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Evaluating the unequal impacts of Hurricane Harvey: A critical GIS analysis in systems of governmental risk assessment and mitigation

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This thesis uses flooding driven by Hurricane Harvey in 2017 and a history of inundation in Houston, Texas to critique the systems of floodplain mapping through the National Flood Insurance Program (NFIP). The role of Geographic Information Systems becomes a subject of interest in the context of U.S governance and the role of property as a driving force in urban development. The shortcomings of existing systems of mitigation are examined through mappings that bring measures of risk, damage, and recovery into contrast with each other. Racial and economic inequality are integrated into the analysis through a deeper consideration of the NFIP as the main form of federal protection against losses. Seeing that the NFIP has not protected the true status quo of urban life, it is argued that public perceptions of risk are formed contrary to the logic of home insurance, leading to observable inequalities in preparation and recovery.

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CHAPTER I

INTRODUCTION

The 2017 Atlantic Hurricane season has been typified in subsequent years as especially active, with three record-breaking storms that have gone on to embody different sources of risk from tropical cyclones: The prolonged intensity of Hurricane Irma was marked by devastation across the Caribbean. Hurricane Maria demonstrated the ability of the compound risks of intense wind and rainfall to cause failures in unprepared infrastructure in Puerto Rico, and Hurricane Harvey created record-breaking precipitation across the Gulf Coast due to its relatively slow speed and extended track. It is striking that these storms all occurred within the same season, but it is perhaps more important to note that the effects of these storms diverged from one another: one category of weather event was marked in three different ways. Thus, while physical scientists continue researching tropical cyclones as phenomena in themselves the existing dynamics of their effects on people should also be advanced in the face of potential increasing hurricane activity and the features of intensifying storms (see Risser and Wehrner, 2012). The subject of this thesis is the National Flood Insurance Program and the system of flood risk mapping that supports governmental flood risk mitigation in the United States, using Houston, Texas and Hurricane Harvey as a way of identifying a specific time and place where it was called into action.

Hurricane Harvey made landfall near Houston as a Category 4 Hurricane, lasting a total of 6 days over land, moving back over the ocean at least once before dissipating further inland in

Kentucky. By dropping as much as 1520 millimeters of rain in the Houston area, drainage channels in multiple watersheds were overwhelmed, leading to emergency discharges from the Addicks and Barker flood retention reservoirs (Blake and Zelinsky, 2018). The inability of the affected to remove themselves from hazardous areas directly lead to at least 70 deaths, most of which were observed *outside* of the Special Flood Hazard Area and the 500-year floodplain that FEMA uses to assess flood risk, raising the question of how flood risk is mapped and understood in the city (Jonkman et al, 2018). Significant portions of these drowning fatalities were associated with transit in some form, as individuals attempted to navigate a dangerous landscape of flooded infrastructure, finding themselves trapped by unexpectedly deep and strong flows of water. Houston is a city of suburban sprawl, seen in its spatially distributed development and marked by arterial highways. The structure of cities determines the distribution of hazard, both through its built environment and underlying topology. Although Houston had a far lower fatality rate during Hurricane Harvey compared to Hurricane Katrina, the natural hazards of Houston have a geography that creates its own context but can also be compared with other cities and their environments.

Houston thus provides rich ground for hazard studies generally, and hurricanes provide a paradigmatic hazard to examine the crises of environmental adaptation in the urban setting. The study of cities and hazards calls upon the research fields such as political science, meteorology, and urban studies, but their findings are ultimately incorporated into a conclusion on hazards and adaptation. The epistemological walls between these subjects are part hindrance and part organizational tool; this work of synthesis seeks to join knowledge where it meets. The logic of one approach will not be adopted at face value (e.g. research from fields such as insurance will be considered beyond the subject of insurance). Despite seeking to critique existing practices, this research will use existing methods and sources of information in order to investigate the state of preparation before Hurricane Harvey and the ways that damage was recorded after it passed. Geographic Information Systems (GIS), mapping, and governmental data are subjects of critique here, but their utility and persuasiveness are irreplaceable, Balancing the assertions of these tools with the realities that they create and shape is important and uses the precedence of other critical research. Ideally, conscious usage will avoid the harms driven by unconscious or unquestioned use, producing understandable visualizations of spatial knowledge that expose the function of mitigation measures within the greater regime of property, capital, and social inequality.

This study uses two research questions to shape inquiry:

1. How does adaptation to the inundation derived from Hurricane Harvey relate to mapped flood risk?
2. How does unpredicted flooding relate to social inequalities in vulnerability?

In Chapter II, the theoretical backing behind this study is introduced, exploring vulnerability in hazards literature, with attention paid to Social Vulnerability Indices (see Cutter, 2003) as one attempt of creating spatial information on vulnerability that can be compared between regions. Chapter II concludes with an extended discussion of the role of Geographic Information Systems and governments in shaping authoritative spatial data, leading to a need for critical approaches to GIS that find new configurations of information that avoid the earliest conclusion. To better empower this effort, Chapter III is a case study that describes the history of Houston as it relates to its social and urban environment, adding important context on histories of mitigation in the United States and the political history of the National Flood Insurance Program (NFIP) and flood mapping in the United States. Using that context, Chapter IV is an analysis of flooding in Houston, relating specially to mapped flood risk, household adaptation strategies beyond the NFIP, and the ways that unpredicted flooding relates to the social inequalities introduced in Chapter III. Chapter V concludes with a discussion of the findings of Chapter IV in relation to Chapters II and II.

CHAPTER II

THEORIES OF HAZARDS, GEOGRAPHIC INFORMATION AND GOVERNANCE

Theory takes an especially prominent role in this thesis because it takes a critical approach to the subject of flood mapping and the role of Geographic Information Systems (GIS) through an investigation of the effects of Hurricane Harvey on Houston. The powerful tools of spatial analytics and Geographic Information Systems are bolstered by a consideration of how models and analysis have developed over time, including examples such as Social Vulnerability Indices (SVIs) or examining the role of the state in shaping spatial data. While the area of study is limited to Harris County, multiple governments operate within its boundaries each bringing a different approach to the concept of risk. Risk is perceived from observable phenomena in the environment, but governments, communities, and individuals have differing abilities to share their perception and act upon them in way that limits the exposure of people to hazards: risk and vulnerability are connected in the hazards experience, and even the objective ability to assess flood risk is directly tied to subjective abilities to adjust to communicated risk.

A. Hazards and Vulnerability

The effects of hurricanes on the urban environment go beyond physical measurements of a storm's magnitude, intensity, and duration, and measuring the total economic cost of a disaster is not enough. A paradigmatic provocation on the subject was given by Smith (2006), titled

“There is No Such Thing as a Natural Disaster”, an argument that does not deny the role of natural process but instead emphasizes the importance of social forces in differentiating exposure to hazards. In Smith (2006), critical failures in infrastructure, preparedness, and response are identified as human-derived sources of vulnerability, drawing directly from the situated example of Hurricane Katrina and New Orleans, proving that not only are certain groups of people exposed to more harm but that their recovery is shaped by social factors. Recognizing the role of social factors prevents the naturalization of disaster; existing social hierarchies and inequality stand to be replicated when the processes that produce them are unquestioned.

However convenient Smith’s essay may be in giving a time and place to the human element of vulnerability, hazards research does not start with Hurricane Katrina. Grossman (1977) understood contemporary distinctions between hazard-specific conditions and their systemic impacts as a development from the older environmental perception approach in human geography. In the work of scholars such as Ian Burton, Robert W. Kates, and Gilbert F. White, the study of human cognition and perception is directly tied to risk, making direct reference to human choice as a variable factor that affects vulnerability among others. In fact, the work of Burton et al in “The Environment as Hazard” (1993) further traces this thread back to White’s (1945) “Human Adjustment to Floods”, a dissertation that both characterized the history of floodplain management in the United States and criticized its focus on engineered controls, suggesting that multiple forms of adjustment should be evaluated and undertaken in a flood zone. This comprehensive approach to loss reduction has been reported as a major influence across multiple fields of study (Macdonald, 2012), and drives much of the thinking on flood management in the United States today.

If a hazard is a potential source of danger and risk is the possibility of exposure, then vulnerability is the potential for loss (Cutter, 1996). That said, loss has been defined in divergent ways, with Cutter (1996) noting that broader definitions exclude the most important qualities of loss, such as what is lost and by whom. Understanding vulnerability thus requires an accounting of its shifting conditions across space and across populations. In Blaikie et al (2003), these conditions are presented as "the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard" (p. 11*)*. Blaikie et al (2003) provide extensive elaboration on the concepts of risk and vulnerability, identifying distinct trends in vulnerability within different hazards. In flooding, for example, inundation can serve as a necessary part of agricultural cultivation, or it may ruin an entire season's harvest based on the time window in which a hazard is considered. Likewise, tropical cyclones may 'miss' cities and still have adverse impacts because the hazard is of a sufficient magnitude that direct hits are not necessary to cause significant impact (e.g. Tropical Storm Camille 'missing' New Orleans leading to more than 200 deaths). Inundation is a compound threat, with injury/disease, property damage, and direct mortality all examples of severe disruption that leaves some places disproportionately vulnerable.

Given the amount of attention spent on defining risk and vulnerability, it should be clear that these terms are important for studying hazards and preparing against harm, even though vulnerability is understood from different positions. 'Social vulnerability' describes the subset of vulnerability derived from social factors, but given the socially-mediated nature of these factors, definitions may vary. One construct used to provide a quantitative estimate of vulnerability is the Social Vulnerability Index (or SVI).

1. Social Vulnerability Indices

The original index (SoVI) in Cutter et al (2003) builds on the 'hazards-of-place' model advanced in Cutter (1996), which establishes a theoretical model of vulnerability that identifies it as a product of multiple hazardous factors, identifying the environment and the social fabric as elements of biophysical and social vulnerability. Ultimately, both aspects of vulnerability are assessed for a given place, and it is this vulnerability that brings risk and mitigation. Cutter et al (2003) take up the decades-old sociological institution of social indicators and apply it to vulnerability, reviewing literature on social vulnerability to establish key aspects of a population that are associated with greater vulnerability. From more than 250 U.S. Census variables, a subset of 11 factors was eventually derived through factor analysis, describing 76.4% of variance between the counties chosen. The top three factors by percent variation explained were personal wealth, age, and the density of the built environment, explaining around 35% of variance (Cutter et al, 2003). The utility of the SoVI went beyond producing a numerical account of social inequality because it also gave a spatial location for inequality through the administrative geographies it was calculated at, allowing direct comparisons between environmental and social data. In certain SVIs that followed the SoVI, this allows for longitudinal analyses of vulnerability over time (Cutter, 2008) as well as inter-scalar comparisons of different regions (Cutter, 2013). SVIs embody the advantages of GIS integration into vulnerability studies because of the possibility for replication and reconfiguration across times and spaces.

However, there are SVIs beyond the SoVI, because structural designs have been used to generate different SVIs, with Tate (2012) identifying at least 24 different indexes and 3 categories of thought (deductive, hierarchical, and inductive). The influence of social vulnerability in the discipline is still developing, seen in Cho and Chang (2017), where a survey of research articles on urban flood vulnerability found that socioeconomic vulnerability was the least frequent category of research, although comprehensive approaches were observed to dramatically increase after 2013. Social vulnerability indices seem to provide more value in research that intentionally combines different frames of vulnerability (a methodological inheritance from the comprehensive hazards-of-place model). Effectively, this means that information regimes surrounding social vulnerability research are also valuable subjects in themselves, we may include the priorities a user has when creating a specific model.

The Centers for Disease Control in the United States operates its own SVI (see Flanagan et al, 2018), and a joint effort by the Federal Emergency Management Agency and the National Oceanic and Atmospheric Administration has drafted a set of vulnerability indicators described as 'Community Resilience Indicators' (see Mitigation Framework Leadership Group, 2016). Resilience is not the opposite of vulnerability, but rather a related term that seeks to measure the effect that hazards will have; if vulnerability is potential for loss, resilience is the potential for recovery after loss. In a direct comparison, a social vulnerability index and a community resilience index (CRI) were found to have a relationship, although there were regional differences that demonstrated that the two elements can diverge from each other (Bergstrand et al, 2015). By choosing resilience, the Mitigation Framework Leadership Group (MFLG) orients the search for social influence away from investigating harm and towards evaluating how mitigation is already being carried out.

Choosing community resilience instead of social vulnerability is more than a rhetorical choice: in a draft paper introducing the CRI, the MFLG describes the importance of community indicators in direct reference to existing federal goals, such as the Natural Preparedness Goal. Indeed, the MFLG operates within a very specific context within the federal government of the

United States, making frequent reference to Presidential Policy Directives, official Federal definitions, and other constructs of bureaucratic origin (MFLG, 2016). They provide significant restriction, but these developments are necessary elements of the information processing function in governance because they provide a basis for standardization between agencies and across scales. Compatibility is key to the MFLG's resilience indicators, because FEMA intended CRIs to describe the state of an area's preparedness in order to understand where federal intervention is needed and how potential interventions might interact with existing adaptations to hazards. In direct contrast to the Social Vulnerability Index, CRIs are not derived through principal component analysis, despite the shared reliance on social factors and indicators more generally. This results in an increased branching in variables, rather than the reduction in count that forms the basis of the SoVI. The MFLG manually identified several themes of resilience, assigned variables to serve as indicators of each theme, but did not ultimately perform the statistical tests to reduce these indicators down to those which were associated with the most variance. Thus, while social vulnerability can be represented within an index, individual governmental entities choose to evaluate data differently, demonstrating that the applications of one Social Vulnerability Index can be limited in practice by the authority which operates geospatial technology and that there is no singular technological 'fix' for the issue of social inequality in the hazards experience. The significance of this control extends beyond the selection of methods, it also affects the methodology by which information is processed into data on the state level.

B. Geographic Information in Governance

Given that safety is a public good central to the existence of the state, closer attention should be paid to governments and their involvement in measuring and reporting information on hazards and risk. State involvement in geographic information precedes its current iteration under GIS in the Digital Age. In Crampton (2010), it is argued that earlier systems of governmental spatial organization in Western Europe, such as drawing territorial boundaries, gave way to more complex classification schemes, the rationale being that mercantilist expansion stretched traditional ideas of territory. Mapping thus forms a key linkage as classification regimes change, functioning as an item of political communication while the act of mapping still makes knowledge claims to support itself. This dual function is especially visible in early cartography and during the development of thematic mapping in the 19th century, when activities such as choropleth mapping or political cartooning required significant resources to present a single configuration of political space, contrasted with the interconnected information networks of the present day, where non-governmental organizations such as OpenStreetMap operate cartographic databases with thousands of contributors and codified rules for visual representation and classification of space. The proliferation of classification schemes for spatial information does not mean that mapping has now escaped authoritative control. “Geographic Information Systems” (GIS) is a term to describe this modern paradigm for computerized spatial data, where ‘layers’ of spatial information can be superimposed, altered, and analyzed to map out limitless configurations. Thus, the strongest state influence on geography is applied at the earliest stage of information processing. By deciding what will be measured and by what means data will be recorded, the tools of territory are reserved for government use.

Geographic Information Systems (GIS) are widely used to organize urban space, not only through the construction and maintenance of structures, but also by shaping how individuals act within the boundaries of the city. For some, this integration is seen as a promising trend that could lead to technologically sophisticated 'smart cities' in which geospatial technology is directly tied to nigh everything in the urban context (Tao, 2013). Against this ideal, an earlier criticism of spatial technology exists in Esnard (1998), where the integration of GIS into city governance is seen as ethically problematic, with key concerns being transparency and accountability. Geographic information provides the basis for action within the city: where problems are, which environment it exists in, and what political boundaries surround it. By controlling this information and how it is processed, governments create a specific vision of spatial reality, one which a user of GIS is obliged to accept. The role of the government is not totally disruptive, because work and research continue even after the data has been shaped, but this amount of processing has left its mark.

Thus, questions must be asked of hazards research, which will almost certainly rely on government-collected data (e.g., the Census Bureau's demographic surveys, the Federal Emergency Management Agency's Flood Insurance Rate Maps). Even at the level of Harris County in Texas, all land has been divided into property parcels and evaluated for the purposes of taxation. Drawing boundaries is the first step of governing, and spatial data is one of the most obvious forms by which areas become known and able to be governed (see Shelton, 2017). In practical observation of history, Haque (2001) found that federal and local governments had a mismatch in the years following the establishment of the National Spatial Data Infrastructure in 1994. In the earliest days, city governments were said to form the first regional networks for GIS data sharing, generating as much as 90% of spatial data (Haque, 2001). Local governments are both mandated to share data and privileged by being the sole creators and caretakers of these datasets, creating an entire policy dimension that surrounds the dissemination of state knowledge. In the context of austerity and the privatization of state functions, information control also demonstrates a specific economic function, where public-private partnerships and the promises of technological solutions in the 'Smart City' lead to an information regime in which citizens have the lowest priority in accessing information. Following Hurricane Harvey, governmental sources of data controlled access to information; claims data was not made publicly available until two years after the event, and even then, it was aggregated only to the census tract level (above the block *and* the block group level). Even so called 'open' data is often hosted on ESRI platforms, designed to be most accessible for ESRI's ArcMap software, to the detriment of any other alternative.

State information control through GIS extends beyond bureaucratic adjustments to dissemination. The act of mapping on behalf of the state is presented by Crampton (2004) as an extension of the modernizing state. The organization of this information reinforces nascent political concepts; for example, choropleth maps subtly gave meaning to political boundaries, and maps of population density in the early United States did not count indigenous populations and thus gave illusions of 'unsettled' land fresh for the taking. Given the precedents of Crampton (2004), Haque (2001), and Shelton (2017), mapping done in disaster zones needs to take caution and avoid accepting the 'closing' and the 'conditioning' offered by governmental datasets. The data made available by FEMA, Harris County, and the City of Houston is useful, but each comes with its own methodology that structures data for a specific use. My uses for this information are not the same as those who created it, so my methods and my reasoning must also deviate from theirs.

C. Critical GIS

Geographic Information Systems become a subject of critique in geography through multiple pathways. The clearest line of theoretical development in the practice is derived from critical cartography, which approaches map-making with questions about the ideas it takes for granted, with key publications such as Harley (1989) leading the way by adopting postmodern theories of deconstruction and applying them to maps. By treating maps as texts to be 'read' and interpreted, critical cartographers seek to reveal the hidden ideology that supports mapping by giving attention to precise elements of the mapping process. Harley (1989) framed cartography as an inherently rhetorical process (mapping requires that we 'omit' information to make good maps), while forecasting a 'culture of technics' in cartography that would increasingly value the technological elements of mapping. This is further encouraged by a 'digital turn', in which the role of computers and digital data became practically inseparable from the act of mapping. These developments demonstrate that Geographic Information Systems indeed inherit the ideology of maps and the same practices of mapping. Just as the cartographer has to decide what information will be displayed on a map, working with GIS requires an active decision to remove something. This connection is not a complete one: to say that critical cartography and critical GIS have some form of shared origin is not meant to imply that they fundamentally joined. Rather, cartography and GIS the act of mapping is something held in common between these fields, although the end result differs widely in form (see Crampton and Kyrgier, 2006).

The process of critique necessarily questions the fundamental basis of things, but critique does not demand the elimination of the subject. Such is the subject of Pavlovskaya (2006) and Elwood (2010), where the products of critical inquiry are integrated into geographical practice, with special attention on the social processes and effects of GIS. Using GIS and cartography while being self-critical enables a comparison between the common practices of today and the unexplored associations that drive that reality. This search for unexplored associations is driven by social theory and practical empirics surrounding the experience of crisis and disaster. Sheppard (2005) notes that the usage of 'critical' as an umbrella term to describe alternative approaches to geography does not diminish the existence of 'critical GIS' as a field. As a tool, GIS is certainly powerful. Research on human subjects is greatly aided by geolocative technology and the existing economic and political organization of space, but a truly critical usage of GIS does more than reintroduce humans to machines, it asks questions, some directed at the technology (why the machine occupies its position, who designed its functions, what resource powers it, etc.) and some directed at the human. In this paper, the questions and answers have their place, but at the core of the issue, Hurricane Harvey brought a severe disruption to the way of things the features of this disruption should be explored beyond the map because questions about GIS have limited uses on their own.

GIS (as Geographic Information Systems) is already known to its users as an assemblage made up of many different pieces of technology and specific implementations that have shaped their use. Indeed, the spirit of the field may be defined through debates that bring the knowledge bases of human geography and GIS into direct confrontation, with its ultimate potential seen in a negotiated collaboration between the two (seen in Schuurman, 2000) in which criticism can guide progress forward. Critical GIS is more than the critique of Geographic Information Systems from the outside; the term must also include the work done after the critique, when new perspectives are brought back into practice *inside* GIS. When geographers (and other science and technology researchers) have critiqued GIS, mapping, and cartography, the end goal has not been the abolition of these spatial practices. GIS thus is problematic but not a problem in itself, ideological but not an ideology, revolutionary but not the revolution, critique is limited only to direct conflict with the present; to be facing the past while the machines and industries of power evade any actual change. Indeed, Public Participation in Geographic Information Systems (PPGIS) is an early example of critique being adapted into practice (Schuurman, 2000). However, critique should not be treated as just a means to an end (the 'end' here being 'better GIS'). Critique should also be reflexive, which is to say that it should include itself as a subject.

Envisioned directly, this interpretation of critical GIS appears bleak. If the search for better GIS is a repetitive cycle of criticism, what significance does critique have outside of the applications of critical GIS? As a concept, performativity offers an option with which to consider critical GIS practice. Performative work in GIS embraces the significance of doing, an alternative to GIS methodologies which focus exclusively on results. While results are important parts of analysis, they are only one end of a process; they do not capture causality in total. Methods and methodology also shape how the world is understood; 'doing' GIS generates geographies of knowledge about the world. These geographies are not neutral, even when created to scientific standards, because they reproduce the conditions of power and knowledge that influenced them (Aalbers, 2014). Mapping and analyzing spatial data produce results that can be used to assert an image of reality, but the steps taken to bring about that image are part of the same phenomenon.

Thus, while geographic inquiry can always stand to be improved, each map is an expression of a larger process of knowledge production, even when new ways of mapping are developed. For Crampton (2009), the way that mapping is done creates its own meaning: each 'performance' of mapping reinforces the assumptions taken to create it. Nash (2000) draws from Judith Butler and the theory of performative gender to imagine a nonrepresentational way of being critical, moving from ‘reading’ maps and instead examining how a map comes to be. The performativity and dance of Nash (2000) is in constant negotiation, seeing opportunities and pitfalls alike in questions of body/embodiment and being/becoming, seeking a way out of the social order that does not require textual deconstruction (although it does not entirely discount the method, either). Thus, after looking at the products of GIS for Hurricane Harvey, the history and geography of the Houston area will also be evaluated for the potential for better methodologies in flood risk mapping and hazard mitigation.

CHAPTER III

A CASE STUDY OF THE CITY OF HOUSTON AND HURRICANE HARVEY

Floodplain mapping in the United States Gulf Coast is a subject of geographic practice that especially enables critical GIS, because it integrates the social and technological elements of GIS practice (and the hydrological and meteorological knowledge it processes) with the larger systems of property and governance in the southern United States. By creating a flood-risk classification scheme that spans across the entire country, FEMA uses GIS from a position of authority that is exceedingly powerful in the context of civic governance in the United States. Characterizing the priorities of urban policy as dedicated to being a ‘growth machine’ (see Molotch, 1976) finds one of its greatest examples in Houston, Texas, with economic growth driven by boosterism and conditioned by a hands-off form of urban policy which has embraced the city’s laxity in areal governance and zoning laws (Cook and Kaplan, 2012). The geospatial assessments of risk created by the National Flood Insurance Program thus serve as a significant form of spatial authority, determining which areas are ‘hazardous’ and which are not. The fact that flood insurance rates are determined on these boundaries of probability again acts as a government-derived force of development in a situation where the City of Houston government does not operate. To enhance my analysis of these effects, I undertake significant evaluations of the history of the Houston area, flood control in the United States, federal flood insurance, risk evaluation, and Hurricane Harvey itself.

A. Houston

For the purposes of this thesis, I use Harris County as the bounds of my study area because it encloses the city of Houston without excluding so much of the suburban development that surrounds it. Harris County does not fully capture the size of the Houston metropolitan area, but if I were to include Galveston, Fort Bend, and Montgomery Counties, the amount of context gained would be small in comparison to the divergent geographies it would bring (levees in Fort Bend County, barrier-island risks for Galveston, separation from the coast for Montgomery county). Even with this limitation, there are 51 Census-Designated Places in Harris County, some of which are enclaves within the City of Houston (Figure 3.1). Explaining the strange shape of Houston's boundaries requires a look into the city's history.

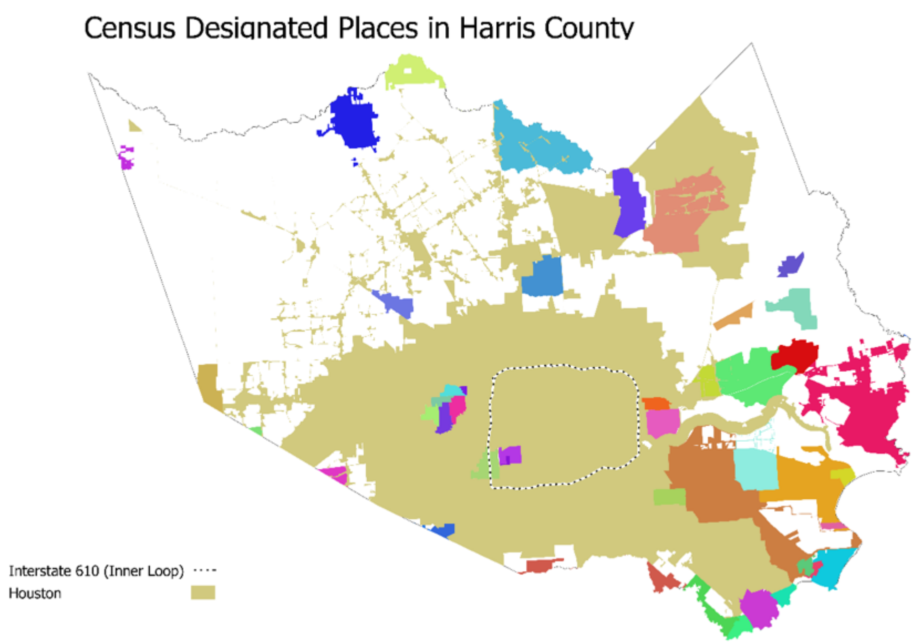

Figure 3.1 Multiple communities exist within Harris County. The City of Houston is the largest, but its boundaries include other communities.

Interstate 610 is a looping circuit added to Interstate 10. Also called the Inner Loop, this road is used as an indicator for the center of urban development in Houston.

The history of the City of Houston is one of aggrandizement, booming at several times through the efforts and expenses of wealthy landowners who act as 'boosters' taking overt action to shape Houston's growth and secure competitive advantages versus other towns (Vojnovic, 2003). These methods of economic growth are by no means unique for cities in the United States, but the sudden jump that Houston experienced is of note. For most of the 19th century and the first few decades of the 20th, Houston could be unfavorably compared to the nearby port cities of Galveston or New Orleans, both older remnants of colonial rule with larger populations and wealthier economies. At its very start, Houston was a 'paper town', nothing more than partitioned land being sold out of newspaper advertisements; the Allen brothers displayed their penchant for boosterism by lobbying for Houston to become the new capitol, winning over the cash-starved government by promising to fund the construction of their assembly hall, even though the capitol was moved to Austin after a year of mud, humidity, and high temperatures (Lozano and Espinosa, 2013). The Texas Government would also fund early dredging of the Buffalo Bayou in order to live up to the promises that the Allens had made regarding the Bayou and its suitability for steamboat traffic (Muir, 1960). Most of the adaptations that allow Houston to exist and provide an economic function are produced through government involvement, especially through funding infrastructure.

Beyond its short stint as capital, boosterism also brought resources to Houston that would have otherwise been unearned by its small size: state and municipal measures were passed to fund the first railroad linking Houston to existing railroads, and the 'Houston and Texas' railroad had by 1858 already been responsible for sprawl and speculation, with quick urbanization happening along its projected line (Muir, 1960). Transportation infrastructure projects in other areas benefited Houston because each railroad track added to the city increased the value of a potential new track, and regular cotton exports from across the South ensured constant traffic for railroads, although the tracks did not all have the same width and lacked a union station that would assist loads in traveling between the two varieties, even as late as 1960 (Muir, 1960). Cotton may have driven commerce in Houston and kept its economy moving (as does petroleum in the present day), but the Port of Galveston also had its own sheltering effect on the development of Houston, as infrastructure projects intended for Galveston (new rail construction, bridges, dredging, etc.) often benefited Houston, with Houston forming a relay point to-or-from Galveston, and less of a destination in itself (Muir, 1960).

This status of inferiority changed over the first two decades of the 20th century when Galveston was devastated by a direct-hit hurricane in the Great Storm of 1900, sending a 3meter storm surge into a city without a sea wall (Horowitz, 2015). The more resilient port would prove to be one located behind the barrier islands, and the federal government was convinced to use the U.S Army Corps of Engineers to dredge a deeper shipping channel through Galveston Bay and into the San Jacinto River and the shallow Buffalo Bayou, enabling Houston to become the prime port in the region (Pratt, 2007). The discovery of oil at nearby Spindletop and the increasing need for petroleum further enhanced the importance of Houston. After securing a reliable resource which additional development could be centered around, Houston was set up for massive spatial and population expansions as oil became a more commonly desired resource. To reflect its attachment to these ideals of uncompromising expansion and exploitation, Houston never adopted formal land use and zoning rules (Cook & Kaplan 2012). While this reduces the regulatory delays involved in developing properties and frees up the access of capital to urban space, the lack of structure also leaves a gap in protecting existing land uses when new developments move in. Perhaps the real estate market does not encourage building housing next to a refinery, but will a refinery refuse to build next to housing? The ability to place oneself advantageously and avoid disruptive land-uses requires capital, as seen in the example of the River Oaks suburb, one of Houston's earliest examples of spatial segregation being explicitly chosen to benefit the wealthy.

First, the city's expansion was limited to its normal systems of transit, featuring trams, autobuses, and other such forms of limited flexibility, but the early automobile age of the 1920s opened up new utilization of Houston's transportation, allowing for the mass creation of suburbs. These suburbs offered segregation from the perceived harms of the city, placing its residents in a quieter, more wooded zone and thus preserving them from the pollution and the increased activity of the expanding, industrializing city (Cook & Kaplan, 2012). These areas are privileged in multiple ways: they avoid the property instability of the zoneless city by using restrictive deeds to ensure land use, while their separation from the city center allow residents to travel and use its built environment without having to share in its downsides. In fact, the founders of these subdivisions saw their work as providing order to the chaos of the city; eventual incorporation into the boundaries of the city would retroactively make suburbanization civic work (Fisher 1989). A major downside to a piecemeal political landscape is a diminished ability to apply political action across a region, where smaller municipal bodies with varying resources are tasked with adapting to a regional problem on very small scales. Despite Harris County sharing some level of flood risk across itself, having so many political jurisdictions forces a government response to be refracted across multiple municipal bodies. The history of Houston within Harris County confirms that this is not a fringe detail of the city's structure but a central part of its urban development.

‘Boom’ growth in Houston is powered by the cost of petroleum and the relatively low price of Houston real estate compared to other cities, seen especially during the 1970s as an energy crisis drove up the value of oil. An office construction boom in the 1980s followed, driven not by ‘petro-dollars’ but instead by financial capital and the ‘herd mentality’ (Feagin, 1987). The low cost of land in Houston and the potential for high returns on investment led to the further decentralization of Houston, with new construction being carried out in ‘sweet spots’ between existing commercial and residential developments. Just as before in Houston history, governmental support formed the backbone of civic development. Serious lobbying has been (and will be) performed to shape Houston into a valuable source of land and capital, but the lobbying is done on behalf of the wealthy and privileged.

The consequences of this development are seen in the landscape of Harris County in 2017. As the urban center grew more valuable, investment has been encouraged on the periphery of the more expensive core. This does not appear unusual in Harris County, where the City of Houston co-exists with dozens of other suburban and exurban ‘cities’ which all pay homage to the same urban process. Even communities outside of Houston (such as Sugar Land and The Woodlands) are connected by shared usages. The breadth of this physical connection introduces some issues. Going by a ‘distributed development’ of ‘herd-mindedness’ suggested in Feagin (1987), the construction of ex-urban neighborhoods also affects land closer towards the core. A prime result of this conditioning has been the continued expansion of impervious cover (roads, parking lots, etc.) into previously undeveloped prairie land in the West-Northwest areas of Harris County. Even without an extensive analysis of the hydrology of the region, these developments have been notably doomed in one particular area: The Addicks Park Ten development and similar residential construction in the Barker Reservoir.

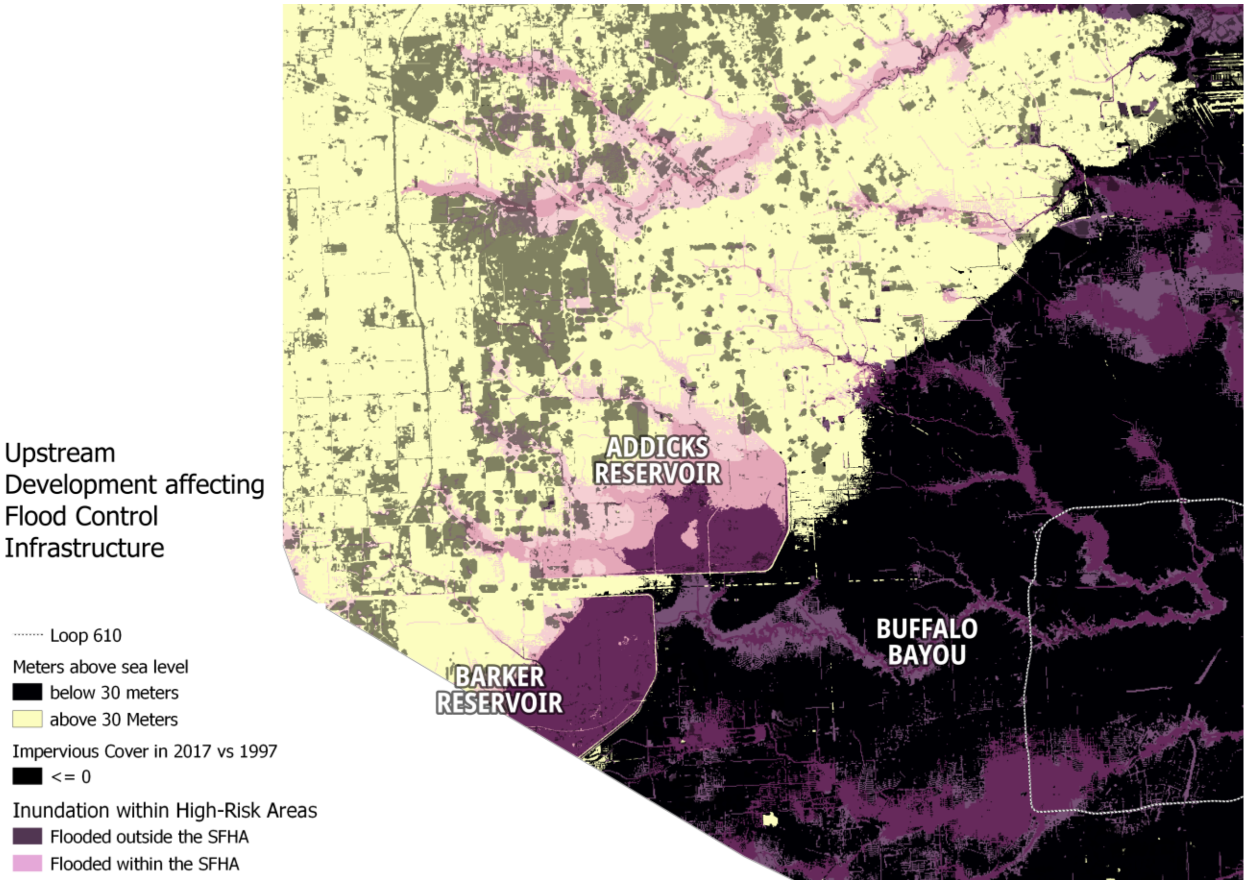

Figure 3.2 The growth of impervious cover upstream of reservoirs affects downstream inundation in the Buffalo Bayou.

The SFHA is the Special Flood Hazard Area, the zone where FEMA has attributed a flood interval rate of 100 years, also known as a 1% chance of flooding in a given year.

The boom city means something else for those with lower statuses, people and places which experience inequality through race and wealth. In the heavily developed city, the opportunities to promote growth and profit are limited. The city's performance as an economic machine for growth is tied to property values, and the ability to redevelop sections of the city are part of the city's function of growth. This movement can be analyzed in the terms of economic markets, but the history of racial segregation in Houston, Texas is very important to note: old injustices have been replicated throughout the phases of Houston's boom growth, with one of the clearest examples being the Fourth Ward. The neighborhood started at the end of the Civil War, with formerly enslaved people settling in a community westward of Houston's downtown, and held about a third of Houston's Black population until the 1920s. Slum clearance, highway construction, and discriminatory lending practices continually wore away at the population (Lin, 1995). In a city that prioritizes the economic opportunities of growth, the blight brought on by decades of neglect and discrimination could be seen as an opportunity to build new structures in a cheaper property market, but focusing on the market hides the central function of this redevelopment; racist policies and racist attitudes have made the urban environment beneficial to the white and wealthy to the detriment of people that had long-term histories of residence and a cultural attachment to their homes.

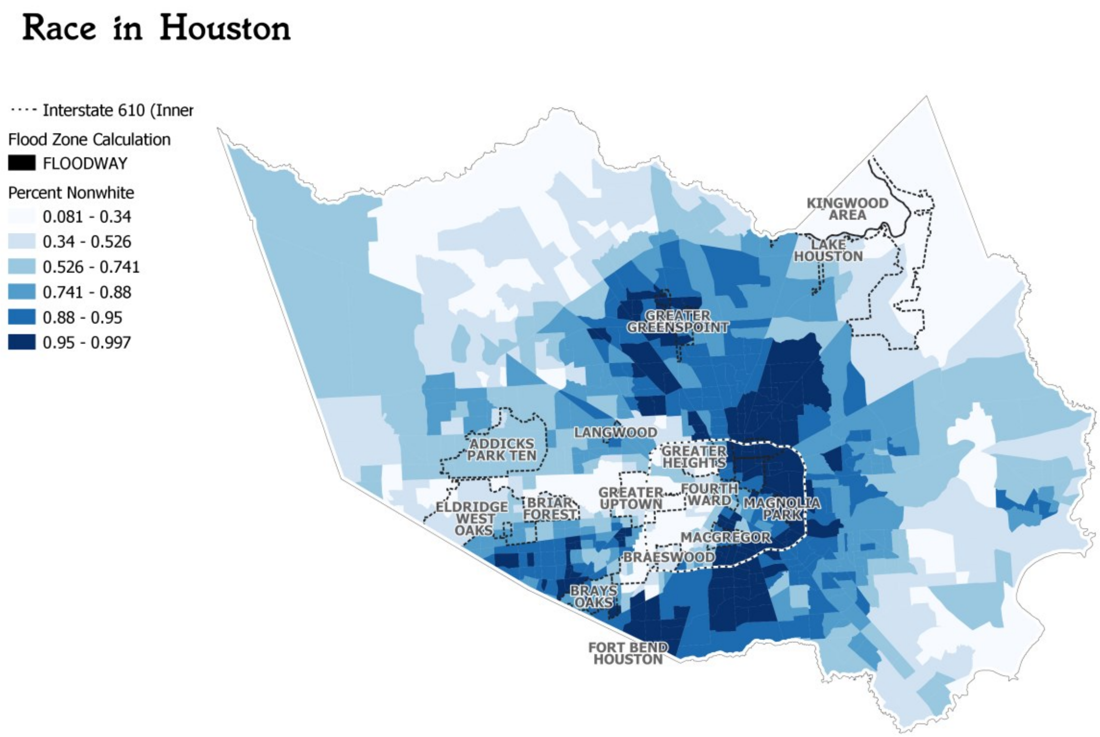

Figure 3.3 Census Tracts in Houston shaded by percent Non-White population and labeled with neighborhoods.

Figure 3.3 demonstrates that racial segregation is a feature of the urban landscape of Houston. Areas such as the Fourth Ward have gentrified, while the eastern half of the Inner Loop shows high concentrations of Non-White populations (in stark contrast to the western Inner Loop). The zone of relatively high Whiteness extends westward along the Buffalo Bayou up until the Addicks and Barker reservoirs. Also of note are the Braeswood and Meyerland neighborhoods, both heavily flood damaged neighborhoods.

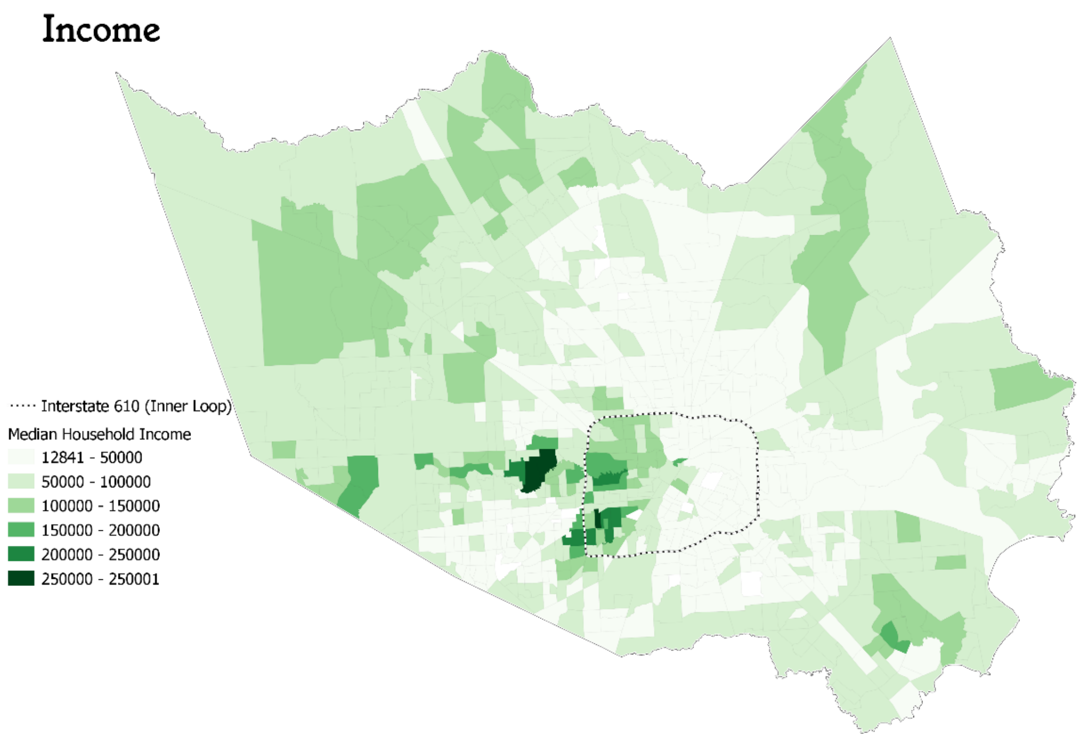

Figure 3.4 Median Household Income in Harris County

The east-central areas of the Houston area around the Inner Loop show low median household incomes, the lowest possible tier. The highest median incomes are in the Meyerland area in the southwest corner of the Inner Loop and in the River Oaks/Buffalo Bayou chain of neighborhoods that extend west from the center of Houston to the reservoirs.

When the Barker and Addicks reservoirs were completely filled during Hurricane Harvey, entire swathes of the Addicks neighborhood within the basin were flooded. The reservoirs were constructed by the U.S Army Corps of Engineers as part of a plan to protect downtown Houston from repeated inundation in the 1940s, but the state of governance in Harris County is such that construction continued in spaces specifically designed to flood. Neighborhoods such as Meyerland and Kingswood also recorded multiple flood events at nearannual intervals, but the only interventions in practice seem to be anemic: proposed action includes the requirement for new construction to be elevated above the Base Flood Elevation (using FEMA data), rules requiring disclosure if a house has been flooded or is in a floodplain (again using FEMA data from the NFIP), and offering buybacks (to homes determined to be at risk under the NFIP). FEMA operates rescue and recovery operations, in addition to other preparedness measures it is tasked with under the Department of Homeland Security. The National Flood Insurance Program serves as a focal point for any potential action on the issue of flood risk, but it relies upon estimates of flood risk that are inaccurate (Blessing et al, 2017) for a system of flood insurance that is forever imperiled by a political struggle that seeks to preserve a malfunctioning assemblage of policy against dedicated partisan resistance.

B. Histories of Mitigation in the United States

Before looking at the National Flood Insurance Plan as a policy in itself, it will be useful to consider what forms of flood control interventions existed before state flood insurance was implemented. The famous 1945 dissertation "Human Adjustment to Floods" by Gilbert Fowler White describes historical patterns of flooding as well as the contemporary state of flood control, even discussing the possibility of federal flood insurance as a new form of adjustment. One immediate impression from White (1945) is the lack of organized structure: Federal, state, and county policy coexisted in an unplanned mesh of disconnected responsibilities. The Army Corps of Engineers has existed as the main force of federal flood infrastructure construction since at least 1850, but White (1945) reports that actual federal responsibility for flood control did not exist until the passage of the Flood Control Act in 1936 after the disastrous floods of that year. Until that point, the Corps of Engineers mainly surveyed floodplains to provide specifications for flood control infrastructure, responding to individual acts of Congress that commissioned studies of specific floodplains.

Newly empowered, federal flood control now worked on the national scale, enabling the development of flood control beyond ‘levee only’ plans. In addition to levees, flood walls, and other such direct physical interventions, White (1945) reports the addition of more systemic interventions into water flow, soil erosion, and hydroelectric power, but this increased scale is also associated with a massive growth in federal expenditures. Despite a new scale for intervention and more funding, the main form of adjustment offered by the United States government had been centered on engineered solutions that precluded any need to alter patterns of human settlement. Disaster relief from public and private sources alike served to soften the impact of failed or absent flood control infrastructure.

In the context of an already expanded federal government, White (1945) explores the potential for a federal insurance program. Given the vulnerability of flood control infrastructure to failure and the significant time and labor burdens of new construction, flood insurance would potentially mitigate flood harms. Private flood insurance was not evaluated highly by White (1945), with a documented history of flood insurance companies coming into being, operating for a few years, and then going out of business during significant flood events. By operating on a nationwide level, White saw a federal insurance plan as capable of weathering these regional crises through the aggregate of many different flood regions (with ostensibly different flood risks). A deeper discussion of federal flood programs will follow the analysis of mitigation, but it should be noted to the credit of the NFIP’s earliest supporters that federal flood insurance managed to stay solvent far longer than smaller private initiatives, incurring a deficit only after an especially damaging hurricane season (Craig, 2018).

C. The National Flood Insurance Program

The National Flood Insurance Program was not always in the threatened position it occupies at the current time. It was created by Congress in 1968 to manage the unpredictability of inundation within flood-protected areas, managing insurance rates in order to foster economically wise decision-making on the part of individuals (Elliott, 2017). The ultimate narrative, however, was of socialized risk versus a flood insurance industry that would not extend protection to vulnerable people. The program stayed under the authority of the Department of Housing and Urban Development (HUD) until 1979, when FEMA was given responsibility for it. By creating a system of low rates on flood insurance (in order to encourage participation) and requiring federally backed mortgages to acquire a flood insurance policy, the total number of homes built in risk areas could increase alongside the number of households covered under the NFIP. The NFIP remained profitable until 2005, when Hurricane Katrina and the 2005 Atlantic Hurricane season threw the program into debt, with it being remarked that prior to Tropical Storm Allison in 2001, not a single hurricane caused more than a billion dollars of damage, while Hurricanes Katrina and Sandy caused $148 billion and $65 billion in damages (adjusted) within a decade of each other (Craig, 2018). After both multibillion-dollar storms, FEMA had to raise their borrowing authority, first above $20 billion after Katrina and then to $30 billion after Sandy. This financial insolvency problematized the NFIP as a wasteful government expense, and subsequent reauthorizations were tied to reform bills that attempted to adjust the balance between affordable rates and fiscally sound prices. Its financial and political troubles have not calmed with the passing of time, either. The dysfunctions of repetitive-loss properties and the increase in its debt to $25 billion dollars are additional reasons that the process of reauthorization has become more politically challenging (Craig, 2018). The record-breaking rainfall events driven by tropical cyclones have damaged the political reputation of the NFIP, and a closer examination of the NFIP in Houston may serve as part of the search for potential legitimacy. If the NFIP cannot provide a fiscally sound insurance system, does it at least provide a safety net that mitigates against property damage? Does the NFIP protect the vulnerable?

Alternatives to the NFIP must also be subject to critique. The aforementioned buyout programs that operate today are surprisingly unproblematic from the standpoint of political feasibility. Buyout programs respond to the over-construction of homes in flood zones that occurred under the protection of flood insurance. The lax federal restrictions on grandfathered houses and discounted rates at the earliest stage of the NFIP allowed for an illusion of safety, an illusion maintained through floodplain maps in which the highest flooding risk was at the 100-year interval level. The science behind these calculations is sophisticated, even in the 20th century, but the map product is necessarily simple. As far as public-facing information goes, information is only available to tell if one is in the riskiest area (only a 1% chance), the less-risky area (0.2% chance), or otherwise in 'a zone of minimal hazard'. There is much, much more that remains implicit or unstated. As development continued and watersheds became more and more altered, the silent scarcity of the NFIP became a cost sink, as properties began to repeatedly flood, be repaired, and then flood again. These 'Repetitive Loss Properties' and 'Severe Repetitive Loss Properties' grew as items of political opposition, with reforms passed in 2004 and 2006 intended to reduce costs by removing their eligibility for the NFIP and financing one-time grants to elevate or otherwise reduce their flooding risk (Craig, 2018). However, these programs are limited in reach because homeowners must apply for grants and a repetitive loss classification usually comes after multiple flood events, each of which draws costs from the

NFIP. A pre-emptive method to remove flood losses from the NFIP are federally funded buyout programs.

Buyouts mitigate against repetitive loss by buying properties in the highest risk flood areas, demolishing existing structures, and using land as part of the floodplain. A piece-by-piece buyout plan threatens communities that would prefer to stay together, but a complete community buyout also misunderstands the essential nature of a community and the ways that places are created socially (Marino, 2018). Indeed, Loughran et al. (2019) found in a study of Hurricane Harvey buyouts in Houston that the 'social ecology' of an area ties the physical environment with the wider social institutions of race and ethnicity (white homeowners participated less frequently in buyouts).

D. Flood Risk Modeling

Geographic Information Systems are central to the work of floodplain mapping in the current day, but the NFIP and its cartographic demands pre-exist the familiar context of desktop-based GIS mapping. Mapping flood zones was done quantitatively even before the process was fully digitally adapted. Burkham (1978) describes flood mapping as a three-step process where flood-frequency information is used to develop a frequency curve, along which a given probability interval is selected to calculate the volume of discharge. Given this discharge, the dimensions of the water's surface are calculated, and the profile is intersected with ground elevation to determine where the boundaries of a flood are. It should be noted that the entire process accepts some very large errors. One example from Burkham (1978) was the standard error of flood frequency analyses, which averaged 46%, with subregions of the United States displaying standardized errors anywhere from 16% of discharge to 115% of discharge, with no contemporary alternative analyses that could have given measures of smaller magnitude. At the time, flood boundary modeling was especially affected by the need to transfer information from multiple print maps in order to calculate parts of the result because each map transferal added another source of inaccuracy. The recent development of modeling techniques and the added benefits of working in a digital medium might be expected to improve accuracy at every step of the modeling process, but error and inaccuracy are built into recorded information, and new technology brings with it new problems. Indeed, there are some forms of error that are magnified in high-resolution data, such as false-confidence assertions based on limited observation sets, or the issues of combining data of different resolution during the modeling process. Thus, increasing the technological sophistication of the modeling process must be accompanied by more comprehensive changes that accompany the purposes of models (Dottori et al, 2013). The consequences of these errors are magnified by the context in which floodplain mapping is used: even with floodplains calculated at the 100-year and 500-year frequency intervals, static boundaries are being drawn that will directly influence the adoption of insurance and the perception of danger. Smemoe et al, (2007) describes new methods of mapping uncertainty, but these are cartographic adjustments that could improve the risk-perception function of floodplain mapping, not the insurance-rate delineation function.

The meteorological context of flooding as a natural hazard deserves its own discussion alongside the nationwide flood insurance program because the Gulf Coast of the United States has a regional pattern of risk derived from tropical cyclones that creates a different paradigm for flood risk mapping. The warm waters of the mid-Atlantic provide large amounts of potential energy for convection, and the low-lying coastline of the Gulf ensures that storms can make landfall at high intensities. The compound threat of high winds, intense rainfall, and storm surge create temporal periods of intense risk that diverge from purely-precipitation driven models of riverine inundation. Flooding in cities on the Gulf Coast thus presents a large problem for the NFIP, one that is only partially resolved with the inclusion of additional zones of classification based on risk type (riverine/ponding vs coastal flooding). The variation in size, intensity, and velocity in tropical cyclones adds yet another set of factors for the calculation of probabilities: A Category 5 hurricane brings intense winds but may not share the same intensity of rainfall as another storm. Indeed, slower moving hurricanes could provide the largest inundation risk, seen in Hurricane Harvey and the 'stalling' demonstrated that resulted in extremely high measurements of precipitation. The variability of precipitation in a hurricane has a spatial probability distinct from riverine flooding and the calculation of rates of discharge through watersheds.

Emanuel (2017) acknowledges the challenges of modeling extreme meteorological events in conditions of climatological shift before attempting a physics-based risk assessment that would evade traditional model concerns surrounding the shortage of meteorological data over time. The ultimate conclusion of Emanuel (2017) was that Harvey-level rainfall events had an estimated return internal of 325 years (more frequent than the 500-year interval), but that frequencies of less severe 100-year rain events could potentially be at a 16 year interval in Texas. By the end of this century, rainfall intervals above 500 mm of rain would have increased to 5.5-year intervals. For the most part, this analysis does not provide much more than proof of alternative probabilities that contradict the entire premise of the NFIP mapping project in the Gulf Coast. Even the hurricane simulations encountered here do not have the highest granularity, with each tropical cyclone 'seeded' backwards in time in order to evade the absence of detailed data on tropical cyclone formation and the association of certain environmental conditions on rainfall. In addition to alternative calculations, Emanuel (2017) includes a valuable section that exposes more of the data regime that empowers meteorological calculations. Because rainfall data is collected at rain gauges, any account for rainfall from those sources does not serve as a true aggregate. Likewise, relying on streamflow gauges to collect measurements of water flow in a catchment area falls into a similar problem because the path of rainwater is altered in urban land use. In acknowledging the shortcomings of Harvey data, historical data, and the model itself, Emanuel (2017) presents a rebuttal to FEMA estimates while also refusing truly authoritative ground with the physically based tropical cyclone model.

To face the challenge of intensifying flood risk, analysis should focus on the consequences of unpredicted flooding, given the increasing likelihood of severe rainfall and the consequences of development on the total population exposed to inundation. The large extents of flooding and the multiple watersheds of Harris County provide a method to examine the consequences of intense precipitation and outdated maps.

CHAPTER IV

AN ANALYSIS OF INUNDATION AND ADAPTATION

This thesis has thus far referred to the theoretical issues surrounding the National Flood Insurance Program and the empirical qualities of urban development which condition the inhabited space surrounding Houston, Texas and the Harris County area. To characterize the effects of Hurricane Harvey on the Houston area, information from multiple sources is used to better represent the performance of flood insurance among other forms of assistance. By highlighting gaps in coverage and the associated factors social vulnerability, a spatial image of inequality in loss will be created and compared to the social and environmental context of Houston (as described in Chapter III). The importance of context and existing modes of adaptation mean that, paradoxically, a significant amount of information surrounding Hurricane Harvey originates from before inundation occurred. The importance of pre-event data is especially strong in the case of flooding in the United States, where the National Flood Insurance Program forms the cornerstone of floodplain management and where the specific financial role of insurance has shaped assessment, preparation, and response to flood risk.

As the federal government attempts to balance the profitability of flood insurance with the affordability necessary to secure public participation in the NFIP, flood risk is factored into the price of insurance as a static probability for the purposes of insurance, while affordability, conversely, is a highly dynamic factor that varies from household to household. In either case, the U.S government has attempted to forecast risk and costs from information available beforehand. The goal of this thesis is to understand how inaccuracy in risk assessment has changed Houston and how the Houston area adapts to the risk of flooding through a comparison of pre-Harvey and post-Harvey information.

A. Data

The attempt to classify the damage in the Harris County area is affected by the perception of flood risk and previous histories of inundation. This is best supported by the observation of specific neighborhood-based clusters of flood damage and insurance. Using the FEMA-provided claims data at the Census tract level allows for an intensive cross-consideration of multiple elements of vulnerability versus the eventual utilization of flood insurance as part of the recovery process. An important element in this analysis is the usage of multiple sources of data to break away from the idea of a single figure of 'true damage'. While it is useful to create estimates of damage after flood events, the ultimate measure of its significance is beyond one figure: there is meaning behind types of damage, the extent of damage, and the ability of those affected to respond to damage, and this information is not all derived from the same source.

The differences between these sources of data are important to note because they are created within varying geographies that literally shape it. For example, data on flood insurance claims is only provided publicly at the Census Tract level (reportedly in the interest of privacy) even though policies and claims are made on a house-by-house basis. On the other hand, FEMA provides information on Individual Assistance grants at the Census Block level, the highest resolution Census geography possible. Census Blocks are combined into Block Groups and Block Groups sit within Tracts, but every change in geography requires a form of calculation to summarize the spatial information within it, and data can only be compared accurately within the same set of geographies. Comparing different measurements of loss means standardizing measurements into a singular set of geographies, and even though they will exist in the same spatial context for the purposes of GIS, the methodology of assigning data to the world varies between datasets.

Data on NFIP flood insurance claims was released by FEMA in June 2019. Its spatial context is derived from the Census GEOID codes attached to each policy, which were restricted to the Census Tract level for open release. Claims data gives one measure of flood damage, but it is limited to recording policy owners who have made claims, creating an obstacle in assessing damage because the mandate for flood insurance is weak even within the SFHA; only those with federally backed mortgages are required to purchase flood insurance. Although correlated with damage, claims counts are directly related to the socioeconomic conditions of an area because of the costs of insurance policies). To better capture non-insurance records of loss, a further data source comes from Individual Assistance grants within FEMA's Individual Assistance program, which provides grants and services to those affected by a disaster. Individual Assistance housing grants thus offer another representation of people affected by the disruption of Hurricane Harvey, even including renting households that were displaced by inundation. IA grants were provided at the Census Block level but can be summarized at the Block Group and Tract level. Alongside records of households applying for services, FEMA generated a daily estimate of which properties would be damaged up until September 2, 2017 using their HAZUS-Multi Hazard (HAZUS-MH) system. The final FEMA damage assessment generated on September 2, 2017 is used as a computational baseline for the estimated number of damaged properties because HAZUS-MH projections for damaged properties are closest to an external estimate of damage without the institutional barrier of aid applications.

Outside of FEMA's own data, information from the municipal and county level is also used to provide alternative conceptualizations of loss. The City of Houston assembled its own counts of affected households on the Block Group level by using a combination of FEMA and municipal services information (e.g., 911/311 calls and debris removal requests). Information on Harris County properties is taken at the property parcel level from the Harris County Appraisal District's records for 2017 and 2018, mainly records relating to ownership and the market value of a piece of property. If properties were observed to change owners between the years of 2017 and 2018, it could be part of a larger phenomenon of migration out of flooded regions and individual decisions to avoid the rebuild/renovation process. Furthermore, these properties can be tested on whether their value also changed within the year, with the logic being that a drop in value would reflect a loss in equity. The decline in property values associated with a flood event remains an important component in the recovery process, even in cases where a property has not been flood damaged; flood events can affect even properties that have not been inundated by changing the perceived value of a property.

The final component involved in an analysis of damage is the use of demographic information as provided through the U.S Census. Because multiple data sources will already be summarized at the Census Tract level, the addition of social demography is a straightforward action to again add context to observed damage and thus differentiate harms through the potential vulnerabilities of areas. Drawing on the histories of unequal development in the region, emerging patterns of unequal recovery can also reveal more information about the role of Hurricane Harvey (and inundation more generally) in affecting the process of urban development.

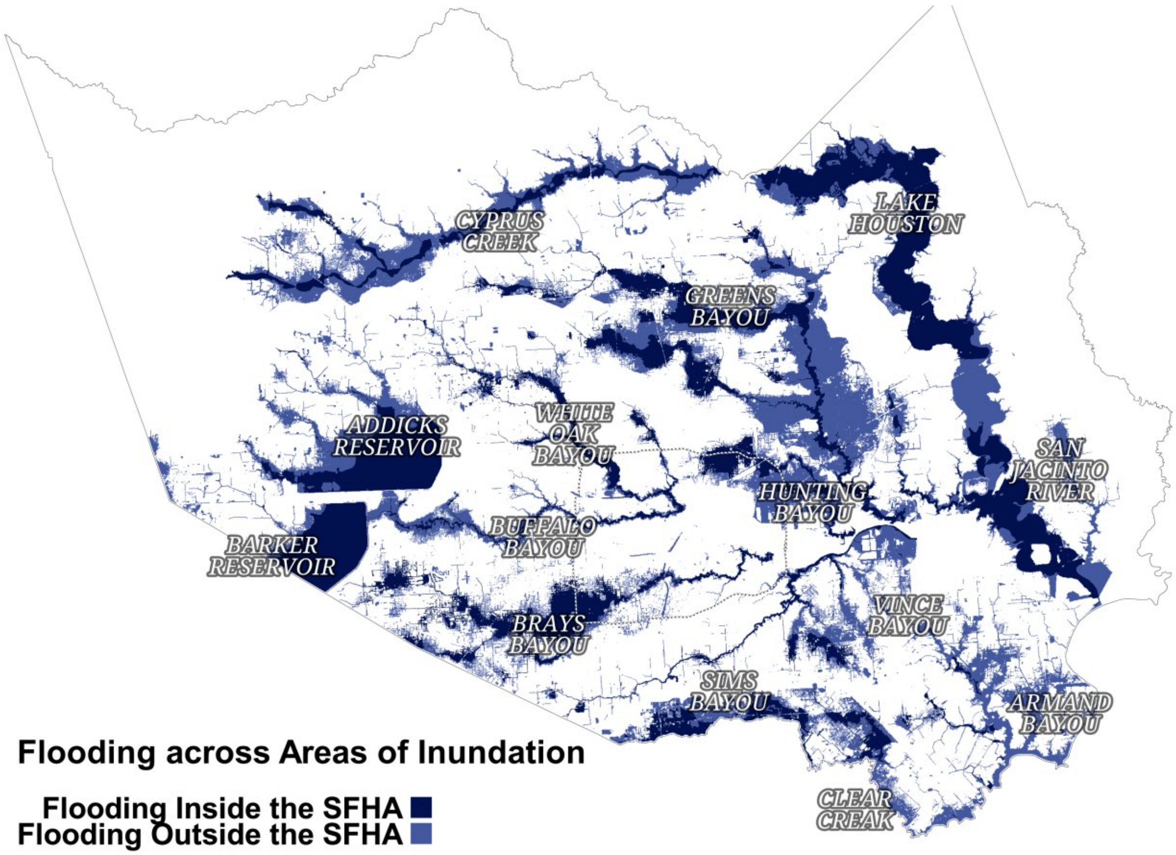

Figure 4.1 Flooding across Areas of Inundation. There are 14 AoIs in Harris County

Areas of Inundation can also be described as watersheds, and FEMA uses these to calculate floodplains.

Areas of Inundation (Figure 4.1) and Super Neighborhoods (Figure 4.2) are two forms of geometry that can be used to describe the widespread flooding of Harris County. Key neighborhoods dominated by flooding include Braeswood, Meyerland, Westwood, Kashmere Garden, Kingwood, and the Addicks Park Ten development. Areas of Inundation describe areas where floodplains are calculated, with the Addicks Reservoir and Barker Reservoirs being connected to the Buffalo Bayou to create one of the more notable assemblages of diffused risk and responsibility. The dark shades of flooding within the SFHA show how even expected flood boundaries were filled, inundating both above the reservoir and then later into Buffalo Bayou during an emergency release. The Brays Bayou area (containing the Meyerland and Braeswood neighborhoods, among others) had significant flooding, but it appears to be mostly flooding within the 100-year floodplain. Compared to massive overruns outside the SFHA in Cyprus Creek, Armand Bayou, and Hunting Bayou, the Meyerland neighborhood is almost entirely inundated within the Special Flood Hazard Area.

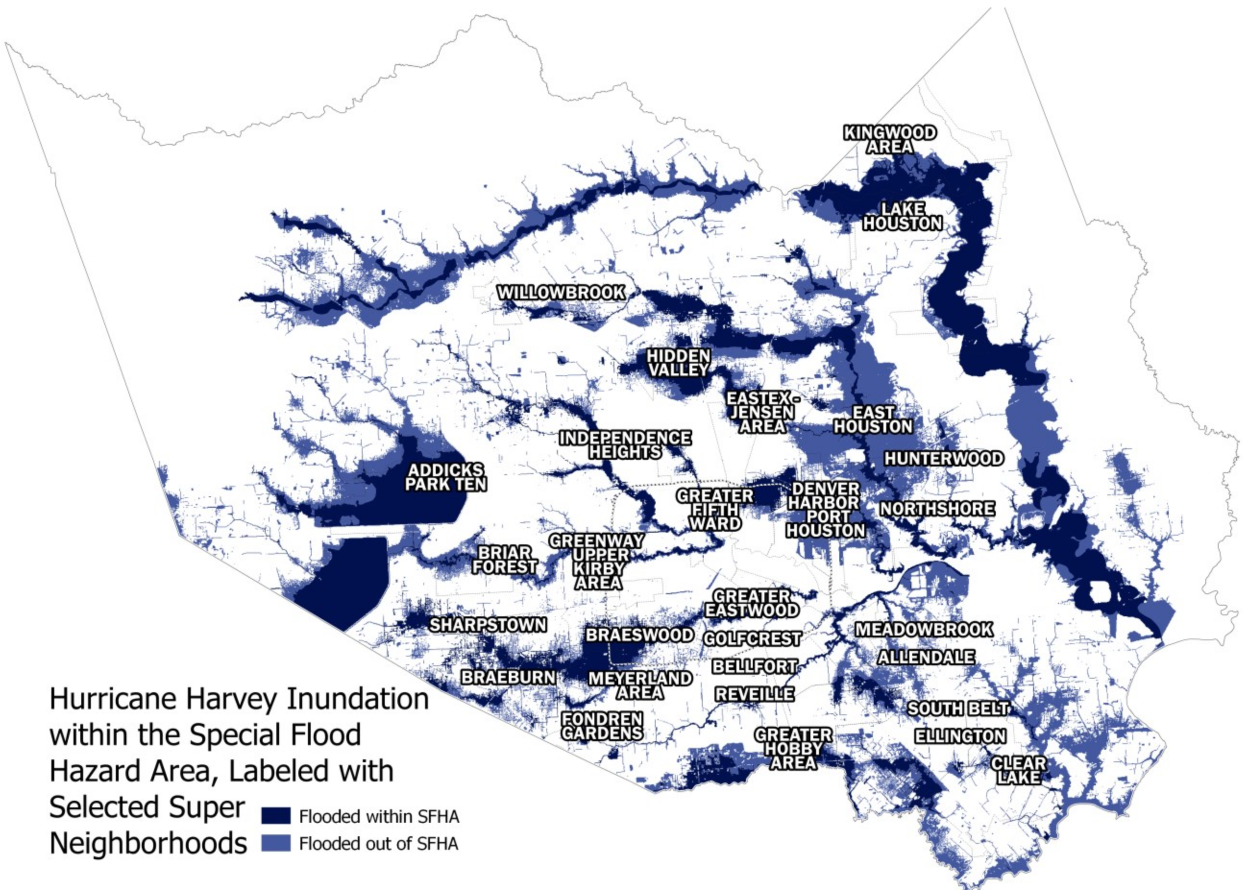

Figure 4.2 Neighborhoods and flooding in Harris County

Areas generally excluded from flooding in Figure 4.2 include high-elevation areas in the North-West of the county, and much of the area within the Inner Loop (although overflow from Brays Bayou did inundate portions of the Southwest Loop and there was predictable flooding around Buffalo Bayou in the Western Inner Loop). High value construction in the central area of Houston is given some protection from total inundation by the dual reservoirs further up the Buffalo Bayou, yet these decades-old reservoirs created their own risks, including the risk of legal action (based upon the Army Corps of Engineers and their decision to perform an emergency release during Harvey). The question of responsibility has importance for the political and legal dimensions of the NFIP, but there is also a cartographic element to these decisions. To examine the ability of the NFIP to serve its responsibilities in the Harris County area, this rudimentary inspection of where flooding occurs needs to be reinforced with specific inquiries into where damage occurred and how loss was distributed across the city. After identifying the dimensions of loss, we consider forms of relief and their ability to restore the urban function.

B. Damage and Loss

Sixty-eight fatalities were directly associated with Hurricane Harvey, 36 of which occurred within Harris County. The majority of these fatalities were related to transportation and inundated roads, where attempts to evacuate from flooded neighborhoods or transfer to workplaces through moving floodwater resulted in drowning deaths. The National Oceanic and Atmospheric Administration estimated between $90-$160 billion dollars of damage in the total affected area, with more than 160,000 inundated structures reported in Harris County and Galveston County (Blake and Zelinsky, 2018). While these losses are important to note, their most mutable aspect across the Harris County area is observed in the total disruptive effect of losses. From household to household, specific factors of inundation will have their own meanings, both in the ability for individuals to adapt and the magnitude of the loss that they face. The HAZUS-MH preliminary damage assessments generated by FEMA provided estimates of damage in Table 4.1.

Table 4.1 Preliminary Damage Assessment Estimates by FEMA

Status	Count of Properties	Percent of Total
Affected	38956	56.62%
Minor	19882	28.90%
Major	5854	8.51%
Destroyed	4111	5.98%
Total	68803	

In FEMA's damage classification scheme, 'Affected' properties are the least damaged, where flood waters have observably affected a house or its foundation but have not caused substantial damage. Properties described as 'Minor' display inundation depths up to 18 inches (457 mm), and 'Major' damaged properties show inundation above this and larger amounts of damage. To be 'Destroyed', enough structural damage has been done to eliminate walls or otherwise necessitate the demolition of the structure or its foundation. These estimates are generated using the depth of water on a property, but it confirms that more than 80% of homes were estimated as having floodwaters less than 18 inches (457 mm), with the 56% 'Affected' subset suggesting that these structures may not need major renovations to restore its habitability, although the cost of repair should not be totally dismissed. Even when a house has not been destroyed, the cost of repairs might exceed a resident's financial capacity, hence all levels of flood damage present concerns that vary with the economic status of a household. In these situations, insurance policies under the NFIP are meant to provide support for repairs (or replacements).

1. Measurements of Loss

In this case of flooding caused by Hurricane Harvey, where a large amount of inundation has been observed and modeling has forecasted high numbers of affected structures, identifying the magnitude of damage is a potential challenge for mapping loss. It is important to distinguish between 'lost' and 'damaged' houses because a core principle behind the NFIP is the ability of insurance to prevent flood events from becoming catastrophic by providing resources for recovery. As a system of insurance, the NFIP relies on managing property as a financial resource, where a certain threshold of damage would effectively void an owner's structure as a resource. Tracking the places where damage was too much and became total loss is a challenge, but tracking properties and value offer new opportunities in quantification.

The ability of the NFIP to provide repair funds is of much importance, but this ability can be expected to vary: not every flooded structure is a home, not every home is owned by its occupant, and homeowners are not guaranteed to have flood insurance, especially if they did not perceive a threat that would justify its costs. These dynamics are represented in Harris County: the 2012-2016 American Community Survey reported that 54.5% of housing units were owner-occupied, while 45.5% were renter occupied. Within renter-occupied homes, there is another distinction: only 23.6% of renters were occupying single-unit homes (i.e., single-family residences). 51.7% of renter-occupied housing units were in multi-family buildings with more than 10 apartments. The structure of the National Flood Insurance Program was created for small-scale property ownership: for residential properties with up to 4 units, the NFIP's coverage limit is $250,000. Beyond 5 housing units, the coverage limit is only extended to a maximum of $500,000 dollars. Thus, for more than 3 quarters of all renters in Harris County, any potential insurance coverage will be split with many neighbors who co-occupy the property. The NFIP is thus unsuited for the significant portion of the urban population who do not own their own residence. This is reflected in the claims made after Hurricane Harvey (Table 4.2), where 77.6% of policyholders were claiming for their primary residence (and thus not conventional rental properties). Within the remainder, multi-family units are unlikely to take precedence. Before even considering the degree to which the NFIP covered flood risks, its mitigation is structured to prefer one group over another. Whether it achieves success in its goal is another.

Table 4.2 NFIP Claims by Owner Residency

Status of residence	Count	Percentage
Primary Residence	71237	77.63%
Other	20525	22.37%

Table 4.3 Individual Assistance by housing type compared to total residency type

Type	Claims	Total Households
Owner	41.11%	54.50%
Renter	58.89%	45.50%

Despite taking only 45.5% percent of housing units in Harris County, nearly 59% of households obtaining housing assistance funds were renters, not owners (Table 4.3). At face value, this suggests a larger vulnerability of renters compared to owners in Harris County, even when considering the total number of people in renting households versus owning households.

The ratio of owners to renters in disasters can be compared to Corpus Christi, another Texas city further south on the Gulf.

Table 4.4 Renter-Owner proportions of Individual Assistance claimants compared across Hurricane Harvey affected geographies

Claimant	Harris County	Corpus Christi	All IA Claims
Owner	41.11%	51.31%	50.06%
Renter	58.89%	48.69%	49.94%

The 2016 ACS 5-year estimates for Corpus Christi, Texas, reported 44% of housing units were renter-occupied, which is yet a larger share compared to the national renter occupancy rate of 36.4%. Renting households thus display a larger vulnerability both between cities and on the national level, where the share of renters applying for aid is larger than their share of the total population, Corpus Christi has the smallest gap, with only 4.7% more renting applicants (Table 4.4). The figure for the entire United States, where 49.9% of applications were renters, shows a 13.4% higher share, which is matched in Harris County. Thus, while Harris County renters display vulnerability, it cannot be concluded that this renter vulnerability is beyond that of other urban areas (although some cities may display lower vulnerabilities in their renting population). This vulnerability matters because property already implicates renters more than property owners; residential properties are a financial resource, but home-owners are unique in being able to manipulate their residences as property and take action following a disaster (although the capacity for financial maneuvering varies with the socioeconomic status of individual owners).

Two years after Hurricane Katrina, flood losses in New Orleans created a housing scarcity that increased the median value of houses by 59%, but also caused a 48% increase in rent (Vigdor, 2008), improving the general value of property for owners directly as it increased the economic burden of housing for renters. In Houston, a loss of 6% of all rental housing was amplified in economic effect by the need of displaced home-owners to secure short-term rental housing, at the same time that a full 25% of Houston's low-income and public housing was inundated (Dickerson, 2017). Because renters are signed into leases, finding new, long-term housing is complicated by the decision-making of landlords. Under some circumstances, renters may remain in housing that is unsafe or needs repairs because the costs and resources needed to find new housing exceeds their financial capability. Ultimately, the disruption that Hurricane Harvey had on non-homeowners in Harris County proves to be greater in intensity; more renters needed housing aid than owners, they had to pay more to find replacement housing, and had less authority to manage their places of residence. When inundation occurs, renters have more disadvantages. However, homeowners also have their own set of vulnerabilities that do not exclude them from consideration, but instead introduce new considerations for risk mitigation.

2. Houses

Houses (and the land they occupy) are generally the largest financial resource (and liability) in a household, and the low cost of property in Houston has historically driven its booming growth. The availability of lending and insurance conditions enable development in an environment with as much risk as the Houston area, but has the potential to worsen economic inequality. The contents and the structure of a house are both at risk during a flood, and even small amounts of floodwater will ruin many types of flooring. The contents and the structure of a house can be treated separately for the purpose of insurance. FEMA advertises its contents-only insurance policies as an affordable alternative to full policies that would protect the house itself.

According to tax code information from the Harris County Appraisal District, 70% of all properties are single-family residential parcels. Thus, while the total number of households affected might skew towards renters in Houston, most of the properties in the area are subject to household decision-making. Thus, properties sold with a decrease in value from the previous year would suggest some form of damage or devaluation. Given the documented scarcity of housing following Hurricane Harvey, decreased values are distinct from the wider market trend of higher pricing where the scarcity of houses increases the values of homes. The core of the destruction is the Meyerwood area in Brays Bayou, the Kingwood Area by Lake Houston, and the chain of developments along the banks of Buffalo Bayou, heading West from the Inner Loop to the Barkers and Addicks Reservoirs. For multi-family residences, commercial buildings, and investment properties, property owners exercise a different set of logic than homeowners. For those who do not own their residences, their crises are less visible on the map. Traditional narratives of natural disasters and the loss of homes are often tied directly to an ideal of middle class living (seen in the existence of the National Flood Insurance Program as a mandate only on federally backed mortgages). Those who rent are not given their own plot on the city map, their name is not listed directly in its digital records. Their existence in property data is as a given number summed up among other tenants. By summing property parcels to the Census tract, owners and renters are taken together in the aggregate, but it does not change the essential lack of renter information in publicly available data.

3. Property

The density of properties varies across Harris County, strongly represented in its urban core within the Inner Loop of Interstate 610 and maintaining moderate densities in branches that form connections between developed areas. Blank areas with no hexagons indicate areas where the HCAD does not have property values listed in the years 2017 and 2018, often because of the existence of waterways, reservoirs, or other expanses of uninhabited (and undeveloped) space. The space around these gaps is demonstrably less dense as it is not yet primed for residential development (other such areas are observed in the eastern and northwestern fringes of the county). Thus, while there are many properties to be found in the Harris County area, the actual vulnerability to hazards is not uniform.

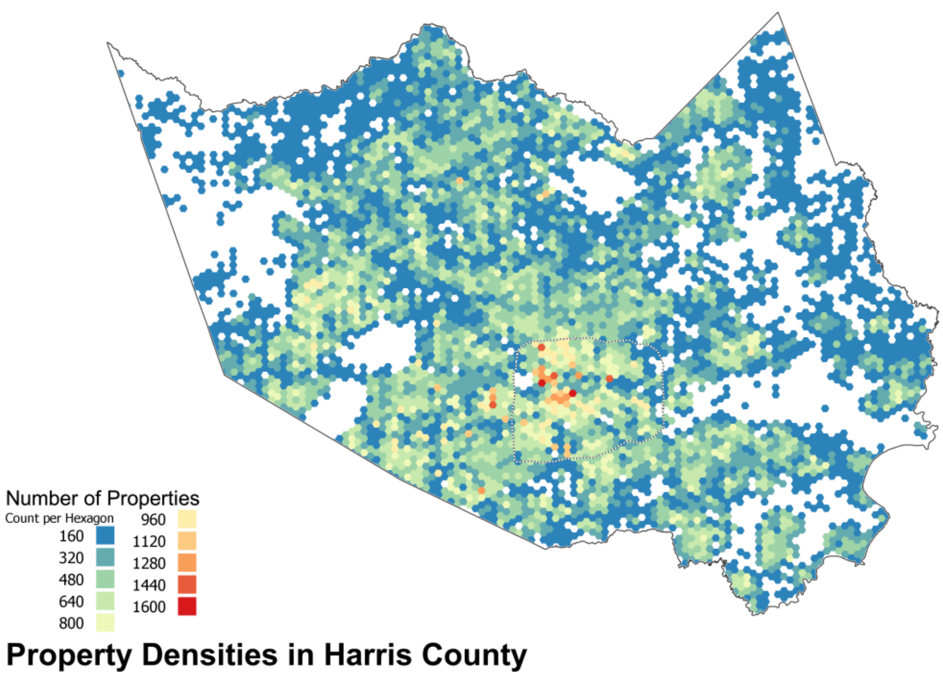

Figure 4.3 Property Densities in Harris County

Using .67 square kilometers hexagons, the number of property parcel centroids were summed per hexagon. Blank areas did not have property values in 2017 and 2018.

Individual houses also demonstrate vulnerability in Figure 4.3. Although owner-occupied single-family households have the slim majority in the Harris County area, the value of this housing as wealth for a family is another unequal factor that inundation makes costly. Given that housing structures generally depreciate in value even with maintenance (Harding et al, 2006), the high age of homes in East Houston reflects the unequal balance of development in Houston and the patterns of segregation that concentrate White populations in some areas (namely the central West), compared to nonwhite (and especially Black) areas in the East.

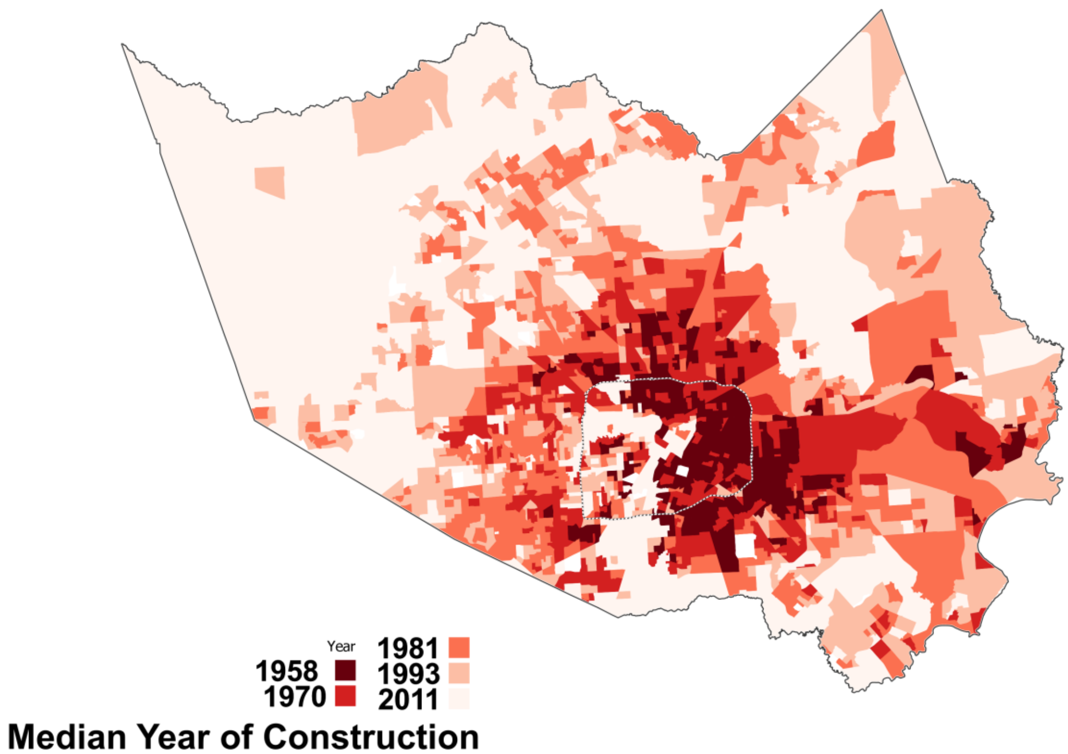

Figure 4.4 Median year of construction in Harris County

For the entirety of Harris County, the median year of home construction was 1977. Figure 4.4 shows that development within the Inner Loop and towards the western portion of Harris

County had more recent years of construction, with many areas in East Houston having the oldest median years of construction (1939-1958). This inequality is especially important to note with regard to Hurricane Harvey claims because the median year of construction for household claims was 1 year less, with 75% of claims originating from houses built in the years 1965 to 1990, demonstrating further that the older parts of the city that haven't seen recent development are also not engaging with the recovery mechanism of flood insurance. Recency in construction date only correlates with equity for the earliest owners of a house because subsequent owners will have new policies instead of continually renewed flood insurance policies. As an example, the median starting year of NFIP policies was 2013, with an interquartile range of 6 years (2010-2016). Although home ownership is considered an important part of economic function in the United States, home construction and real estate speculation move the most capital and garner the most political support. In the Houston area, the NFIP has been used mainly as a tool that supports growth and the liquidity of property as a resource for exchange, with a mandate that targets federally-backed mortgages and a rate of adoption that supports newer development over older, disinvested parts of the urban landscape, facilitating the growth of the city while allowing it to reproduce its inequalities.

4. Properties Sold for a Loss

The nature of Houston's real estate market means that large volumes of property transactions are not unusual phenomena, which suggests that sales should be presented in relation to the wider population to better visualize spatial patterns. Figure 4.5 uses a hexagonal mesh over Harris County to sum property parcels, and an Odds Ratio is calculated to represent each polygon as it relates to a) sales as a share of the polygon's parcels and b) sales as a share of the whole county's sales.

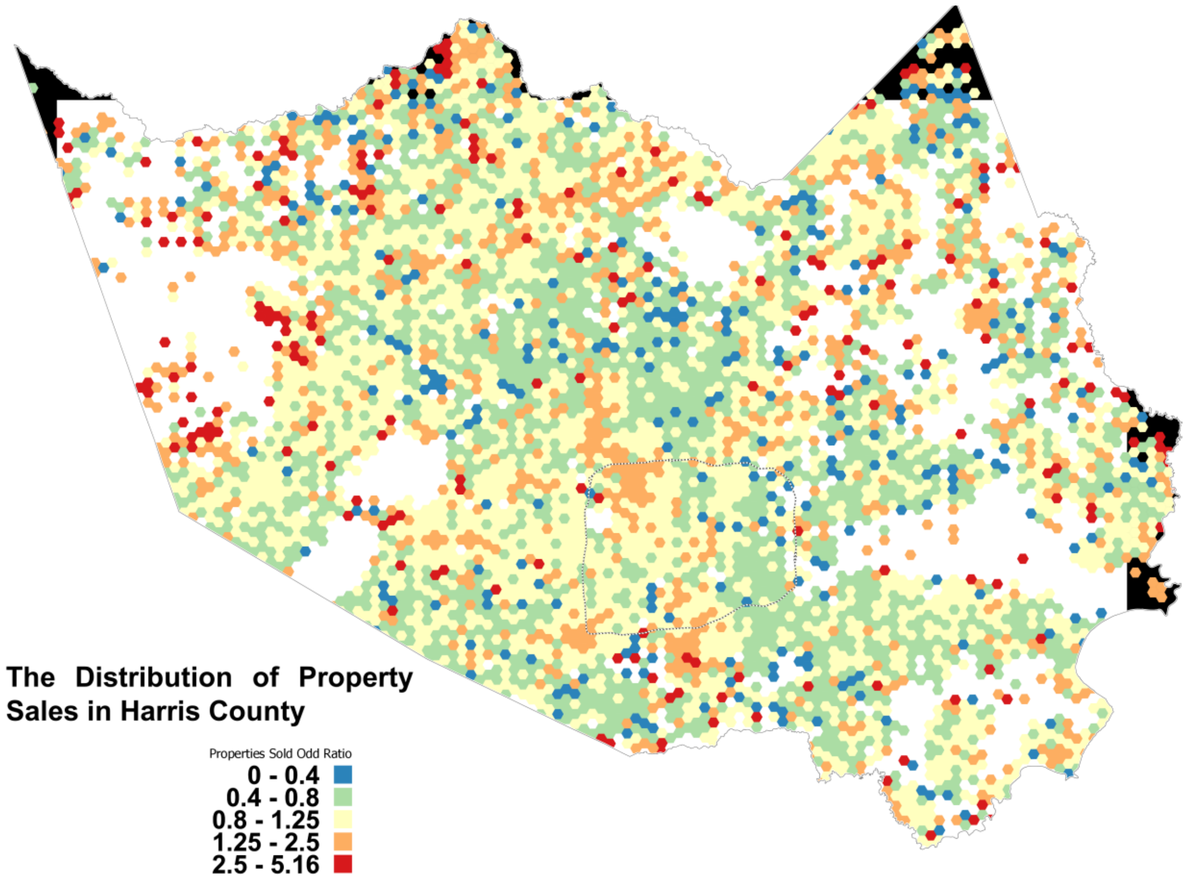

Figure 4.5 Distribution of property sales in Harris County, displayed in an Odds Ratio

$$OR = \frac{p_i/p}{r_i/r} \tag{4.1}$$

Equation 4.1 shows how Odds Ratios are calculated for property sales dividing p_i (the observed number of property transactions) by p, the total number of property transactions in the study area, creating the share of one polygon's sales from the total. Likewise, r_i is the number of properties within a hexagon regardless of their transaction status divided by r to detail its share of all properties. Dividing the sale share by the property share creates OR, the odds ratio that describes the relationship of p and r in relation to the county-wide figure.

Values above 1.0 show areas overrepresented in sales and values below 1.0 are less active. Thus, the hexagons in Figure 4.5 with Odds Ratios above 1.25 and below 0.8 could be said to substantially diverge from the normal. Such areas such the Northwest of the county (with Odds Ratios above 2.5), are potentially explained by sub-urban clusters when the area around it shows reasonable activity (or a complete lack of activity indicating undeveloped land). While Figure 4.5 can demonstrate how certain areas participate in real estate, what is most important in identifying disruption is the presence of property sales for a loss. Using the same Odds Ratio calculation for transactions made with a loss in value (loss-sales) thus reveals an effective figure for areas that are damaged (Figure 4.6). Using the Odds Ratio, areas known to have significant amounts of damage are well represented: The Meyerland neighborhood at the southwest corner of the Inner Loop, the neighborhoods downstream of the Barker and Addicks reservoirs along Buffalo Bayou, and areas of high damage along Lake Houston and the San Jacinto River.

While property sales in Figure 4.5 show the Houston area as an area of real-estate activity, using the share of properties sold at a loss, as seen in Figure 4.6, displays how the mechanism of property exchange can contain signs of damage without overriding the general pattern of the market. These are reflected clearly in the region-wide market, where the Harris County housing market continued, even as thousands of homes had been inundated. Another thing unique about the metric of loss-sold property is that it may also capture changes in risk perception that alter the value of a parcel given its potential to flood and incur costs later. Flood insurance may offer some form of support for development in potentially risky areas, but an insurance policy has limits, and the initial incidence of loss is not erased by the resources spent on repairing damage and replacing items. In addition, the phenomenon of a 'natural disaster' has a psychological and social significance that might pressure existing decisions (such as migrations to other neighborhoods or cities).

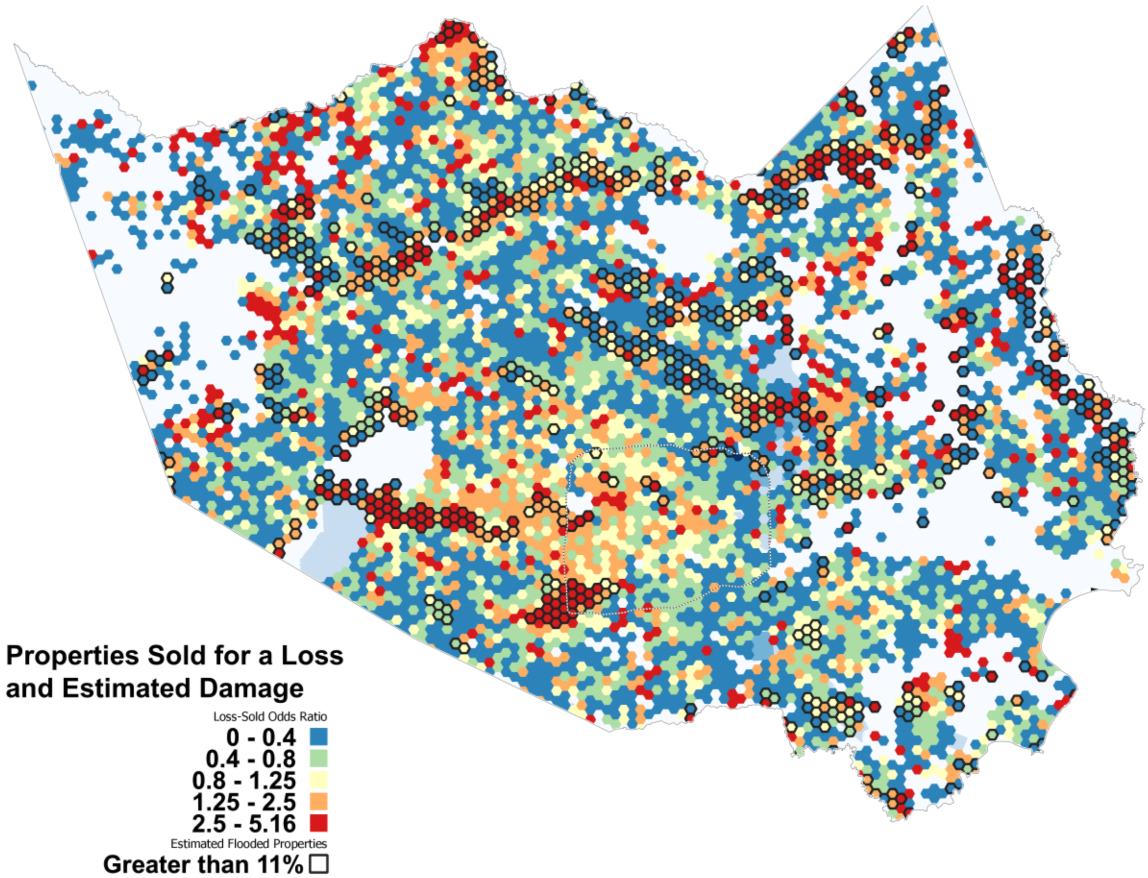

Figure 4.6 Distribution of properties sold for a loss, displayed in an odds ratio and with selected polygons displaying significantly damaged areas.

C. Recovery and Adaptation

The relationship between a resident's tenure, flood insurance, and the age of a house is complicated, and its level of detail challenges the image of fixity in the modern city. A flood insurance policy is not tangible flood adaptation infrastructure, it is a financial instrument surrounded by state bureaucracy that requires conditioned spaces to exist; individual properties and individual policyholders are the most uneven elements of the urban landscape. All that is infrastructural about the NFIP is external to its central mechanism of insurance and instead takes place at the level of rate adjustment. Thus, the largest federal intervention into flood risk does not directly adjust human exposure to flood risk but is instead meant to mitigate its harms. This distinction is be important in the context of political participation: whatever the issues of physical flood control infrastructure, one advantage over insurance is that the individual burden to be protected is nowhere near the requirements of a flood insurance policy.

Adaptations to flood risk are meant to have a combined effect. These forms of mitigation can be tested together, from the widest federal program (NFIP insurance) to other forms of governmental aid (Individual Assistance grants) and individual-level maneuvers (property sales and sales for a loss). Insurance policies would seem to be the most cost-effective form of mitigation because insurance policies are engineered to yield profits, but the usage of discounted rates might encourage construction in places otherwise considered too hazardous, an effect already theorized as the 'levee effect' in White (1947) where flood control infrastructure increases the time interval between flood events and thereby creates the illusion that an area lacks any of the earlier risks. Indeed, the worsening financial performance of the NFIP (discussed in Chapter III) could indicate that the total exposure to inundation has increased to the point of surpassing the original intention of the NFIP (reducing vulnerability to floods through insurance). In Figure 4.6, it can be observed that NFIP claims well outnumbered loss-sales in areas of flood loss, despite the prevalence of sales in damaged areas (seen in Figure 4.7), demonstrating that engagement with the NFIP has been high even as the conditions of flood risk are unfavorable around it.

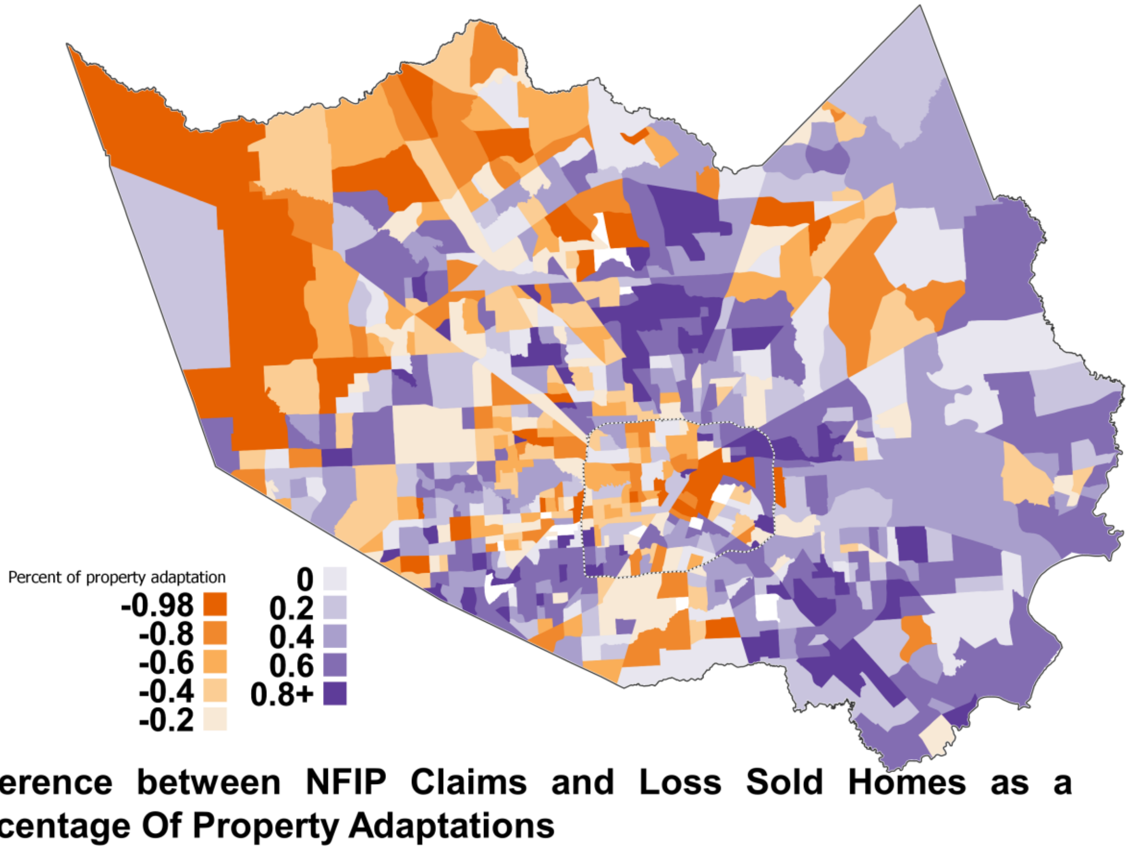

Figure 4.7 Difference between insurance claims and sales for a loss as a proportion of total property decisions.

In flood damaged areas, properties are more likely to have FEMA claims filed than be sold for a loss. There are several possible explanations for this, the first and most obvious being that these forms of adaptation are not mutually exclusive because of the 60-day time limit for submitting Proof of Loss claims after an event, resulting in a complete list of claims within a year. The decision to sell a home operates on a different time scale than flood insurance, varying with access to disaster loans, Housing Assistance, personal savings, and income. Thus, testing the performance of the NFIP as a form of adaptation is not as straightforward as observing how these systems of adaptation work in the short term: an individual owner might immediately be represented in their flood insurance claim and their Housing Assistance application, but the metric of loss-sold property could follow disaster at a distance. This places more pressure on the process of risk assessment by which flood risks are mapped and insured again because these adaptations are implemented *before* the incidence of inundation, as opposed to other forms of household adaptation which can only react to flood damage.

D. Inequalities in Mapping

Maps and the act of mapping are crucial to flood hazard mitigation: beyond mapping floodplains, the NFIP also incentivizes floodplain management under the Community Ratings System (established in 1990), where communities (i.e., governmental entities as defined by FEMA) can be assigned enhanced discount rates for undertaking certain floodplain management practices. It should be noted that while the Harris County Flood Control District is the largest single authority in the region, communities located within Harris County can have different discounts. For example, the City of Houston operates a 25% discount on flood insurance inside the SFHA but only a 10% discount outside, even as the City exists within the larger Harris County, which offers a 15% discount at the maximum (proving that flood insurance is more affordable within communities than can fulfill CRS guidelines). For all claims being made *with* discounts, better discounts correspond with higher adoption, indicating the importance of the SFHA and the CRS in assessing risk within these boundaries.

However, Table 4.5 shows that despite all residents having access to some form of a CRS discount, nearly half of all insurance claims were being made on policies with no discount, indicating Preferred Risk Policies (PRPs). PRPs are described by FEMA as a lower-cost alternative to the Standard Flood Insurance Policy (SFIP), with eligibility only outside the Special Flood Hazard Area. The PRP is another intervention into the calculus of flood insurance by ignoring the CRS (which predates it) is intended to incentivize entire governments to manage floodplains, the PRP demonstrates the highest amount of adoption, bypassing a system of incentives in exchange for the basic economic incentive of price. Effectively, the PRP has placed even more weight on effective risk assessment (as opposed to governmental methods of floodplain management) to control flood insurance adoption. In the case of inaccurate flood mapping or newly hazardous conditions, properties have temporary access to PRPs, but the political instability of the NFIP and its consistently increasing rates threaten to displace it.

Table 4.5 Community Ratings System Discounts by Rate and Adoption

Rate	Policies	Claims
No Discount	75.18%	49.97%
5% Discount	1.51%	2.95%
10% Discount	2.08%	4.55%
15% Discount	7.19%	13.91%
20% Discount	0.19%	0.44%
25% Discount	13.85%	28.18%

The current NFIP is an immense techno-political assemblage, a deeply detailed system with a country-wide scope that has consistently grown more intricate as floodplains only become more populated. Despite the singular importance of the NFIP within the United States' floodplain management system, all of its functions rely upon accurately assessing risk: risk assessments influence insurance prices, the CRS supports floodplain risk management, and risk perception through the National Flood Hazard Layer drives decision-making at the individual and political level. Thus, in the decades-long history of the NFIP, floodplain mapping and the probabilistic assessment of risk has remained its core. In the above map, the higher value discounts demonstrate the typical logic of the NFIP where higher risks are associated with higher adoption of flood insurance. However, this correlation is not followed so strictly in East Harris county, where areas of the east Inner Loop and Clear Lake had average rates lower even than the 10-15% discount one might expect outside the Special Flood Hazard Area. In those areas, Preferred Risk Policies and their 0% CRS discount rate exceeded Standard Flood Insurance Policies reflecting the county-wide statistic of 75% of policies being PRPs (with the lower share of 49% of claims being PRPs).

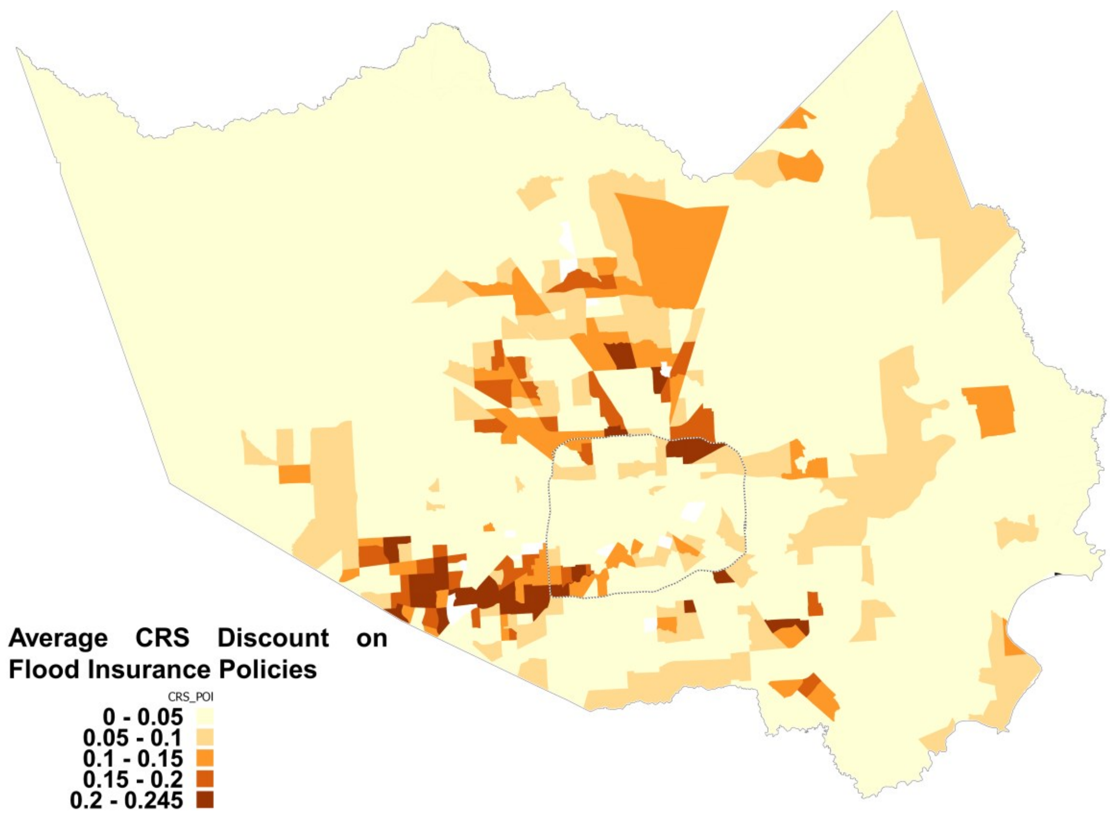

Figure 4.8 The average discount for insurance policies in force during Hurricane Harvey.

The total impact of the predominance of PRPs is not clear. While PRPs are less expensive than standard flood insurance policies, coverage can be lost after two flood incidences, and eligibility is determined on a building-by-building basis, once again contributing to the economic advantage of owning a newer property: as long as risk has not been proven under the NFIP, the cheaper insurance policy will be available, and can even be grandfathered in if new flood risk maps place a PRP policy owner into a high-risk area. A cheaper insurance policy for lower-risk flood zones encourages more participants in the scheme of insurance, but the PRP offers the most flexibility and economic value for the first policyholders of a building. In the existing schema of inaccurate flood mapping, the recency bias of the PRP is amplified in effect, seen in Table 4.5 where at least half of all claims were made by PRPs

The long history of the NFIP and its floodplain mapping has created a large volume of assessed spatial risk that continually becomes obsolete through floodplain-altering development, additions to technology, and changing protocols of risk assessment. FEMA reports that a cost-benefit analysis is used to prioritize the large corpus of studies, prioritizing areas with the most development in the previous year and the oldest floodplain maps. Because of long intervals between re-study, modifications to the floodplain are open through Community-initiated revisions. Communities, as recognized under FEMA, are made responsible for reporting changing conditions within the Special Flood Hazard Area and may even be involved in the process of modeling and mapping, if they become recognized as a Cooperating Technical Partner. Changes made to the map are made through either Physical Map Revisions (PMR) or Letters of Map Revision (LoMR), with an intended scalar distinction: the PMR is a more intensive process that requires the reconstitution and reprinting of the floodplain map, while the LoMR is intended for smaller scale adjustments to the floodplain, with the added caveat that a community is responsible for funding the change and that only the affected tile will be immediately updated with the new floodplain information.

Entirely new mappings are expensive, and new models for Harris County after wild flooding may take until 2023 to complete. Systems of community-initiated mapping are the main action to be taken in the interim, but bypassing further action to communities and the Physical Map Revision / LoMR system, alterations are forced to become small-scale and costly at the local level. This inertia is represented in the total changes made to risk maps since Hurricane Harvey, which were marginal (Figure 4.9).

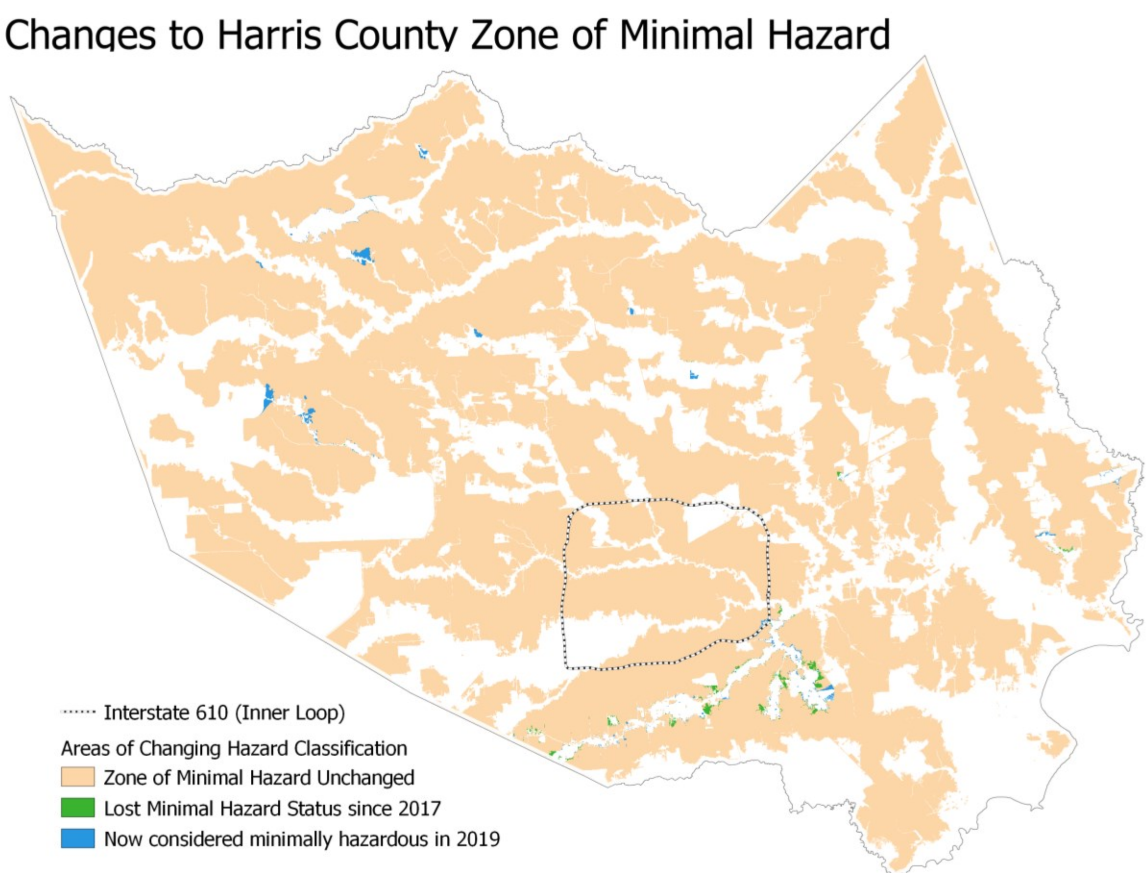

Figure 4.9 Comparing changes in the Zone of Minimal Hazard to the total area unchanged.

The largest share of flood losses occurred in the 'Zone of Minimal Hazard', yet the changes taking place in the two years after Hurricane Harvey do not constitute an immediate response to the inaccuracy of 'Minimal Flood Hazard Zones' in defining areas of safety. Most of the areas being reclassified were not being added to the Special Flood Hazard Area (and thus becoming 'protected' under insurance subsidies). By altering zonal classification mainly to correct the predictive skill of the model, the changes made to 2017's flood maps are not part of a paradigm-shift or a revolution in how flood mapping is done following the boundary-breaking flooding of Harvey. With new flood maps more than 5 years separated from this recovery period, the remediation of flood maps has been limited in scope and in area.

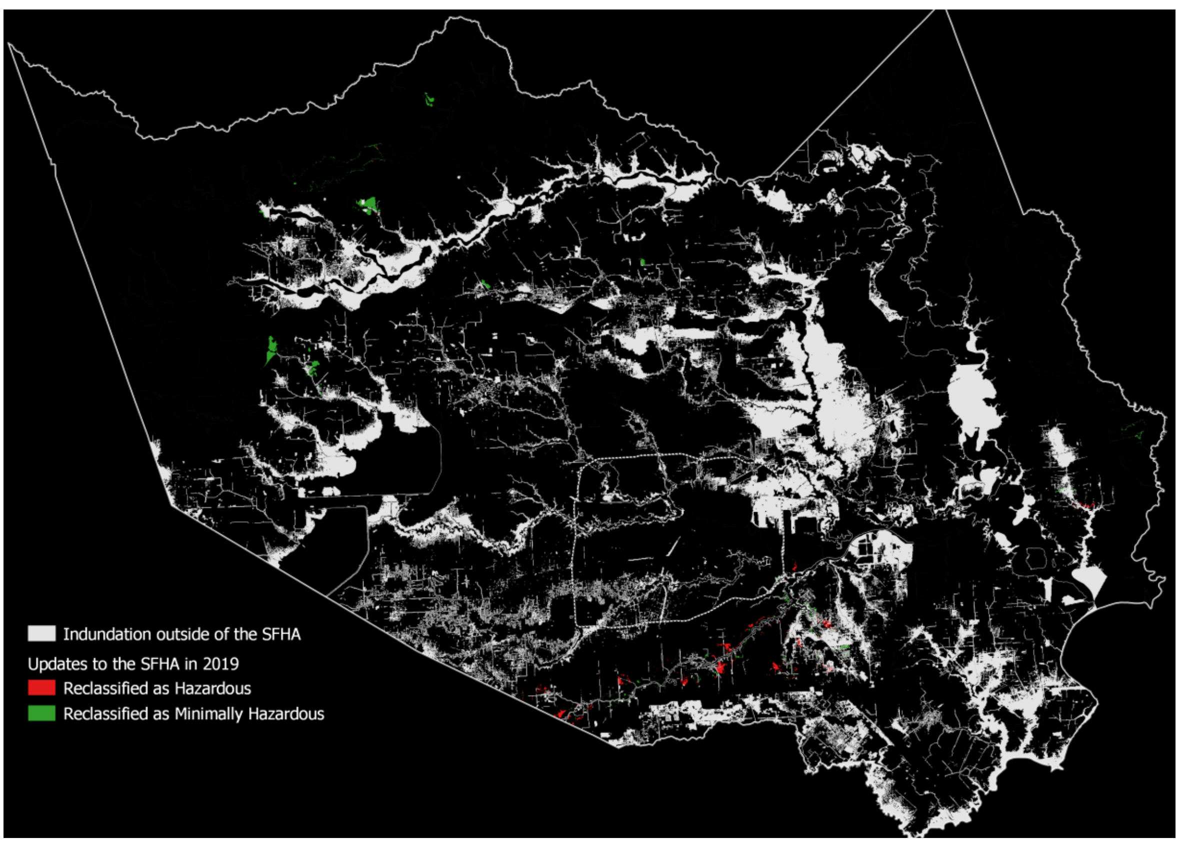

Figure 4.10 Highlighting unpredicted flooding in the Zone of Minimal Hazard and comparing changes to where the SFHA was inaccurate

Compared with flooding in 'minimally hazardous' areas, the relatively low volume of changes visible in Figure 4.10 reveals important phenomena of spatial distribution. The center 'inner loop' of Houston has the most predictable flooding and thus has the least adjustment. Flooding in several other areas, however, has less accuracy in modeling. The topographic conditions of Harris Country offer serious drainage issues, but the flooding of Hurricane Harvey relies partially on existing alterations to the environment (the overflowing Barker and Addicks reservoirs specifically directed patterns of flooding) rainfall from Hurricane Harvey pushed flood control infrastructure to 'worst case' scenarios. The Zone of Minimal Hazard was intended to function as an area of low risk, but instead comes to occupy the largest share of flood claims, with the policies within this area largely composed of PRPs, which are marked by their low cost. The developed downtown section of Houston within the bounds of Highway 610 is free of some of the unexpected flooding of other areas, begging the question of why some areas are safe while others are not. In the case of Downtown Houston, a history of flooding from its founding as a city was altered when the Barker and Addicks reservoirs were built. Upstream reservoirs protect downstream watersheds from flooding, but this did not prevent inundation in the downtown core, it merely made it more predictable than in other watersheds without large-scale federal infrastructure protecting them. On the other end of risk adjustment, reservoirs and dams in Harris County also were associated with risks. The Kingwood development in the Northeast section of Harris County and the Addicks Park neighborhood both were flooded as a direct result of downstream interventions.

Flooding can be analyzed outside of the traditional geographies of neighborhoods or the Census. In Carr et al. (1992) hexagon mosaic maps are advanced as a preferred shape in polygonal tessellations in GIS and cartography given a number of advantages: hexagons are the most complex geometric form that nests perfectly within each other, which allows for lines and borders at different angles than the 90 degree intersection of square mosaic maps, while also favoring cluster analysis due to each polygon having six neighbors as opposed to the four neighbors that a square would share sides with. This is especially valuable for flooding because the topology of waterways in Houston follows diagonal courses more than orthogonal courses, thus hexagons are able to measure inundation in 4.11 more than other shapes.

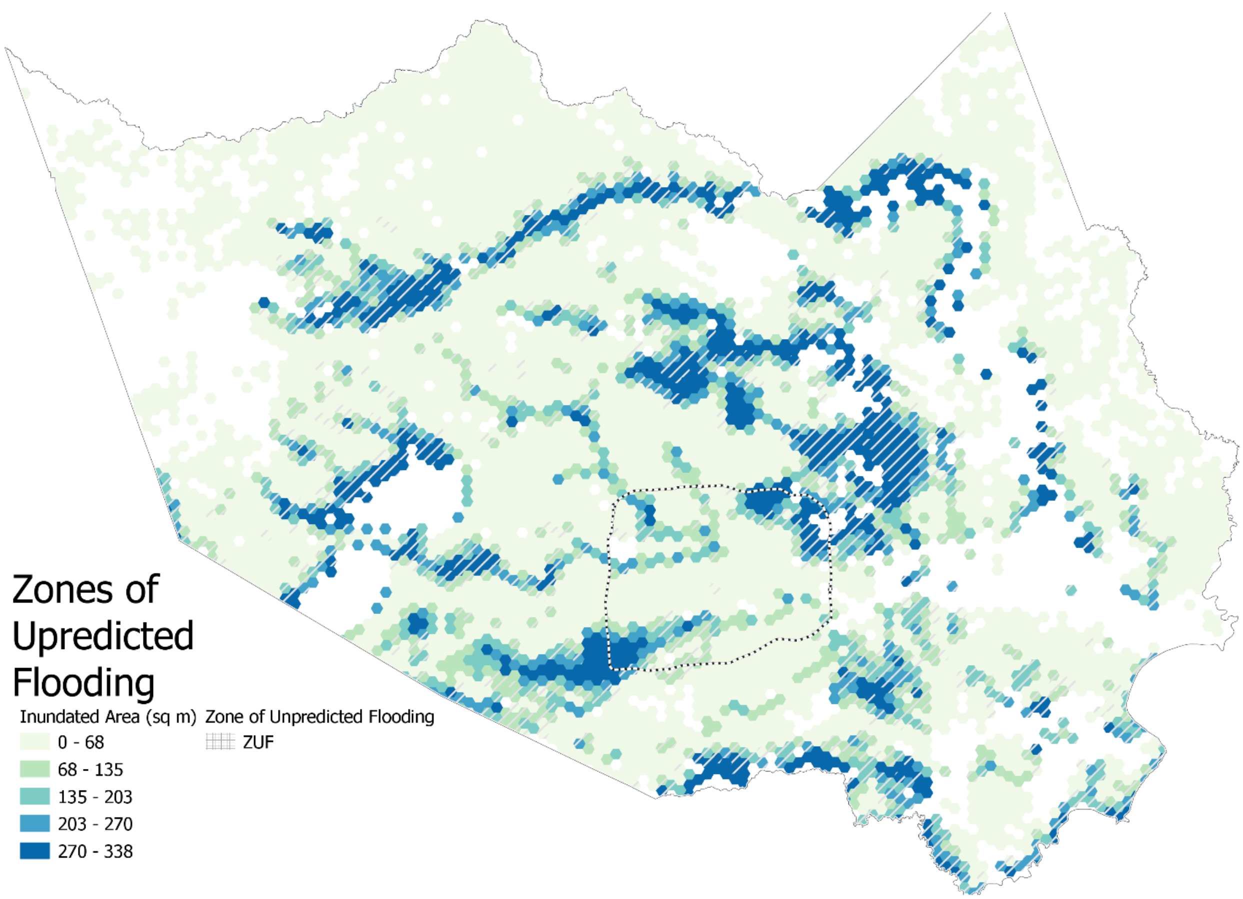

Figure 4.11 Creating Zones of Unpredicted Flooding using flooded area

Using a hexagon mesh like that used in Figures 4.5 and 4.6, the distribution of 'unpredicted' flooding outside the Special Flood Hazard Area can be compared to Harris County in general, using new polygons that gather multiple forms of data together and compare potential differences of inundated areas from the county at large. A 'Zone of Unpredicted Flooding' (ZUF) is calculated for polygons based on the amount of non-SFHA flooding observed within. When observed inundation area for a polygon was higher than the median figure and is mostly outside of the SFHA, it is classified as a ZUF. Under those conditions,1,222 polygons are in the ZUF, totaling 23.6% of the total area.

Taking data from a variety of sources, a simple comparison between the ZUF and the rest of Harris County reveals a few observations about the state of flood risk in the Houston area. Naturally, the City of Houston figures for affected population are higher than the county average, but it is also interesting to note that Individual Assistance applicants had higher rates of home insurance and flood insurance inside of the ZUF than the county average. Given the fact that Individual Assistance is averaged only across flood-affected polygons, it would appear that residents of the ZUF are not as unprepared as the county as a whole: homeowners have invested their own resources into flood insurance even when not required to by the law. Directly following insurance, the Loss Sold Odds Ratio (as derived from property records) is next in widest difference. Following direct correlates to flood exposure, social variables have the next highest degree of difference. Black and Hispanic populations were more strongly represented in the ZUF, which is important to note given the existing inequalities in socioeconomic status that predominate the Houston area (see Chapter III). However, before making definitive claims on the causal relationship between race and flood risk, multiple urban areas would have to be examined. Hurricane Harvey encapsulates only one flood event and only one edition of the National Flood Hazard Layer.

Table 4.6 Selected Variables in Zones of Unpredicted Flooding During Hurricane Harvey

Dataset	Alias	Greater in ZUF	Percent Difference
City of Houston	Percent of Population Affected	TRUE	16.67%
Individual Assistance	Home Insured	TRUE	10.31%
Individual Assistance	Flood Insured	TRUE	9.17%
Harris County Appraisal District	Loss Sold Odds Ratio	TRUE	7.24%
Harris County Appraisal District	Percentage of Homes Sold for Loss	TRUE	7.20%
Census	Black Population	TRUE	7.19%
Census	Hispanic Population	TRUE	4.59%
Census	Vacant Houses	TRUE	1.79%
Census	Renting Population	TRUE	1.46%
Census	Percent NH White	FALSE	1.28%
Census	Median Household Income	FALSE	0.89%
Census	Impoverished Population	TRUE	0.29%

Similar notes of caution must be made regarding the economic variables observed in Table 4.6, with emphasis on the lower degrees of difference seen in household income and poverty rates. Although Black and Hispanic populations are observed at higher rates in the ZUF, there are still other communities outside of flood risk zones. The Zone of Unpredictable Flooding fulfills the wider paradigm of uncertainty in the face of flood risk in the Houston area by itself being spread over a large amount of urban space. Thus. In the ZUF, the rich and highly white neighborhoods along the Buffalo Bayou are packaged together with primarily black neighborhoods such as Northside and Kashmere Gardens. Although they may share the very rudimentary classification of being in a ZUF, these areas differ from each other socially and environmentally; it cannot be concluded that risk is experienced in the same way in these areas. The ZUF is an attempt to create new geographies of risk in a setting in which information is dense and deeply variegated. While it shows the existence of socially vulnerable populations and household adaptations to risk in the aftermath of Hurricane Harvey, it also reveals that new geometry brings with it new problems: the challenge of capturing external phenomena through GIS is not a new one, but it is doubly replicated in this context. The physical existence of inundation and flood risk is paired with the ability of individual households to adapt to damage or to changing perceptions of risk; the Zone of Unpredictable Flooding attempts to unify these two experiences, but its rudimentary structure was intended to reflect the very complex nature of the issue. For one hurricane and one city, conclusion and analysis are best limited in time and place to the study area, but creating the ZUF, exploring loss sales, and mapping the shortcomings of the NFIP Community Rating System suggest future directions for geographic inquiry into other storms and other cities.

CHAPTER V

CONCLUSION

While Hurricane Harvey broke precipitation records, it does not require Category 4 hurricanes to cause flooding in Houston, or even classified tropical cyclones. 2015, 2016, and 2017 all saw flooding in Houston that exceeded the '500-year' probability interval, and Tropical Storm Imelda in 2019 again proved that flood risk is a dynamic feature of the Houston urban landscape that changes between flood events alongside shifting weather conditions and changing landscape. The growth of Houston has been substantial, and the city serves as a site for considerable amounts of economic activity, but its history of development occurs within coastal lowlands diffuse with waterways and floodplains. Flood hazards in Houston, Texas are a threat that will not diminish with continued growth, and the political challenge of assessing risk and mitigating against harm on the federal level has resulted in a strategy that changes perhaps as fast as hazardous conditions do, with constant renovations to the NFIP driven by the economic performance of flood insurance, and flood control infrastructure that needs federal funding and maintenance to remain standing.

The changing nature of flood insurance as a political concept emerges strongly in this thesis: the National Flood Insurance Program is a key example of the central role of government in spatial data processing (discussed in Chapter II). The requirements of insurance demand authoritative maps that assign definitive probabilities to space, leading to the National Flood Hazard Layer and the creation of flood risk as a time interval (the 100-year and 500-year floodplains) and not as a stronger advisory of risk. Although the proliferation of GIS now assures that flood maps can be created by any entity, only the government (and FEMA especially) can create flood maps that will matter in terms of public policy.

For example, the City of Houston reacted to widespread flooding in the Meyerland area by requiring new structures to be built at least 1 foot (304 mm) above the basal flood elevation determined in the NFHL. Despite functioning as the central pillar of governmental flood mitigation, the NFHL is inconsistently updated across the country and indeed is outdated in Harris County. Seemingly, the Harris County Flood Control District seeks to remedy this through the MAAPnext program, funded by a FEMA grant to first map upstream watersheds, but the results will first be available as preliminary maps in 2022, with 1.5-2 years before these updated maps become official. Furthermore, the use of flood maps in the NFIP is changing: The Risk Rating 2.0 program (in force in October 2021) will generate flood risk on the basis of individual structures. Thus, the promise of geospatial technology finds itself hampered by the realities of governing in the United States: anything can be mapped, but most mapping will not be empowered by political force (and political force is a capricious standard for contested programs such as the NFIP).

In some sense, factors of vulnerability remain the most reliable elements of flood risk: the histories of inequality in Houston are as developed as its economy and histories of booming growth. This is not to say that the same areas will have the same hazards experience between flood events, but rather that similar social conditions influence vulnerability even as exposure to hazards varies between events; Social Vulnerability Indices are one attempt to capture this phenomena in GIS (discussed further in Chapter II), but focusing predominately on the current distribution of social data can obscure other questions relating to the subject. If SVIs generate computational accounts of vulnerability, they do not create similar accounts of responsibility or the ability for these conditions to change. Indeed, it is not some inherent quality to these social factors that determine vulnerability; to be White or Black or Hispanic does not have an inherent meaning because these categories are socially determined. The processes that create racial segregation and make renters vulnerable extend beyond disasters and are features of existing systems that limit what can be done politically and economically. Without identifying the causes of inequality, observing inequality and assigning it a spatial location does not reveal much about methods to mitigate vulnerability.

Alternatively, vulnerability can be investigated through the ability of the state to assess risk for these populations. Because there are no true cartographic standards for mapping most floods (especially outside of FEMA), the critical GIS analysis of this thesis explores the availability of other metrics of flood damage without official geographic measurements of loss. Measuring loss-sales as an indicator of residential property disruption revealed areas of disruption were centered in places with more owners than renters, with higher degrees of activity in newer inundated areas than older inundated areas. By using claims data, it was confirmed that the NFIP is overwhelmingly used by owner-occupied single-family houses, although Individual Assistance applications confirmed that renting households were over-represented compared to their share of the general population (although the difference between renting and owning percentages did not exceed the nationwide average). To examine the performance of risk-assessment and hazard mitigation programs by FEMA in relation to vulnerability, it was confirmed that NFIP claims were more likely than Loss-Sales in the year after Harvey, showing that flood insurance is still the most frequent form of adaptation to inundation. However, the Community Ratings System program and its form of incentives for governments seems to have been entirely surpassed by the existence of Preferred Risk Plans. Although CRS discounts on policies are still at use in the Special Flood Hazard Area, discounts in the 500-year floodplain are almost entirely eschewed for PRPs. While PRPs are more affordable in the short term, their long-term stability is called into question by the limited eligibility of the PRP and the pending changed to flood insurance in FEMA's Risk Rating 2.0 system, which purportedly does away entirely with floodplain mapping for risk rates and instead calculates risk on a per-household basis.

The continuing decline of federal flood insurance as a valid financial instrument is paired with continually shifting policy interventions following increasingly embattled congressional reauthorizations, ensuring that paradoxically, the most constant element of flood mitigation in the United States are aging flood maps. As the interval between mapping increases and development continues in Houston, flood risk will become increasingly unpredictable and the exposure of unprepared people stands to increase. By using figures such as the Zone of Unpredicted Flooding, this thesis reveals that minorities and renters are more likely to be present in areas of unpredicted flooding. This stands to become another element of inequality, where homeowners and renters alike are unequipped to perceive risk and adapt on the household level, while governments struggle to negotiate a plurality of jurisdiction and funding sources in order to act outside of the scope of the NFIP. On the inside of the 'box' of GIS and flood mitigation policy, many limitations exist that prevent direct changes in in flood mapping methodology, although legislative bodies are privileged with the ability to pass reform and reauthorization bills that have immediate changes in the function of FEMA and the NFIP. Ultimately, the largest possible changes in observing vulnerability and identifying social vulnerability in imprecision must happen outside of the 'box' of the NFIP. The spatial tools of home flood insurance have been expanded to cover the entire country, but this singular implementation has created a unclear and inconsistent image of flood risk that causes harm that, in Houston, Texas, weighed heavier on minority populations and those of lower socioeconomic statuses.

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