focused specifically on subsidized housing residents (Hamideh and Rongerude 2018; Hernandez et al. 2018), previous research on low-income renters is relevant to this population. These studies found substantially higher vulnerability for low-income renters compared to more economically affluent renters and homeowners. This vulnerability has been linked to poorer quality construction of affordable rental housing, location in hazardous areas and lower pre-disaster preparedness, as well as greater difficulties in finding adequate shelter, temporary homes and affordable housing after the disaster (Fussell and Harris 2014; Hamideh and Rongerude 2018; Lee and Van Zandt 2019). While previous studies have examined the vulnerability of subsidized housing residents and low-income renters based on post-disaster outcomes and recovery, unequal exposures experienced by subsidized housing developments and their inhabitants have not been adequately examined. With regard to Hurricane Harvey, recent estimates indicate that more than 2,000 subsidized housing units were damaged in the state of Texas (Vanderpool 2018), including 25% of Houston’s affordable housing stock (NLHIC 2019). The storm caused the displacement of numerous low-income rental

housing residents in Houston, which led to a 18% increase in homelessness in the city (Ward 2018).

More research is necessary to elucidate the unequal impacts of natural disasters and exposure to flooding caused by Hurricane Harvey, in particular, for residents of subsidized rental housing. Our study responds to this need with the first systematic analysis of the relationship between spatial patterns of flooding caused by Hurricane Harvey and federally subsidized housing developments, as well as social inequalities within the population of subsidized housing residents in flooded areas. Our study area is Harris County, the most populous county in Texas, which encompasses the city of Houston and was severely affected by Harvey-induced inundation.

Our analyses are framed to answer two related research questions. First, we seek to determine whether federally subsidized rental housing units and their residents are significantly overrepresented in neighborhoods with greater Harvey-induced flood extent, after controlling for relevant social factors and clustering. Following this neighborhood-level analysis of Harris County, we explore additional social inequalities within subsidized housing developments. Our second question thus seeks to determine whether the areal of extent of flooding was significantly greater around subsidized housing developments where higher proportions of socially vulnerable households reside. Our analyses are conducted at the census tract level for the first research question and housing development level for the second research question.

This study combines cartographic information from the Harvey Flood Depths Grid developed by the US Federal Emergency Management Agency (FEMA) with the US Department of Housing and Urban Development (HUD) data for public housing and project-based assistance programs and census tract-level sociodemographic data from the 2016 American Community Survey (ACS). Statistical analyses are based on generalized estimating equations (GEEs) that account for spatial clustering of tracts and subsidized housing development locations in our study area and provide statistically valid inferences regarding relationships relevant to our research questions.

## 2 Study area: disaster and vulnerability context

Harris County is located in southeastern Texas and is part of the nine-county Greater Houston MSA. With a population of about 4.4 million (2016), Harris is the third-largest county in the USA. Its county seat is Houston, the largest city in Texas and fourth largest nationally. While Houston is among the most economically segregated cities in the USA (Taylor and Fry 2012; Dickerson 2018), it is also highly diverse in terms of race and ethnicity. Hispanics and non-Hispanic Blacks comprise 41.8 and 18.5% of the Harris County population, respectively. Additionally, 17.4% of county residents had incomes below the federal poverty level in 2016. Before Hurricane Harvey, this county was already experiencing a substantial shortage in the availability of affordable rental homes for low-income individuals. Recent data for Houston indicate that there were only 18 affordable homes available for every 100 of the lowest income households and 75% of all extremely low income households paid more than 50% of their income on rent because affordable alternatives were absent (NLIHC 2019). Socioeconomically disadvantaged residents of this urban area thus had limited resources to evacuate during a disaster or adequately support themselves during recovery.

Harris County is considered to be one of the most exposed urban areas in the world with regard to tropical storms and hurricanes, because of its location in the humid Gulf Coast ecoregion. In the last two decades, this urban area has been impacted by as many as eight major events: Tropical Storm Allison (2001), Hurricane Rita (2005), Hurricane Katrina (2005), Hurricane Ike (2008), Memorial Day floods (2015), Tax Day floods (2016), Hurricane Harvey (2017) and Tropical Storm Imelda (2019). The frequency and intensity of such flood events are expected to increase because of climatic change and future land use conversion associated with population growth and urbanization (Hsiang et al. 2017; Wang et al. 2018). Additionally, the Greater Houston MSA has become more susceptible to flooding because of exponential growth in impervious cover and substantial wetland losses, which have collectively reduced the region's ability to absorb and slow flood water (Zhang et al. 2018). Harris County, in particular, has lost almost 30% of its freshwater wetlands between 1992 and 2010 (Jacob et al. 2012). Subsidence has also increased likelihood of flooding, as parts of this county have lost 10–12 feet in elevation since the 1920s (Harden 2016).

Hurricane Harvey made landfall in Texas on August 25, 2017, and caused widespread flooding due to record rainfall, which severely impacted Harris and other counties of the Greater Houston MSA. Four-day rainfall totals ranged from 26 to 47 inches across Harris County, including two feet in the first 24 h (Linderman 2017). Consequently, almost 70% of Harris County was covered by a foot and a half of water (Amadeo 2018), as creeks and bayous reached water levels that had never been recorded before. Controlled releases of water from both the Addicks and Barker Reservoirs by the US Army Corps of Engineers to manage flood levels also led to increased flooding (US Army Corps of Engineers 2017). Most flooding receded within a week, but some areas remained flooded for several weeks (Jonkman et al. 2018).

Reports indicate that about one-third of Houston's housing stock was damaged or destroyed by Harvey-induced flooding (Elliott 2017). Although detailed estimates of Harvey's impact on federally subsidized housing residents in Harris County are unavailable, recent reports suggest that Harvey flooded or damaged 25% of the Houston Housing authority's public housing and low-income housing tax credit developments, which led to a substantial shortage of affordable rental housing (Dickerson 2018). Given the limited supply of affordable housing before Harvey and increased demand for rental housing after the disaster, low-income renters and affordable housing residents of Harris County are likely to face years of housing insecurity (Dickerson 2018).

Recent studies have drawn attention to social inequalities in exposure to flooding caused by Harvey in the Houston area (Chakraborty et al. 2019a, b; Collins et al. 2019), as mentioned previously. To our knowledge, no previous study has examined the distribution of flood exposure with respect to subsidized rental housing developments or populations at the neighborhood level. Additionally, prior research has not investigated whether social vulnerability characteristics of subsidized housing development residents are associated with greater or lesser flood extent around their locations. Our study seeks to address these gaps by focusing on federally subsidized housing developments and sociodemographic characteristics of their residents in Harris County, Texas.

## 3 Data and methods

### 3.1 Key data sources

#### 3.1.1 Hurricane Harvey flood exposure

Our data source for estimating flooding caused by Hurricane Harvey is a cartographic data product referred to as the Harvey flood depths grid developed by the FEMA Region 6 Mitigation Division (TX-DR-4332) to support response and recovery operations (FEMA 2018). High water marks and related information from many different federal, state, local and private sector resources were used to derive this flood inundation database that has been used in several recent studies on flooding caused by Hurricane Harvey (e.g., Chakraborty et al. 2019a, 2019b; Collins et al. 2019; Flores et al. 2020a; Grineski et al. 2020). A more detailed description of this geographic information systems (GIS) raster map layer which contains flood extent and depth values for each 3 m by 3 m grid pixel is available in Chakraborty et al. (2019a).

#### 3.1.2 Federally subsidized housing

Rental assistance programs administered by the US Department of Housing and Urban Development (HUD) subsidize rents for low-income tenants who meet specific program eligibility requirements. Households typically pay rent equaling 30% of their incomes, while the federal government pays the remaining rental costs. To qualify for a subsidy, an applicant's income must fall below a certain income limit based on median family income estimates and fair market rent definitions specified for each metropolitan area. There are five main HUD rental assistance programs (Perl and McCarty 2017), including Section 8 Housing Choice Vouchers (HCVs) which provide rent subsidies tenants can use to subsidize their rents in the private market housing of their choice. Our analysis focuses on the following four HUD programs:

- *Public housing*: Includes housing developments owned and operated by local Public Housing Authorities for which the federal government provides capital and operating assistance.
- *Section 8 project-based rental assistance*: Subsidies are provided directly to private owners of multifamily housing to subsidize the rents of specific units.
- *Section 202 supportive housing for the elderly*: Multifamily housing developments owned by private nonprofit organizations for which the federal government provides capital grants and project-based rental assistance.
- *Section 811 supportive housing for persons with disabilities*: This program is similar to Section 202, but serves people with disabilities.

Information on federally subsidized rental housing for our study area was derived from the online HUD *Picture of Subsidized Households* for 2016 (HUD 2020). For each housing development, this database provides detailed data on geographic location, number of occupied and unoccupied rental units, sociodemographic characteristics of resident households and other attributes. It covers housing developments associated with public housing and project-based programs (i.e., Section 8 project-based, Section 202 and Section 811); units affiliated

with the Section 8 HCV program are not included. As of December 31, 2016 (latest inventory before Hurricane Harvey) there were 124 federally subsidized housing developments in Harris County, Texas: 18 public housing, 64 Section 8 project-based, 12 Section 202 and 30 Section 811 projects. These housing developments included a total of 13,216 occupied rental housing units and 27,657 residents. In their *Picture of Subsidized Households* database, HUD suppresses data for variables with values smaller than 11 (coded as -4) for reported households to preserve confidentiality. There were five subsidized housing developments (out of 124) in Harris County where the number of housing units and resident population were listed as -4, respectively. To address suppressed data for these two variables, we substituted a value of 1 for -4, which likely undercounts actual subsidized housing units and residents but provides a conservative nonzero estimate.

### 3.2 Dependent variables

The dependent variables for this study include the areal extent of flooding caused by Hurricane Harvey within each census tract and the area surrounding each subsidized housing development site, respectively. We used a multistep GIS-based methodology to estimate these two variables, as detailed below. Additionally, a high-resolution version of the National Hydrography Dataset for Texas was utilized to remove all permanent water features (areas containing water during nonflood periods) from grid pixels in the Harvey's flood depths grid raster database.

For the first phase of our study (census tract-level analysis), a map layer representing tract boundaries without water areas was first overlaid on the 3 m by 3 m resolution flood depth grid. Second, we counted the total number of flooded pixels (depth > 0) within each tract. Third, the total area covered by these pixels was divided by the land area of the tract to derive the proportion of the tract area flooded by Hurricane Harvey. This areal tract proportion, referred to as flood extent, was used as a continuous dependent variable.

For the second phase (housing development-level analysis), the locations of all 124 subsidizing housing developments in Harris County were first geocoded using ArcGIS 10.6.1 software and geographic coordinates provided in the HUD *Picture of Subsidized Households* database. Second, circular buffers (100 m and 200 m radii) were constructed around all geocoded housing development locations. Third, we summed the area covered by all flooded pixels (depth > 0) within each buffer. Fourth, the flooded area sum was divided by the area of the circular buffer (square meters) to derive the proportion of the area surrounding each subsidized housing development that was flooded due to Hurricane Harvey. We used this areal proportion measure (flood extent within 100 m) as a continuous dependent variable in the second phase of our analysis. The use of this variable and the 100-m circular buffer are both consistent with a recent study that estimated Harvey-induced flooding around home locations of residents (survey respondents) in the Greater Houston area (Collins et al. 2017). To examine whether statistical results from phase two were sensitive to the circular buffer radius used to measure flood extent, we conducted a sensitivity analysis using an alternative flood extent measure based on a 200-m radius circular buffer.

### 3.3 Independent variables

#### 3.3.1 Census tract-level analysis

The first phase of our study sought to examine whether federally subsidized housing units and residents are overrepresented in tracts with greater Harvey-induced flood extent, after controlling for relevant sociodemographic factors. Our key independent variables thus included the number of occupied subsidized housing units and residents, respectively, expressed as a percentage of the total number of occupied housing units and population in each tract from the 2012–2016 ACS five-year estimates. To ensure stable proportions for our variables, we first removed tracts with incomplete data or small population counts. The first phase of our analysis encompasses 783 tracts in Harris County with at least 500 persons and 50 housing units. The names, definitions and summary statistics associated with all explanatory variables are provided in Table 1.

We also created categorical variables for our two subsidized housing variables (i.e., percentages of occupied subsidized housing units and residents), since they had skewed distributions due to a small number of tracts in the county hosting a relatively large number of housing developments and residents. Specifically, we recoded each of these two continuous variables into four categories: none (0), smaller than mean (low); 1 standard deviation greater than the mean (medium); and more than 1 standard deviation greater than the mean (large). These categorical versions of the subsidized housing variables are used in a sensitivity analysis.

To control for neighborhood-level sociodemographic characteristics, we used variables from the 2012–2016 ACS estimates that have been found to be significantly related to flood risks in previous research (Maantay and Maroko 2009; Chakraborty et al. 2014; Rufat et al. 2015) and Harvey-induced flooding in recent studies conducted in the Houston area (Chakraborty et al. 2019a, b; Collins et al. 2019). To examine the effect of race/ethnicity, our analysis included the percentages of individuals who identified themselves as non-Hispanic Black, Hispanic, non-Hispanic Asian and non-Hispanic non-White race, other than Black or Asian. To measure socioeconomic status, we used a combination of five variables: the proportions of the population aged 25+ with no high school education, population aged 5+ with limited English language proficiency, individuals with an annual income below the federal poverty level, households with no vehicles available and civilians aged 16+ who are unemployed. Following Chakraborty (2019a, 2019b), we created an index of socioeconomic deprivation based on these five variables (Cronbach's  $\alpha=0.79$ ) using principal components analysis, since they were significantly and positively correlated with each other. We included two additional control variables that represent housing characteristics, as recommended by recent studies on Harvey flood impacts. The first was the proportion of owner-occupied housing units, which is often used as an indicator of wealth or assets (Chakraborty et al. 2014) and lower vulnerability to natural disasters (Fussell and Harris 2014). The second variable was the proportion of vacant housing units classified as vacant for seasonal, recreational, or occasional use, referred to as vacation homes. Prior studies have used this variable as a proxy for water-related amenities and found significantly higher vacation home percentages in neighborhoods with greater flood risks (Chakraborty et al. 2014; Montgomery and Chakraborty 2015) and flooding (Chakraborty et al. 2019a).

**Table 1** Variable definitions and summary statistics for variables used, Harris County, Texas

Variables	Definition	Min	Max	Mean	SD
<i>Census tract level (n = 783):</i>					
Proportion of tract area flooded	Area of census tract flooded by Harvey divided by total area of tract	0.049	0.964	0.552	0.144
Percent occupied subsidized housing units	100 * number of occupied federally subsidized housing units divided by total number of occupied housing units in tract	0.000	42.269	0.946	3.775
Percent subsidized housing population	100 * population residing in federally subsidized housing units within tract divided by total tract population	0.000	41.439	0.742	3.498
Percent non-Hispanic Black	Percentage of tract population identifying as non-Hispanic (ethnicity) and Black (race)	0.000	92.410	18.711	20.870
Percent Hispanic	Percentage of tract population identifying as Hispanic (ethnicity)	2.160	98.860	41.992	25.805
Percent non-Hispanic Asian	Percentage of tract population identifying as non-Hispanic (ethnicity) and Asian (race)	0.000	52.110	6.219	7.423
Percent non-Hispanic Other non-White	Percentage of tract population identifying as non-Hispanic (ethnicity) and not White, Black, or Asian (race)	0.000	17.260	1.709	1.669
Socioeconomic deprivation	Factor based on five variables (percentages): pop aged 25 + with no high school education, pop aged 5 + with limited English language proficiency, individuals with annual income below federal poverty level, households with no vehicles and civilians aged 16+ unemployed	- 1.585	4.639	0.126	1.071
Percent owner-occupied housing units	Percentage of occupied housing units in tract that are classified as owner-occupied	0.000	99.080	55.412	24.604
Percent vacant: seasonal or recreational use	Percentage of vacant housing units in tract classified as vacant for seasonal, recreational or occasional use	0.000	100.000	6.308	14.264
<i>Subsidized housing development level (n = 119):</i>					
Proportion of area within 100 m radius flooded	Area flooded by Harvey within circle centered on housing development divided by total area of circle (100 m radius)	0.000	0.994	0.540	0.285
Proportion of area within 200 m radius flooded	Area flooded by Harvey within circle centered on housing development divided by total area of circle (200 m radius)	0.003	0.990	0.525	0.248
Percent minority headed households	Percentage of households: race of head of household is Black, Native American, or Asian/Pacific Islander, or ethnicity is Hispanic	0.000	100.000	80.590	24.473
Percent extremely low income households	Percentage of households: income below 30% of local area median family income, as defined by HUD, adjusted for household size	44.000	100.000	84.250	10.303
Percent female-headed households	Percentage of households headed by a female resident	28.000	98.000	72.940	16.362



**Table 1** (continued)

Variables	Definition	Min	Max	Mean	SD
Percent aged 62 or more years headed households	Percentage of households in which the older of the household head or spouse is age 62 or older	2.000	100.000	51.160	40.307
Public housing developments	Type of HUD assistance program: public housing (1); Section 8 project-based, Section 202, or Section 811 (0)	0.000	1.000	0.150	0.360

### 3.3.2 Housing development-level analysis

The second phase of our study focused on determining whether areal flood extent in circular buffers surrounding subsidized housing development sites was greater for developments containing higher proportions of socially vulnerable households. This phase utilizes 119 out of 124 subsidized housing developments in Harris County for which detailed sociodemographic data on resident household characteristics were available (no missing data for included variables) in the *Picture of Subsidized Households* database for December 31, 2016. Variable definitions and summary statistics are provided in Table 1.

For racial/ethnic minority status, we included the percentage of households where the head of the household was non-White, i.e., either Hispanic or belonged to a non-Hispanic minority group such as Black, Asian, Pacific Islander or Native American. Information on the percentage of households belonging to specific racial/ethnic subcategories (e.g., non-Hispanic Black and Hispanic) is available, but data on these variables were missing or underreported for a majority of developments in Harris County. To measure socioeconomic status, we used the percentage of extremely low-income households (HUD definition), as described in Table 1. A considerable amount of empirical research has documented disproportionate housing damages and recovery associated with major flood events for both minority and economically disadvantaged residents (e.g., Elliott et al. 2009; Highfield et al. 2014; Rufat et al. 2015; Graham et al. 2016). Our analysis included two additional indicators of social vulnerability: the percentage of female-headed households and those in which the eldest of the household head or spouse was aged 62 or older. Female-headed households are likely to experience increased difficulties coping with health problems during a disaster because of their relative lack of resources and, for those with children, reliance on a single provider (Grineski et al. 2013). Previous studies have also documented unequal disaster recovery for female-headed households that is linked to their lower wages and multiple social burdens (Van Zandt et al. 2012; Rufat et al. 2015). Elderly populations are considered to be more vulnerable because of their potential limitations during and following a disaster, budget inflexibility due to fixed incomes and constrained access to medical assistance due to structural damages and higher demand (Cutter et al. 2003; Fatemi et al. 2017). Other measures of social vulnerability such as disability status of subsidized housing residents were also considered, but not included due to missing or underreported data for a large proportion of housing developments. Finally, we also included a variable to represent the type of federally assisted housing program. This variable was coded with a value of 1 for public housing developments and 0 for developments funded by project-based HUD programs (i.e., Section 8 project-based, Section 202 and Section 811).

### 3.4 Statistical analysis

For the first phase of the analysis, multivariable statistical models are used to independently examine the association of the proportion of occupied subsidized housing units and population residing in these units with tract flood extent (proportion of area flooded), after controlling for sociodemographic variables using in prior studies on social vulnerability to Harvey flooding in Houston area. In the second phase, multivariable models are used to examine the relationship between flood extent around each subsidized housing development location (100 m and 200 m circular buffers) and selected variables that represent sociodemographic characteristics of housing developments.

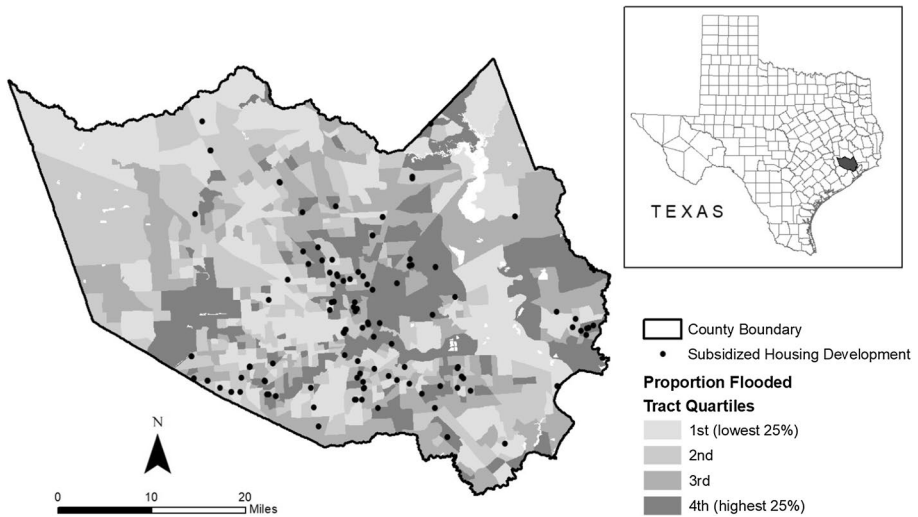
Our multivariable models for both phases are based on generalized estimating equations (GEEs) with robust (i.e., Huber/White) covariance estimates, which extend the generalized linear model to accommodate clustered data (Liang and Zeger 1986). GEEs relax several assumptions of traditional regression models and impose no strict distributional assumptions for the variables analyzed (e.g., normality), while accounting for clustering of analytic units. Recent studies indicate that GEEs are more advantageous for analyzing social inequalities in the distribution of environmental hazards compared to other techniques such as spatial autoregressive models, mixed models with random effects and multilevel modeling approaches (Collins et al. 2015; Chakraborty et al. 2019a, b).

For estimating a GEE, clusters of observations are defined based on the assumption that observations from within a cluster are correlated, whereas observations from different clusters are independent. The cluster definition for our study was based on the city within which the tract (phase one) or subsidized housing development site (phase two) is located. This definition yielded 12 spatial clusters for our tract-level analysis ( $N=783$ ) and nine clusters for the subsidized housing development-level analysis ( $N=119$ ).

GEEs also require the specification of an intracluster dependency correlation matrix, known as the working correlation matrix. For the GEEs presented here, the working correlation matrix structure was specified as exchangeable, since this specification assumes constant intracluster dependency (Garson 2012; Collins et al. 2015). For selecting the best-fitting model, we explored six model specifications: normal, gamma and inverse Gaussian distributions with identity and log link functions. An identity link function models relationships between the dependent and independent variables linearly, while a log link function represents natural logarithmic relationships. We selected the inverse Gaussian distribution with log link function for our tract-level models and the normal distribution with a log link function for the housing development-level models. These specifications yielded the lowest values of the quasi-likelihood under the independence (QIC) model criterion, indicating the best statistical fit. The QIC is considered to be the most appropriate statistic for evaluating several aspects of GEE model fit, including the distribution and link function (Pan 2001).

All independent variables were standardized before inclusion in these models, and standardized GEE coefficients are provided to compare the relative contribution of each variable. The multicollinearity condition index was calculated for the combination of explanatory variables included in each GEE. The values of this index for our multivariable models ranged from 3.02 to 4.48, indicating the absence of serious collinearity problems. The statistical significance of independent variables was estimated on the basis of the Wald Chi-squared test.

For the sensitivity analysis, we reran the Phase 1 GEE models using the percentages of subsidized housing units and residents variables recoded as discrete categories. This included three dummy variables: values smaller than mean (low), 1 standard deviation greater than the mean (medium) and more than 1 standard deviation greater than the mean (large), with no subsidized housing units/residents (0) treated as the reference category. These variables were used to replace the continuous versions (i.e., percentages of subsidized housing units and residents) variables and examine whether our statistical results were sensitive to our treatment of these two subsidized housing variables as continuous measures.



**Fig. 1** Proportion of census tract area flooded by Hurricane Harvey and locations of federally subsidized housing developments in Harris County, Texas

## 4 Results

The spatial distributions of Harvey-induced flooding and federally subsidized housing developments are depicted in Fig. 1, where tracts are grouped into four quartiles based on the proportion of the tract area flooded by Hurricane Harvey. Tracts in the highest quartile (top 25%) of flooding are located in western, central and eastern areas of Harris County, including the entire northeastern section of the City of Houston which contains several large public housing developments. Tracts in the lowest quartile (bottom 25%), in contrast, are more evenly dispersed throughout the county.

Before conducting multivariable analysis, we used descriptive comparisons to examine the distribution of federally subsidized housing developments across the flood extent tract quartiles shown in Fig. 1. Specifically, the number of occupied subsidized housing units and total population residing in these units within the set of tracts associated each quartile are estimated and compared (as a percentage of each total). These results are summarized in Table 2, which also includes the corresponding percentages of all occupied housing units and population in each tract quartile. The percentages of both occupied subsidized housing units and population indicate a gradual increase from the lowest (bottom 25%) to the highest (top 25%) quartile. More than 38% of all occupied subsidized housing units and almost 40% of the subsidized housing population reside within tracts in the highest quartile of areal flood extent, compared to only about 17% and 15%, respectively, in the lowest quartile. The  $z$  test of proportions indicated that these percentage differences between the highest and lowest quartile were significantly greater than zero for both subsidized housing units and populations, as shown in Table 2. In contrast, percentages of all occupied housing units and the overall population do not suggest an increasing pattern from the lowest quartile, with these variables reaching their minimum values in the highest quartile of flood extent. Only about 20% of all occupied housing units and 20% of the entire population in Harris County are located within tracts in the highest flood extent quartile.

**Table 2** Distribution of housing and population by census tract flood extent quartile

Quartiles: proportion tract area flooded	County totals	Q1: lowest 25%	Q2	Q3	Q4: highest 25%	Q4 – Q1: difference
Occupied subsidized housing units	13,216	16.96%	16.93%	27.95%	38.17%	21.21%**
All occupied housing units	1,536,250	26.42%	27.07%	26.03%	20.48%	– 5.94%***
Subsidized housing population	27,657	14.88%	15.89%	30.07%	39.15%	24.27%***
Total population	4,428,405	24.87%	27.48%	27.55%	20.10%	– 4.77%***
<i>N</i> (census tracts)	783	195	196	196	196	

\*\*\* $p < 0.01$ ; based on two-sample  $z$  test of proportions

**Table 3** GEEs for predicting proportion of census tract area flooded: standardized model coefficients and significance

	Model 1					Model 2						
	Beta	Lower 95% CI	Upper 95% CI	Exp (Beta)	Beta	Lower 95% CI	Upper 95% CI	Exp (Beta)	Beta	Lower 95% CI	Upper 95% CI	Exp (Beta)
Percent occupied subsidized housing units	0.010**	0.003	0.016	1.010	0.011**	0.006	0.017	1.011	0.011**	0.006	0.017	1.011
Percent subsidized housing population												
Percent non-Hispanic Black	0.044**	0.026	0.061	1.045	0.043**	0.026	0.061	1.044	0.043**	0.026	0.061	1.044
Percent Hispanic	0.016	-0.005	0.037	1.016	0.016	-0.004	0.037	1.016	0.016	-0.004	0.037	1.016
Percent non-Hispanic Asian	-0.026**	-0.037	-0.015	0.974	-0.026**	-0.037	-0.015	0.974	-0.026**	-0.037	-0.015	0.974
Percent non-Hispanic Other non-White	-0.015**	-0.026	-0.005	0.985	-0.015**	-0.026	-0.005	0.985	-0.015**	-0.026	-0.005	0.985
Socioeconomic deprivation	0.021**	0.011	0.031	1.021	0.022**	0.012	0.031	1.022	0.022**	0.012	0.031	1.022
Percent owner-occupied housing units	0.031**	0.023	0.040	1.031	0.032**	0.023	0.040	1.033	0.032**	0.023	0.040	1.033
Percent vacant: seasonal or recreational use	0.017*	0.003	0.031	1.017	0.017*	0.003	0.031	1.017	0.017*	0.003	0.031	1.017
Intercept	-0.598**	-0.605	-0.592	0.550	-0.598**	-0.605	-0.592	0.550	-0.598**	-0.605	-0.592	0.550
Scale	0.126	0.126										
Model fit (QIC)	136.340	136.290										
N (tracts)	783	783										

\* $p < 0.05$ , \*\* $p < 0.01$

Models are based on an inverse Gaussian distribution with log link function and an exchangeable correlation matrix

The results from GEEs summarizing associations between tract flood extent and the percentages of subsidized housing units and residents, respectively, are presented in Table 3. Numbers in the Exp(Beta) column can be interpreted as the percentage change in the proportion of tract area flooded by Harvey for every one standard deviation increase in each of the independent variables (after subtracting one and multiplying by 100). After controlling for sociodemographic and housing characteristics of tracts (Models 1 and 2), the areal extent of flooding indicates a statistically significant and positive relationship with both the percentage of subsidized housing units ( $p = 0.004$ ) and the percentage of subsidized housing residents ( $p < 0.001$ ). More specifically, a one standard deviation increase in the percentages of subsidized housing units and population is, respectively, associated with 1.10% and 1.11% increases in the proportion of tract area flooded. With regard to the sociodemographic and housing variables used as controls, both GEEs (Models 1B and 2B) indicate similar statistical associations. The proportion of flooded area is significantly greater in tracts characterized by higher percentages of non-Hispanic Black ( $p < 0.001$ ) and socioeconomically deprived residents ( $p < 0.001$ ), as well as higher percentages of owner-occupied ( $p < 0.001$ ) and seasonal/vacation homes ( $p < .05$ ).

In our sensitivity analysis using discrete measures (tables not shown), results from both Models 1 and 2 aligned closely with those in Table 3. Tracts hosting medium and large percentages of both subsidized housing units and residents had significantly greater tract area flooded than tracts with no units/residents ( $p < 0.01$  for both dummy variables). Switching these subsidized housing variables did not impact associations between our sociodemographic control variables and flooded area in terms of direction and statistical significance.

Multivariable GEEs summarizing the association between flood extent around housing development sites and sociodemographic characteristics of resident households are summarized in Table 4. The proportion of flooded area within the 100-m circular buffer around development sites reveals a positive and significant relationship with the percentages of extremely low-income ( $p = 0.002$ ) and female-headed households ( $p < 0.001$ ), as well as households headed by residents aged 62 or more years ( $p < 0.001$ ). Specifically, a one standard deviation increase in the percentages of extremely low-income, female-headed and older (aged 62 or more)-headed households is, respectively, associated with 13.8%, 33.8% and 21.0% increases in the proportion of buffer area (100 m radius) flooded. Flood extent is also significantly higher within the 100-m buffer around public housing developments ( $p < 0.001$ ), compared to housing developments funded by other federal assistance programs. The percentage of minority-headed households was the only nonsignificant variable in this model ( $p > 0.05$ ). Table 4 also depicts that GEE results for the 200-m buffer are almost identical to those for the 100-m buffer in terms of the direction and significance of relationships for the explanatory variables with areal flood extent. A one standard deviation increase in the percentages of extremely low-income, female-headed and older-headed households is, respectively, associated with 10.5%, 24.9% and 12.5% increases in the proportion of buffer area (200 m radius) flooded.

## 5 Discussion

This study sought to extend research on social vulnerability to natural hazards by focusing on exposure to flooding caused by Hurricane Harvey in Harris County, Texas, for residents of federally subsidized rental housing developments. Our first research question focused on determining whether subsidized rental housing units and populations are overrepresented

**Table 4** GEEs for predicting proportion area flooded within 100 and 200 m of subsidized housing development locations: standardized model coefficients and significance

	100 m					200 m						
	Beta	Lower 95% CI	Upper 95% CI	Exp (Beta)	Beta	Lower 95% CI	Upper 95% CI	Exp (Beta)	Beta	Lower 95% CI	Upper 95% CI	Exp (Beta)
	Percent minority-headed households	-0.101	-0.221	0.020	0.904	-0.081	-0.189	0.027	0.922			
Percent extremely low income households	0.129**	0.046	0.212	1.138	0.100**	0.033	0.167	1.105				
Percent female-headed households	0.291**	0.197	0.385	1.338	0.222**	0.128	0.317	1.249				
Percent aged 62 or more years headed households	0.191**	0.127	0.256	1.210	0.118**	0.053	0.183	1.125				
Public housing developments	0.289**	0.214	0.365	1.335	0.245**	0.162	0.327	1.278				
Intercept	-0.676**	-0.705	-0.646	0.509	-0.694**	-0.718	-0.670	0.500				
Scale	0.072	0.056										
Model fit (QIC)	11.810	10.190										
N (housing developments)	119	119										

\* $p < 0.05$ ; \*\* $p < 0.01$

Models are based on a normal distribution with a log link function and an exchangeable correlation matrix



in tracts with greater Harvey-induced flood extent. Descriptive comparisons indicated that both occupied subsidized housing units and their residents were almost twice as likely to be located in neighborhoods with greater flood extent (tracts in the top 25%) compared to the corresponding proportions of all occupied housing units and population. Multivariable GEE analysis indicated that the overall percentages of both subsidized housing units and residents are significantly greater in neighborhoods with higher proportions of flooded area, even after accounting for spatial clustering-, race/ethnicity-, socioeconomic deprivation- and housing-related factors. This spatial concentration of subsidized housing in high-flood areas can be partially explained by their disproportionate location in segregated neighborhoods containing significantly higher proportions of non-Hispanic Black and socioeconomically deprived residents (Chakraborty et al. 2019a).

The second research question focused on investigating whether areal flood extent in circular buffers around subsidized housing development sites was greater for developments characterized by higher percentages of socially vulnerable households. Multivariable GEEs revealed that housing developments with greater flooded area within both the 100-m and 200-m buffers contained significantly higher percentages of extremely low income, female-headed and older (62+ years)-headed households, after controlling for spatial clustering and HUD subsidy program. Additionally, public housing developments were associated with significantly greater flood extent compared to those affiliated with other federal assistance programs. These findings reflect higher concentrations of public housing developments hosting a disproportionately large number of socially vulnerable households in northeastern Houston and other areas of the county that experienced more extensive flooding.

While we documented more extensive Hurricane Harvey-induced flood exposures based on the prevalence of subsidized housing developments with Harris County neighborhoods and social vulnerability indicators within the subsidized housing developments, we did not assess the consequences of these unequal exposures. Measures of Harvey-induced flood exposure such as the extent of flooding around homes, mold in homes, home damage and personal exposure are documented predictors of increased physical health problems, post-traumatic stress, depression, anxiety, adverse event experiences, food insecurity and unmet recovery needs (Schwartz et al. 2018; Bevilacqua et al. 2020; Clay and Ross 2020; Flores et al. 2020b). Additionally, post-Harvey studies have found social vulnerability indicators that characterize Harris County's subsidized housing residents to independently predict (i.e., adjusting for flood exposures) those same disparate consequences as well as constrained access to health care (Karaye et al. 2019; Clay and Ross 2020; Flores et al. 2020b). Thus, the increased risks associated with greater hazard exposure and amplified social vulnerability found across post-Harvey studies and the disaster literature more generally (Cutter et al. 2003; Wisner et al. 2004; Walker 2012; Rufat et al. 2015; ; Lee and Van Zandt 2019; Mehta et al. 2020) suggest that Harris County's public housing residents in all likelihood experienced myriad disproportionate impacts in the hurricane's aftermath.

A particularly debilitating consequence for Harris County's public housing residents was the exacerbation of their short- and long-term housing insecurity. Since Hurricane Harvey damaged a substantial proportion of Houston's affordable and public housing stock (Dickerson 2018; NLHIC 2019; Vanderpool 2018), many residents experienced displacement, difficulties accessing shelter or temporary accommodation and, in some cases, homelessness over the short term (Ward 2018). Additionally, because Harvey reduced the already short supply of affordable rental housing in Harris County—and at the same time increased the overall demand for rental accommodation—housing insecurity among public

assistance-eligible residents was substantially worsened over the long term (Dickerson 2018).

It is important to consider the limitations of this study, which need to be addressed in future research. First, our study focused only the areal extent of flooding and not flood depth, duration, intensity and other factors that are likely to adversely affect subsidizing housing developments or residents. Second, our analysis is limited to subsidized housing developments associated with public housing and project-based programs in the HUD *Picture of Subsidized Households* database. Although our development-level data cover four of the five main HUD assistance programs, they do not include other housing subsidy programs such as Section 8 HCVs, Community Development Block Grants, HOPE and Indian Housing, as well as programs affiliated with the US Department of Agriculture's Rural Housing Service, unless they also received subsidies from the four HUD programs considered in this study. The exclusion of residents receiving Section 8 HCVs is an important limitation, given that almost 46% of US households receiving rental assistance use vouchers in the private housing market (Center of budget and policy priorities 2019). With regard to rental assistance, neoliberal policies such as HOPE VI have contributed to a major shift away from affordable public housing and project-based programs to the use of vouchers that subsidize private owners of rental properties (Khare 2013). Although locations of households using Section 8 HCVs are not publicly available and renter-related data published by the ACS do not provide rental assistance information, future research should explore local data sources that can be used to evaluate vulnerabilities faced by residents in private housing markets.

## 6 Conclusion

Our results indicate that federally subsidized housing residents of Harris County were disproportionately located in neighborhoods with more extensive Harvey-induced flooding, in addition to living in rental housing developments around which more extensive flooding occurred. These findings have important implications for future research and practice. Future analyses should focus on actual damages suffered by subsidized housing developments, displacement of residents and other relevant disaster-related impacts. Although our analysis was based on secondary data sources, the use of surveys and/or interviews could help clarify factors influencing statistical relationships presented here and determine the specific ways in which households residing in subsidized rental housing developments were negatively impacted by Hurricane Harvey. Future research should explore additional data sources to include low-income households in tenant-based programs such as Section 8 HCVs, as well as low-income housing tax credit units listed in other databases. However, some of these units are likely to overlap with subsidized housing developments listed in the HUD dataset utilized for this study which provides more detailed information on each housing development compared to other data sources (HUD 2020).

The socio-spatial inequalities associated with subsidized rental housing and flooding reported in this article have several policy implications, because socially vulnerable households residing in subsidized housing face multiple difficulties at all disaster stages. Public and nonprofit sector institutions seeking to build flood resilience through various programs in Harris County and other metropolitan areas should pay greater attention to the needs of subsidized housing populations, including extremely low income, female-headed and elderly-headed households and residents of public housing developments.

Since a disproportionately large percentage of socially vulnerable households reside in housing developments that were severely exposed to Harvey-induced flooding, identifying appropriate evacuation routes and contingencies should become key priorities, in addition to ensuring the availability of emergency shelters and affordable temporary housing during future disasters. Public officials must also consider whether to rebuild or relocate subsidized housing developments that suffered higher Harvey-induced flood damage or are located in flood-prone areas. Additionally, it is necessary to develop more equitable housing development policies that make it more difficult for economically affluent residents to prevent developers from siting affordable housing in higher income areas with better protections from flood risks (Dickerson 2018). Because residential land market forces continue to encourage developers to build homes in areas at high risk to flooding, officials should consider designating such areas as unsuitable for residential construction. Without addressing the inequitable processes that lead socially vulnerable residents to pursue affordable housing options in highly exposed areas, the patterns we observed for Hurricane Harvey are likely to be reproduced following future climate change-related disasters, which are projected with a high degree of certainty to impact not just the Houston area, but numerous other cities within and beyond Texas.

**Acknowledgements** This research was funded by the US National Science Foundation (NSF; grants CMMI-1760655 and CMMI-1841654). Any opinions, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the NSF. We thank Mark English, who contributed to the generation of the Hurricane Harvey Flood Depths Grid by the US Federal Emergency Management Agency under Disaster Operations within the Mitigation Branch, as the Hazard and Performance Analysis's Geospatial Unit Lead.

## References

- Amadeo J (2018) Hurricane harvey facts, damage and costs. <https://www.thebalance.com/hurricane-harvey-facts-damage-costs-4150087>. Accessed 28 January 2020
- Bevilacqua K, Rasul R, Schneider S, Guzman M, Nepal V, Banerjee D, Schulte J, Schwartz RM (2020) Understanding associations between Hurricane Harvey exposure and mental health symptoms among greater Houston-area residents. *Disaster Med Public Health* 14(1):1–8
- Blake, E.S., & Zelinsky, D.A., (2018). Hurricane Harvey. National Hurricane Center: Tropical Cyclone Report. [https://www.nhc.noaa.gov/data/tcr/AL092017\\_Harvey.pdf](https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf). Accessed 28 January 2020
- Center on Budget and Policy Priorities (2019). U.S. Federal Rental Assistance Fact Sheet. <https://www.cbpp.org/research/housing/federal-rental-assistance-fact-sheets#US>. Accessed 13 November 2020
- Chakraborty J, Collins TW, Montgomery M, Grineski S (2014) Social and spatial inequities in exposure to flood risk in Miami. *Florida Natural Hazards Rev* 15:04014006
- Chakraborty J, Collins T, Grineski S (2019a) Exploring the environmental justice implications of Hurricane Harvey flooding in greater Houston. *Texas Am J Public Health* 109(2):244–250
- Chakraborty J, Grineski S, Collins T (2019b) Hurricane Harvey and people with disabilities: disproportionate exposure to flooding in Houston, Texas. *Soc Sci Med* 226:176–181
- Clay L, Ross A (2020) Factors associated with food insecurity following Hurricane Harvey in Texas. *Int J Env Res Public Health* 17(3):762. <https://doi.org/10.3390/ijerph17030762>
- Collins TW, Grineski S, Chakraborty J, Montgomery M, Hernandez M (2015) Downscaling environmental justice analysis: determinants of household-level hazardous air pollutant exposure in Greater Houston. *Ann Am Assoc Geogr* 105(4):685–703
- Collins TW, Grineski SE, Morales DX (2017) Environmental injustice and sexual minority health disparities: a national study of inequitable health risks from air pollution among same-sex partners. *Soc Sci Med* 191:38–47

- Collins TW, Grineski SE, Chakraborty J, Flores AB (2019) Environmental injustice and Hurricane Harvey: a household-level study of socially disparate flood exposures in Greater Houston, Texas, USA. *Environ Res* 179:108772
- Cutter SL, Boruff BJ, Shirley WL (2003) Social vulnerability to environmental hazards. *Soc Sci Quart* 84(2):242–261
- Dickerson MA (2018) Hurricane Harvey and the Houston housing market. *Tex Law Rev Online* 96:102–113
- Elliott, R. (2017). Tens of thousands displaced by Harvey still yearn for home. *Houston Chronicle*. <https://www.houstonchronicle.com/news/houston-texas/houston/article/Houston-news-12378756.php>. Accessed 1 March 2020
- Elliott JR, Hite AB, Devine JA (2009) Unequal return: the uneven resettlements of New Orleans' uptown neighborhoods. *Organ Environ* 22(4):410–421
- Emanuel K (2017) Assessing the present and future probability of Hurricane Harvey's rainfall. *P Natl Acad Sci USA* 114(48):12681–12684
- Fatemi F, Ardalan A, Aguirre B, Mansouri N, Mohammadfam I (2017) Social vulnerability indicators in disasters: Findings from a systematic review. *Int J Disast Risk Reduct* 22:219–227
- Federal Emergency Management Agency [FEMA] (2018) Hurricane Harvey mitigation portfolio: Harvey's inundation Footprint. <https://fema.maps.arcgis.com/apps/MapJournal/index.html?appid=70204cf2762d45409553fd9642700b7f>. Accessed 22 June 2018
- Flores A, Collins TW, Grineski SE, Chakraborty J (2020a) Social vulnerability to Hurricane Harvey: unmet needs and adverse event experiences in Greater Houston. *Texas Int J Disast Risk Reduct* 46:10152
- Flores A, Collins TW, Grineski SE, Chakraborty J (2020b) Disparities in health impacts and access to healthcare among Houston area residents after Hurricane Harvey. *Public Health Rep.* 135(4):511–523
- Fussell E, Harris E (2014) Homeownership and housing displacement after Hurricane Katrina among low-income African-American mothers in New Orleans. *Soc Sci Quart* 95(4):1086–1100
- Garson GD (2012) Generalized linear models and generalized estimating equations. Statistical Associates Publishers, Asheboro, NC
- Grabar H (2017). Harvey Is an Equal-Opportunity Disaster. The Poor Won't Be Left Behind Until the Recovery. *Slate Magazine*. <https://slate.com/business/2017/08/harvey-is-an-equal-opportunity-disaster-the-poor-wont-be-left-behind-until-the-recovery.html>. Accessed 1 March 2020
- Graham L, Debuquoy W, Anguelovski I (2016) The influence of urban development dynamics on community resilience practice in New York city after superstorm sandy: experiences from the lower east side and the rockaways. *Glob Environ Change* 40:112–124
- Grineski SE, Collins TW, Chakraborty J, McDonald YJ (2013) Environmental health injustice: exposure to air toxics and childrens respiratory hospital admissions in El Paso. *Texas Prof Geogr* 65(1):31–46
- Grineski SE, Flores AB, Collins TW, Chakraborty J (2020) Hurricane Harvey and Greater Houston households: comparing pre-event preparedness with post-event health effects, event exposures and recovery. *Disasters* 44(2):408–432
- Hamideh S, Rongerude J (2018) Social vulnerability and participation in disaster recovery decisions: public housing in Galveston after Hurricane Ike. *Nat Hazards* 93(3):1629–1648
- Harden JD (2016) For years, the Houston area has been losing ground. *Houston Chronicle*. <https://www.houstonchronicle.com/news/houston-texas/houston/article/For-years-the-Houston-area-has-been-losing-ground-7951625.php>. Accessed 12 November 2020
- Hernandez D, Chang D, Hutchinson C, Hill E, Almonte A, Burns R, Evans D et al (2018) Public housing on the periphery: vulnerable residents and depleted resilience reserves post-Hurricane Sandy. *J Urban Health* 95(5):703–715
- Highfield WE, Peacock WG, Zandt SV (2014) Mitigation planning: why hazard exposure, structural vulnerability and social vulnerability matter. *J Plan Educ Res* 34(3):287–300
- Hsiang S, Kopp R, Jina A, Rising J, Delgado M, Mohan S, Houser T et al (2017) Estimating economic damage from climate change in the United States. *Science* 356(6345):1362–1369
- Jacob, J., Pandian, K., Lopez, R., Biggs, H. (2012). Houston-area Freshwater Wetland Loss, 1992–2010. <https://tcwp.tamu.edu/files/2015/06/WetlandLossPub.pdf>. Accessed 1 March 2020
- Jonkman SN, Godfroy M, Sebastian A, Kolen B (2018) Brief communication: loss of life due to Hurricane Harvey. *Nat Hazards Earth Syst Sci* 18(4):1073–1078
- Karaye I, Ross A, Perez-Patron M, Thompson C, Taylor N, Horney J (2019) Factors associated with self-reported mental health of residents exposed to Hurricane Harvey. *Prog Disaster Sci* 2:100016
- Khare AT (2013) Market-driven public housing reforms: inadequacy for poverty alleviation. *Citiescape* 15(3):193–203
- Lee JY, Zandt SV (2018) Housing tenure and social vulnerability to disasters: a review of the evidence. *J Plan Lit* 34(2):156–170
- Liang K, Zeger S (1986) Longitudinal data analysis using generalized linear models. *Biometrika* 73:13–22

- Linderman, J. (2017). An equal opportunity storm: 'Harvey didn't spare anyone'. Washington Times. <https://www.washingtontimes.com/news/2017/sep/2/an-equal-opportunity-storm-harvey-didnt-spare-anyone/>. Accessed 1 March 2020
- Maantay J, Maroko A (2009) Mapping urban risk: flood hazard, race, environmental justice in New York. *Appl Geography* 29(1):111–124
- Mehta A, Brennan M, Steil J (2020) Affordable housing, disasters and social equity: LIHTC as a tool for preparedness and recovery. *J Am Plan Assoc* 86(1):75–88
- Montgomery MC, Chakraborty J (2015) Assessing the environmental justice consequences of flood risk: a case study in Miami. *Florida Environ Res Lett* 10(9):095010
- National low income housing coalition [NLIHC] (2019). Impact of Hurricane Harvey. [PDF file]. <https://nlihc.org/sites/default/files/Hurricane-Impact-Harvey.pdf>. Accessed 1 March 2020
- Pan W (2001) Akaike's information criterion in generalized estimating equations. *Biometrics* 57(1):120–125
- Perl, L., & McCarty, M. (2017). Income Eligibility and Rent in HUD Rental Assistance Programs: Frequently Asked Questions. [PDF file] Washington DC: Congressional Research Service. [https://www.everycrsreport.com/files/20170328\\_R42734\\_8fe45bab6d999a7b32ab6138f448b13ee185a2a9.pdf](https://www.everycrsreport.com/files/20170328_R42734_8fe45bab6d999a7b32ab6138f448b13ee185a2a9.pdf). Accessed 10 April 2020
- Rufat S, Tate C, Burton C, Maroof A (2015) Social vulnerability to floods: review of case studies and implications for measurement. *Int J Disast Risk Reduct* 14:470–486
- Schwartz R, Tuminello S, Kerath S, Rios J, Lieberman-Cribbin W, Taioli E (2018) Preliminary assessment of Hurricane Harvey exposures and mental health impact. *Int J Environ Res Public Health* 15(5):974
- Taylor, P., & R. Fry. (2012). The Rise of Residential Segregation by Income. [PDF file]. <https://www.pewresearch.org/wp-content/uploads/sites/3/2012/08/Rise-of-Residential-Income-Segregation-2012.2.pdf>. Accessed 1 March 2020
- U.S. Department of housing and urban development [HUD]. (2020). Assisted housing: national and local. <https://www.huduser.gov/portal/datasets/assths.html>. Accessed 28 January 2020
- United States Army Corps of Engineers. (2017). Corps releases at Addicks and Barker Dams to begin. <https://www.swg.usace.army.mil/Media/News-Releases/Article/1291369/corps-releases-at-addicks-and-barker-dams-to-begin/>. Accessed 12 November 2020
- Vanderpool, T. (2018). Climate change is worsening Houston's housing crisis. NRDC Southwest Dispatch. <https://www.nrdc.org/stories/climate-change-worsening-houstons-housing-crisis>. Accessed 1 March 2020
- Walker G (2012) Flood vulnerability: uneven risk and injustice of disaster. *Environmental justice: concepts*. Routledge, London, pp 156–178
- Wang SY, Simon LZ, Yoon J-H, Klotzbach P, Gillies RR (2018) Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas. *Environ Res Lett* 13(5):054014
- Ward, A. (2018). Homeless after Harvey: For some, the historic flooding in Houston washed away shelter and security. *Houston Chronicle*. <https://www.houstonchronicle.com/news/houston-weather/hurricane-harvey/article/Homeless-after-Harvey-For-some-the-historic-13171309.php> Accessed 1 March 2020
- Wisner B, Blaikie P, Cannon T, Davis I (2004) *At Risk: natural hazards, people's vulnerability and disasters*, 2nd edn. Routledge, London
- Zandt SV, Peacock WG, Henry DW, Grover H, Highfield WE, Brody SD (2012) Mapping social vulnerability to enhance housing and neighborhood resilience. *Hous Policy Debate* 22(1):29–55
- Zhang W, Villarini G, Vecchi GA, Smith JA (2018) Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. *Nat Int J Sci* 563:384–388