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Federally Overlooked Flood Risk Inequities in Houston, Texas: Novel Insights Based on Dasymetric Mapping and State-of-the-Art Flood Modeling

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In the United States, the Federal Emergency Management Agency (FEMA) delineates 100-year flood zones to define risks, regulate flood insurance premiums, and inform flood management. Evidence indicates that FEMA flood maps are incomplete, calling much of our current knowledge of U.S. flood hazard inequities into question. We use a state-of-the-art flood hazard model and census tract-level dasymetrically mapped sociodemographic data to examine flood risk inequities in the Greater Houston area, where increasingly frequent and damaging flood events are occurring. We innovate by analyzing *federally overlooked* 100-year flood risks (100-year flood zones delineated by the flood hazard model that are outside of FEMA 100-year flood zones). Results indicate that nearly 1 million Greater Houston residents live in federally overlooked 100-year flood zones. Black and Asian neighborhoods experience disproportionate risk in federally overlooked pluvial and fluvial flood zones, and Hispanic neighborhoods experience disproportionate risk in all federally overlooked zones (coastal, pluvial, and fluvial). High flood risk and the relative lack of protective resources in federally overlooked 100-year flood zones doubly jeopardizes racial and ethnic minority communities. Our findings and recent flood disasters suggest that future flood impacts in Greater Houston will be catastrophic and unjust unless FEMA revises their risk mapping and management approach to promote long-term public safety and social equity. *Key Words: dasymetric mapping, environmental justice, FEMA, flood risk, Houston, race/ethnicity.*

Flooding has greater impacts on infrastructure, human life, and the economy than any other hazard (NASEM 2019). Major precipitation events have intensified due to rising greenhouse gas concentrations accompanied by higher land and sea surface temperatures (Min et al. 2011), amplifying flood risk in many U.S. localities. Ongoing urbanization of flood-prone areas contributes to greater flood exposure (Qiang et al. 2017). Inadequate federal, state, and local governmental planning for development exacerbates flood risks (Brody, Highfield, and Kang 2011; Smiley and Hakkenberg 2020), as rapid transitions to residential, commercial, and recreational land uses reduce the capacity of watersheds to absorb and release surface water runoff (Brody, Highfield, and Kang 2011). Consequently, large urban areas in the United States, such as Houston, Texas, have experienced increasing flood risk over the last several decades (Kim and Newman 2019; Smiley and Hakkenberg 2020). Houston remains the only major U.S. city without land use zoning policies, contributing to its rapid, haphazard urban expansion (Qian 2010). Furthermore, Houston's lack of zoning has generated environmental risks that disproportionately burden socially disadvantaged groups (Bullard, Grigsby, and Lee 1994; Vojnovic 2003).

In the United States, the Federal Emergency Management Agency (FEMA) uses the 100-year flood zone (any area with a 1 percent or greater chance of flooding in any given year) to delineate flood risk, regulate flood insurance premiums, and inform floodplain management activities. FEMA

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delineates 100-year flood risk through Flood Insurance Rate Maps (FIRMs) as a basis for the National Flood Insurance Program (NFIP), which was established in 1968 to allow residents and businesses to purchase flood insurance. FIRMs are often outdated, meaning that they fail to account for changes in the built environment (Wing et al. 2017), such as residential development, which could alter hydrologic systems and increase flood losses (Patterson and Doyle 2009). Additionally, FEMA has not conducted flood hazard mapping across substantial swaths of the United States. Large areal gaps in FEMA FIRMs exclude isolated and rural areas from the risk identification and management process. Even small spatial gaps in FIRM coverage might reflect gaps wherein large numbers of residents are at great risk. Politicization of FEMA flood zone delineation could also introduce errors into FIRMs. For instance, research conducted in Houston has documented the politicization of FEMA flood zone mapping via pressure exerted by real estate developers on city representatives to exclude particular areas from 100-year flood risk zonation (Barrios et al. 2020). Others have shown how the drive for capital accumulation via real estate development is produced and sustained by neoliberal ideologies that prioritize improvements to flood protection infrastructure in the service of political and economic elites yet exacerbate environmental problems for socially marginalized groups (Chang et al. 2020; Coates and Nygren 2020; Grove, Cox, and Barnett 2020). Thus, FEMA might overlook many areas at risk of 100-year flooding due to outdated flood hazard modeling, incomplete mapping, or political maneuvering.

Research shows that FEMA 100-year flood maps perform poorly in predicting the locational risks of flooding associated with actual events (Brody et al. 2013; Collins et al. 2019; NASEM 2019; Smiley 2020), which underscores the inadequacy of the traditional flood risk modeling that informs the production of FIRMs. FEMA's long-standing approach to defining and mapping 100-year flood zones relies heavily on spatially discontinuous (sparse) streamflow and gauge data coupled with areal interpolation methods (Highfield, Norman, and Brody 2013). In recent years, flood hazard modeling has improved dramatically through computational approaches that integrate small watershed, elevation, and flood defense data (Bates et al. 2021). For example, new flood hazard modeling by First Street Foundation (a U.S.-based climate advocacy nonprofit) and Fathom (a company formed from the University of Bristol [UK] Hydrology Research Group) integrates fine-scale data for every U.S. watercourse, whereas FEMA FIRMs capture approximately 60 percent of the United States (Bates et al. 2021). Their modeling also integrates changes in the built environment and generates prospective flood risk estimates based on climate change scenarios, rather than relying on historical observations (like FEMA), and the underlying model framework has been validated in reference to flood events as well as multimillion-dollar models (Wing et al. 2017; Wing et al. 2018; Wing et al. 2019; Wing et al. 2021). This state-of-the-art flood modeling indicates that 5.9 million properties in the United States are at risk to 100-year flooding beyond FEMA-delineated 100-year flood zones, and that half of the top ten cities in Texas with the greatest number of properties at risk to 100-year flooding are located within the Greater Houston area (First Street Foundation 2020).

Major flooding outside of FEMA 100-year flood zones highlights inaccuracies in their modeling approach nationally and in Greater Houston. Nearly one quarter of claims made to FEMA for flood damage occurred beyond FEMA 100-year flood zones between 1999 and 2009 (Highfield and Brody 2013). During the same period, Armand Bayou in Houston had an estimated 80 percent of claims originate outside of FEMA 100-year flood zones (Blessing, Sebastian, and Brody 2017). Approximately half of claims in Harris County over thirty years occurred outside of FEMA-delineated 100-year flood zones (Highfield, Norman, and Brody 2013). The corresponding absence of flooding within substantial portions of FEMA-delineated flood zones during flood events further highlights inaccuracies (Smiley 2020). This has major policy implications, as people with home mortgages within FEMA-delineated flood zones are mandated to purchase flood insurance for their built structures through the NFIP. In contrast, only a small percentage of residents living outside of FEMA 100-year flood zones purchase flood insurance policies for their homes (Kousky, Kunreuther, et al. 2020). Moreover, studies of Hurricanes Sandy and Harvey have documented socially inequitable flood impacts beyond the boundaries of FEMA 100-year

flood zones (Elliott 2019; Smiley 2020), which suggests that the distribution of federally overlooked flooding might be unjust.

FEMA's traditional approach to delineating 100-year flood risk has underpinned federal flood hazard mitigation and flood insurance policymaking as well as much of the U.S.-based research on human dimensions of flood risk. Although substantial and potentially inequitable residential flood impacts occur outside of FEMA-delineated 100-year flood zones, there is substantially less investment in flood protection within those zones. Given those limitations, it is unfortunate that most prior U.S.-based studies of flood risk inequities have analyzed FEMA's FIRMs (Maantay and Maroko 2009; Montgomery and Chakraborty 2013, 2015; Chakraborty, Collins, Montgomery, et al. 2014; Grineski et al. 2015, Maldonado et al. 2016; Grineski, Collins, and Morales 2017; Qiang 2019). Additionally, most studies of flood risk inequities have analyzed aggregated data on sociodemographic characteristics while making the untenable assumption that residential populations are distributed evenly across areal units (e.g., counties, census tracts; Chakraborty, Collins, Montgomery, et al. 2014; Grineski et al. 2015; Montgomery and Chakraborty 2015; Chakraborty, Collins, and Grineski 2019; Shao et al. 2020).

In this study, we address these issues by using flood risk maps from the Bates et al. (2021) model as well as FEMA's FIRMs and by employing dasymetric mapping to assess population exposure to 100-year flood risk in the Houston–The Woodlands–Sugar Land Metropolitan Statistical Area, Texas (Greater Houston). Specifically, we examine the scope and socially inequitable distribution of flood risk within federally overlooked 100-year flood zones; that is, 100-year flood zones delineated by the Bates et al. (2021) model that are outside of FEMA 100-year flood zones. Our analysis focuses on coastal, fluvial, and pluvial flooding and tests for inequities based on race or ethnicity and socioeconomic status (SES), adjusting for geographic clustering and confounding effects of environmental (dis)amenities. We address three research questions: (1) How many Greater Houstonians live in federally overlooked 100-year flood zones? (2) Which neighborhood indicators of social disadvantage are associated with federally overlooked 100-year flood risk? (3) How do social inequities in federally overlooked 100-year flood risk vary by flood type?

Literature Review

Environmental Injustice and Flooding

Distributional environmental justice (EJ) research examines inequities in exposures to environmental hazards and access to environmental amenities based on race or ethnicity, SES, gender, age, and other social characteristics (Mohai, Pellow, and Roberts 2009; Collins et al. 2015). Hurricane Katrina in 2005 led researchers to examine the EJ implications of actual flood events as well as modeled flood risks (Bullard and Wright 2009; Curtis et al. 2011). In terms of flood events, Hurricanes Katrina, Sandy, and Harvey had inequitable impacts (Curtis et al. 2011; Lieberman-Cribbin et al. 2021). Specific to Harvey and Greater Houston, higher Black-composition neighborhoods and Black households experienced disproportionate exposure to flooding (Chakraborty, Collins, and Grineski 2019; Collins et al. 2019) as did neighborhoods and households of low SES (Chakraborty, Collins, and Grineski 2019; Collins et al. 2019).

In terms of inequities in modeled flood risks, research has indicated that socially disadvantaged groups in some U.S. contexts experience greater residential risks than socially privileged groups. For example, in the southern United States, racial and ethnic minorities and those of low SES clustered in flood risk zones (Tate et al. 2021). Studies analyzing FEMA-delineated flood risk have less consistently found patterns that align with expectations based on the EJ literature. For example, Maantay and Maroko (2009) did not find inequities in exposure to 100-year flood risk based on minority race and ethnicity or low SES in New York City. In Miami, Florida, research found that neighborhoods with a higher composition of Whites, those of higher SES, and those with higher property values had greater FEMA 100-year flood risk (Grineski et al. 2015; Grineski, Collins, and Morales 2017). A study of Birmingham, Alabama, found that White (vs. racial or ethnic minority) populations were more highly concentrated in FEMA 100-year flood zones (Hossain and Meng 2020). Research that split FEMA 100-year flood zones into coastal and inland subzones found that Black and Hispanic residents in Miami and Tampa Bay were overrepresented in inland but not coastal flood zones (Montgomery and Chakraborty 2013; Chakraborty, Collins, Montgomery, et al. 2014). Another study found that Texas counties

with higher levels of social vulnerability had less FEMA-delineated 100-year flood risk (Shao et al. 2020). Using measures from actual flood events, however, the same study found that social vulnerability was more consistently associated with greater flood exposure (Shao et al. 2020).

In Greater Houston, EJ studies using FEMA-modeled 100-year flood risk measures have had mixed results. A neighborhood-level analysis found that racial and ethnic minorities had less exposure to FEMA-delineated 100-year flood risk compared to Whites (Grineski et al. 2015). A household-level analysis, however, showed that Hispanic immigrants in particular were overrepresented relative to Whites as residents of FEMA-delineated flood zones there (Maldonado et al. 2016). A recent study focused on Harris County used FEMA 100-year flood zone data in conjunction with data on Hurricane Harvey inundation and found that flood exposure inequities from Harvey were predominately attributable to flooding beyond FEMA-delineated 100-year flood zones (Smiley 2020).

In sum, prior studies of flood inequities have reported inconsistent findings between indicators of social disadvantage and flood hazards, with much stronger support for race- and class-based inequities coming from studies of actual flood events. No prior research, though, has examined social inequities in exposure to federally overlooked 100-year flood risks, despite the important policy implications of such work. Using recently released flood risk estimates from the Bates et al. (2021) model, our study addresses this important gap.

Environmental (Dis)Amenities

When analyzing FEMA 100-year flood zone data, some studies have found that neighborhoods of higher (vs. lower) SES exhibit greater 100-year flood risk (Maantay and Maroko 2009; Maldonado et al. 2016; Grineski, Collins, and Morales 2017). This is because the presence of water-based amenities (e.g., waterfront views, access to beaches) makes certain areas highly desirable places to live regardless of the increased flood risk (Bin and Kruse 2006). Such amenities characterize particular coastal, riverine, and lacustrine areas across the United States, which might confound associations between social status and flood risk in those settings (Collins, Grineski, and Chakraborty 2018). Similarly, tree canopy cover is an amenity that has been examined in the EJ literature and might correlate with flood risk based on proximity to water (Landry and Chakraborty 2009). Several studies focused on flood risk have implemented neighborhood-level proxies for water-based amenities, such as median housing value or the percentage of housing units designated for seasonal or recreational uses (Chakraborty, Collins, Montgomery, et al. 2014; Grineski et al. 2015; Montgomery and Chakraborty 2015). Socially privileged people might choose to reside in amenity-rich but risky locations because they can afford structural and nonstructural forms of mitigation, reducing risks and protecting property values (Collins 2010; Brody, Lee, and Highfield 2017). In other words, flood zones endowed with substantial water-based amenities could be highly desirable and thus accessible primarily for socially privileged groups.

On the other hand, socially disadvantaged groups tend to reside in areas with environmental disamenities, such as impervious surfaces (e.g., pavement, concrete) and polluting industries. Impervious surfaces significantly reduce rainwater infiltration, increasing surface runoff (Brody, Highfield, and Kang 2011; Yao, Wei, and Chen 2016). U.S. communities with greater urban imperviousness have higher levels of racial and ethnic minority composition and poverty (Ogneva-Himmelberger, Pearsall, and Rakshit 2009). Furthermore, many industrial activities require access to surface water; thus, industrial land uses often coincide with flood zones (Flores, Castor, et al. 2020). In Greater Houston, the petrochemical industry has rapidly expanded, especially along the Gulf Coast and the Houston Shipping Channel (HSC), where racial and ethnic minority and economically deprived communities concentrate. Neighborhoods adjacent to the HSC have become increasingly socially vulnerable and more susceptible to hazards associated with the petrochemical industry in recent decades (Bernier et al. 2017). Areas that host such facilities tend to lose residential property value.

To summarize, environmental (dis)amenities are associated with flood risks, influencing people's decisions to reside in specific places. It is therefore important to control for those confounding factors when examining social inequities in flood risk. Prior studies of flood risk inequities have mostly overlooked potential confounding by (dis)amenities or have only examined a few proxy measures. In this

study, we more comprehensively adjust for confounding based on environmental (dis)amenities associated with tree canopy cover, seasonal and recreational housing, urban imperviousness, and proximity to petroleum industrial sites.

Estimating Flood Risk Inequities

Spatial analyses of flood risk inequities present technical challenges. Estimating the population at risk to flooding is complicated by the fact that the boundaries of flood risk zones are inconsistent with those of census-defined areal units. Most prior studies have assumed that the geographic distribution of residential populations and their flood risks are uniform within census units (Chakraborty, Collins, Montgomery, et al. 2014; Montgomery and Chakraborty 2015; Chakraborty, Collins, and Grineski 2019). Studies typically generate flood risk measures by intersecting census tract boundaries with flood zone boundaries and applying polygon containment or areal apportionment techniques using geographic information systems (GIS) software. These approaches unnecessarily introduce error into the estimation of populations exposed to or at risk of flooding, which influences inferences regarding inequities (Maantay 2002).

Dasymetric mapping enables more accurate estimation of population distribution than polygon containment or areal apportionment techniques through disaggregation of population estimates within census areal units based on ancillary data (Mennis 2003; Mennis and Hultgren 2006; Maantay 2007; Maantay and Maroko 2009; Montgomery and Chakraborty 2013). Using the dasymetric approach, we start from the premise that residents are nonuniformly distributed within areal units and proceed to estimate more precisely where people live, before we more accurately characterize their residential hazard exposures. Some local-level studies using dasymetric techniques have removed nonresidential parcels from census areal units and redistributed populations and their sociodemographic characteristics to areas coincident with residential parcel polygons (Maantay 2007; Maantay, Maroko, and Herrmann 2007). National- and regional-level studies have used land-cover data to redistribute populations within areal units to the portions of units dedicated to residential uses (Mennis 2003; Mennis and Hultgren 2006). For example, Dmowska and Stepinski (2014) generated a high-resolution dasymetric model of population distribution for the entire United States using the National Land Cover Dataset (NLCD), and Mennis (2003) used remotely sensed land-cover data to generate an accurate, fine-scale population distribution surface within census block groups of southeast Pennsylvania. To examine current and future flood risk in the United States, Wing et al. (2018) used the Environmental Protection Agency's (EPA) Intelligent Dasymetric Mapping (IDM) Toolbox, which applies the NLCD as ancillary input.

Only a few studies of flood hazard inequities have used dasymetric mapping techniques (Maantay and Maroko 2009; Montgomery and Chakraborty 2013; Debbage 2019; Qiang 2019; Tate et al. 2021). Debbage (2019) and Qiang (2019) used the NLCD and dasymetric mapping. Both studies, though, used FEMA-delineated FIRMs and applied dasymetric techniques that considered only developed land-cover classes (i.e., low-, medium-, and high-intensity development), even though populations reside outside of those land-cover classes and population density varies greatly within them (Debbage 2019; Qiang 2019). Tate et al. (2021) used flood risk data from the Bates et al. (2021) model and included all habitable land-cover classes from the NLCD; they assumed, however, that population density was homogenous across all habitable areas. This binary dasymetric technique applied by Tate et al. (2021), which defines areas as either habitable or nonhabitable, might underestimate the population within flood zones (Montgomery and Chakraborty 2013).

In this study, we improve on dasymetric techniques previously used in studies of flood inequities by generating population density estimates within all habitable land-cover classes, rather than assuming homogeneity across those classes or limiting our technique to only developed land-cover classes. This advanced dasymetric technique excludes nonhabitable areas based on ancillary land cover and census block-level data and accurately gauges the density of population within inhabited areas, which enables us to estimate residential risks to federally overlooked 100-year flooding with greater precision than that achieved by prior aggregated data analyses of flood inequities.

Study Area

Greater Houston consists of nine counties and has a population of approximately 6.8 million (Figure 1). White or Caucasian (non-Hispanic/Latino) people

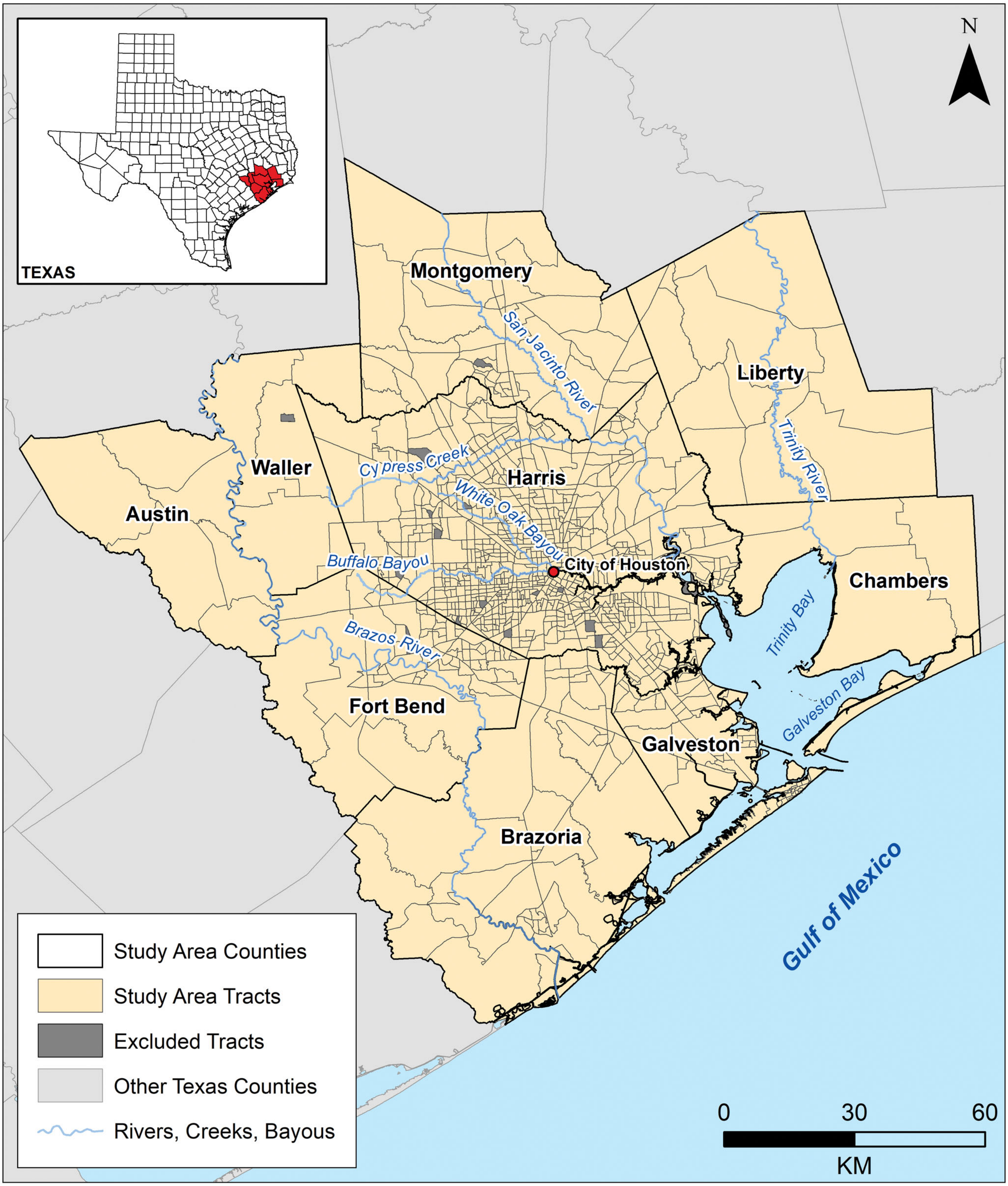

Figure 1. Greater Houston, Texas counties and census tracts. *Note*: Excluded tracts ($n = 17$) are those with populations of less than 500 or missing data for any of the analysis variables.

account for 35 percent of the population, whereas Black and African Americans (non-Hispanic/Latino), Hispanic and Latino people, and Asian Americans (non-Hispanic/Latino) represent 17 percent, 39 percent, and 6 percent of the population, respectively. Adjacent to the Gulf of Mexico, Greater

Houston is highly susceptible to flooding from tropical cyclones. In 2001, Tropical Storm Allison dropped more than sixty centimeters of rainfall on parts of Greater Houston in under twenty-four hours, resulting in over $5 billion in damages (Blackburn 2017; Harris County Flood Control District [HCFCD] 2021). Hurricane Harvey in 2017 caused record-breaking flooding in the region, generating up to 121 centimeters of rainfall and causing an estimated $125 billion in damages (Blake and Zelinsky 2017). Myriad bayous, streams, and rivers crosscut the area, meaning extreme precipitation events can cause water levels to rise rapidly, overflowing banks (Blackburn 2017). Due to rapid urbanization (Smiley and Hakkenberg 2020), the region is also vulnerable to pluvial flooding from extreme precipitation events. Streets in Houston can only withstand a twenty-five-year rainfall event before widespread inundation occurs. When Houston's stormwater drainage system becomes overwhelmed, watersheds overflow and residential areas flood rapidly (Blackburn 2017). The Memorial Day floods (2015 and 2016) and Tax Day flood (2016) all dropped more than twenty-five centimeters of rain in less than twenty-four hours, flooding watersheds and inundating thousands of structures (Blackburn 2017; HCFCD 2021). Tropical Storm Imelda produced more than fifty centimeters of rain in less than twenty-four hours, causing deeper flooding than Hurricane Harvey (2017) in some areas (HCFCD 2019).

Greater Houston provides an ideal site for analyzing the EJ implications of federally overlooked flood risk for several reasons. First, frequent flooding beyond FEMA 100-year flood risk zones has been well documented locally (Highfield and Brody 2013; Highfield, Norman, and Brody et al. 2013; Blessing, Sebastian, and Brody 2017). Second, it is highly prone to all types of flooding, the risks of which are amplified by anthropogenic influences (Zhang et al. 2018; Wehner and Sampson 2021). Third, prior research indicates that the petrochemical industry, environmental degradation, residential segregation, and weak planning institutions have unjustly exacerbated people's vulnerabilities to hazards and disasters in Greater Houston (Bullard 1990; Chakraborty, Collins, Grineski, et al. 2014; Collins et al. 2015; Chakraborty, Grineski, and Collins 2019; Collins et al. 2019; Flores, Castor, et al. 2020; Flores, Collins, et al. 2020).

Prior to the 1940s, when the population was under 1 million, land-use patterns were primarily oriented by trade and railroads, making Houston an important port city. Following World War II, the region experienced rapid urbanization and population growth due to the construction of major highways serving new residential developments on the outskirts of the metropolitan area (Smiley and Hakkenberg 2020). As Greater Houston continued to expand, the petrochemical and real estate development industries emerged as the engines of economic growth, contributing to the development of stark social inequalities across residential landscapes and environmental injustices with regard to flooding that burden people of color in particular (Collins, Grineski, and Chakraborty 2018; Flores, Collins, et al. 2020).

Data and Methods

Dependent Variables: Population within Federally Overlooked 100-Year Flood Zones

To delineate federally overlooked 100-year flood zones, we used 10-m resolution raster products from the Bates et al. (2021) model, which contain two-dimensional hydrodynamic models with information on multiple return intervals. For this study, we examined data on 100-year flood zones in Greater Houston. We focused on all types of flooding delineated by the model, including pluvial, fluvial, and coastal flooding. To model pluvial flooding (i.e., flooding from rainfall directly on the land surface), the raster products integrate return period discharges and rainfall amounts from small water catchments, as well as urban development and drainage, which are not captured in fluvial modeling. To model fluvial flooding (e.g., flooding of river channels), the raster products integrate hydrology data from the U.S. Geological Survey National Elevation and National Hydrography data sets, and flood defense data from the U.S. Army Corps of Engineers National Levee Database and National Inventory of Dams and other sources (Bates et al. 2021). To model coastal flooding, the raster products integrate storm surge from high tides and atmospheric events (i.e., tropical cyclones). This model covers every watercourse in the contiguous United States and has been validated in reference to flood events and other high-cost, high-precision flood model output (Wing et al. 2017; Wing et al. 2018; Wing et al. 2019; Bates et al. 2021; Wing et al. 2021).

Next, we downloaded FEMA digital FIRMs from the National Flood Hazard Layer (NFHL). FIRMs integrate information on fluvial and coastal flood risk, but do not consider surface flooding from precipitation events (i.e., pluvial flooding). We then overlaid the two flood zone data sets and extracted all 100-year flood zones recognized by the Bates et al. (2021) model that fell outside of FEMA-delineated flood zones. These are the flood zones that we define as federally overlooked (Figure 2).

To implement the dasymetric technique, we used the EPA IDM Toolbox to redistribute census tract populations and their social characteristics according to the distribution of land-cover-adjusted census block populations (based on the 2010 Decennial Census). The IDM Toolbox samples NLCD pixels (ancillary data) within source zones (i.e., census blocks), removes uninhabitable areas (i.e., open water, emergent herbaceous wetlands), and produces a revised population density (30-m pixel) raster (U.S. EPA 2019). The methods are detailed by Mennis and Hultgren (2006).

Next, we overlaid the dasymetric population density raster with federally overlooked 100-year flood zones to calculate fine-scale estimates of population exposure. We then aggregated those fine-scale exposure estimates to the census tract level (using zonal statistics) and created dependent variables that represent counts of people within each tract exposed to federally overlooked 100-year flooding by type (i.e., combined, coastal, pluvial, fluvial; Table 1). We employed census tracts as the source units for dasymetric disaggregation because they are the finest scale areal units for which reliable estimates are available for key sociodemographic indicators, which we used as independent variables to assess federally overlooked 100-year flood risk inequities. Census blocks are the U.S. Census Bureau's finest-scale units, but they do not provide data on many of the indicators of social disadvantage needed to examine flood risk inequities.

Independent Variables

We assembled sociodemographic data for census tracts from the 2015–2019 American Community Survey (ACS) estimates. For race and ethnicity, we constructed variables representing the proportions of non-Hispanic/Latino (NH) Black, Hispanic, NH Asian, and NH other (i.e., multiple or other races) residents at the census tract level. To examine SES, we used median household income and median household income squared because its relationship with risk might be curvilinear (Collins, Grineski, and Morales 2017; Grineski, Collins, and Morales 2017).

To construct four control variables representing environmental (dis)amenities, we used the ACS 2015–2019 estimates to calculate the proportion of each census tract's total housing units dedicated to seasonal or recreational purposes (i.e., vacation homes). We used tree canopy cover estimates at 30-m resolution from the Multi-Resolution Land Characteristics (MRLC) Consortium (2016) to calculate the mean percentage of tree canopy cover for each census tract by overlaying the 30-m resolution raster with the dasymetric population density raster and by assessing tree canopy coverage only in habitable areas of tracts. We used estimates of urban imperviousness based on 30-m resolution data from the MRLC Consortium (2016) to calculate the mean percent of urban imperviousness for each census tract by overlaying the 30-m resolution raster with the dasymetric population density raster and calculating tract-level urban imperviousness measures only for habitable areas. In addition, we used facility-level geocoded point data from the U.S. EPA Toxic Release Inventory (TRI) Explorer (2019). We drew 1-km buffers around each TRI facility classified with Industry Sector codes 324 (Petroleum) and 4247 (Petroleum Bulk Terminals) by the North American Industry Classification System (NAICS). We then overlaid the buffers with the dasymetric population density raster and calculated tract-level measures of the number of people living within 1-km buffers of petrochemical TRI facilities.

We also control for the urbanicity of census tracts using rural–urban community area (RUCA) codes (U.S. Department of Agriculture 2019). Ten primary RUCA codes designate metropolitan, micropolitan, small town, and rural areas based on population size and the direction of commuting flows for U.S. census tracts. Following Flores, Castor, et al. (2020), we combined the codes into three categories: urban core (RUCA code 1), suburban/exurban (RUCA codes 2–3), and small town/rural (RUCA codes 4–10). We excluded urban core (RUCA code 1) from our models as the reference group.

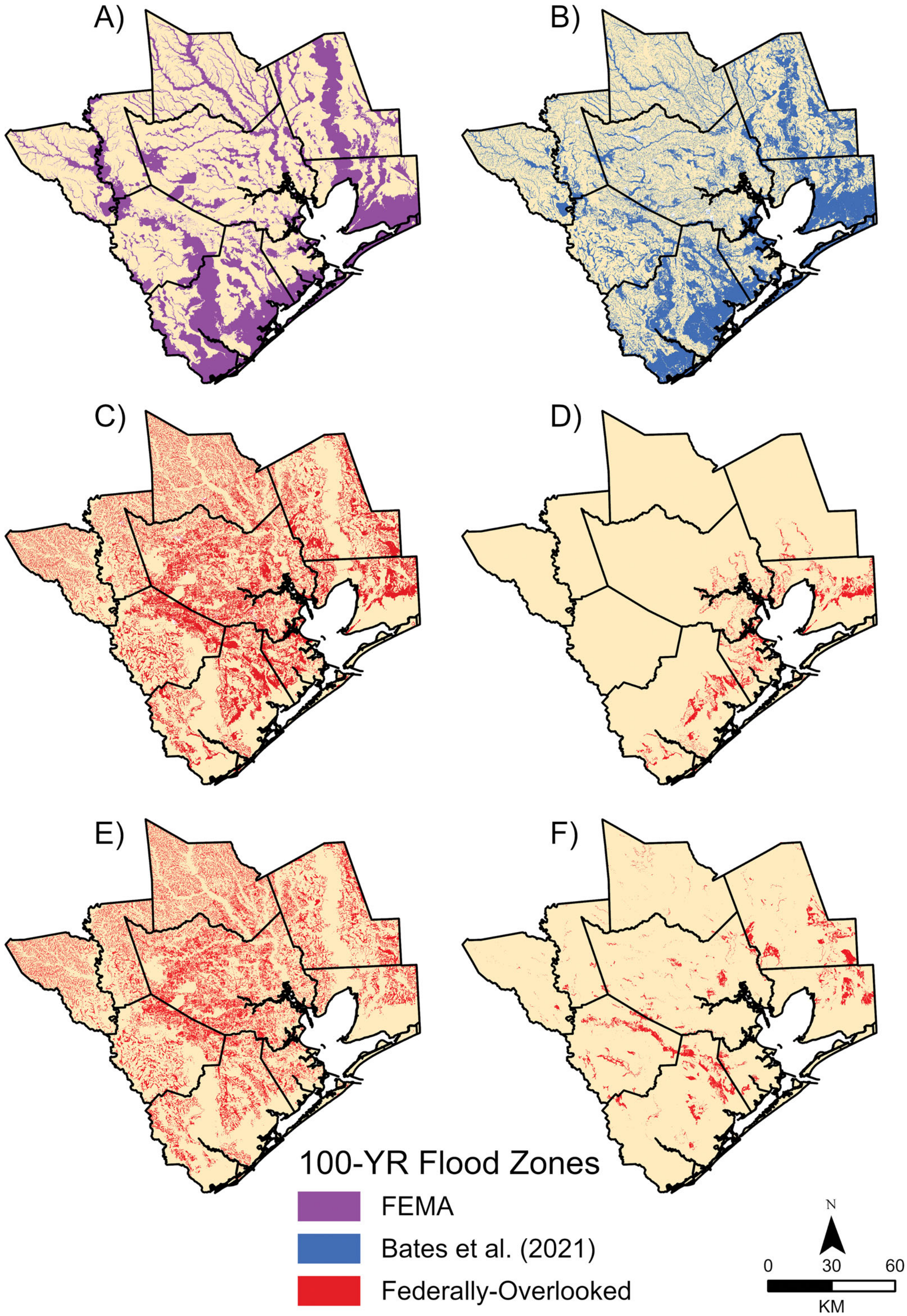

Figure 2. Greater Houston, Texas flood risk zones: (A) Federal Emergency Management Agency (FEMA) 100-year; (B) Bates et al. (2021) 100-year; (C) federally overlooked 100-year combined; (D) federally overlooked 100-year coastal; (E) federally overlooked 100-year pluvial; and (F) federally overlooked 100-year fluvial. *Note*: Federally overlooked flood zones are all 100-year flood zones delineated by Bates et al. (2021) that fall outside of FEMA-delineated 100-year flood zones.

Table 1. Descriptive statistics for analysis variables, Greater Houston, Texas

Continuous variables	M	SD	Minimum	Maximum
Dependent variables (counts of people)				
Combined overlooked flood zone	908	1,084	0	8,941
Coastal overlooked flood zone	153	469	0	7,301
Pluvial overlooked flood zone	559	609	0	6,544
Fluvial overlooked flood zone	196	667	0	7,263
Independent variables				
Proportion non-Hispanic (NH) Black	0.172	0.187	0.000	0.921
Proportion Hispanic/Latino	0.393	0.246	0.000	0.976
Proportion NH Asian	0.064	0.087	0.000	0.758
Proportion NH multiple/other races	0.019	0.017	0.000	0.112
Median household income ($)	70,399	38,945	13,886	250,000+
Proportion mean imperviousness	0.480	0.150	0.064	0.927
Proportion mean tree canopy	0.449	0.181	0.000	0.903
Proportion Toxic Release Inventory petroleum facilities	0.007	0.055	0.000	0.897
Proportion vacation households	0.076	0.159	0.000	1.000
Dichotomous independent variables	Yes	No		
Suburban/exurban[a]	79	973		
Rural/small town[b]	33	1,019		

Note: $N = 1{,}052$ census tracts. NH White is the reference group for NH Black, Hispanic, NH Asian, and NH multiple and other races. Federally overlooked flood zones are all 100-year flood zones delineated by Bates et al. (2021) that fall outside of Federal Emergency Management Agency-delineated 100-year flood zones.
[a]Rural–urban community area (RUCA) codes 2–3 (reference RUCA code 1 [urban core]).
[b]RUCA codes 4–10 (reference RUCA code 1 [urban core]).

Analysis Approach

We used generalized estimating equations (GEEs) to predict the population-adjusted count of people living in federally overlooked 100-year flood zones at the census tract level. GEEs allow us to analyze inequities in flood risk by relaxing several assumptions of traditional regression models; they are appropriate for nonnormally distributed dependent variables and they account for geographic clustering (Liang and Zeger 1986). We defined our clusters based on the median year of housing stock (i.e., 1939 or earlier, 1940–1949, 1950–1959, 1960–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009, 2010 or later) by county ($n = 9$), which resulted in forty-seven clusters with between 1 and 194 census tracts. This cluster definition corresponds with the residential development contexts within which census tracts are nested.

GEEs require the specification of an intracluster dependency correlation matrix (Liang and Zeger 1986). For this study, we tested unstructured, exchangeable, and independent correlation matrices. Our dependent variables are counts (of residents within federally overlooked flood zones), making Poisson or negative binomial distributions most appropriate (Garson 2013). Because of overdispersion (i.e., variance larger than the conditional mean), the negative binomial distribution was most appropriate (Garson 2013). We estimated negative binomial GEEs using each alternative correlation matrix specification. We then selected the best fitting model based on the quasi-likelihood under the independence model criterion (QIC) values (Garson 2013). For each GEE, the exchangeable correlation matrix with a negative binomial distribution and a logarithmic (log) link function produced the lowest QIC value, and thus the best fit. We used the natural log of the total population for each census tract as an offset in the negative binomial models to adjust for varying population sizes and to make model results interpretable as incidence rate ratios (Garson 2013).

We standardized all continuous independent variables before inclusion in models so that coefficients were directly comparable. We tested for multicollinearity by inspecting bivariate correlations and collinearity statistics. Collinearity statistics indicate that none of our independent variables have tolerance values less than 0.1 nor inflation factor values greater than 10. The multicollinearity condition index scores ranged from 3.1 to 9.5. A condition index of 30 or more is generally considered indicative of multicollinearity problems (Hair et al. 2013). We concluded that inferences from our models are

not affected by multicollinearity. We excluded census tracts with missing data for any analysis variables and with populations lower than 500 ($n = 17$), resulting in a sample size of 1,052.

Results

Univariate Analysis

We found that more than 950,000 Greater Houstonians—16 percent of the total population—resided in federally overlooked 100-year flood zones. The largest component of that population (~588,000) resided within federally overlooked pluvial flood zones. The federally overlooked fluvial and coastal flood zones contained approximately 160,000 and 206,000 residents, respectively. Table 1 reports descriptive statistics for the analysis variables.

Figure 3 shows the spatial distribution of federally overlooked 100-year flood risk by census tract in Greater Houston. Census tracts with the highest counts of residents in federally overlooked 100-year flood zones were primarily concentrated in northeastern Fort Bend and Brazoria counties (north of the Brazos River), in southern Liberty County, in northwestern Chambers County, and in western, northern, and eastern Harris County. Tracts with the highest counts of residents in federally overlooked 100-year coastal flood zones were in Brazoria, Galveston, Harris, Chambers, and Liberty counties, adjacent to the Gulf of Mexico. Tracts with the highest counts of residents in federally overlooked 100-year pluvial flood zones were in northwestern (near Cypress Creek and White Oak Bayou) and southern (south of Buffalo Bayou and downtown Houston) Harris County, and along the northeastern border of Fort Bend County. Tracts with the highest counts of residents in federally overlooked fluvial flood zones were located in northeastern Fort Bend and Brazoria counties. Additionally, relatively high counts of residents in tracts of eastern and northeastern Harris County, along the HSC and near Lake Houston, lived in federally overlooked fluvial flood zones.

Multivariable GEE Analysis

Table 2 summarizes GEE results. In terms of the federally overlooked 100-year combined flood risk model, one standard deviation increases in the proportions of NH Black, Hispanic, and NH Asian residents were associated with respective increases of 21.1 percent, 25.6 percent, and 12.4 percent in the number of residents at risk in tracts. Median household income was a significant nonlinear predictor of flood risk in the federally overlooked combined flood risk model. The association takes a concave shape with the strongest relationship with flood risk at middle income.

To illustrate the strength of the associations between higher minority racial and ethnic composition and increased federally overlooked 100-year flood risk, we calculated estimated marginal means for each race or ethnicity variable that was associated with a significant increase in the population-adjusted count of residents in federally overlooked 100-year flood zones (Figure 4). Holding all other independent variables constant, when proportion NH Black was at the minimum (0), 50th percentile (0.10), and 100th percentile (0.92) for census tracts, the respective point estimates for the proportion of residents living in federally overlooked 100-year flood zones were 0.14, 0.15, and 0.35. Thus, when the proportion of tract population that was NH Black was at the minimum versus the maximum compared to the proportion that was White, the estimated proportion of residents living within federally overlooked 100-year flood zones was 2.5 times greater. When proportion Hispanic was at the minimum (0), 50th percentile (0.33), and 100th percentile (0.98), the respective point estimates were 0.11, 0.15, and 0.28, indicating that when the Hispanic composition was at the minimum versus the maximum compared to the White composition, the estimated proportion of residents within federally overlooked 100-year flood zones was nearly three times greater. Similarly, when proportion NH Asian was at the minimum (0), 50th percentile (0.03), and 100th percentile (0.76), the respective point estimates were 0.15, 0.16, and 0.42, indicating that the proportion of residents within federally overlooked 100-year flood zones was nearly three times greater at the maximum versus minimum for proportion NH Asian.

In the federally overlooked 100-year coastal flood risk model, one standard deviation increases in NH Black and NH Asian neighborhood composition were associated with 48.8 percent and 67.3 percent decreases in risk, respectively, and a one standard deviation increase in Hispanic neighborhood

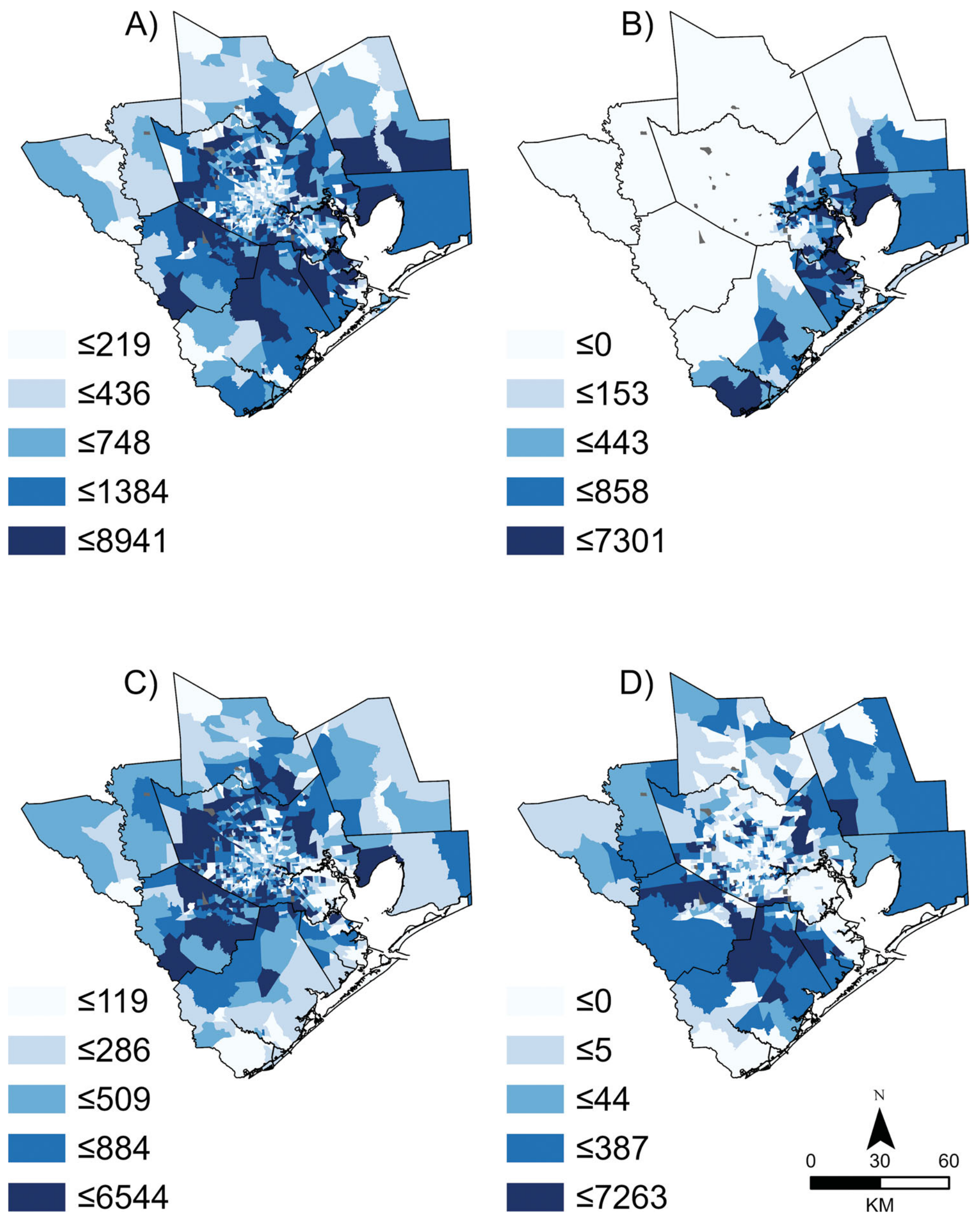

Figure 3. Quantile classification of the number of people per census tract residing in Greater Houston, Texas flood risk zones: (A) federally overlooked 100-year combined; (B) federally overlooked 100-year coastal; (C) federally overlooked 100-year pluvial; and (D) federally overlooked 100-year fluvial. *Note*: Federally overlooked flood zones are all 100-year flood zones delineated by Bates et al. (2021) that fall outside of Federal Emergency Management Agency (FEMA)-delineated 100-year flood zones.

composition was associated with a 48.2 percent increase in risk (Table 2). Median household income was a significant nonlinear predictor in the federally overlooked 100-year coastal flood risk model, whereby flood risk increased going from low to middle income and then decreased from middle to high income.

In the federally overlooked 100-year pluvial flood risk model, one standard deviation increases in NH Black, Hispanic, and NH Asian were associated with 30.7 percent, 11.7 percent, and 12.3 percent increases in risk, respectively. Median household income was a significant nonlinear predictor in the federally overlooked 100-year pluvial flood risk model, in a similar manner to the relationship observed in the other models.

In the federally overlooked 100-year fluvial flood risk model, one standard deviation increases in NH Black, Hispanic, and NH Asian were associated with 87.3 percent, 125.7 percent, and 91.0 percent increases in risk, respectively. Median household income showed no statistically significant relationship with federally overlooked fluvial flood risk.

Table 2. Generalized estimating equations predicting population-adjusted federally overlooked 100-year flood risk for census tracts in Greater Houston, Texas

	Combined federally overlooked flood risk		Coastal federally overlooked flood risk		Pluvial federally overlooked flood risk		Fluvial federally overlooked flood risk	
	B	IRR [95% CI]	*B*	IRR [95% CI]	*B*	IRR [95% CI]	*B*	IRR [95% CI]
Intercept	–1.814	0.163 [0.143, 0.186]***	–4.125	0.015 [0.010, 0.021]***	–2.414	0.089 [0.085, 0.094]***	–3.696	1.873 [1.375, 2.551]***
Prop. hon-Hispanic (NH) Black	0.192	1.211 [1.087, 1.349]***	–0.669	0.512 [0.403, 0.651]***	0.267	1.307 [1.236, 1.381]***	0.628	1.873 [1.375, 2.551]***
Prop. Hispanic	0.228	1.256 [1.131, 1.394]***	0.394	1.482 [1.149, 1.912]**	0.110	1.117 [1.042, 1.197]**	0.814	2.257 [1.519, 3.354]***
Prop. NH Asian	0.117	1.124 [1.052, 1.202]**	–1.117	0.327 [0.214, 0.500]***	0.116	1.123 [1.068, 1.180]***	0.647	1.910 [1.607, 2.271]***
Prop. NH other	0.012	1.012 [0.924, 1.087]	0.183	1.201 [0.913, 1.580]	–0.004	0.996 [0.944, 1.050]	–0.088	0.916 [0.762, 1.101]
Median income	0.700	2.014 [1.481, 2.738]***	1.052	2.863 [1.128, 7.267]*	0.708	2.031 [1.644, 2.508]***	0.574	1.775 [0.692, 4.550]
Median income (squared)	–0.538	0.584 [0.457, 0.745]***	–1.201	0.301 [0.141, 0.643]**	–0.545	0.580 [0.477, 0.705]***	–0.115	0.892 [0.419, 1.897]
Prop. mean imperviousness	–0.003	0.997 [0.905, 1.099]	–0.222	0.801 [0.561, 1.143]	0.033	1.033 [0.928, 1.151]	–0.660	0.517 [0.346, 0.772]**
Prop. mean tree canopy	–0.025	0.975 [0.893, 1.065]	0.315	1.371 [0.944, 1.990]	0.019	1.020 [0.940, 1.106]	–0.298	0.742 [0.517, 1.065]
Prop. Toxic Release Inventory petroleum facilities	0.005	1.005 [0.994, 1.017]	0.120	1.128 [1.086, 1.171]***	–0.021	0.979 [0.953, 1.006]	–0.182	0.834 [0.718, 0.968]*
Prop. vacation housing	–0.016	0.984 [0.933, 1.037]	–0.095	0.909 [0.822, 1.006]	–0.125	0.882 [0.813, 0.957]**	–0.185	0.831 [0.723, 0.955]**
Suburban/exurban	–0.028	0.937 [0.732, 1.292]	0.417	1.517 [0.920, 2.504]	–0.319	0.727 [0.541, 0.978]*	0.172	1.187 [0.480, 2.940]
Rural/small town	0.064	1.066 [0.702, 1.620]	2.778	16.093 [6.453, 40.135]***	–0.676	0.509 [0.236, 1.098]	–0.441	0.643 [0.086, 4.807]

Note: $N = 1{,}052$. IRR = incidence rate ratio or Exp(B); CI = confidence interval.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

Discussion

In response to Research Question 1, findings indicate that nearly 1 million people lived at risk to 100-year flooding outside of FEMA-delineated zones in Greater Houston—16 percent of the total population. The U.S. federal government has overlooked this alarmingly large at-risk population because it relies on an incomplete flood modeling approach as the foundation for official flood risk assessment, mitigation, and policymaking nationwide. Our results indicate that reliance on FEMA

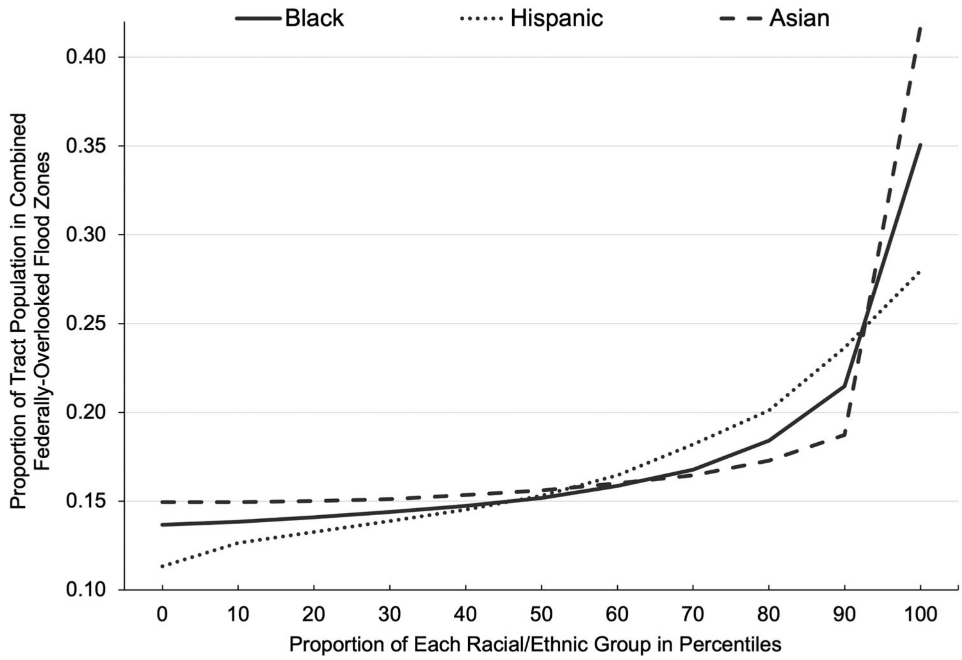

Figure 4. Estimated marginal mean federally overlooked flood risks based on race or ethnicity variables in percentiles, Greater Houston census tracts ($N = 1{,}052$). *Note*: Values derived from Table 2 and predicted holding each other independent variable in the generalized estimating equation at its mean.

flood risk assessment to guide management into the indefinite future in Greater Houston will eventually be catastrophic in terms of the scale and inequities of flood impacts. Studies of Hurricane Harvey have already documented large-scale, inequitable impacts beyond FEMA-delineated flood zones in Greater Houston (Chakraborty, Collins, and Grineski 2019; Collins et al. 2019; Elliott 2019; Smiley 2020). Although more research is needed to clarify the scope and inequities in federally overlooked flood risk beyond Greater Houston, this is undoubtedly a serious and worsening problem nationwide as risks continually increase due to climate change and urbanization in hazardous zones.

In terms of Research Questions 2 and 3, we found that greater racial and ethnic minority composition in neighborhoods was associated with increased federally overlooked 100-year flood risk, but inequities varied by flood type. Higher Black neighborhood composition was associated with increased federally overlooked 100-year combined, pluvial, and fluvial flood risk, but decreased coastal flood risk, possibly due to the socioenvironmental exclusivity of some coastal settings. These results partially align with prior studies indicating that Black residents in Florida were more likely to live in inland flood zones rather than coastal flood zones with water-related amenities (Montgomery and Chakraborty 2013, 2015; Chakraborty, Collins, Montgomery, et al. 2014). Our main findings for inequitable exposure to federally overlooked flood risk based on Black neighborhood composition align with decades of research documenting how Black neighborhoods and people in Houston have been disproportionately burdened by hazards (Bullard 1990; Chakraborty, Collins, Grineski, et al. 2014; Collins et al. 2015; Chakraborty, Collins, and Grineski 2019).

Greater Hispanic neighborhood composition was associated with increased federally overlooked 100-year flood risk in reference to all types of flooding. The increased flood risk in coastal overlooked flood zones for Hispanic neighborhoods is likely due to a combination of factors, including the lack of flood risk mapping by FEMA in tracts along the HSC where Hispanic residents concentrate. Studies focused on FEMA-delineated 100-year flood zones in Miami, Florida, have shown the opposite—that Hispanic neighborhood composition was associated with less coastal flood risk (Montgomery and Chakraborty 2013, 2015; Chakraborty, Collins, Montgomery, et al. 2014). The divergence in findings between those studies and ours could be explained by discrepancies between the FEMA and Bates et al. (2021) flood models as well as

differences in coastal environmental (dis)amenities between the two contexts. In reference to the latter explanation, whereas Miami's coastline is rich in water-based amenities, some of Greater Houston's federally overlooked coastal flood zones are endowed with the disamenities of the petrochemical industrial complex and HSC (Collins, Grineski, and Chakraborty 2018). Other distributional EJ studies have documented inequitable exposures to hazards in Greater Houston based on Hispanic neighborhood composition (Linder, Marko, and Sexton 2008; Chakraborty, Collins, Grineski, et al. 2014), and that exposures have worsened through time (Bernier et al. 2017).

Higher Asian neighborhood composition was associated with increased federally overlooked 100-year combined, pluvial, and fluvial flood risk, but decreased federally overlooked coastal flood risk. Prior EJ research on the Asian American community in Greater Houston is limited, but other U.S.-based studies have documented increased hazard exposure based on Asian neighborhood composition (Grineski, Collins, and Morales 2017; Fahy et al. 2019). Neighborhoods with higher proportions of Asian Americans are primarily located in northeastern Fort Bend County (on the outskirts of Houston) near the Brazos River (at risk to fluvial flooding). This suburban zone is characterized by new residential development (Bauman 2021). Fort Bend County has a median household income 46 percent greater than the whole of Greater Houston, suggesting that overall levels of social vulnerability are lower than for most other Greater Houston neighborhoods at high federally overlooked flood risk (Tate et al. 2021).

Findings for SES indicate that middle-income neighborhoods experienced the highest risk in federally overlooked combined, coastal, and pluvial flood zones. Although this does not align with many EJ studies, several studies of flood risk have observed that neighborhoods with higher SES experience the greatest exposure (Maantay and Maroko 2009; Grineski et al. 2015; Maldonado et al. 2016; Grineski, Collins, and Morales 2017), particularly in coastal settings (Montgomery and Chakraborty 2013, 2015; Chakraborty, Collins, Montgomery, et al. 2014). Additionally, FEMA FIRMs do not model pluvial flooding, making that type of flood risk the most prevalent in federally overlooked zones; and middle-income areas of Greater Houston are characterized by high pluvial flood risks, which underpins our results.

Prior research in Greater Houston has highlighted how race- and class-based oppression is historically entwined in the production of regional environmental injustices (Bullard, Grigsby, and Lee 1994; Vojnovic 2003; Collins, Grineski, and Chakraborty 2018; Flores, Castor, et al. 2020; Flores, Collins, et al. 2020). Nevertheless, our results suggest that racial and ethnic composition is a more important influence than median household income on the unequal distribution of federally overlooked flood risks in Greater Houston. This is perhaps due to the complex relationships that exist between SES, water-based amenities, and flood hazards (Bin and Kruse 2006; Collins, Grineski, and Chakraborty 2018). An analysis of all flood zones might find a different relationship, whereby SES is not associated or is negatively associated with flood risk.

Residents of federally overlooked flood zones—especially those disadvantaged based on race or ethnicity—are more vulnerable to flooding than residents of FEMA 100-year flood zones due to the underinvestment in structural and nonstructural flood hazard mitigation strategies, which amplifies the risks they face (Muñoz and Tate 2016; Hendricks and Van Zandt 2021). An analysis of local and regional plans in place prior to Hurricane Harvey in the western portion of Greater Houston showed that flood hazard mitigation efforts had focused on FEMA 100-year flood zones and neglected areas beyond that experienced heavy damage from Harvey's floodwaters (Malecha, Woodruff, and Berke 2021). Structural flood hazard mitigation efforts failed to address risks in neighborhoods outside of FEMA 100-year flood zones, yet Harvey produced catastrophic and socially inequitable flooding in those areas (Smiley 2020; Malecha, Woodruff, and Berke 2021). Thus, the focus of structural mitigation efforts within FEMA 100-year flood zones and concomitant failure to recognize flood risks beyond those boundaries exacerbated social inequities in flood impacts. Based on Smiley's (2020) findings, Harvey-induced flooding had disparate impacts based on minority race and ethnicity primarily in areas beyond FEMA 100-year flood zones. Our analysis indicates a similar pattern with respect to neighborhoods at risk to federally overlooked 100-year flooding.

Furthermore, residents of Greater Houston's federally overlooked 100-year flood zones are poised to experience disparate impacts due to substantially

lower rates of flood insurance coverage relative to residents of FEMA-designated 100-year flood zones, which greatly amplifies their risks. Rates of flood insurance coverage are significantly higher in FEMA 100-year flood zones than elsewhere (Brody, Highfield, et al. 2017; Kousky, Kunreuther, et al. 2020). In comparison to households affected by Hurricane Harvey living within FEMA 100-year flood zones, those affected outside of FEMA 100-year flood zones had lower rates of flood insurance, an increased likelihood of needing mortgage loan modifications, and an increased likelihood of being delinquent on mortgage payments (Kousky, Palim, and Pan 2020). Lower rates of flood insurance in areas outside of FEMA 100-year flood zones are a key driver of reduced coping capacities, leading to slower recovery and higher rates of residential displacement after major flood events (Kousky, Kunreuther, et al. 2020).

Our results align with other EJ studies of Bates et al. (2021)-modeled flood risk (Rhubart and Sun 2021; Tate et al. 2021) and flood events (Curtis et al. 2011; Chakraborty, Collins, and Grineski 2019; Collins et al. 2019; Elliott 2019; Smiley 2020; Lieberman-Cribbin et al. 2021)—which highlight race- and class-based inequities in the distribution of U.S. flood hazards—yet diverge from some EJ studies focused on FEMA-delineated flood risk (Maantay and Maroko 2009; Montgomery and Chakraborty 2013; Chakraborty, Collins, Grineski, et al. 2014; Grineski et al. 2015; Grineski, Collins, and Morales 2017; Qiang 2019; Shao et al. 2020). More specifically, our findings run counter to those from a study in Greater Houston that found less FEMA-delineated 100-year flood risk based on greater Black and Hispanic neighborhood composition (Grineski et al. 2015). Given the well-documented inaccuracies of FEMA flood maps and findings from EJ studies of Bates et al. (2021)-modeled flood risk and flood events, the bulk of evidence highlights social inequities in the actual distribution of U.S. flood hazards, despite inconclusive evidence from studies of FEMA-delineated 100-year flood risks. Moreover, the presence of race-based 100-year flood risk inequities beyond, but not within, FEMA flood zones suggests that FEMA's (inclusionary–exclusionary) flood risk delineation and management processes might shape inequities. Residents within FEMA 100-year flood zones are the primary recipients of federal flood protection resource provisioning for communities and individuals nationwide. In contrast, areas outside of FEMA 100-year flood zones are characterized by acute flood risks, whereby socially disadvantaged groups are overrepresented and where flood risk reduction activities are comparatively lacking. Thus, although our findings indicate race-based inequities within federally overlooked 100-year flood zones, in light of the broader literature, they suggest that risk inequities between federally overlooked and FEMA flood zones have been produced through the federal government's approach to mapping and managing flood hazards. Future research should examine that proposition in Greater Houston and beyond.

This study has some limitations. First, although the Bates et al. (2021) model is currently the best available, it propagates error due to incomplete data regarding flood defense and drainage infrastructure, terrain, channel bathymetry, and so on, particularly at fine spatial scales. The model is currently being updated by integrating such data. Second, even though our dasymetric mapping increased the accuracy of our residential population distribution and hazard exposure estimates, we assumed that population density was homogenous in each 30-m resolution pixel. These 30-m pixels, however, are much smaller in size than more commonly used census areal units (e.g., census blocks, census tracts), for which homogeneity assumptions are far more problematic in terms of measuring hazard exposure. Third, although our use of 2010 U.S. Decennial Census block-level population counts likely underestimated the actual number of people living in federally overlooked flood zones, block-level population counts from the 2020 Decennial Census were not yet available.

Conclusions

In terms of contributions, our application of state-of-the-art spatial analytic techniques, including high-resolution hazard modeling and dasymetric mapping, offers a general model for advancing geographical research in the EJ and hazards fields. More specifically, our study provides the methodological basis for future research that should investigate inequities in federally overlooked flood risks nationwide. By documenting the scope and inequities of federally overlooked flood risks across Greater Houston, we clarified a major, albeit largely unrecognized, public policy issue. Residents in federally

overlooked zones are inadequately protected from flooding and our results suggest that these spaces need targeted investments to reduce risks and redress environmental injustices.

Federally overlooked 100-year flood zones are not mandated for protection via the NFIP and generally lack the investments in flood protections that are directed toward FEMA-delineated 100-year flood zones. FEMA's estimates suggest that approximately 13 million U.S. residents are living within 100-year flood zones, whereas analysis based on a previous version of the Bates et al. (2021) model indicate that approximately 41 million are (Wing et al. 2018). Accurate flood risk mapping is foundational for effective and equitable flood protection. Our findings and those of others suggest that effective and just flood protection will be impossible to achieve without transforming FEMA's flood modeling approach. Given advances in computational big data analytic methods, more accurate, cost-effective, and easily updatable flood risk modeling approaches are available that FEMA could embrace, particularly for areas and flood types not covered by their maps.

We recognize that revising FEMA's flood mapping approach is not only technical but also deeply political, with the political dimension presenting the most formidable obstacles to change. First are the EJ issues that attend such revisions. Based on current protocol, official amendments to FEMA's flood maps require extensive supporting evidence from engineers, which can be too costly for financially strapped communities (Pralle 2019). Without changes to the protocol, remapping efforts will continue to overlook low-resource rural communities, many of which FEMA's maps currently exclude (Pralle 2019). Our own results show that rural and small-town areas in Greater Houston experience increased federally overlooked 100-year coastal flood risk, highlighting their exclusion from FEMA mapping. Our results also show that widespread, small area gaps in FEMA flood map coverage underpin large and inequitable population risks to federally overlooked 100-year flooding in many urbanized areas of Greater Houston, particularly in neighborhoods at risk of pluvial flooding. Expanding FEMA 100-year flood zone boundaries to include overlooked areas at risk could help address inequities in flood protection, but it also raises EJ issues surrounding the ability of low-income and disadvantaged racial and ethnic minority homeowners to pay for federally mandated flood insurance via the NFIP. When a revision places socially disadvantaged residents in a newly delineated flood zone, it might also devalue their properties, further marginalizing them in the process.

Second, the process to update FEMA FIRMs is slow (Pralle 2019). In portions of Greater Houston, FEMA FIRMs have not been updated since 2007. Revisions were initiated following Hurricane Harvey, but years remain before new FIRMs will be adopted, and those maps will fail to account for intensified rainfall scenarios based on climate projections. Updating flood maps in response to real-time climatic and built environmental changes based on the current protocol is thus impossible.

Third, and perhaps most significant, FIRM revisions are highly contested by powerful interest groups, including real estate developers and their growth machine associates in local and state governments who view flood map revisions as a threat to capital accumulation and tax base expansion (Logan and Molotch 2007; Barrios et al. 2020). For example, powerful interest groups in Miami that profit from real estate development have sought to maintain the status quo, which requires expensive resilience initiatives in areas at risk to flooding and reproduces environmental injustices in the process (Grove, Cox, and Barnett 2020). The federal government must first confront, then assuage, such powerful interests in seeking to overhaul FEMA's approach, which might prove intractable in the current political-economic climate. To conclude, we have the technical knowledge to accurately map emerging flood risks and to implement adaptive, equitable flood protection approaches. Acting on that knowledge will require broad-based mobilization of collective political will.

Supplemental Material

Supplemental data for this article can be accessed on the publisher's site at: http://dx.doi.org/10.1080/24694452.2022.2085656. Materials include bivariate correlations, maps of analysis variables, and results from an exploratory supplemental analysis in which we introduced the independent variables in four stages using a stepwise approach.

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