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Short communication

Hurricane Harvey and people with disabilities: Disproportionate exposure to flooding in Houston, Texas

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ABSTRACT

While numerous environmental justice (EJ) studies have found socially disadvantaged groups such as racial/ethnic minorities and low-income individuals to be disproportionately affected by environmental hazards, previous EJ research has not examined whether disabled individuals are disproportionately exposed to natural hazards. Our article addresses this gap by conducting the first distributive EJ study of the relationship between flooding caused by Hurricane Harvey and locations of people with disabilities in Harris County, the most populous county in Texas that was severely impacted by this disaster. Our objective is to determine whether the areal extent of flooding at the neighborhood (census tract) level is disproportionately distributed with respect to people with any disability and with specific types of disabilities, after controlling for relevant socio-demographic factors. Our study integrates cartographic information from *Harvey's Inundation Footprint* developed by the U.S. Federal Emergency Management Agency with data on disability and socio-demographic characteristics from the 2012–2016 American Community Survey. Statistical analyses are based on bivariate correlations and multivariate generalized estimating equations, a modeling technique appropriate for clustered data. Results indicate that the areal extent of Harvey-induced flooding is significantly greater in neighborhoods with a higher proportion of disabled residents, after controlling for race/ethnicity, socioeconomic factors, and clustering. Disabled individuals with cognitive and ambulatory difficulties are more likely to reside in neighborhoods with a higher proportion of flooded area, compared to those facing other types of difficulties. These results represent an important starting point for more detailed investigation on the disproportionate impacts associated with Hurricane Harvey for people with disabilities. Our findings also highlight the growing need to consider individuals with physical and mental disabilities in future EJ research, as well as planning and management of natural disasters.

1. Introduction

Under the rubric of environmental justice (EJ) research, a wide range of empirical studies have examined social inequalities in the distribution and impact of both natural and technological hazards. Although the primary focus has been on risk burdens faced by non-White and low-income residents, the EJ research framework has recently expanded to examine other socially vulnerable groups, such as linguistically isolated households (Chakraborty et al., 2014a), immigrants (Maldonado et al., 2016), and sexual minorities (Collins et al., 2017), as well as specific subcategories of Hispanics (Chakraborty et al., 2017) and Asian Americans (Grineski et al., 2017). Physically vulnerable populations, however, have received limited attention in the distributive EJ research literature. Although a few studies have found people with disabilities to reside near technological hazards (Chakraborty and Armstrong, 2001; Chakraborty, 2019), the impact of natural disasters on disabled individuals has not been systematically investigated.

Research on social vulnerability to natural disasters has drawn attention to the amplified risks faced by people with disabilities from flood-related events, in terms of the resources and services necessary for evacuation, medical care, and recovery (Hemingway and Priestly, 2014; (Stough et al., 2017). Compared to other disadvantaged groups, disabled residents are often the first victims of a disaster (Walbaum, 2014) and likely to face discrimination during all phases of the disaster cycle (Peek and Stough, 2010). The disabled are also more likely to lose their homes, suffer property damage, die in disasters, get separated from family members, be ignored by relief volunteers in shelters, and suffer injuries or health-related complications (Stough, 2017). Recent reports suggest that disaster relief efforts and emergency shelters in

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Table 1
Disability variable definitions and summary statistics for census tracts in Harris County.
Source: 2012–2016 American Community Survey.

Variable Name	Definition	Min Prop	Max Prop	Mean Prop	Std. Deviation
Persons with a disability[a]	Civilian noninstitutionalized individuals who reported at least one of the six disability types listed below.	0.028	0.336	0.103	0.044
Hearing difficulty	Deaf or having serious difficulty hearing.	0.000	0.094	0.027	0.015
Vision difficulty	Blind or having serious difficulty seeing, even when wearing glasses.	0.000	0.105	0.023	0.015
Cognitive difficulty	Having difficulty remembering, concentrating, or making decisions.	0.000	0.173	0.039	0.022
Ambulatory difficulty	Having serious difficulty walking or climbing stairs.	0.000	0.202	0.055	0.030
Self-care difficulty	Having difficulty bathing or dressing.	0.000	0.110	0.023	0.015
Independent living difficulty	Having difficulty doing errands alone such as visiting a doctor's office or shopping.	0.000	0.194	0.036	0.022

[a] All proportions are based on total civilian noninstitutionalized population; N = 721 tracts.

Texas have failed to adequately serve the needs of disabled individuals affected by Hurricane Harvey (Willison, 2018). More research is clearly needed to elucidate the EJ implications of natural disasters for people with physical and mental disabilities.

Our article addresses this need by conducting the first distributive EJ study of the relationship between flooding caused by Hurricane Harvey and locations of disabled individuals in Harris County, the most populous county in Texas that was severely impacted by Harvey-induced inundation. Our goal is to determine whether the areal extent of flooding at the neighborhood (census tract) level is disproportionately distributed with respect to people with any disability and specific types of disabilities, after controlling for relevant socio-demographic factors and spatial clustering.

2. Materials and methods

2.1. Study area

Harris County, the study site for our analysis, is located in southeastern Texas and is part of the nine-county Greater Houston Metropolitan Statistical Area (MSA). With a population of about 4.4 million (2016), Harris is the third largest county in the U.S. Its county seat is Houston, the largest city in Texas and fourth largest nationally. This county also contains the highest number of individuals with disabilities in Texas (Texas Workforce Investment Council, 2016).

Harris County is one of the most vulnerable urban areas in the world with regards to tropical storms and hurricanes, because of its proximity to the Gulf of Mexico. Hurricane Harvey struck Texas on August 25, 2017 and caused catastrophic flooding due to record rainfall. Almost 70% of Harris County was covered by a foot and a half of water (Amadeo, 2018), while creeks and bayous across the Greater Houston MSA reached water levels that have never been recorded before. Most flooding receded within a week, but some areas remained flooded for several weeks (Jonkman et al., 2018). While Harvey flooded 154,170 homes or about 12% of the total number of buildings in Harris County, only 36% of these homes were covered by flood insurance. Additionally, 36 of the 68 Harvey-related deaths recorded in Texas occurred in Harris County (Blake and Zelinsky, 2018). While details on disabled individuals affected by Harvey in this county are unavailable, estimates suggest that approximately a million Texas residents living with mobility, sensory, cognitive, and/or mental health disabilities have been directly impacted by this disaster (Stough, 2017). However, the relationship between Harvey-induced flooding and people with disabilities have not been investigated–a shortcoming we seek to address.

2.2. Dependent variable: Harvey flood extent

Our data source for estimating the extent of flooding caused by Hurricane Harvey is a cartographic product referred to as *Harvey's Inundation Footprint* that was prepared by the FEMA Region 6 Mitigation Division (TX-DR-4332) to support response and recovery operations (FEMA, 2018). This digital flood inundation grid is derived from a range of federal, state, local, and private sector resources. Specifically, high water marks were obtained from the U.S. Geological Survey, Harris County Flood Control District, federal contractors, and FEMA's Recovery Division to compile a comprehensive inventory of flood depth throughout the impacted area. We obtained a geographic information systems (GIS) raster dataset from FEMA's Hazard and Performance Analysis's Geospatial Unit that contains flood depth values (feet) as an attribute of each grid cell (pixel) and covers all counties impacted by Hurricane Harvey.

The extent of flooding within each census tract in Harris County was estimated using a GIS-based methodology that comprised multiple steps. First, we used a high-resolution version of the National Hydrography Dataset for Texas to remove all permanent water features (i.e., areas containing water during non-flood periods) within tract boundaries of Harris County. Second, this map layer representing tract land areas (without waterbodies) was overlaid on the 3-m by 3-m resolution Harvey inundation raster grid. Third, we counted the total number of pixels with non-zero flood depth values within each tract. Finally, 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 proportion, referred to as flood extent, was used as our dependent variable. The proportions of tract area flooded in Harris County range from 0.049 to 0.964, with a mean of 0.556 and SD of 0.139.

2.3. Explanatory variables

The spatial distribution of tract area flooded was analyzed with respect to a set of disability variables from the 2012–2016 ACS. Census tracts represent the smallest unit for which information on disability characteristics are published by the ACS. Definitions for our disability variables and related summary statistics are provided in Table 1. To ensure stable proportions for our variables, we first removed tracts with incomplete data or small population counts. Recent studies have also drawn attention to the data quality problems associated with the ACS five-year estimates at the tract or smaller levels, when compared to the 2000 U.S. Census (Bauzin and Fraser, 2013; Folch et al., 2016). To address this issue, we excluded tracts where the ACS margin of error for the total number of disabled individuals was greater than half of its estimated value (i.e., coefficient of variation [CV] > 0.5), following Folch et al. (2016) and Liévanos (2018). Our analysis encompasses 721 tracts (out of 786) in Harris County with at least 500 persons, 50 housing units, and a CV of 0.5 or smaller for the disability variable estimate. To examine the sensitivity of our findings to the exclusion of 65 tracts, we compared our statistical results to those obtained from analyzing all 786 tracts in the county.

In addition to disability characteristics, we used explanatory variables from the ACS that have been found to be significantly related to flood risks in previous EJ research (Maantay and Maroko, 2009;

Chakraborty et al., 2014b; Montgomery and Chakraborty, 2015). To examine the effect of race/ethnicity, our analysis included the two largest minority groups in Harris County: the proportions of individuals identified as non-Hispanic Black and Hispanic/Latino origin (of any race). To measure socioeconomic characteristics, we used five specific ACS 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. We created a robust index of socioeconomic deprivation based on these five variables (alpha = 0.79) using principal components analysis, since they were significantly correlated with each other ($0.5 < r < 0.9$).

We also included two additional variables that represent housing characteristics. The first was the proportion of owner-occupied housing units (i.e., home ownership rate). This variable has been used in previous EJ research in the Houston area as an indicator of wealth and assets (Chakraborty et al., 2014a). 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 EJ studies have used this variable as a proxy for water-related amenities and found significantly higher vacation home percentages in neighborhoods facing flood risks (Chakraborty et al., 2014b; Montgomery and Chakraborty, 2015).

2.4. Statistical methodology

The first phase of the analysis uses descriptive statistics to explore the effect of each disability variable on tract level flood extent. Specifically, mean values of each disability variable are examined with respect to the proportion of tract area flooded, based on the subdivision of tracts into five quintiles. The second phase uses bivariate linear correlation to examine relationships between flood extent and the disability variables. The final phase uses multivariate statistical models to independently examine the association of each disability variable with tract flood extent, after controlling for socio-demographic factors commonly used in EJ research.

Our multivariable models 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, while accounting for clustering of neighborhoods (tracts) in the study area. For our analysis, they are more advantageous than other modeling approaches. GEEs are more appropriate than spatial autoregressive models in which spatial dependence is estimated somewhat arbitrarily based on contiguity or distance-based parameters. GEEs are also preferable to other modeling approaches that consider non-independence of data such as mixed models with random effects, because GEEs estimate unbiased population-averaged or marginal regression coefficients, which makes this approach suitable for analyzing general patterns of inequality across subgroups (Liang and Zeger, 1986; Collins et al., 2015). Additionally, GEEs are more suitable here than multilevel modeling approaches because the intracluster correlation estimates are adjusted for as nuisance parameters and not modeled (Collins et al., 2015; Grineski et al., 2017).

To fit a GEE model, clusters of observations must be defined based on the assumption that observations from within a cluster are correlated, while observations from different clusters are independent. For this study, the cluster definition was based on median year of housing construction (2012–2016 ACS) for tracts in Harris County. Specifically, tract clusters were defined using the median decade of housing construction (ranges from “2000 or later” to “1930 to 1939”), which yielded a total of 8 different clusters. This cluster definition was selected because the median decade of home construction can be expected to closely correspond with the urban developmental context within which tracts are nested. This cluster definition has been used in recent EJ studies utilizing the GEE approach (Collins et al., 2015, 2017; Grineski et al., 2017; Chakraborty, 2019).

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 intra-cluster dependency (Collins et al., 2015). For selecting the best-fitting model, we explored the normal, gamma, and inverse Gaussian distributions with identity and log link functions, for a total of six model specifications. An identity link function models relationships between the dependent and independent variables linearly, while a log link function represents natural logarithmic relationships between the variables. We selected the normal distribution with log link function for our GEE models, since this specification yielded the lowest value of the quasi-likelihood under the independence model criterion, indicating the best statistical fit.

All independent variables were standardized before inclusion in these multivariate models and standardized GEE coefficients are provided to compare the relative contribution of each variable. The multicollinearity condition index (MCI) was calculated for the combination of explanatory variables included in each GEE. The MCI for these models were found to be smaller than 6.0, indicating the absence of serious collinearity problems. The statistical significance of independent variables was estimated on the basis of the Wald's chi-squared test. We ran separate multivariate GEEs to analyze the relationship between tract flood extent and each disability variable, using race/ethnicity, socioeconomic deprivation, and housing variables as controls. The first GEE (Model 1) uses the overall proportion of people with disabilities as the key explanatory variable, while the primary explanatory variable in the remaining GEEs (Models 2 to 7) focus on each type of difficulty reported by individuals with a disability.

3. Results

The distribution of flood extent in Harris County is depicted in Fig. 1, where tracts are grouped into five quintiles based on the proportion of the tract land area flooded by Hurricane Harvey. Tracts in the highest quintile (top 20%) of flooding are located in western, central, and eastern areas of Harris County, including the entire northeastern section of the City of Houston. Tracts in the lowest quintile, in contrast, are more evenly dispersed throughout the county.

Table 2 provides the mean values of each disability variable associated with the flooded area quintiles shown in Fig. 1, along with the statistical significance of the linear trend across these five levels of tract flood extent. The mean overall disability proportion indicates a gradual increase from the lowest (bottom 20%) to the highest (top 20%) quintile. The mean proportions for all six disability categories show a similar increasing pattern with respect to the lowest quintile, with values reaching their maximum in the highest quintile. Cognitive difficulty indicates the largest difference between the lowest and highest quintiles; its mean value in the highest quintile is almost 50% higher than the mean for its lowest quintile. All disability variables show a statistically significant linear trend ($p < .05$), which suggests an increasing concentration of people of all disability types as the areal extent of flooding increases. When bivariate linear correlations are examined, Pearson's coefficients also indicate statistically significant and positive relationships ($p < .05$) between tract flood extent and the proportion of individuals in all disability categories. The strongest linear association is observed for the proportion with cognitive difficulty, followed by those with ambulatory difficulty.

The results from the multivariate GEEs are summarized in Table 3. Model 1 shows a significant and positive relationship ($p < .01$) between the overall disability proportion and proportion of flooded area for tracts in Harris County, after controlling for the socio-demographic and housing characteristics of tracts. Similar statistically significant

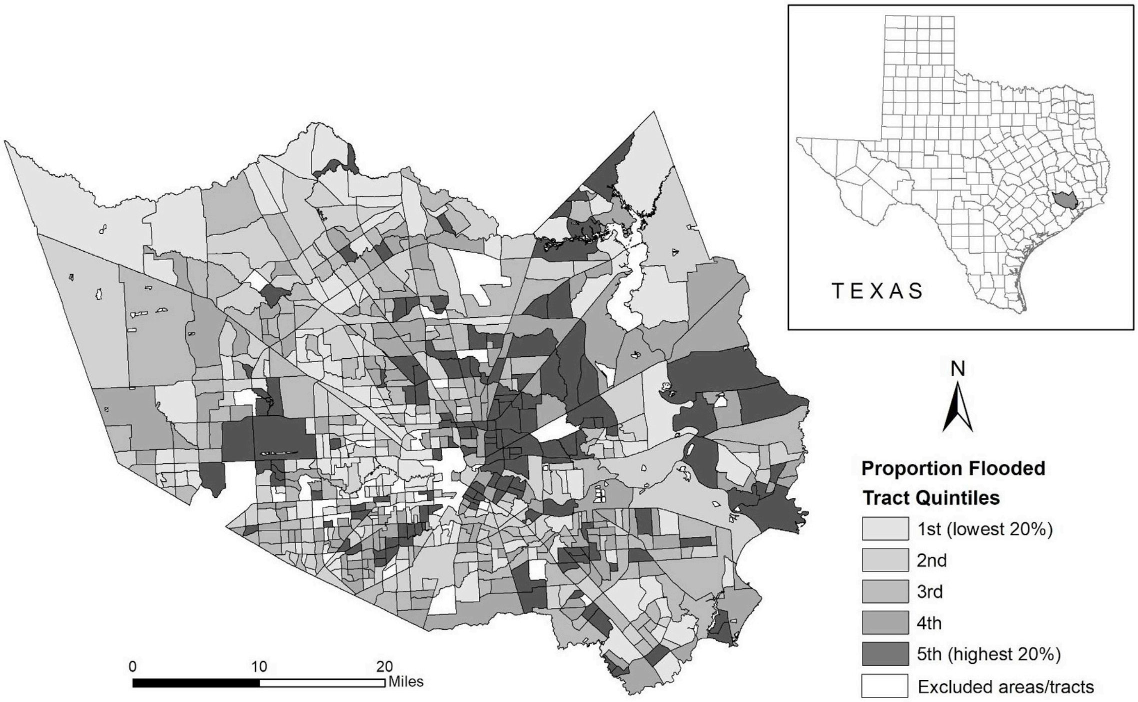

Fig. 1. Proportion of census tract area flooded by Hurricane Harvey in Harris County, Texas.

associations ($p < .05$) with tract flood extent are indicated by all disability variables in Models 2 to 7. The proportions of the population with hearing, cognitive and ambulatory difficulty, respectively, yield the largest standardized coefficients in the GEEs presented in Table 3. With regards to other explanatory variables, all seven GEE models indicate similar statistical associations. The proportion of flooded area is significantly greater in tracts characterized by higher proportions of non-Hispanic Black and Hispanic residents, as well as higher proportions of owner-occupied homes and vacation homes. When all tracts in the county (n = 786) were used instead of those with reliable ACS estimates (n = 721), no changes were observed in the signs and significance of the variable coefficients in Table 3.

4. Discussion and conclusions

This study has sought to extend distributive EJ research on natural disasters by focusing on a particularly vulnerable subgroup that has received limited attention in previous research (i.e., the disabled) and flooding caused by Hurricane Harvey in Harris County, Texas. Statistical findings indicate that the overall proportion of civilian noninstitutionalized persons with a disability is significantly greater in neighborhoods with higher proportions of flooded area, even after accounting for geographic clustering, race/ethnicity, socioeconomic deprivation, and housing-related factors. The results also suggest that disabled individuals with cognitive and ambulatory difficulties are particularly more likely to reside in neighborhoods with higher flooded area, compared to those burdened with other types of difficulties. This evidence of distributive injustice associated with flooding in Harris County represents an important starting point for more detailed investigation of the impacts associated with Hurricane Harvey for people with disabilities.

Although our study analyzed the spatial association between residential patterns of disabled individuals and Harvey-induced flooding in Harris County, the results cannot be used to infer the sequence of events or processes that caused greater flooding in tracts with higher proportions of disabled people. However, many disabled individuals in this county reside in Houston Housing Authority's public housing developments that offer subsidized rents for people with disabilities (Freemantle, 2013). The distributive injustices we found can be explained, in part, by the fact that most public housing projects in Harris County are located in non-White and low-income neighborhoods (Livesley-O'Neill, 2016) that also indicated higher Harvey-induced flooding.

Our results highlight the need to consider disabled populations in

Table 2
Relationship between disability variables and proportion of tract area flooded.

Variables	Proportion Flooded: Quintile Means					Trend	Correlation
	Q1 (lowest)	Q2	Q3	Q4	Q5 (highest)	Linearity: F-test	Pearson's *r*
Proportion with any disability	0.091	0.098	0.100	0.105	0.119	32.364**	0.237**
Proportion hearing difficulty	0.026	0.027	0.026	0.028	0.030	3.373*	0.083*
Proportion vision difficulty	0.019	0.022	0.021	0.023	0.027	18.094**	0.191**
Proportion cognitive difficulty	0.031	0.037	0.037	0.040	0.046	32.304**	0.237**
Proportion ambulatory difficulty	0.048	0.050	0.053	0.056	0.066	29.612**	0.217**
Proportion self-care difficulty	0.020	0.021	0.020	0.023	0.028	21.278**	0.186**
Proportion independent living difficulty	0.033	0.034	0.034	0.038	0.043	17.018**	0.186**
Number of tracts (N)	144	144	145	144	144		721

*$p < .05$; **$p < .01$.

Table 3
Generalized estimated equations for predicting proportion flooded: Standardized model coefficients and significance.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Proportion with any disability	0.036**						
Proportion hearing difficulty		0.020**					
Proportion vision difficulty			0.022*				
Proportion cognitive difficulty				0.036**			
Proportion ambulatory difficulty					0.027**		
Proportion selfcare difficulty						0.020*	
Proportion independent living difficulty							0.019*
Proportion non-Hispanic Black	0.046**	0.061**	0.053**	0.048**	0.048**	0.052**	0.052**
Proportion Hispanic	0.048**	0.044*	0.043**	0.047**	0.045**	0.044**	0.046**
Socioeconomic deprivation	0.007	0.020	0.017	0.008	0.012	0.018	0.017
Proportion owner-occupied housing units	0.020**	0.026**	0.027**	0.023**	0.023**	0.025**	0.025**
Proportion vacant: seasonal/recreational use	0.019*	0.017*	0.017*	0.017*	0.017*	0.017*	0.017*
Intercept	−0.590**	−0.591**	−0.590**	−0.590**	−0.590**	−0.590**	−0.599**
Scale	0.018	0.018	0.018	0.018	0.018	0.018	0.018
Model fit (QIC)	20.163	19.575	20.884	19.463	20.112	19.998	20.295

*$p < .05$; **$p < .01$.

future research on environmental injustice and vulnerability to hazards, in addition to the commonly used categories such as race/ethnicity and socioeconomic status. The findings also have important policy implications, because individuals with disabilities are likely to need special assistance when evacuation is needed. Since a disproportionately large proportion of people with disabilities reside in neighborhoods that were severely flooded by Harvey, identifying appropriate evacuation routes and contingencies should become key priorities, in addition to ensuring that emergency shelters are adequately equipped to meet the needs of the disabled. There is a State of Texas Emergency Assistance Registry to identify people with disabilities needing assistance during a disaster, but it is unclear how many people knew about it or received help through this registry, during Harvey (Evans, 2018). Disaster preparedness and management plans need to include more disability-related guidelines and recognize that different approaches are required for different types of disabilities.

It is important to consider the limitations of our analysis, which need to be addressed in future research. First, we examined only the areal extending of flooding, and not flood depth, duration, intensity, and other characteristics that contribute to negative health or social consequences. Second, our reliance on neighborhood (tract) level data prevents us from concluding whether disabled individuals resided within flooded areas and how they were impacted by flooding. The use of surveys and/or interviews could help clarify factors influencing neighborhood level associations and determine how people with disabilities were unequally burdened by Hurricane Harvey. Third, although we analyzed neighborhood-level disparities in Harvey-induced inundation based on ACS-defined disability status and nature of difficulty, we were unable to examine other axes of difference within the population reporting disabilities known to influence environmental inequalities and disaster vulnerability. Future research should seek additional data to disaggregate the disabled category based on race/ethnicity, socioeconomic status, age, and gender. This would enable clarification of how physical or mental disability interacts with other dimensions of social disadvantage to amplify or attenuate vulnerability.

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