Environmental Research 179 (2019) 108772

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Environmental injustice and Hurricane Harvey: A household-level study of socially disparate flood exposures in Greater Houston, Texas, USA

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ARTICLE INFO

Keywords:
Hurricane Harvey
Flood
Environmental justice
Race/ethnicity
Socioeconomic status

ABSTRACT

Environmental justice research on flooding has relied heavily on analyses of aggregated geographic areal units and assessing exposure to 'pre-flood' risks (e.g., residence in 100-year flood zones) rather than actual flood events. To address these limitations, we examined disproportionate exposure to flooding caused by Hurricane Harvey in 2017 in Greater Houston (Texas). Using primary survey data collected from 377 representative households before Harvey and spatial data on Harvey-induced inundation developed by the US Federal Emergency Management Agency, we found that the areal extent of flooding around residents' home sites was distributed inequitably with respect to race/ethnicity and socioeconomic status (SES). Hispanic, black and other racial/ethnic minority households experienced more extensive flooding than white households, and lower SES households faced more extensive flooding than higher SES households. Findings align with prior flood risk research in Greater Houston and provide cause for concern, as social inequities in flood exposure may have influenced social disparities in flood impacts and post-disaster needs. Since flood events in Greater Houston are expected to increase in frequency and magnitude due to climate change, socially disparate impacts are likely to become an increasingly salient public policy issue. Thus, proactive approaches for reducing flood risks and ameliorating disparities should be implemented.

1. Introduction

Distributive inequities in the societal impacts of environmental hazards have become increasingly important in scientific risk assessment and public discourse. Recognition of social inequalities in the distribution of toxic pollution hazards—first in the US and then globally—has informed a social movement, policy debates, and a large body of empirical research that have engaged the theme of environmental justice (EJ) (Mohai et al., 2009; Walker et al., 2012). The US Environmental Protection Agency (2019) adopts this definition of EJ:

> The fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. This goal will be achieved when everyone enjoys the same degree of protection from environmental and health hazards, and equal access to the decision-making process to have a healthy environment in which to live, learn, and work.

Distributive EJ scholarship, utilizing statistical and spatial analysis techniques, has focused on determining whether, and examining the extent to which, socially disadvantaged groups are disproportionately exposed to environmental health hazards. The majority of these studies indicate that racial/ethnic minorities, people of low socioeconomic status (SES), and other socially disadvantaged groups experience disparate residential exposure to technological hazards (Collins et al., 2017; Downey and Hawkins, 2008; Grineski et al., 2015b; Grineski et al., 2017b; Grineski and Collins, 2018; Mohai et al., 2009; Walker, 2012; Zhao et al., 2018).

Hurricane Katrina stimulated EJ research on social inequalities associated with events such as hurricanes and floods. Concerns regarding the inequitable impacts of Katrina on African-American and low-income residents of New Orleans led to an expansion of empirical EJ research to include the unjust implications of flooding (Bullard and Wright, 2009; Colten, 2007). Extending from those concerns, our study objective was to clarify household-level factors influencing exposures to flooding caused by Hurricane Harvey in 2017 in the Greater Houston metropolitan statistical area (MSA) of Texas, one of the most racially/

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https://doi.org/10.1016/j.envres.2019.108772
Received 13 June 2019; Received in revised form 20 September 2019; Accepted 22 September 2019
Available online 25 September 2019
0013-9351/

ethnically diverse and populous MSAs in the US and one severely affected by Harvey. We specifically aimed to: (1) determine whether the areal extent of Harvey-induced flooding around a random sample of residents' home sites was distributed inequitably with respect to race, ethnicity, and SES; (2) test relationships between additional factors known to influence human relationships with flood hazards—including water-based amenities, self-protection from flooding, and flood risk perceptions—and residential exposure to Harvey-induced flooding; and (3) assess whether modeled pre-flood estimates of risk were predictive of actual home site exposures to Harvey-induced flooding, which is important since the vast majority of prior EJ research on flooding has been based on such pre-flood risk estimates.

EJ research on flooding, following the distributive EJ literature more broadly, has relied heavily on ecological (i.e., aggregated secondary data) analyses of geographic areal units to determine if particular populations are disproportionately exposed to flood hazards (Collins et al., 2018). Few studies have examined flood exposure disparities at individual or household levels. This widespread reliance on ecological study designs has limited EJ research in accounting for fine-scale individual- or household-level factors that structure aggregate patterns. For example, the roles of social inequalities and behavioral factors in patterning environmental injustices cannot be directly examined using the traditional approach of analyzing aggregated population data across areal units. The only inferences that ecological analyses support relate to coarse-scale (neighborhood-level) influences on environmental inequality. In contrast, the analysis of household-level data addresses the ecological fallacy of assuming that statistical associations found for areal units apply to relationships at the micro-level, supporting a fine-grained understanding of factors influencing disparate exposures.

The vast majority of ecological studies have examined disparities in exposure to modeled 'pre-flood' risks (e.g., residence in 100-year flood zones) rather than actual flood events. These studies have not consistently found associations between indicators of social disadvantage and pre-flood hazard exposure (see Burton and Cutter, 2008 for an exception). In fact, previous studies in the US and UK have found that areas with socially privileged residents may experience the highest pre-event exposure to flood hazards (Chakraborty et al., 2014; Fielding and Burningham, 2005; Grineski et al., 2015a; Ueland and Warf, 2006). Fewer studies have found no clear patterns of disproportionate exposure in the US context (Maantay and Maaroko, 2009; Masozera et al., 2007).

Some have found that the type of potential flooding (inland/riverine vs. coastal) may closely relate to social patterns of risk. In the UK, no SES disparities were found in reference to the distribution of riverine/inland pre-flood risks across small census areas, but lower SES areas were found to be disproportionately burdened by coastal pre-flood risks (Fielding, 2007; Walker and Burningham, 2011; Walker, 2012). Studies in the US have documented the opposite pattern: specifically, areas of concentrated social disadvantage were associated with greater inland pre-flood risks, while areas with more socially advantaged populations were associated with greater coastal pre-flood risks (Qiang, 2019; Ueland and Warf, 2006; Chakraborty et al., 2014). Such differences in the US are explainable based on the enhanced water-based amenity values that tend to characterize areas prone to coastal (vs. inland/riverine) flooding (Chakraborty et al., 2014; Collins et al., 2018; Grineski et al., 2017b).

Several distributive EJ studies of flooding have focused on Greater Houston, Texas. Chakraborty et al. (2019a, 2019b) found that the areal extent of Harvey-induced flooding was significantly greater in neighborhoods with higher proportions of non-Hispanic black, socioeconomically-deprived, and disabled residents (Chakraborty et al., 2019a, 2019b). In one of the few individual/household-level distributive EJ studies of flood exposure, Maldonado et al. (2016a, 2016b) found that pre-flood risk (i.e., residence within US federally-designated 100-year flood zones) in Greater Houston was associated with being Hispanic immigrant (as compared to being US-born Hispanic, non-Hispanic black, and non-Hispanic white), having less property-level flood hazard mitigation, and having lower perceptions of flood risk. In sum, prior studies indicated that markers of social disadvantage tend to correlate with heightened flood hazard exposure in Greater Houston, which contrasts with patterns revealed in some US locales, such as Miami (Collins et al., 2018).

Other factors not typically examined via ecological EJ research—including water-based amenities, self-protection from flooding, and flood risk perception—are important to consider as individual- or household-level determinants of exposure to flooding (Maldonado et al., 2016a, 2016b). Since water-based amenities and flood risks are not easily divisible (i.e., separable from one another), as both are natural features of proximity to bodies of water, the presence of such amenities is often correlated with heightened exposure to flood hazards (Collins, 2010; Collins et al., 2018). Thus, living at risk to flooding may be driven in part by corresponding locational environmental benefits (Bin et al., 2008; Chakraborty et al., 2014; Montgomery et al., 2015). Additionally, self-protection strategies can measurably buffer residents against negative impacts of flooding. Structural self-protection strategies—such as elevating and flood-proofing homes—enable residents to minimize flood losses (Botzen et al., 2013; De Moel et al., 2014; FEMA, 2014; Kriebich et al., 2005; Poussin et al., 2012). In terms of non-structural self-protection, flood insurance compensates residents for property losses due to flooding. In 100-year flood zones (i.e., designated by the US Federal Emergency Management Agency (FEMA)), flood insurance is required on home structures with mortgages from federally-regulated lenders. The vast majority of US flood insurance policies are obtained through the FEMA-administered National Flood Insurance Program (NFIP). While renter-occupants are not responsible for maintaining flood insurance for home structures, renter- and owner-occupants may purchase NFIP flood insurance coverage for the home's contents. People's flood risk perceptions may also relate to their flood exposures, as their pre-conceptions of risk may influence their selection of home locations exposed to a lesser or greater extent to potential flooding. Additionally, studies indicate that higher levels of flood risk perception may be associated with living within or more proximate to flood zones (Harlan et al., 2019; Heitz et al., 2009; Kellens et al., 2011; Lindell and Hwang, 2008).

2. Materials and methods

Our study integrated spatial data for 2017 from Hurricane Harvey's Inundation Footprint, developed by FEMA, with primary social survey data collected in 2012 through a probability-based, random sample of Greater Houston residents. To analyze the EJ implications of flooding from Hurricane Harvey, we used generalized estimating equations (GEEs) that accounted for geographic clustering for survey respondents in the study area and provided statistically valid inferences regarding the relationship between flood extent and explanatory factors.

2.1. Study area: Greater Houston, Texas, USA

As shown in Fig. 1, Greater Houston is a nine-county MSA located in Texas, which is bordered on the southeast by the Gulf of Mexico. With a total population of 6,892,427 in 2017, it is the fifth largest MSA in the US. Non-Hispanic whites account for about 38% of the MSA population, with Hispanics (36%), and non-Hispanic blacks (17%) representing the largest minority groups. Greater Houston is one of the most vulnerable metropolitan areas in the world to tropical storms and hurricanes, which crisscross the Gulf of Mexico. Prior to Hurricane Harvey, Greater Houston suffered major losses due to Tropical Storm Allison (2001), as well as Hurricanes Rita (2005), Katrina (2005), and Ike (2008). More recently, the Memorial Day (2015) and Tax Day (2016) floods directly resulted in at least 13 deaths and major property damage. Hurricane Harvey made landfall on the Texas coast on August 25, 2017. Harvey

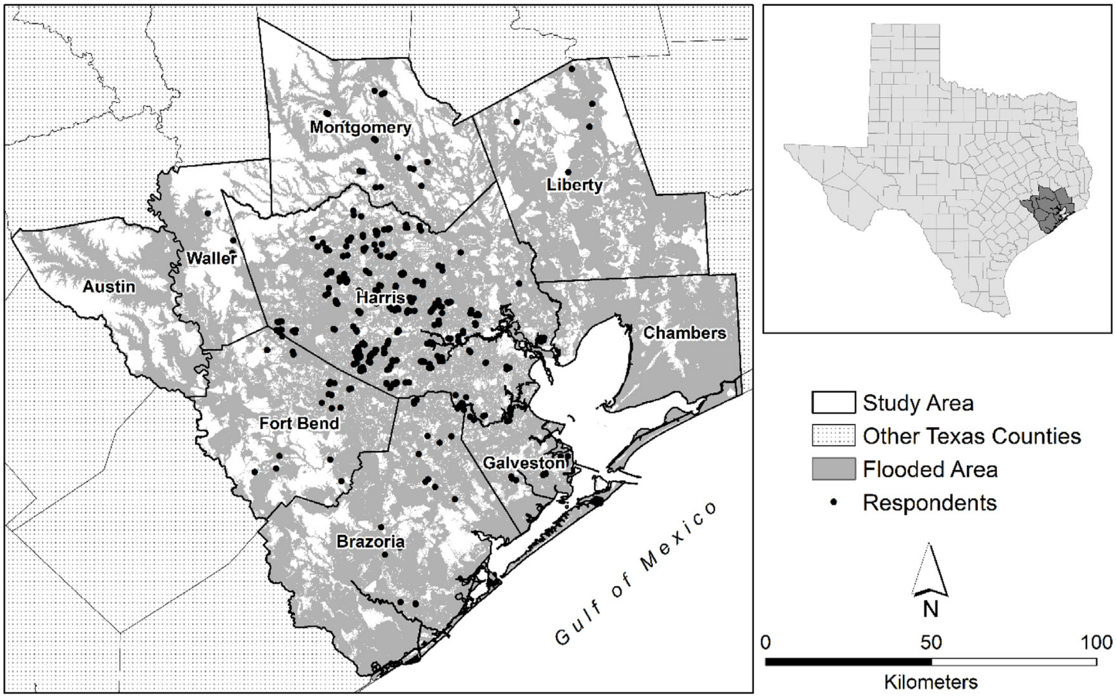

Fig. 1. Counties, Hurricane Harvey flooded area, and approximate home locations of survey respondents within the Greater Houston metropolitan statistical area, Texas, 2017.

was an unprecedented tropical storm system. Average total rainfall amounts across Greater Houston were between 36 and 48 inches, which caused widespread flooding and an estimated $125 billion in damages, making Harvey the second-costliest disaster in US history, behind only Hurricane Katrina in 2005 (Blake and Zelinsky, 2017). More than 156,000 homes were destroyed and at least 70 people died (Emanuel, 2017). Recent studies indicate that the equivalent magnitude of Harvey's rainfall has become 3 times more likely because of climatic changes occurring over recent decades (Emanuel, 2017; Wang et al., 2018).

2.2. Survey data collection and sample

The analysis relies on a sample of 377 Greater Houston households that completed a 2012 survey and still resided in the same home in Greater Houston at the time of Harvey. During summer 2012, study participants were randomly selected using a probability-based design for a institutional review board-approved survey about social vulnerability to flood hazards (see Collins et al., 2015; Maldonado et al., 2016a, 2016b). Participants completed 30-min landline-based phone surveys in Spanish or English. The response rate to the survey was 33%, which is similar to that achieved in other published survey studies using random digit dialing conducted at that time. In comparison to US census data for Greater Houston, our sample was broadly representative in terms of household income (mean of $62,709 vs. Houston MSA mean of $56,876), and the percentages of adults who were non-Hispanic black (21% vs. 17%) and non-Hispanic white (49% vs. 44%); it somewhat underrepresented the percentage of Hispanic adults (22% vs. 32%).

The survey instrument focused on residents' experiences with, perceptions of, and protective actions taken with respect to flood and air pollution hazards, as well as environmental factors influencing participants' residential decision-making. Most SES and demographic survey items were derived from the American Community Survey instrument (version 2011). The survey was conducted in English and Spanish. It was written in English, and then subjected to three translation iterations, including a back translation. The telephone interviews were conducted by trained, English–Spanish bilingual interviewers employed by a firm with expertise in survey research with Hispanic populations. Incentives of $10 in cash were provided to all survey participants. All responding householders verbally consented to participate and were 18 years of age or older. Data on respondents' home addresses were also obtained, which enabled us to overlay data on their residential exposure to flood hazards and enable distributive EJ analyses.

In order to conduct this distributive EJ study of Hurricane-Harvey induced flooding, which occurred in 2017, we needed to update the sample of study participants based on their locations of residence at the time of Harvey, because they could have moved since 2012. As detailed by Grineski et al. (2019), to update the sample, we acquired home addresses of the 2012 survey participants as of 25 August 2017 through a marketing research firm specializing in sampling. We then excluded from the analysis 63 households no longer residing at their 2012 place of residence as of 25 August 2017. It was important to exclude these movers from the analysis, because their 2012 survey responses—used to construct measures of residential decision-making, property flood mitigation, and flood risk perception—would no longer be applicable to their new residential locations. Respondents who did not complete at least 50% of the survey items relevant to this analysis in 2012 were also excluded. We analyzed data for 377 survey respondents. We integrated spatial data on Hurricane Harvey's flood extent in 2017 for this analysis, but we did not collect new survey data from study participants after 2012.

2.3. Analysis variables

Table 1 provides details on the construction of the analysis variables.

2.3.1. Dependent variable

Our measure of flood extent at respondents' home sites derives from Harvey's Inundation Footprint, a cartographic product developed by the FEMA Region 6 Mitigation Division (TX-DR-4332) to support response and recovery operations (FEMA, 2018). This raster map layer contains flood extent and depth values for each 3-m by 3-m grid pixel in the

Table 1
Analysis variables, survey question, and coding.

Variable	Survey Questions	Coding
Hurricane Harvey Flood Extent	N/A (Source: US Federal Emergency Management Agency)	Continuous
Hispanic	Are you of Hispanic, Latino, or Spanish origin?	0 = No 1 = Yes
Non-Hispanic Black	(1) Are you of Hispanic, Latino, or Spanish origin? (2) Which of the following best describes your race? Black of African-American	0 = No 1 = Yes
Non-Hispanic Other	(1) Are you of Hispanic, Latino, or Spanish origin? (2) Which of the following best describes your race? American Indian or Alaskan Native, Asian, Pacific Islander, or Some other race	0 = No 1 = Yes
Non-Hispanic White	(1) Are you of Hispanic, Latino, or Spanish origin? (2) Which of the following best describes your race? White	0 = No 1 = Yes
Socioeconomic Status Factor		Continuous
Household Income[a]	What was your total HOUSEHOLD income in US$ for the year 2011 before taxes?	1 = < $10,000 2 = $10,000–19,999 3 = $20,000–29,999 4 = $30,000–39,999 5 = $40,000–49,999 6 = $50,000–74,999 7 = $75,000–99,999 8 = $100,000–149,999 9 = $150,000–249,999 10 = > $249,999
Education[a]	Thinking about the person in your household who is 18 years of age or older with the highest educational degree received or level of school completed—what is the highest grade or level of school that this person has completed?	0 = No formal education – 21 = Ph.D. degree
Housing Tenure	Is this home … ? (1) … owned by you or someone in this household with a mortgage or loan—including home equity loans? (2) … owned by you or someone in this household free and clear—without a mortgage or loan? (3) … rented? (4) … occupied without payment of rent, but not owned?	0 = Owner (options 1, 2, 4) 1 = Renter (option 3)
Water-based Amenities Factor		Continuous
Waterfront/beachfront property[b]	What level of consideration was given to having "Waterfront or Beachfront Property" when you constructed, purchased or rented your current home?	1 = Not a consideration at all 5 = A very important consideration
Proximity to Coast or Beach[b]	What level of consideration was given to being "Close to the Coast or Beach" when you constructed, purchased or rented your current home?	1 = Not a consideration at all 5 = A very important consideration
Proximity to River or Lake[b]	What level of consideration was given to being "Close to a River or Lake" when you constructed, purchased or rented your current home?	1 = Not a consideration at all 5 = A very important consideration
Flood Mitigation Composite	Which of the following flood protection methods have been used to protect the home site you occupy from flooding? (2) Electric components of the home were elevated (1) Home structure elevated to protect against flooding (3) Indoor heating, ventilation and air conditioning system components were elevated (4) Outdoor service equipment were elevated (5) Floodwalls, berms or levees were built on site (6) Back flow valves or check valves were installed (7) Interior drainage system was installed	0 = No mitigation actions taken 7 = All 7 mitigation actions taken
NFIP Flood Insurance (Contents)	Are the contents of the home currently covered by the NFIP?	0 = Not covered by NFIP 1 = Covered by NFIP
Risk Perception Factor		Continuous
Risk Perception[c] (Property)	How concerned are you about the possibility of a flood causing damage to your home or property?	1 = "Not concerned at all" 5 = "Extremely concerned"
Risk Perception[c] (Health)	How concerned are you about the possibility of a flood causing injuries or health problems to you or to members of the household?	1 = "Not concerned at all" 5 = "Extremely concerned"
Risk Perception[c] (Livelihood)	How concerned are you about the possibility of a flood preventing your or members of your household from being able to work or causing disruption to daily activities?	1 = "Not concerned at all" 5 = "Extremely concerned"
100-Year Flood Risk	N/A (Source: US Federal Emergency Management Agency)	0 = Outside of a 100-year flood zone 1 = within a 100 year-flood zone
500-Year Flood Risk	N/A (Source: US Federal Emergency Management Agency)	0 = Outside of a 500-year flood zone 1 = within a 500 year-flood zone

[a] Included in the Socioeconomic Status Factor in the analysis.
[b] Included in the Water-based Amenities Factor in the analysis.
[c] Included in the Risk Perception Factor in the analysis.

study area, and has been used in recent Hurricane Harvey studies (Chakraborty et al., 2019a, 2019b; Grineski et al., 2019). See Chakraborty et al. (2019a) for a more detailed description. We estimated the extent of flooding surrounding each respondent's home using a geographic information system-based methodology that comprised several steps. First, we used the address-matching capabilities of TransCAD 7.0 software and Google Earth to geocode the locations of the survey respondents to the street network based on their home addresses. Second, using ArcGIS Desktop 10.5.1, circular buffers (100-m radius; as well as 30-m radius buffers for the sensitivity analysis) were created around respondents' geocoded home 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 respondent's home that flooded due to Hurricane Harvey. We used this areal proportion measure—referred to as “flood extent”—as a continuous dependent variable in our analysis. To determine whether results were sensitive to the areal size of the circular buffer used to measure flood extent, we conducted a sensitivity analysis using an alternative flood extent measure based on a 30-m radius circular buffer, since study participants reside in a dense urban area where property sizes are relatively small.

2.3.2. Independent variables

Race/Ethnicity. We employed categorical race/ethnicity measures, which were constructed by re-coding self-identified data from householders on ethnic status and racial status in order to define the groups. The following categorical measures of race/ethnicity were used in analyses: *1* for “Hispanic” (Hispanic/Latino of any race) and *0* for not; *1* for non-Hispanic “black” (black/African American respondents who were not Hispanic) and *0* for not; *1* for non-Hispanic “Other Minority” (American Indian/Alaska Native, Asian/Pacific Islander, or “other race” respondents who were also not Hispanic and not black) and *0* for not; and *1* for non-Hispanic “white” (white only respondents who were not Hispanic) and *0* for not. We utilized the non-Hispanic white group as the reference group in our models, since it is the largest (with 48% of study participants).

Socioeconomic Status. We analyzed SES using two variables. First, we used a factor constructed through principal components analysis (PCA) that comprised two variables: educational attainment and annual household income (Cronbach's alpha = 0.603). Educational attainment was measured with a survey question that gauged the level of education completed by the individual in the household with the highest level of education. Household income was measured based on response options to a survey question that gauged the total pre-tax household income of survey respondents in 2011. Second, we used renter-occupancy as a SES indicator, measured by a survey item that determined whether they rented or owned their residences. Householders were asked to indicate if their home was: (i) owned by them or someone in the household with a mortgage of loan; (ii) owned by them or someone in the household free and clear; (iii) rented; or (iv) occupied without payment of rent, but not owned. For our analysis, this variable was coded as *1* for renter (iii) and *0* for owner (i, ii, or iv).

Water-based Amenities. We measured the role of water-based amenities in residential decision-making among householders using survey items that gauged their preferences when making their residential location choice. We used three survey measures that represent the degree to which survey respondents were influenced in moving to their residences by specific considerations, which focus on the following features: (i) waterfront or beachfront property; (ii) proximity to the coast or beach; and (iii) proximity to a river or lake. Survey respondents indicated the importance of each of those features in the choice of their home using a scale ranging from *1* to *5*, with 1 = “not a consideration at all” to 5 = “a very important consideration.” We applied PCA to the responses to these three items in order to create one water-based amenities factor that we used in our analysis (Cronbach's alpha = 0.708).

Self-Protection. Our composite variable of structural self-protection—flood mitigation—is based on yes/no responses to seven survey items that gauged whether protective action against flooding had been taken at respondents' home sites (Table 1). Responses to each were coded as *1* for “yes” and *0* for “no” and all seven items were summed into one composite variable that ranges from 0 to 7, indicating how many flood mitigation actions were implemented at each home site. We summed the items instead of using PCA to construct this composite flood mitigation measure because factor analysis is inappropriate for use with dichotomous variables. Our measure of non-structural self-protection—contents flood insurance—is based on a survey question that gauged whether or not the contents of respondents' homes were insured through the NFIP. We focused on maintenance of contents insurance since homeowner- and renter-occupants alike are eligible to maintain NFIP contents insurance, whereas only homeowners are eligible to maintain insurance for home structures. Thus, this form of flood insurance was applicable to all survey participants. “Yes” responses were coded *1* and “no” options as *0*.

Flood Risk Perception. Three Likert-scale type survey items were used to assess respondents' levels of concern regarding potential flood impacts upon their households (in terms of property damage, health problems, and disruption to daily activities). Table 1 reports coding for each of the three items used to construct the flood risk perception measure. We applied PCA to responses to those items in order to create one factor (Cronbach's alpha = 0.873).

Pre-Flood Risk. In order to assess associations between modeled pre-flood risks—the outcome of focus in most prior flood EJ studies—and actual Hurricane Harvey-induced flooding, our analysis included two variables measuring the presence/absence of respondents' homes in the (1) 100-year and (2) 500-year pre-flood zones. These variables were derived using householders' geocoded home locations and FEMA Digital Flood Rate Maps (DFIRMs). Each gauges a given respondent's pre-flood risk as *1* for within the pre-flood zone (100-year, 500-year) and *0* for outside the pre-flood zone.

2.4. Analysis approach

We employed generalized estimating equations (GEEs), a multivariate analysis technique, to analyze social determinants of residential flood exposure resulting from Hurricane Harvey. GEEs are an appropriate analysis technique for this study since they provide a general method for the multivariate analysis of clustered and non-normally distributed data (Liang and Zeger, 1986; Zeger and Liang, 1986). GEEs have been used in distributive EJ research, including flood analyses as well as both ecological and household-level studies (e.g., Chakraborty, 2019a; 2019b; Collins et al., 2015, 2019; Maldonado et al., 2016a, 2016b). Prior to modeling GEEs, we applied multiple imputation (MI) techniques to address missing values in the 2012 survey data (Enders, 2010; Baraldi and Enders, 2010; McPherson et al., 2012; Van Buuren, 2012). MI is a best practice for reducing bias associated with missing data values, which is a common problem in survey research. Implementing MI begins by first predicting missing values based on the pattern of responses in a dataset, and imputing values for missing data points across multiple versions of the dataset. It then involves statistically analyzing those multiple versions of the dataset, before pooling output from those analyses in one composite set of results using established procedures (Rubin, 2004). We imputed missing values for 20 versions of the dataset, as is recommended (Enders, 2010), and, here, we report pooled GEE results from analyses of all 20 versions of the dataset.

Data were analyzed by modeling a GEE that employed the independent variables described above as predictors and the Hurricane Harvey flood extent measure at respondents' home sites as the outcome, while accounting for clustering at the county level. The models adjust for clustering based on the county of residence because previous studies of EJ and vulnerability in the context of flood hazards have identified counties as geographic units that strongly influence human-flood hazard relationships in the US (Brody et al., 2008a, 2008b; 2009; Chakraborty et al., 2014).

GEEs require the specification of an intracluster dependency correlation matrix (Liang and Zeger, 1986; Zeger and Liang, 1986). Three correlation structure specifications were substantive candidates: (1) independent, which assumes the nonexistence of dependency, so that all off-diagonal elements of the working correlation matrix are zero; (2) exchangeable, which assumes constant intracluster dependency, so that all the off-diagonal elements of the correlation matrix are equal; and (3) unstructured, which assumes a completely general correlation matrix, which is estimated without constraints. We modeled the GEE with the three correlation matrices, using quasi-likelihood under the independence model criterion (QIC) goodness-of-fit coefficients to determine the best specification (Garson, 2013). The exchangeable correlation structure specification was selected for the results reported here, as it was better fitting than the independent and unstructured specifications. To further select the best fitting model, we estimated a series of GEEs by varying the model specifications. We tested normal and Tweedie (index parameter = 1.5; i.e., compound Poisson-gamma) distributions with logarithmic and identity link functions. Visual inspection of a histogram of our dependent variable suggested that these were the most appropriate options, given that the dependent variable included zero values. The Tweedie distribution with a logit link function was the best fitting model, and results for that GEE are presented here. Additionally, we examined possible multicollinearity among the analysis variables. Based on results of diagnostic tests, inferences from the GEE are not affected by multicollinearity. All continuous independent variables were standardized before inclusion in the GEE.

3. Results

Table 2 summarizes descriptive statistics for the analysis variables. Table 3 reports pooled GEE results of the model predicting home site Hurricane Harvey-induced flood extent among Greater Houston study participants. Accounting for county effects as a nuisance parameter and other covariates in the models, we found that Hispanics, non-Hispanic blacks, and non-Hispanic other racial minorities experienced statistically significantly greater flood extent ($p < 0.05$) than non-Hispanic whites. In terms of the strength of these main effects, Hispanic households experienced a 23.1% increase relative to non-Hispanic whites in the mean proportion of area flooded around their home sites, after adjusting for the effects of other independent variables and county-level clustering (Table 3). Similarly, compared to being non-Hispanic white, being of non-Hispanic black or non-Hispanic other race were respectively associated with adjusted increases of 33.5% or 31.8% in the mean proportion of area flooded around their home sites.

Additionally, lower SES and having NFIP contents insurance were statistically significantly associated with more extensive flooding around study participants' home sites, and renter-occupancy was associated with less extensive flooding (Table 3). While no other explanatory variable exhibited a significant relationship with flood extent, the parameter estimates indicated positive directionality with respect to flood extent for some variables (i.e., flood mitigation, 500-year pre-flood risk) and negative directionality for others (i.e., water-based amenities, risk perception, 100-year flood risk).

In the sensitivity analysis (not shown here), which utilized an alternative flood extent measure based on a 30-m radius circular buffer, results were nearly identical in terms of the direction and significance of relationships for the explanatory variables with flood extent. In the sensitivity model employing a 30-m buffer instead of the 100-m buffer, having NFIP contents insurance maintained the same directionality but became non-significant ($p = 0.084$). The directionality of the flood mitigation variable switched from positive to negative, but both coefficients were statistically non-significant.

Table 2
Descriptive statistics of variables included in the analysis for survey respondents from Greater Houston, Texas, USA ($n = 377$).

Variable	N	Min	Max	Mean	SD	% Missing
Hurricane Harvey Flood Extent	377	0	1	0.489	0.324	0.000
Hispanic	82 (1) 292 (0)	0	1	0.219	N/A	0.796
Non-Hispanic Black	77 (1) 294 (0)	0	1	0.208	N/A	1.592
Non-Hispanic Other	14 (1) 352 (0)	0	1	0.038	N/A	2.918
Non-Hispanic White	177 (1) 194 (0)	0	1	0.477	N/A	1.592
Socioeconomic Status Factor[a]	296	−2.809	2.321	0.000	1.000	21.485
Household Income	299	1	10	4.806	2.552	20.690
Educational Attainment	373	2	21	14.920	3.186	1.061
Housing Tenure (renter = 1)	72 (1) 298 (0)	0	1	0.195	N/A	1.857
Water-based Amenities Factor[b]	371	−0.964	2.416	0.000	1.000	1.592
Waterfront/Beachfront Property	373	1	5	1.912	1.472	1.061
Proximity to Coast or Beach	376	1	5	2.463	1.552	0.265
Proximity to River or Lake	374	1	5	2.032	1.436	0.796
Flood Mitigation Composite	261	0	7	3.720	1.611	30.769
Home Elevated	184 (1) 170 (0)	0	1	0.520	N/A	6.101
Home Electric Components Elevated	273 (1) 90 (0)	0	1	0.752	N/A	3.714
Home Ventilation System Elevated	311 (1) 61 (0)	0	1	0.836	N/A	1.326
Outdoor Service Equipment Elevated	222 (1) 146 (0)	0	1	0.603	N/A	2.387
Floodwalls, Berms, or Levees Installed	108 (1) 248 (0)	0	1	0.303	N/A	5.570
Backflow Valves Or Check Vales Installed	158 (1) 160 (0)	0	1	0.497	N/A	15.650
Interior Drainage System Installed	59 (1) 292 (0)	0	1	0.168	N/A	6.897
NFIP Contents Insurance	165 (1) 198 (0)	0	1	0.455	N/A	3.714
Risk Perception Factor[c]	377	−1.807	1.714	0.000	1.000	0.000
Concern about Property Damage	377	1	5	2.846	1.396	0.000
Concern about Health Problems	377	1	5	2.782	1.407	0.000
Concern about Disruption	377	1	5	2.984	1.423	0.000
100-Year Flood Risk	47 (1) 330 (0)	0	1	0.125	N/A	0.000
500-Year Flood Risk	104 (1) 273 (0)	0	1	0.276	N/A	0.000

Notes: "% Missing" denotes the percentage of respondents for whom there were missing values. For example, 0% of respondents were missing values for Hurricane Harvey Flood Extent, while 3.7% were missing values for NFIP Contents Insurance. Means for the dichotomous indicators are presented because they can be interpreted as the proportion of the respondents in the category coded as 1. For example, the mean for Hispanic is 0.219, which means that 21.9% of respondents are of Hispanic ethnicity. Descriptive statistics are provided for original data, prior to multiple imputation.

[a] Cronbach's alpha = 0.603.
[b] Cronbach's alpha = 0.708.
[c] Cronbach's alpha = 0.873.

Table 3
Pooled results of generalized estimating equations predicting Hurricane Harvey flood extent surrounding respondents' home sites.

Parameter	Parameter estimate	Exp(B)	Standard error	Lower 95% confidence interval	Upper 95% confidence interval	*p*
Intercept	−0.830	0.436	0.0660	−0.960	−0.701	< 0.001
Hispanic	0.208	1.231	0.0810	0.049	0.367	0.010
Non-Hispanic Black	0.289	1.335	0.0511	0.189	0.389	< 0.001
Non-Hispanic Other	0.276	1.318	0.0918	0.095	0.457	0.003
Socioeconomic Status Factor	−0.062	0.940	0.0271	−0.116	−0.009	0.022
Renter Housing Tenure	−0.246	0.782	0.0822	−0.407	−0.085	0.003
Water Amenities Factor	−0.003	0.997	0.0109	−0.024	0.019	0.804
Flood Mitigation Composite	0.012	1.012	0.0184	−0.024	0.048	0.529
NFIP Contents Insurance	0.109	1.115	0.0462	0.018	0.199	0.019
Risk Perception Factor	−0.021	0.979	0.0220	−0.064	0.022	0.333
100-Year Flood Risk	−0.063	0.939	0.1863	−0.428	0.302	0.734
500-Year Flood Risk	0.080	1.083	0.0804	−0.077	0.238	0.319

Notes: All continuous predictors were standardized. Non-Hispanic whites are the reference group for the other race/ethnicity categories. Participant sex was included as a control variable and has a statistically non-significant relationship with flood extent. Model used an exchangeable correlation matrix, Tweedie (index parameter = 1.5) distribution with a logit link function, and adjusted for clustering at the county level.

4. Discussion

This study expanded the distributive EJ knowledge base through an innovative re-analysis of data on human dimensions of flood hazards collected in 2012 with respect to 2017 Hurricane Harvey inundation. Because we analyzed fine-scale, household-level data, we avoided the ecological fallacy of assuming that statistical associations found for areal units apply to microlevel relationships. We examined household-level survey data, which were collected prior to Hurricane Harvey, in reference to flood exposures that subsequently occurred in the disaster. This enabled us to evaluate alternative explanations for differential residential exposure during an actual flood disaster, gain novel insights into fine-scale determinants of environmental injustices associated with Hurricane Harvey, and evaluate whether statistical associations found for geographic units in ecological distributive EJ research translated to relationships at the household level.

In response to our first study objective, we found that the areal extent of flooding around a random sample of Greater Houstonians' home sites was distributed inequitably with respect to race/ethnicity and SES, after adjusting for relevant explanatory factors and clustering at the county level. While being non-Hispanic black emerged as the strongest predictor of more extensive home site flooding, we found that all of the minority racial/ethnic groups experienced more extensive Hurricane Harvey-induced flooding at their home sites than non-Hispanic whites. We also found that lower household SES was associated with more extensive Hurricane Harvey-induced home site flooding. Those results align in some important ways with findings from a recent ecological distributive EJ study of Hurricane Harvey-induced flooding in Greater Houston that examined associations between the percentages of racial/ethnic minority groups in census tracts and flood extent (Chakraborty et al., 2019a, 2019b). Specifically, both analyses provide evidence of environmental injustices experienced by racial/ethnic minority and low SES groups due to Harvey-induced flooding. However, our results differ from those of Chakraborty et al. (2019a) in that this household-level analysis found that all minority householders experienced more extensive flooding that non-Hispanic whites, whereas Chakraborty et al. (2019a) documented disproportionate flooding based on tract-level percentage of non-Hispanic black residents only. We did not directly examine racial/ethnic segregation, but we suspect based on prior EJ studies that our findings with respect to Hispanic, black and other minority households facing more extensive flooding were influenced to a degree by residential segregation in Greater Houston (Ard, 2016; Bravo et al., 2016; Morello-Frosch and Jesdale, 2005). Future research should aim to clarify the how segregation affects flood risk disparities within and across US cities.

Counterintuitively, we also found that renter-occupancy, a marker of lower SES in Greater Houston and the US context more generally, was predictive of less extensive flooding. The bivariate relationship between renter-occupancy and flood extent was negative but statistically non-significant (results not shown); the association became significant when adjusting for the effects of other variables in the multivariate GEE. It is important to note that, because we excluded households who changed their location of residence between 2012 and 2017 from the analysis, the renter-occupants included in our analysis represent those who exhibited residential stability for a long period. Renter-occupants in our original sample who moved between 2012 and 2017, but were excluded from this analysis, demonstrated the residential mobility characteristic of renter-occupants more generally in the US and elsewhere (Rohe and Stewart, 1996; Aarland and Reid, 2019). In a separate GEE model that included non-movers with movers who still resided within Greater Houston at the time of Hurricane Harvey (n = 44 movers, including nine renter-occupants), we found that renter-occupancy was not associated with flood extent (results not shown here). Thus, we conclude that the association between renter-occupancy and lower flood extent applies only to Greater Houstonians who exhibited residential stability between 2012 and 2017. Given that residential stability has been associated with a range of social benefits (Lindblad and Quercia, 2015; Oishi et al., 2007), it is plausible that it may also correlate with environmental benefits (including protection from flooding), which might help explain the counterintuitive result for renter housing tenure in the multivariate model.

Regarding our second objective, we tested relationships between additional factors known to influence flood exposure, including desiring proximity to water-based amenities, self-protection from flooding, and flood risk perceptions. The only significant finding for those factors was that maintaining insurance on the contents of one's home through the NFIP was associated with more extensive Hurricane Harvey-induced flooding at participants' home sites. In other words, the decision among participants to adopt a nonstructural approach in order to protect themselves from flooding (as opposed to structural approaches gauged by the flood mitigation variable) was associated with the actual areal extent of flooding that occurred in Harvey. This presumably reflects a degree of awareness among participants regarding potential flood impacts, perhaps based on past flood experience, which translated for some into self-protective decision-making.

Overall, however, we found that race, ethnicity, and SES were the most important predictors of the areal extent of Hurricane Harvey-induced flooding in Greater Houston. Thus, variables representing the traditional EJ domains of race, ethnicity, and social class emerged as key household-level explanatory factors in flood exposure—more salient than water-based amenities, flood mitigation, and flood risk perception, which have received far more attention in individual and household-level studies of human dimensions of flood hazards (e.g., Bin et al., 2008; Botzen et al., 2013; Ge et al., 2011; Harlan et al., 2019;

Heitz et al., 2009; Kellens et al., 2011; Kellens et al., 2012; Lindell and Hwang, 2008). In terms of plausible reasons why these variables were not associated with the extent of Hurricane Harvey flooding, prior research suggests that water-based amenities in particular may be a relatively unimportant influence on human-flood hazard relationships in Greater Houston, which aligns with our findings (Collins et al., 2018; Maldonado et al., 2016a). We suspect that the fundamental reason, however, is that Hurricane Harvey's unprecedentedly widespread inundation exhibited little spatial correspondence with federally-designated 100- and 500-year flood risk zones. Thus, even if Greater Houstonians' awareness of federally-designated flood risk zone locations had influenced their patterns of settlement, mitigation behavior, and flood risk perception prior to Hurricane Harvey, one might expect that such human responses to anticipated flood risks would lack correspondence with the surprisingly extensive flooding caused by Harvey.

With respect to our third objective, we found that modeled pre-event estimates of 100- and 500-year flood risk were not predictive of actual home site exposures to Hurricane Harvey-induced flooding. This finding aligns with other studies that have documented the poor performance of current spatial flood risk models in estimating locational risks associated with actual flood events, especially in urban areas (Brody et al., 2011, 2013; NASEM, 2019). While differing frequency/magnitude characteristics might explain the lack of correspondence between modeled 100-/500-year flood risk zones and the extent of Hurricane Harvey inundation, the likelihood of large-scale flood events occurring in Greater Houston is increasing through time. This was recently recognized by the US National Oceanic and Atmospheric Administration, when it redefined the amount of rainfall it takes to qualify as a 100- or 1000-year event in Greater Houston (Perica et al., 2018). Such changing environmental conditions bring into question the predictive accuracy and practical utility of modeling current and future flood patterns based on historic flood event data. In the three years prior to Hurricane Harvey, for example, three 500-year flood events occurred in Greater Houston (Trenberth et al., 2018); and the area experienced a 1000-year flood event due to Tropical Storm Imelda in 2019, just two years after Harvey (Mack, 2019). This finding is important to highlight because the vast majority of prior distributive EJ assessments of flooding have relied on pre-flood risk estimates (e.g., Chakraborty et al., 2014; Fielding, 2007; Fielding and Burningham, 2005; Grineski et al., 2015a; Grineski et al., 2017a; Maldonado et al., 2016a, 2016b; Maantay and Maaroko, 2009; Qiang, 2019; Walker, 2012; Walker and Burningham, 2011). By extension, future distributive EJ studies of flooding should utilize spatial data from actual flood events, if such data are available, and/or seek new data sources for spatially characterizing flood risks, such as those described in NASEM (2019) and Wing et al. (2017, 2018). Better spatial characterization of flood risks has become imperative for all analysts of human dimensions of flood hazards, given the ongoing changes to precipitation patterns, sea levels (in coastal zones), and flood regimes that are occurring due to climate change (Emanuel, 2017; NASEM, 2019; Wang et al., 2018).

There are two important limitations of this study. First, we used data on study participants' sociodemographic characteristics, residential decision-making regarding water-based amenities, self-protection from flooding, and flood risk perceptions that were collected in 2012, and we applied those data to an analysis of flooding due to Hurricane Harvey that occurred in 2017. While we focused the analysis only on participants who resided in the same home in 2012 and at the time of Harvey, their levels of household income, flood mitigation, and flood risk perception could have changed between 2012 and 2017. While the sample was generally representative of Greater Houston area residents, it excluded households without landline telephones. We believe, however, that our pre-event data collection approach offered more strength than weakness in analyzing household-level factors influencing flood exposure, as it would have been impossible to collect reliable data on Greater Houston residents' pre-event decision-making regarding water-based amenities, flood mitigation, and risk perception in the aftermath of Hurricane Harvey. Overall, our use of household-level data enabled us to address a key limitation of recent ecological EJ studies of Hurricane Harvey flooding (Chakraborty et al., 2019a, 2019b). Second, we only examined the areal extent of Harvey-induced flooding. Other attributes of the flood event, such as depth, duration, intensity, might also have contributed to adverse outcomes. Thus, future EJ analysis should examine multiple physical attributes of flood events.

5. Conclusions

In summary, our key findings indicate that the areal extent of flooding around study participants' home sites was distributed inequitably with respect to race/ethnicity and SES, with Hispanic, black, and other racial/ethnic minority participants facing more extensive flooding than white participants, and lower SES households facing more extensive flooding than higher SES households. These findings have important implications, since social inequities in Hurricane Harvey-induced flood exposure may have contributed to other socially disparate outcomes. For example, given that a wide variety of physical and mental health problems have well-documented associations with flooding (Collins et al., 2013; Guidry and Margolis, 2005; Lamond et al., 2015; Liu et al., 2018, 2019; Riggs et al., 2008), racial/ethnic minority and lower SES people residing in highly inundated locations may have suffered the additional burden of negative health effects. Findings also imply that social inequalities based on race and class may have enduring effects on disaster vulnerability, as measures of inequality/disadvantage from 2012 were associated with Harvey-induced flood exposures in 2017.

Since flood events in Greater Houston are expected to increase in frequency and magnitude due to climate change, socially disparate impacts are likely to become an increasingly salient public policy issue. Research indicates that climate change strongly influences the frequency and intensity of precipitation and flooding (Emanuel, 2017; Forzieri et al., 2016). For example, storms that bring more than 20 inches of rainfall in Greater Houston are about 6 times more likely now than they were at the end of 2000 (Emanuel, 2017). Our findings reveal significant social disparities in the distribution of flood exposure at the household level, which generally align with findings from previous studies conducted at the neighborhood level. In addition to social disparities in flood exposure, prior research indicates that racial/ethnic minorities and those of lower SES are likely to be more adversely impacted by flood-related events due to their amplified social vulnerability, in terms of their constrained access to resources necessary for response, recovery, and medical care (Maldonado et al., 2016b; Rufat et al., 2015). Thus, proactive approaches for reducing flood risks and ameliorating disparities should be developed and implemented in Greater Houston and other urban areas. From an EJ perspective, clarifying the unequal consequences of climate-induced disasters is critically important for informing appropriate risk management actions, as well as planning adaptation and mitigation strategies. More research is needed that assesses linkages between the types of disparities in flood exposure documented here with salient post-event social and health outcomes in order to advance knowledge of the EJ implications of major flood events.

Funding sources

This research was funded by the US National Science Foundation (NSF; grant 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. This manuscript is based on human subjects research. Consent from subjects participating in the study was received prior to conducting the study. The study was reviewed and approved by the appropriate accredited committees. Specifically, it was approved by the University of Utah and University

of Texas at El Paso Institutional Review Boards.

Acknowledgments

We thank Mark English, who, as the Hazard and Performance Analysis's Geospatial Unit Lead, contributed to the generation of the Hurricane Harvey Depth Grid by the Federal Emergency Management Agency under Disaster Operations within the Mitigation Branch. Any opinions, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the NSF.

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