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LETTER

Social inequalities in flooding inside and outside of floodplains during Hurricane Harvey

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Abstract

While previous research often finds flood impacts outside of conventional flood risk zones such as FEMA's 100-year floodplain maps, we have less of a sense of the social and demographic composition of the areas outside of floodplains that experience these impacts, even though social inequalities in flood risk and impacts more broadly is well-documented in the United States. Using data on 100-year floodplains, flood impacts, socio-demographic characteristics, and residential parcels, this study focuses on race as a primary marker of socio-spatial inequality to examine flooding inside and outside of floodplains during Hurricane Harvey in Greater Houston. Descriptive findings show that a large majority of flooding occurred outside of 100-year floodplains. Regression models show that while there is limited evidence of racial inequalities in flood risk as conceptualized as location in 100-year floodplains, there are substantial racial inequalities in flood extent during Hurricane Harvey. Results further show that these overall racial inequalities in flood extent are primarily driven by impacts that occurred outside of 100-year floodplains. Conclusions center on how and why conventional delineations of flood risk can underestimate racial inequalities to natural hazards.

1. Introduction

Flooding from extreme weather events has unequal social impacts, impacts that often occur outside of conventional zones of floodplain risk. The present study examines if and to what extent social inequalities are found in levels of flooding during Hurricane Harvey in areas both inside and outside of floodplains using the most well-used metric of flood risk in the United States, the Federal Emergency Management Agency (FEMA) 100-year floodplains.

Spatial inequalities are evinced across the United States in risk and experience of flooding (NASEM 2019, Chakraborty *et al* 2019a). Environmental justice research has long shown that racial residential segregation in particular maps onto environmental inequalities such that predominantly non-white neighborhoods tend to disproportionately experience environmental degradation (Bullard 1990, Taylor 2014, Ard 2015, Liévanos 2015, Mohai and Saha 2015a, 2015b, Collins *et al* 2016, Ash and Boyce 2018, Jorgenson *et al* 2020). These racial environmental inequalities include not only industrially produced hazards, but also unequal social vulnerabilities to natural hazards (Cutter *et al* 2003, Rufat *et al* 2015, Howell and Elliott 2018, Tierney 2019, Raker 2020).

Demographic research analyzing geographic disparities in natural hazards typically measures these hazards in one of two ways: risks or impacts. Research analyzing *risk* to natural hazards and disasters tends to focus on whether a geographic unit like a neighborhood or county disproportionately lies in a zone of risk such as a floodplain (Maantay and Maroko 2009, Grineski *et al* 2015, Maldonado *et al* 2016, Qiang 2019, Chakraborty *et al* 2019a). Research analyzing *impacts* to natural hazards and disasters tends to focus on mortality and property damages across geographic units (Cutter *et al* 2003, Elliott and Howell 2017, Smiley *et al* 2018). Research on impacts often centers on comparatively large geographic units like U.S. counties as data availability on impacts at smaller scales can be difficult to obtain for demographic research across a large number of cases. Emerging research better accounts for observable impacts across small-scale geographic units like neighborhoods,

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including for Hurricane Harvey where Chakraborty *et al* (2019a) found large racial inequalities in flooding in the Houston metropolitan area (see also Collins *et al* 2019, Chakraborty *et al* 2019b).

Using measures of flood risk instead of impacts remains a favored research design, though, and measures of flood risk, while important, can also be critiqued for four reasons. First, not only do advances in floodplain modeling suggest that the population of people living in 100-year floodplains may be higher than previously thought by a factor of 2.6 to 3.1 (Wing *et al* 2018; see also NYU Furman Center 2017), empirically observable impacts frequently occur outside of flood risk zones, with approximately one third of claims made to FEMA being made outside of 100-year floodplains (Galloway *et al* 2006). In Greater Houston, (Highfield *et al* 2013) found an even higher figure—47%—of claims from outside of the 100-year floodplain across a three decade period. Second, floodplain maps are not always updated regularly, meaning that many jurisdictions rely on older floodplain maps that may not take into account recent urbanization that would create new impervious surfaces and heighten risk to flooding (Cutter *et al* 2018, Zhang *et al* 2018, Sebastian *et al* 2019, Russo and Read 2020). A striking example is that at the time of Hurricane Sandy, New York City was in the process of updating maps that dated primarily from 1983 (Elliott 2019). Third, 100-year floodplain maps conceive of risk as binary: either a structure is located in the 100-year floodplain or it is not. While using a 500-year floodplain or other metrics might relax this binary assumption, little evidence has been found that home owners outside of the 100-year floodplain purchase flood insurance, which is required for those with federally insured mortgages in the 100-year floodplain (Shao *et al* 2019, Harlan *et al* 2019). Finally, climate change will increase the likelihood of the '100-year' storm. In the year 2100, as a case study of New York City shows, it is estimated that the 100-year storm could occur every 3 to 20 years in a place like New York City (Lin *et al* 2012) or a storm of Hurricane Harvey's size in Houston every 5.5 years (Emanuel 2017). More contemporarily, research shows that rainfall during Hurricane Harvey was greater because of climate change (van Oldenborgh *et al* 2017, Wang *et al* 2018). Across these reasons and more, the National Academies' recommends a 'new generation' of flood risk maps (NASEM 2019).

These challenges to accurate measurement of flood risk in the United States suggest an important research gap in our understanding of how social inequalities intertwine with natural hazards. It is well-established that there are social inequalities in flood risk, and it is also known that flood impacts occur outside of these zones of risk. But assessing geographic disparities in flood risk will be incomplete without analyzing where impacts occur outside of these risky zones. Put another way, we do not have a meaningful sense of the social and demographic composition of communities that experience flood impacts outside of floodplains. Using the lens of race as it is a primary marker of socio-spatial inequalities in the United States, the study investigates if and to what extent racial inequalities are present in flood impacts from Hurricane Harvey in Greater Houston both inside conventional zones of risk as well as outside of them.

Hurricane Harvey is a critical case to analyze these research questions as the human costs of the storm were immense: estimates suggest at least 80 deaths from the storm, a majority of which occurred outside of the 100-year floodplain (Jonkman *et al* 2018). The property damages rank among the most destructive in U.S. history. The storm was more severe than a 100-year storm, as research suggests Harvey would be considered a 2000 year storm by twentieth century norms (Emanuel 2017). The sheer size of the storm meant that a majority of the flooded areas were located outside of the 100-year floodplain (see Results), which provides an important window for research questions that seek to identify social characteristics of flooded areas outside of floodplains. It may be the case that future flood scenarios in the era of climate change could have similarly outsized impacts as extreme weather events increase in size and frequency (Lin *et al* 2012, Hallegatte *et al* 2013, Emanuel 2017). More broadly, Greater Houston is characterized by stark spatial environmental inequalities especially by race (Bullard 1987, Nance 2015, Emerson and Smiley 2018, Loughran *et al* 2018, Elliott and Smiley 2019, Chakraborty *et al* 2019a), making it an important site to analyze unequal impacts of disasters.

2. Data and methods

Data in this study is synthesized from four sources. First, data on flood risks is obtained from the FEMA-delineated 100-year floodplain. This floodplain signifies any area that would experience inundation in a flood event that has a 1% (or 1 in 100) chance of occurring in a given year. Second, data on flood extent is from the FEMA Harvey Depths flood map. This map estimates at a 3 meter by 3 meter resolution what areas experienced flooding as determined by FEMA specifications which is delineated as at least 1 foot (0.3 meters) of flooding at the high water mark of Hurricane Harvey. Data for such fine-grained estimates in this map were derived from a synthesis of data on high water marks from the Harris County Flood Control District, United States Geological Survey, federal contractors, and FEMA's recovery division. Third, social and demographic data is collected from the U.S. Census through the National Historical Geographic Information System databases (Manson *et al* 2019). Primary analyses use the 2012–2016

American Community Survey (ACS) five-year estimates; aggregating five years is used to maximize reliability of study estimates. Data for appendix C use 2010 decennial census data. Fourth, Harris County Appraisal District (HCAD) parcel data is used to measure social impacts of flood risk and flood extent. HCAD parcel data includes more than 1.4 million parcels, most of which correspond to a single tract of land under one or more owners. This study only uses non-vacant residential parcels ($n = 1137\,964$) to focus on risks and flood extent to areas in which people reside. In appendix B, residential parcels are disaggregated into two types: single-family parcels ($n = 1060\,512$) and multi-family parcels ($n = 77\,452$). The study area for these data is Harris County, Texas. The unit of analysis is the census tract ($n = 786$), a unit conventionally understood to correspond to a neighborhood.

2.1. Dependent variables

To assess flood risk and flood extent, two complimentary approaches are taken. The first approach measures flood risk and flood extent within a census tract's *land area*, matching approaches in previous studies (Chakraborty *et al* 2019a). The second measures it across a census tract's *residential parcels* using a dasymetric approach (Mennis 2003). This second approach builds on the first approach by more closely conceptualizing flood risk and extent by examining them only in residential space.

The first approach calculates *flood risk* using FEMA floodplain maps by denoting the proportion of land in a census tract that is in the 100-year floodplain. *Flood extent* is calculated using the Harvey Depths flood map by counting the total number of 3 m × 3 m pixels within a census tract, and determining the proportion flooded by dividing the area flooded by the overall area of the census tract. Because this study is centrally interested in flooding inside and outside of floodplains, two additional dependent variables are created: (1) the proportion of land inside the floodplain that flooded and (2) the proportion of land outside the floodplain that flooded. The denominators for each of these variables is the land area for each sub-part of the census tract, i.e. the part of the tract that is in the floodplain or the part of the tract that is not in the floodplain, respectively.

The second approach calculates *flood risk* by denoting the proportion of non-vacant residential parcels in a census tract that are in the 100-year floodplain. Using parcels from the HCAD data is an example of daysmetric mapping, which uses ancillary information to more closely capture the characteristics of a statistical surface (Mennis 2003, 2009, Mennis and Hultgren 2006, Maantay *et al* 2007, Petrov 2012, Montgomery and Chakraborty 2013, Qiang 2019). For this paper, ancillary information from cadastral data with the HCAD tax appraisal data on residential parcels is used to estimate flood risk and flood extent. Previous research using these techniques from New York City show their utility in that conventional areal apportionment methods can underestimate racial inequalities in floodplain location compared to dasymetric methods using cadastral data (Maantay and Maroko 2009).

To determine if the parcel was located in the floodplain, each parcel was intersected with the 100-year floodplain, and a parcel was assigned as being located in the floodplain if at least five percent of the parcel was in the floodplain. Five percent was chosen as the threshold to approximate FEMA's guidelines, which stipulate that if any part of a building on a parcel is in the floodplain then the whole building is in the floodplain; while building data is not available in this study, five percent connotes this guideline. Moreover, most parcels that met this 5% threshold were fully or almost fully in the floodplain; specifically, 96% of parcels that were at least 5% in the floodplain were in actuality at least 90% in the floodplain. The dependent variable, proportion of parcels in a census tract in the floodplain, is then calculated by totaling up the number of non-vacant residential parcels that are at least five percent in the floodplain in a census tract and dividing it by the overall number of non-vacant residential parcels in that census tract. Tracts that had fewer than 25 non-vacant residential parcels overall were dropped from statistical analyses to most validly conceptualize only census tracts that had a sufficient baseline of parcels from which to create these calculations (overall $n = 769$).

Flood extent using the cadastral approach is calculated with the Harvey Depths flood map by denoting the proportion of parcels that experience at least five percent of their land area flooded during Hurricane Harvey. Five percent of land area was chosen as the threshold to match the five percent threshold for the floodplain calculation (see above); appendix A re-analyzes results by only counting parcels as flooded at higher thresholds of flood extent (i.e. 25%, 50%, and 75%). The dependent variable is calculated by summing the non-vacant residential parcels that were at least five percent flooded and dividing it by the overall number of non-vacant residential parcels in a census tract. Two additional dependent variables using the cadastral approach are also created that denote the proportion of non-vacant residential parcels that (1) flooded in the floodplain and (2) flooded outside of the floodplain. One additional important note about flooding extent measures in this study is that these data do not indicate whether properties that experienced flooding also experienced damage from that flooding. One way to partially address this issue is to use the higher thresholds of flooding extent (see appendix A), although this does not directly account for the issue as parcels flooded at higher thresholds also may not have experienced impacts.

2.2. Independent variables

The focal independent variables of interest relate to the racial composition of the census tract. They are (1) proportion non-Hispanic black, (2) proportion Hispanic, and (3) proportion non-Hispanic other race (defined here as the proportion of residents who not black, Hispanic, or white). Additional variables pertain to the class makeup of the census tract, namely the median income and proportion of owner-occupied homes. Population and land area are additional control variables. Finally, for all models that predict flooding extent, the appropriate variable for flood risk (which is used initially as a dependent variable in its own model) is included an independent covariate. Controlling for flood risk in the models predicting flood extent has the effect of netting out the possibility that flood extent, even outside of floodplains, is occurring in tracts that host more flood risk in the first place.

2.3. Model estimation technique

To analyze the study's research questions, descriptive statistics are first discussed, especially the levels of flood extent inside and outside of floodplains across Houston neighborhoods. The regression analysis then employs Generalized Estimating Equations (GEEs). GEEs relax key assumptions about the normality of variable distributions, and are particularly appropriate for this study as several dependent variables (such as the proportion of land or residential parcels in the floodplain) have many zero values and/or non-normal distributions. GEEs are estimated with robust Huber-White estimators of variance and with an exchangeable correlation matrix. Clusters were determined by the decade in which the median home was built (1939 or earlier; 1940 to 1949; 1950 to 1959; 1960 to 1969; 1970 to 1979; 1980 to 1989; 1990 to 1999; 2000 or later) as these decades correspond to the developmental context of the census tracts. All models are designed with a Gaussian family and a log link, the latter of which is used to account for non-normality. These GEEs closely mirror previous research on neighborhood inequalities in flooding during Hurricane Harvey (e.g. Chakraborty *et al* 2019a).

Two approaches are used to analyze the study's research questions, the first examining flood risk and extent in overall land, and the second examining these dependent variables for residential parcels. For each of the two approaches, four models are shown: (1) flood risk, i.e. dependent variables relating to presence of land or parcels in floodplains, (2) flood extent, i.e. dependent variables relating to what census tracts experienced flooding during Hurricane Harvey, (3) flood extent inside of the floodplain, and, most central to the present study, (4) flood extent outside of the floodplain. Importantly, because some tracts do not have any land ($n = 154$) or parcels in the floodplain, they are dropped for the analyses for flood extent inside of the floodplain. This decision was made because it is not possible to compute the proportion of flood extent in tracts that have a denominator of 0, that is no land area (or parcels) inside of the floodplain, and because including a 0 value for these neighborhoods would be a qualitatively different empirical reality from census tracts with area in the floodplain that did not flood.

3. Results

3.1. Descriptive results

Table 1 shows that while only 19% of land in the average Harris County tract is in the floodplain, 55% was flooded during Hurricane Harvey. These unequal impacts extend to residential parcels: 66% of residential parcels in the average neighborhood were at least 5% flooded compared to 14% of parcels in the 100-year floodplain. Still substantial impacts even when counting flooding extent at higher levels (see appendix A), with 49% of residential parcels flooded at least 25%, 38% flooded at least 50%, and 30% of parcels flooded at least 75%. Figure 1 indicates that the majority of flooding occurred outside of floodplains.

Figure 1 also shows evidence of racial inequality in flood extent. For example, the average percentage of residential parcels that were at least 5% flooded (regardless of floodplain location) in a majority black neighborhood was 80%, in a majority Hispanic neighborhood it is 71%, and in a neighborhood with no racial majority it is 64% but in a majority white neighborhood the average is lower (57%). This racial inequality appears to be more driven by differences outside of the floodplains than those inside the floodplain. While differences in the percentage of flooded parcels in the floodplain are relatively low, outside of the floodplains flooding was found in 68% of residential parcels in black neighborhoods, 59% in Hispanic neighborhoods, and 54% in no racial majority neighborhoods compared to 46% in white neighborhoods. In all, the descriptive statistics show that there are (1) large impacts outside of the floodplain, (2) there are racial disparities in flood extent, and (3) there appears to be greater racial inequalities in flood extent outside floodplains compared to inside floodplains.

3.2. Regression results

Table 2 shows the results of four models that use dependent variables relating to flood risk and flood extent for the *land area* of a census tract. Model 1 predicts the proportion of land in the floodplain. While all three racial composition variables are positive, only proportion other race is statistically significant. Model 2 in table 2 analyzes flood extent from Hurricane Harvey and results differ from Model 1's focus on FEMA-delineated flood risk. Most notably, tracts that have a higher proportion of black residents

Table 1. Descriptive statistics of study variables with means (standard deviations).

Variables	*Mean (SD)*
Independent Variables	
Prop. Black	0.19 (0.21)
Prop. Hispanic	0.42 (0.26)
Prop. Other Race	0.08 (0.08)
Median Income (in 1000 s)	55.96 (33.33)
Prop. Owner-Occupied	0.54 (0.25)
Population (in 1000 s)	5.66 (3.11)
Land Area (km^2)	5.66 (10.89)
Dependent Variables	
Prop. Floodplain (Overall Land)	0.19 (0.23)
Prop. Flood Extent (Overall Land)	0.55 (0.14)
Prop. Flood Extent Inside Floodplain (Overall Land)[a]	0.82 (0.18)
Prop. Flood Extent Outside Floodplain (Overall Land)	0.49 (0.16)
Prop. Residential Parcels Floodplain (at least 5% in floodplain)	0.14 (0.25)
Prop. Residential Parcels Flooded (at least 5% flooded)	0.66 (0.23)
Prop. Residential Parcels Flooded Inside Floodplain (at least 5% flooded)[a]	0.84 (0.24)
Prop. Residential Parcels Flooded Outside Floodplain (at least 5% flooded)	0.63 (0.24)
Prop. Residential Parcels Flooded (at least 25% flooded)	0.49 (0.21)
Prop. Residential Parcels Flooded (at least 50% flooded)	0.38 (0.2)
Prop. Residential Parcels Flooded (at least 75% flooded)	0.3 (0.19)

[a]This statistic reflects only census tracts that have area or parcels in the floodplain.

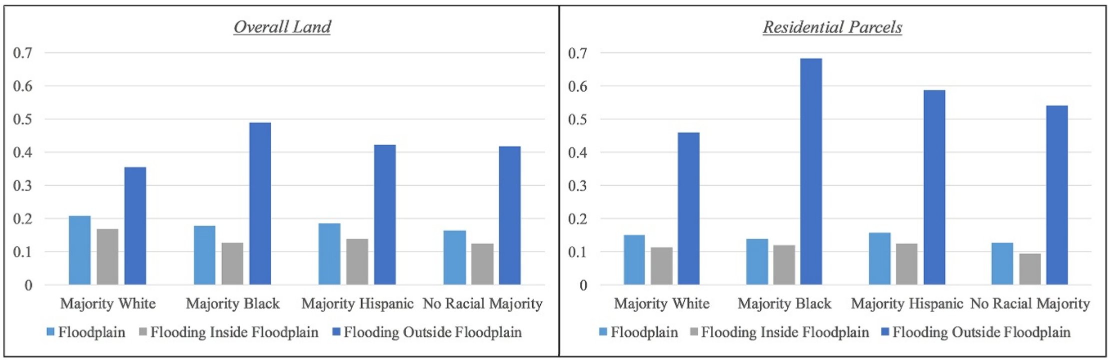

Figure 1. Proportion of flood risk and flood extent by racial composition of neighborhood.

were associated with a greater proportion of land area flooded during Hurricane Harvey. Additionally, a greater proportion of other race residents is linked to lower levels of flood extent and proportion Hispanic is not statistically significant. These findings for flood impacts by race contrast with findings that were not statistically significant for proportion black indicated in Model 1 on flood risk.

Table 2 then showcases if inequalities in flood extent are found in areas inside (in Model 3) and outside (in Model 4) of the floodplain. Model 3 finds little evidence for any racial inequalities in flooding extent among the tracts with areas inside the floodplain: proportion black and proportion Hispanic are not statistically significant. Model 4, in contrast in Model 3, finds that the proportion of black residents is associated with higher proportion of land flooded. This result for Model 4 suggests that the racial inequality for predominantly black census tracts for the overall flood extent during Hurricane Harvey (in Model 2) is driven primarily by inequalities in flood extent outside of the 100-year floodplains.

Table 3 analyzes potential social inequalities in flood risk and flood extent across residential parcels. As with Model 1 in table 2, no statistically significant associations are found for proportion black and proportion Hispanic predicting the proportion of residential parcels in 100-year floodplains. Model 2 examines flood extent during Hurricane Harvey. Results show that neighborhoods with more black residents and more Hispanic residents have a greater percentage of their residential parcels that experienced flooding during the hurricane. These results for proportion black are similar to those for the overall land area, and, importantly, proportion Hispanic is statistically significant here where it was not in Model 2 of table 2, indicating that residential parcels in Hispanic neighborhoods may have experienced particularly high flooding extent that the

Table 2. Results of generalized estimating equations predicting dependent variables: overall land in Harris County, Texas.

	Model 1: Prop. Floodplain		Model 2: Prop. Flood Extent		Model 3: Prop. Flood Extent In Floodplain		Model 4: Prop. Flood Extent Outside Floodplain	
	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
Prop. Black	0.234	0.272	0.268 ***	0.057	−0.039	0.062	0.285 **	0.114
Prop. Hispanic	0.441	0.282	0.123	0.055	−0.146 †	0.078	0.148	0.111
Prop. Other Non-White Race	1.702 **	0.526	−0.361 *	0.128	−0.579 **	0.208	−0.328	0.21
Median Income (in 1000 s)	0.003	0.003	0.000	0.000	0.001	0.001	−0.001	0.001
Prop. Owner-Occupied	0.264	0.229	0.107 *	0.046	0.011	0.039	0.164 *	0.081
Population (in 1000 s)	−0.046 *	0.02	−0.001	0.003	0.001	0.001	0.003	0.004
Land Area (km^2)	0.008 ***	0.001	−0.002 **	0.012	0.002	0.003	−0.007 ***	0.001
Prop. Floodplain	—	—	0.31 ***	0.04	−0.225 ***	0.059	−0.329 ***	0.093
Intercept	−2.192	0.301	−0.777	0.062	−0.085		−0.795	0.095
QIC	63.529		33.389		40.682		38.859	
N	777		777		626		777	

Notes † < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001. SE are Semirobust Standard Errors. QIC is Quasi-Likelihood under the Independent Model Criterion.

Table 3. Results of generalized estimating equations predicting dependent variables: residential parcels in Harris County, Texas.

	Model 1: Prop. Floodplain		Model 2: Prop. Flood Extent		Model 3: Prop. Flood Extent In Floodplain		Model 4: Prop. Flood Extent Outside Floodplain	
	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
Prop. Black	0.34	0.513	0.571 ***	0.095	0.238 **	0.07	0.587 ***	0.114
Prop. Hispanic	0.696	0.608	0.447 ***	0.085	0.169 *	0.078	0.479 ***	0.107
Prop. Other Non-White Race	2.66 ***	0.53	−0.102	0.207	−0.504 **	0.158	−0.117	0.339
Median Income (in 1000 s)	0.005	0.004	−0.001	0.001	0.000	0.001	−0.001	0.001
Prop. Owner-Occupied	−0.226	0.427	0.645 ***	0.147	0.335 ***	0.094	0.636 ***	0.144
Population (in 1000 s)	−0.064	0.042	−0.001	0.002	0.001	0.004	−0.001	0.003
Land Area (km^2)	0.001	0.003	−0.003 †	0.002	−0.004 †	0.002	−0.004	0.003
Prop. Floodplain	–	–	0.179 ***	0.179	−0.173 †	0.093	−0.22 †	0.12
Intercept	−2.382	0.488	−1.012		−0.443		−1.012	
QIC	79.444		61.526		225.692		75.518	
N	764		764		531		764	

Notes † < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001. SE are Semirobust Standard Errors. QIC is Quasi-Likelihood under the Independent Model Criterion.

overall neighborhood land area did not to the same degree.

For Model 3 analyzing flooding in floodplains and Model 4 analyzing flooding outside of floodplains, census tracts with more black and Hispanic residents are associated with greater flooding extent in their residential parcels both inside and outside of the 100-year floodplain. All of these results in both tables 2 and 3 hold when controlling for important covariates, including relating to socio-economic composition such as owner-occupied homes and median income (the latter of which is not statistically significant in any models) and to baseline factors like population, land area, and floodplain risk.

To more closely display results for racial inequalities in flood extent in areas outside of 100-year floodplains, figure 2 presents predicted probabilities based on the results of Model 4 in both tables 2 and 3 with predicted values at the 5th, 25th, 50th, 75th, and 95th percentiles of proportion black and proportion Hispanic. The increasing bars for both blacks and Hispanics for both dependent variables illustrate that neighborhoods with a higher percentage of residents who are black and Hispanic tend to have greater flood extent outside of the floodplains (although proportion Hispanic is not statistically significant outside of the floodplain for overall land (see table 2), but see results in appendix C that show a possible relationship). For instance, a census tract at the 75th percentile of proportion black (where about 25.8% of residents are black) would have a predicted value about 3.1 percentage points higher in flood extent for overall land and 7.9 percentage points higher for residential parcels compared to a neighborhood at the 25th percentile (about 3.5% black). For proportion Hispanic, the same comparison (comparing a neighborhood that is 60.8% Hispanic to one that is 20.4% Hispanic) would yield a difference of 11.9 percentage points for residential parcels. In all, figure 2 showcases the central results of this study, namely that there are large racial inequalities in flood extent outside of the 100-year floodplains.

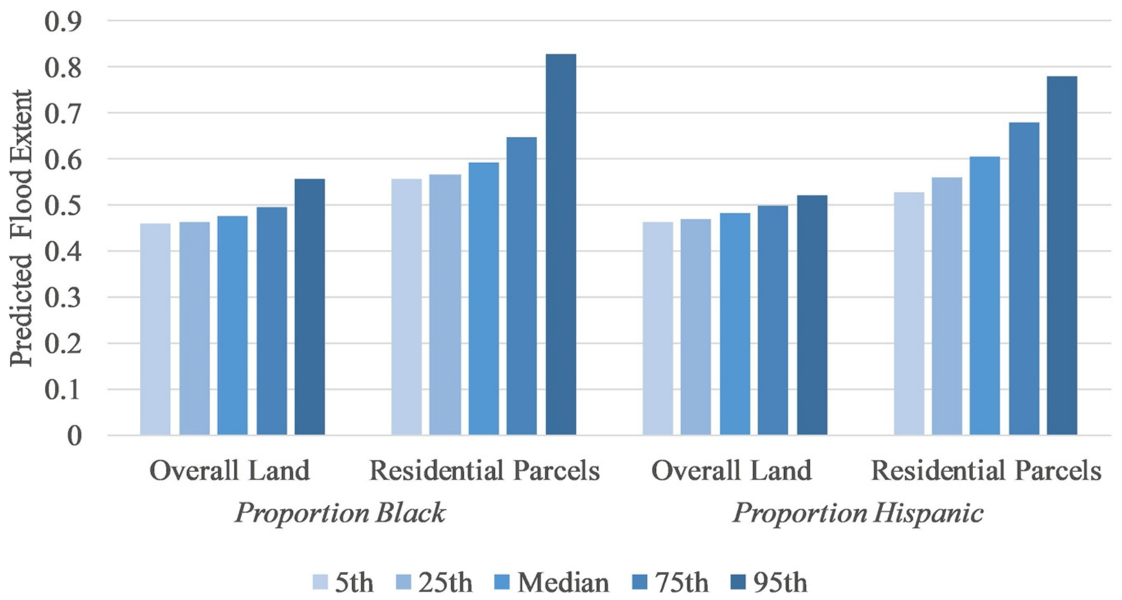

Figure 2. Predicted values of flood extent outside of 100-year floodplains by percentiles of racial composition.

Supplementary results can be summarized in three parts, and detailed further in appendices A–C. First, in appendix A, analyses using greater thresholds of flood extent for parcels (at least 25%, 50% or 75%) is similar to table 3 in that there are positive associations for proportion black and proportion Hispanic for overall flood extent and flood extent outside of floodplains at each of the higher thresholds, although, importantly, these two measures are not statistically significant at the 75% level. Second, in appendix B, results for disaggregating residential parcels into single-family parcels have substantively similar results to table 3 and appendix A; results for multi-family parcels show positive, but not statistically significant, associations. Third, in appendix C, using census-block weighted independent variables also has highly similar findings for racial inequalities to tables 2 and 3 with one important exception: proportion Hispanic was positive but not statistically significant for flood extent outside of floodplains (in Model 4 in table 2), but the block-weighted approach yields a positive, statistically significant association, adding further evidence for racial inequality. In all, these supplementary analyses mostly affirm findings in tables 2 and 3 related to racial inequalities in flood extent especially in areas outside of the 100-year floodplain.

4. Conclusion

Natural disasters create impacts on human populations in uneven ways as they occur across spatially unequal human settlements. In the case of flooding during extreme weather events, these uneven impacts correlate with existing socio-spatial patterns of segregation, including by race. These flooding impacts often occur in areas not typified as at risk for flooding by primary policy mechanisms determining risk, such as FEMA's 100-year floodplain. The present study examines areas both conceptualized as at risk to floods, and those that are *not* conceptualized as at risk to floods, to see if social inequalities are particularly characteristic of one or both areas.

By analyzing a rich synthesis of geospatial data on flood risk, flood extent, and socio-demographic characteristics from Hurricane Harvey in Harris County, Texas, two primary sets of findings were generated. First, evidence is found for racial inequalities in flooding. Neighborhoods with more black residents had consistently higher levels of flooding, and neighborhoods with more Hispanic residents had greater flooding across residential parcels (but results were less robust for overall land in the neighborhood). Importantly, it is also shown that this is *not* because these neighborhoods experience more flood risk as defined by 100-year FEMA floodplains, as little evidence was supplied that there are inequalities in floodplain location by the racial composition of neighborhoods.

The second set of findings show that there are large racial inequalities in flooding in neighborhoods outside of floodplains, and that these areas tend to be predominantly black and Hispanic. Inequalities in flooding inside of floodplains, by contrast, are not as strongly characterized by racial disparities, although some evidence is found and, more broadly, the limited disparities are largely due to the fact that these areas had very high levels of flooding regardless of racial composition. Even with this high degree of flooding inside floodplains, the vast majority of flooding across Harris County during Hurricane Harvey occurred outside of floodplains. The implication of this second set of findings is the racial inequalities found for the overall area in the first set of findings is primarily driven by racial inequalities in flooding outside of the floodplains.

Important limitations also guide the interpretation of this article. As discussed in the Data and Methods section, the research design cannot confirm that parcels that experienced flooding also experienced property damage. Additionally, while impacts outside of floodplains are found across the United States (Galloway *et al* 2006), the greater Houston area tends to experience a greater percentage of these impacts outside of the floodplain than the average community (Highfield *et al* 2013). More than this, cities and countries around the world are contending with the dynamics of human settlement in floodplains, and future research might consider if the inequalities found here map onto other patterns of social stratification in other countries. Further, floodplain management varies considerably by country, introducing another important area of empirical variation to study. Finally, research might discuss how these social inequalities intertwine with risk management by examining not only other major flood events but also risk policy instruments for other extreme weather events.

In all, the differences between areas of flood risk and areas of flood impact in Harris County disproportionately disadvantaged residents of black and Hispanic neighborhoods during Hurricane Harvey. How did this come to be? Future research can examine this question more directly, but a few directions merit mention. First, stormwater catchment and urban infrastructure generally may be of a poorer quality in black and Hispanic neighborhoods because of municipal disinvestment. In this case, it is not that these areas are more flood-prone for 'natural' reasons but rather for anthropogenic ones, that is because of poor infrastructure. Second, one possibility concerns differences in elevation which correlates partly with floodplains. While the lowest areas (which are more likely to be in floodplains) might not have more black or Hispanics residents (as the results here show), it does not mean that the highest areas do not have such disparities. Put another way, black and Hispanic neighborhoods in Greater Houston may be in middle elevations, both relatively prone to flooding but not so at risk to be located in 100-year floodplains. Previous research on the U.S. South and Houston in particular confirm disparities by elevation which suggests possible support for this idea (Ueland and Warf 2006, Lu 2017), and these elevation disparities are likely driven by historical and contemporary processes of residential stratification by race. Third, a climate justice perspective would hold that acknowledging climate change in floodplain management (specifically, in models creating floodplains) might help to identify these areas that may be at expanded risk, how that expanded risk intersects with social inequalities, and how a better conception of risk might improve disaster resilience. In all, these possibilities are not mutually exclusive but rather mutually reinforcing, and have at their root the profound racial inequality that characterizes American society.

How to resolve these inequalities with policy change is as integral as it is complex. For one, the Harris County Flood Control District advises on its website that 'every structure in Harris County should have flood insurance' (Harris County Flood Control District 2019), a much wider range than that from the federal mandates discussed earlier, in effect stating that an additional one million residential properties should purchase such insurance. Other approaches center on more probabilistic flood risk rating systems that might conceptualize flood risk not as binary (i.e. location in or outside the floodplain) as part of larger effort to make flood risk more legible to non-experts. For instance, FEMA has begun examining possible rating systems that consider rating (such as on a scale such as from 0 to 100) for individual structures (TMAC 2017). Incorporating more recent urbanization into more frequently updated maps or taking climate change scenarios into account could also be pivotal.

Across all of these policy possibilities, reconceiving of risk should be recognized as a social process, not just an environmental one. For instance, on one hand, recognizing the risk in black and Hispanic neighborhoods in Houston communities could help in efforts to improve stormwater infrastructure, foster a greater uptake of flood insurance or, more structurally, challenge racial residential segregation. On the other hand, identifying these areas as risky could result in lowered property values, widening already-staggering wealth inequalities by race in the U.S. This tension is but one raised by this research, tensions that are playing out with floodplain policies and politics across the United States (Nance 2015, Shively 2017, Elliott 2019, Koslov 2019, Elliott *et al* 2020, Frazier *et al* 2020). In conclusion, this study's results suggest that the impacts outside floodplains mean that a greater attention to the tensions of delineating flood risk is an idea whose time has come.

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Appendix A. Flood extent in parcels at greater thresholds

Data and methods

This supplemental analysis re-examines conceptualizing flooding extent at different thresholds of 25%, 50%, and 75% of the parcel that is flooded. This additional analysis is conducted as 5% is a relatively low threshold for a parcel to count as flooded, and a parcel that is 5% flooded may not experience any tangible disaster impacts in the form of property damage. More than this, as discussed in the descriptive statistics (see also table 1), the number of properties that would count as experiencing flooding varies dramatically across these levels. Therefore, results are closely followed at these higher levels of flood extent to test to see if regression results vary across these metrics.

Results

Table A re-analyzes key results by conceptualizing flood extent in parcels at greater thresholds (i.e. 25%, 50%, and 75%) than in table 3. (Because 5% is retained as the threshold for floodplain [and few tracts are between 5 and 90% in the floodplain], results predicting proportion in the floodplain [similar to Model 1 in tables 2 and 3] are not shown). Analyses using higher thresholds for flooding extent find similar results to those in tables 2 and 3 for overall flooding extent and flooding extent outside of floodplains, but less so for flooding extent within floodplains. For the three models predicting overall extent of flooding in residential parcels at the three higher thresholds (Model 1), a census tract with more black or Hispanic residents is associated with a greater proportion of flooded parcels. Models examining flooding inside the floodplain (Model 2), though, showcase few statistically significant relationships, indicating that racial inequalities for black and Hispanics found when using the 5% threshold for overall residential parcels does not hold across other measurement strategies for flood extent inside floodplains. In models predicting extent of flooding outside of the floodplain (Model 3), the models show that census tracts with more black and Hispanics residents tend to have more parcels experiencing flooding outside of the floodplain.

One major caveat to these findings, though, concerns that the findings for proportion black and proportion Hispanic are statistically significant for flood extent overall and outside of floodplains when using 25% and 50% as the threshold, but that these two measures, while positive, are not statistically significant at the 75% threshold. This finding can be interpreted in light of the drop of residential parcels that meet this 75% threshold for flood extent outside of floodplains (30%) compared to those that met the 5% threshold used in table 3's analyses (66%). It may be the case that the most severe flooding (as measured by the proportion of a residential parcel that flooded) was not as unequal across residential neighborhoods.

In all, these results further substantiate the findings for racial inequalities for predominantly black and Hispanic neighborhoods in Harris County in flood extent during Hurricane Harvey, and these inequalities are particularly found for flooding outside of 100-year floodplains—and less so within these floodplains.

Appendix B. Disaggregating residential parcels into single-family and multi-family parcels

Data and methods

In a second supplemental analysis, non-vacant residential parcels are disaggregated into two additional measures: only parcels with one single-family home, and all others (i.e. multi-family parcels). The purpose of this disaggregation is to account for the fact that the overall measures relating to non-vacant residential parcels count all parcels equally, even a single-family home compared to a large apartment complex, and that this calculation undercounts population differences between the two parcel types. Therefore, these two additional measures provide a window into if dynamics for the overall measures of flood risk and extent for non-vacant residential parcels hold even when considering specifically single-family parcels or multi-family parcels. As with the overall residential parcels, tracts are included in the statistical analyses if they have at least 25 single family parcels ($n = 751$) or 25 multi-family parcels ($n = 321$).

Results

Table B showcases results that disaggregate residential parcels into single-family and multi-family parcels as a robustness check on previous results. Findings showcase substantively similar findings for single-family parcels. Model 1 indicates few statistically significant predictors of floodplain risk across both single-family and multi-family homes, and no evidence for racial inequalities for the proportion black and proportion Hispanic measures. Model 2 (for single-family parcels) find evidence of racial inequalities in that more of both types of parcel experienced flooding in neighborhoods with more black and Hispanic residents. Examining flood extent in floodplains, Model 3 finds no evidence of racial inequalities for single-family parcels. Most central to this study, Model 4 are consistent with findings for flood extent for overall residential parcels: a greater proportion of black or Hispanic residents is linked to more single-family experiencing flooding outside of the floodplain. Results for multi-family parcels, however, are

Table A. Results of generalized estimating equations predicting residential parcels' flood extent at higher thresholds of flooding in Harris County, Texas.

	Model 1: Prop. Flood Extent			Model 2: Prop. Flood Extent In Floodplain			Model 3: Prop. Flood Extent Outside Floodplain		
	Coef.		SE	Coef.		SE	Coef.		SE
Dependent Variable: Residential Parcels (at least 25% flooded)									
Prop. Black	0.5	***	0.132	0.077		0.128	0.507	***	0.139
Prop. Hispanic	0.453	***	0.123	0.073		0.072	0.49	**	0.147
Prop. Other Non-White Race	−0.706	*	0.306	−1.083	***	0.179	−0.76		0.497
Median Income (in 1000 s)	−0.001		0.001	0.000		0.001	0.002		0.001
Prop. Owner-Occupied	0.511	**	0.192	0.25	*	0.109	0.51	**	0.2
Population (in 1000 s)	−0.013	**	0.004	0.001		0.002	−0.012	*	0.006
Land Area (km^2)	−0.001		0.002	−0.002		0.003	−0.001		0.003
Prop. Floodplain	0.292	***	0.071	−0.301	**	0.107	−0.262	†	0.144
Intercept	−1.13			−0.39		0.128	−1.104		0.142
QIC	68.573			194.884			74.809		
N	764			531			764		
Dependent Variable: Residential Parcels (at least 50% flooded)									
Prop. Black	0.346	*	0.169	−0.13		0.173	0.327	*	0.154
Prop. Hispanic	0.352	*	0.147	−0.031		0.14	0.382	*	0.166
Prop. Other Non-White Race	−1.367	***	0.37	−1.789	***	0.215	−1.556	**	0.539
Median Income (in 1000 s)	−0.001		0.001	0.001		0.001	−0.002		0.001
Prop. Owner-Occupied	0.386	†	0.22	0.269	†	0.148	0.384	†	0.211
Population (in 1000 s)	−0.023	**	0.007	0.001		0.003	−0.024	**	0.009
Land Area (km^2)	0.000		0.002	0.002		0.004	0.000		0.003
Prop. Floodplain	0.354	***	0.093	−0.303	**	0.1	−0.311	†	0.178
Intercept	−1.122		0.138	−0.51		0.196	−1.065		0.149
QIC	79.814			147.854			77.247		
N	769			531			764		
Dependent Variable: Residential Parcels (at least 75% flooded):									
Prop. Black	0.263		0.203	−0.35	***	0.099	0.234		0.172
Prop. Hispanic	0.256		0.177	−0.144		0.179	0.289		0.184
Prop. Other Non-White Race	−1.823	***	0.449	−2.058	***	0.572	−2.18	***	0.538
Median Income (in 1000 s)	−0.001		0.001	−0.001		0.001	−0.002	*	0.001
Prop. Owner-Occupied	0.324		0.26	0.409	*	0.199	0.304		0.236
Population (in 1000 s)	−0.033	***	0.009	−0.004		0.005	−0.036	**	0.012
Land Area (km^2)	0.001		0.002	0.004		0.004	0.001		0.004
Prop. Floodplain	0.378	**	0.109	−0.201	†	0.11	−0.358	†	0.206
Intercept	−1.147		0.175	−0.599		0.232	−1.063		0.17
QIC	86.461			116.82			80.365		
N	764			531			764		

Notes † < 0.1; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. SE are Semirobust Standard Errors. QIC is Quasi-Likelihood under the Independent Model Criterion.

not as robust to these alternate specifications. Specifically, while proportion black and proportion Hispanic are positive in Model 2 and Model 4 (which mirrors key study findings), they are not statistically significant. This null finding points to the need for more research on neighborhood inequalities in flood impacts on multi-family parcels. For instance, the number of neighborhoods that met the 25 parcel threshold for inclusion in the analysis is low ($n = 321$ for Models 1, 2, and 4; $n = 151$ for Model 3). Further, the size of the multi-family parcel—such as it is one unit of a duplex or a condominium in a high-rise apartment building—is highly variable, and there may be further differences by the size of the multi-family home.

In all, results here showcase that neighborhoods with more black and Hispanic residents are linked to greater flood extent in neighborhoods with single-family, and that this unequal flooding tends to occur outside of floodplains; these findings are similar to those in table 3 for overall residential parcels. For multi-family parcels, the findings are less clear: similar in directionality, but not in statistical significance; focusing on multi-family homes in a more nuanced way is a direction for future work.

Table B. Results of generalized estimating equations predicting dependent variables of single-family and multi-family residential parcels in Harris County, Texas.

	Model 1: Prop. Floodplain			Model 2: Prop. Flood Extent			Model 3: Prop. Flood Extent In Floodplain			Model 4: Prop. Flood Extent Outside Floodplain		
	Coef.		SE	Coef.		SE	Coef.		SE	Coef.		SE
Dependent Variable: Single-Family Residential Parcels (at least 5% flooded)												
Prop. Black	0.885		0.612	0.459	***	0.066	0.058		0.054	0.517	***	0.103
Prop. Hispanic	1.265	†	0.754	0.347	***	0.063	0.003		0.046	0.416	***	0.096
Prop. Other Non-White Race	3.648	**	1.22	0.253	†	0.142	−0.469	***	0.103	0.192		0.192
Median Income (in 1000 s)	0.008		0.005	−0.001		0.000	0.000		0.000	−0.001		0.001
Prop. Owner-Occupied	−0.509		0.555	0.224	***	0.061	0.078		0.071	0.258	**	0.087
Population (in 1000 s)	−0.061	†	0.036	−0.004	**	0.001	0.000		0.002	−0.002		0.003
Land Area (km^2)	0.002		0.003	−0.003	*	0.001	−0.005	**	0.002	−0.005	†	0.154
Prop. Floodplain	–		–	0.17	***	0.046	−0.07		0.073	−0.331	*	0.125
Intercept	−2.887		0.572	−0.664		0.082	−0.147		0.05	−0.725		
QIC	83.368			50.716			249.05			77.829		
N	746			746			511			746		
Dependent Variable: Multi-Family Residential Parcels (at least 5% flooded)												
Prop. Black	−0.768	†	0.397	0.745		0.657	0.043		0.302	0.521		0.646
Prop. Hispanic	−0.51		0.852	0.595		0.473	0.016		0.17	0.389		0.512
Prop. Other Non-White Race	0.729		0.503	−2.272	**	0.738	−1.658	***	0.403	−3.522	**	1.152
Median Income (in 1000 s)	−0.007		0.005	−0.02	**	0.008	−0.005		0.004	−0.014	**	0.005
Prop. Owner-Occupied	0.808	*	0.32	1.487	**	0.54	0.323		0.215	1.021	**	0.33
Population (in 1000 s)	0.013		0.05	−0.027		0.025	−0.013		0.011	0.011		0.02
Land Area (km^2)	0.008	†	0.005	0.011	*	0.004	−0.002		0.019	0.015	†	0.008
Prop. Floodplain	–		–	0.065		0.067	−1.766	***	0.27	0.204		0.213
Intercept	−1.593		0.854	−1.079		0.661	0.159		0.229	−1.005		0.644
QIC	93.898			197.633			470.486			176.244		
N	321			321			151			321		

Notes † < 0.1; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. SE are Semirobust Standard Errors. QIC is Quasi-Likelihood under the Independent Model Criterion.

Appendix C. Using census block-weighted independent variables for analyses of units inside and outside of floodplain

A third supplemental analysis employs a 'census block-weighted' approach using the 2010 decennial census on census blocks to build measures relating to socio-demographic characteristics in the portions of census tracts that lie inside and outside of the floodplain. The reason for using these alternative measures is that the social and demographic composition of the area inside the floodplain or outside of the floodplain in a given census tract could vary, and use of this ancillary data on census blocks could provide more precise measurements using this dasymetric approach (Mennis 2003, Montgomery and Chakraborty 2013). For example, in a census tract that is 50% in the floodplain, the residents who reside in the floodplain could be disproportionately high income (or vice versa) compared to those residents outside of the floodplain. Using the overall census tract characteristics attached to the portions of each tract inside or outside of the floodplain might bias results because it is drawing on information that is outside the unit of analysis. To address this issue, raw counts of social and demographic information census blocks, the smallest unit available to geographic researchers from the U.S. Census, are totaled up for the portions of each tract that are inside and outside of the floodplain. All but one of the same independent variables—three measures of racial composition, proportion owner-occupied homes, and population—are calculated based on blocks. The one exception is median income, which is not released on the block level because it was not measured in the 2010 decennial census (only in the American Community Survey), but the overall tract's median income is included to account for this critical control.

Table C1 indicates few differences in the proportional composition of areas inside and outside of the floodplain, but, not surprisingly, the population and land area are considerably lower in the sub-part of the census tract inside the floodplain compared to the sub-part outside of the floodplain. Table C2 reconceptualizes key models from tables 2 and 3 by using the census block-weighted approach, that is, using independent variables created by census block data for each of the portions of the census tract that are or are not in the floodplain. For models analyzing flooding inside the floodplain (Model 1), results are substantively similar for the residential parcel analysis

Table C1. Descriptive statistics of census-block weighted variables with means (standard deviations).

	Inside Floodplain	*Outside Floodplain*
Independent Variables		
Prop. Black	0.17 (0.21)	0.19 (0.22)
Prop. Hispanic	0.38 (0.27)	0.4 (0.26)
Prop. Other Race	0.07 (0.08)	0.07 (0.07)
Median Income (in 1000 s)	57.41 (33.51)	55.95 (33.33)
Prop. Owner-Occupied	0.75 (0.28)	0.77 (0.22)
Population (in 1000 s)	0.83 (1.13)	4.54 (2.65)
Land Area (km^2)	1.64 (4.08)	4.33 (7.99)
Dependent Variables		
Prop. Flood Extent (Overall Land)	0.82 (0.18)	0.49 (0.16)
Prop. Residential Parcels Flooded (at least 5% flooded)	0.84 (0.24)	0.63 (0.24)

Table C2. Results of generalized estimating equations predicting dependent variables with census-block weighted independent variables in Harris County, Texas.

	Dependent Variable: Overall Land					
	Model 1: Prop. Flood Extent In Floodplain			Model 2: Prop. Flood Extent Outside Floodplain		
	Coef.		SE	Coef.		SE
Prop. Black	0.075	*	0.038	0.357	***	0.08
Prop. Hispanic	−0.022		0.047	0.231	**	0.075
Prop. Other Non-White Race	−0.278	***	0.053	−0.184		0.143
Median Income (in 1000 s)	0.001	**	0.000	−0.000		0.001
Prop. Owner-Occupied	−0.028		0.034	0.224	**	0.078
Population (in 1000 s)	−0.058	***	0.008	0.004		0.004
Land Area (km^2)	0.001		0.003	−0.006	***	0.001
Prop. Floodplain	−0.016		0.062	−0.267	**	0.091
Intercept	−0.183		0.051	−0.987		0.072
QIC	35.238			34.492		
N	626			783		
	Dependent Variable: Residential Parcels (at least 5% flooded)					
Prop. Black	0.214	***	0.059	0.658	***	0.09
Prop. Hispanic	0.128	**	0.045	0.517	***	0.074
Prop. Other Non-White Race	−0.457		0.307	−0.209		0.273
Median Income (in 1000 s)	0.001	*	0.000	−0.000		0.001
Prop. Owner-Occupied	0.169	***	0.043	0.933	***	0.171
Population (in 1000 s)	0.033		0.021	0.001		0.004
Land Area (km^2)	−0.002	*	0.003	−0.003		0.002
Prop. Floodplain	−0.342	**	0.107	−0.072		0.107
Intercept	−0.393		0.066	−1.503		0.17
QIC	196.524			70.099		
N	531			764		

Notes † < 0.1; *p < 0.05; **p < 0.01; ***p < 0.001. SE are Semirobust Standard Errors.QIC is Quasi-Likelihood under the Independent Model Criterion.

in table 3, which did find statistically significant relationships for proportion black and proportion Hispanic. One difference is that proportion black is statistically significant and positive in Model 1 for flood extent in floodplains, which this relationship was not statistically significant in table 2. For models examining flooding outside of the floodplain (Model 2), proportion black and proportion Hispanic are associated with greater levels of flood extent in these areas outside of the floodplain for both overall land and for residential parcels. The one difference here is that proportion Hispanic was not statistically significant for overall land in table 2 but it is in this model which uses these more closely conceptualized units with the census block-weighted measurement.

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