ESTIMATING LOSSES FROM HURRICANE HARVEY USING FEMA'S HAZUS-MH MODEL

A Thesis

by

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ABSTRACT

Hurricane Harvey was one of the most destructive and costliest hurricanes to ever make landfall on the Texas coast and one of the many tropical cyclones that impacted the United States during the 2017 North Atlantic Hurricane Season. In recent years, emergency managers and researchers have been using hurricane risk and vulnerability analyses developed using Geographic Information Systems (GIS) to make informed decisions on different aspects of community and regional preparedness when a tropical cyclone is forecasted to impact an area. Though there are many ways to quantify risk and vulnerability, this project uses the Federal Emergency Management Agency's (FEMA) Hazards-US Multi-Hazards (HAZUS-MH) GIS extension to estimate and illustrate the physical, economic, and social losses associated with tropical cyclone impacts along the Texas coast, specifically in the Greater Houston Region.

There are numerous ways to quantify risks associated with tropical cyclones using GIS, most of which focus on one of the three hazards involved in hurricane impact: extreme winds, heavy rainfall, and storm surge. This project addresses this shortcoming by focusing on all three hazards and modelling the physical, economic, and social losses in locations in the Greater Houston Region that were caused by Hurricane Harvey. Heavy rainfall produced the most losses, while storm surge affected the southern-most areas of the Texas coast. Wind damage from Hurricane Harvey was insignificant in comparison to the probabilistic scenarios, with losses estimated to be in the thousands of dollars, instead of in the millions or billions of dollars. The results of

this study are compared to each other to see if the most vulnerable areas of the Greater Houston Region were largely affected by Hurricane Harvey.

DEDICATION

This thesis is dedicated to my mom for supporting me throughout this journey from 1700 miles away and for always encouraging me to keep going no matter what.

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All work conducted for this thesis was completed by the student independently.

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NOMENCLATURE

CDMS	Comprehensive Data Management System
DEM	Digital Elevation Model
DOL	Department of Labor
FEMA	Federal Emergency Management Agency
GFDL	Geophysical Fluid Dynamics Laboratory
GIS	Geographic Information Systems
HAZUS-MH	Hazards U.S. Multi-Hazards
HIFLD	Homeland Infrastructure Foundation Level Data
HURDAT	Hurricane Database
HURDAT2	Hurricane Database (Version 2)
HURREVAC	Hurricane Evacuation
IPCC	Intergovernmental Panel on Climate Change
MHHW	Mean Higher High Water
NHC	National Hurricane Center
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SWAN	Simulating Waves Nearshore
USCB	United States Census Bureau
USPS	United States Postal Service

UTC	Universal Time Coordinated
WHAFIS	Wave Height Analysis for Flood Insurance Studies
WRF	Advanced Research Weather Research and Forecasting

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CHAPTER I

INTRODUCTION

The effects of tropical cyclone impacts on society are becoming more apparent every year, with losses from hurricane events expected to become more financially damaging in the future (Klotzbach et al. 2018). This was evident with Hurricane Harvey, a major hurricane that made landfall in Texas on August 26, 2017 and made significant impacts with its high winds, extreme precipitation, and storm surge in the Greater Houston Region (Blake and Zelinsky 2018). Texas is a state that is vulnerable to hurricanes since it is in the western section of the Gulf of Mexico; there have been 37 tropical cyclones that affected the Houston area from 1950-2017 (Trepanier and Tucker 2018). Though the effects of historical storms have been extensively studied on the state of Texas and the Greater Houston Region, there have been few studies examining the combined effects of the three hazards—winds, precipitation, and storm surge—associated with these storms and the physical, economic, and social losses that result in this area, particularly from the recent Hurricane Harvey.

There have been many studies examining the relationship between climate change and hurricanes, though some results continue to be debated (GFDL 2018a). However, there is agreement in that future hurricanes will most likely have higher rainfall rates than the storms we see currently (Knutson et al. 2010; Knutson et al. 2013; Knutson, Sirutis, and Zhao 2015; Wright, Knutson, and Smith 2015). Hurricane Harvey produced unprecedented rainfall amounts in southeast Texas, with all previous tropical cyclones precipitation records shattered (Blake and Zelinsky 2018). With major demographic shifts around the country, especially the trend of people moving to the southeast U.S. and along the coastlines, property damage and growing populations are becoming more at risk from hurricane impacts (Burton 2010). Improving our understanding of risk and vulnerability in the Greater Houston Region can help to mitigate and prepare communities for future storms, as well as understand the implications of the most recent storm to impact the area (Klotzbach et al. 2018).

Using GIS-based software to make informed decisions on regional and community preparedness has become more popular in recent years, particularly to illustrate hazard impacts on society. Though there are numerous ways to quantify the risks associated with tropical cyclones using GIS, most studies focus on either high winds, extreme precipitation, or storm surge as individual hazards. This project addresses this shortcoming by focusing on all three hazards and modelling the physical, economic, and social losses in the Greater Houston Region, including those from Hurricane Harvey, using FEMA's HAZUS-MH model. This thesis will examine this through three objectives:

1. Update HAZUS-MH with more recent input variables and databases.
2. Identify the areas of Houston that are most vulnerable to the three hazards of extreme winds, heavy rainfall, and storm surge.
3. Assess Houston's specific losses from Hurricane Harvey.

In this study, hurricane event risk will be evaluated for nine counties in southeast Texas that make up the Greater Houston Region. To obtain the most up-to-date assessment, the outdated default data included in HAZUS-MH will be replaced with current information with the use of the Comprehensive Data Management System (CDMS). The updated data will then be used in HAZUS-MH to provide a probabilistic overview of the consequences of hurricanes and to estimate the losses that specifically occurred during Hurricane Harvey. An assessment of the probable and actual losses in the Greater Houston Region can help to establish ways to improve current mitigation and preparedness strategies.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1 Hurricanes

Tropical cyclones are defined by Montgomery and Farrell (1993) as large-scale rotary storms that form over warm ocean waters in tropical regions with outer circulations that can extend more than 1,000 kilometers from a storm center. They are categorized as hurricanes in the Atlantic and Eastern Pacific Oceans and typhoons in the Western Pacific Ocean when they reach sustained surface winds of 33 m/s or higher (Montgomery and Farrell 1993). Tropical cyclones are categorized based on their wind speeds via the Saffir-Simpson Hurricane Wind Scale (Table 1, adapted from Schott et al. 2012), which was updated in 2012 to specifically highlight peak winds. The earlier versions of this scale, originally developed by Saffir (1973) and Simpson (1974),

Category	Sustained Winds (m/s)	Types of Damage Due to Hurricane Winds
1	33-43	Very dangerous winds will produce some damage.
2	43-49	Extremely dangerous winds will cause extensive damage.
3 (major)	49-58	Devastating damage will occur.
4 (major)	58-70	Catastrophic damage will occur.
5 (major)	70 or higher	Catastrophic damage will occur.

Table 1: The Saffir Simpson Hurricane Wind Scale (adapted from Schott et al. 2012)

incorporated other features of hurricanes, such as central pressure and storm surge, so that the scale could describe the impacts of these destructive storms. Changes were made because recent hurricanes, such as Hurricane Charley (2004) and Hurricane Ike (2008) had extents and peak storm surges that exceeded the ranges of earlier versions of the scale. To reduce public confusion about the impacts associated with storms of various categories on the scale, the National Hurricane Center (NHC) removed the storm surge ranges, flood impact, and central pressure descriptions and revised it to be specifically for sustained winds. Each category on the scale, ranging from 1-5, with 5 having the most destructive impacts, has descriptive statements of the damage that can occur if an area is impacted by the strength of hurricane. For example, Category 1 hurricanes have sustained winds between 33 and 42 m/s and can inflict some damage upon landfall, while Category 5 hurricanes have sustained winds of 70 m/s or higher and produce catastrophic damage when within range of populated areas (Schott et al. 2012).

Hurricanes usually start as easterly waves, which have cyclonic vorticity and enough atmospheric instability for tropical cyclogenesis. Easterly waves form in sub-Saharan Africa and make their way across the Atlantic Ocean, becoming more powerful as they progress. The wave becomes classified as a tropical depression when the winds begin to rotate counterclockwise around a low-pressure center, but remain below 16 m/s. A tropical depression can become stronger when the conditions continue to be favorable across the Atlantic Ocean, transitioning to a tropical storm with winds ranging from 17 to 32 m/s or even further to a Category 1 hurricane and beyond. For this to happen, the atmosphere needs to be unstable or have a disturbance to produce strong thunderstorms, sea surface temperatures should be at least 27°C, the ocean depth should be at least 45 meters, and a deep layer of humid air, little to no wind shear, and a strong Coriolis force must be present (Emanuel 2005).

2.2 Damages and Losses from Hurricanes

Damages associated with tropical cyclones are usually due to the three main attributes from this destructive natural hazard: extreme winds, heavy rainfall, and storm surge (Emanuel 2005). However, social factors may be influencing the amount of physical, economic, and social losses that have come out of more recent North Atlantic hurricane seasons, such as risk perception and self-assessment of levels of emergency preparedness (Kashem, Wilson, and Zandt 2016). In recent decades, the United States has experienced several major demographic shifts, with the most significant being a trend in people moving to the southeast and along the coasts of the country (Burton 2010). In Texas, specifically, the population of coastal counties, which includes the three major metropolitan areas of Brownsville, Corpus Christi, and Houston, continues to grow at an unprecedented rate (Dixon and Fitzsimons 2001). In turn, there has been an increase in development, including housing, infrastructure, and commercial buildings, making them more vulnerable to hurricane damages from the winds, rainfall and storm surge (Dixon and Fitzsimons 2001). Although trends in landfalling hurricanes in the contiguous United States have more significantly increased and decreased in frequency, hurricane-related damages have had a notable increase, likely due to the increases in population and development along the Gulf and east coasts (Klotzbach et al. 2018). It is also expected that future losses from hurricane events will be financially damaging to local, state, and federal agencies (Klotzbach et al. 2018).

Storm surge is defined by the NHC as a storm's abnormal rise of water above the predicted astronomical tides and is produced by water being pushed toward the shore by the force of tropical cyclone-strength winds rotating (NHC 2019b). Storm surge is particularly hard to predict for any given location because of different factors, such as storm intensity, forward speed, geographical extent of the storm, angle of approach to the coast, central pressure, and the shape and characteristics of coastal features, such as barrier islands. Storm surge is destructive due to the weight of water (approximately 1008 kg/m^3), and, along with big waves, can destroy any structure that is not specifically designed to withstand those forces. Salt water intrusion from the ocean into estuaries and bayous can endanger public health, kill vegetation, and force wildlife away from the flooded areas (Emanuel 2005; NHC 2019b). The potential impacts of storm surge on the Texas coastline, specifically in the Houston/Galveston area, were studied in the years following Hurricane Ike. Torres et al. (2015) looked at the hydrologic contributions and interactions of hurricane storm surge and rainfall-runoff for the Houston Ship Channel by implementing a hurricane shifting modeling framework that preserves the spatial and temporal characteristics of rainfall and wind fields. While storm surge consistently dominated the flooding potential in the area, the rainfall-runoff volume contributed more than 50% of the volume share in the overall storage budget (Torres et al. 2015). Moreover, using a methodology for estimating the annual probability of the joint hazard of storm surge and extreme winds based on the bivariate copula model for Galveston, Texas, Trepanier et al. (2015) found that the probability peaks in September and a Category 3 hurricane with a storm surge of at least 4 meters has a 1.7% chance of occurring every year.

Hurricanes can result in billions of dollars-worth of losses when they make landfall in the United States. The top five costliest U.S. hurricanes on record include the three major hurricanes of the 2017 season: Harvey, Maria, and Irma. The cumulative cost of 16 separate billion-dollar weather events that occurred in the U.S. in 2017 was $306.2 billion, with approximately $265 billion coming from Harvey, Maria, and Irma. The top vulnerable states in the U.S. to hurricanes when it comes to insured coastal properties are New York, Florida, Texas, Massachusetts, and New Jersey (NOAA 2019).

2.3 Climate Change and Hurricanes

2.3.1 Precipitation

One of the most prominent features of tropical cyclones is the extreme precipitation that causes inland flooding, which can greatly affect the people and environment, as well as result in significant economic damage and loss of life (Paul and Sharif 2018). Precipitation from tropical cyclones accounts for a large percentage of the total annual precipitation and extreme precipitation events along the U.S. Atlantic and Gulf of Mexico coasts (Knight and Davis 2007, 2009). Texas, specifically, receives an average of 123.5 mm of precipitation from tropical cyclones per year, which is about 13% of the state’s mean annual precipitation (Zhu and Quiring 2013).

Though the human influence has not been definitively detected for this feature of hurricanes, tropical cyclone precipitation is expected to increase in the future due to the increase in atmospheric moisture from anthropogenic warming; there is a projected average of 10-15% increase for a 2°C warming scenario (GFDL 2018a). Though there is disagreement and uncertainty on the extent of how much tropical cyclone precipitation will increase in the future, there is a consensus that future hurricanes will most likely have higher rainfall rates than the storms seen today (Knutson et al. 2010; Knutson et al. 2013; Knutson, Sirutis, and Zhao 2015; Wright, Knutson, and Smith 2015).

2.3.2 Intensity and Frequency

In a 2°C warming scenario, it is likely that global tropical cyclone intensity can increase anywhere from 1-10%, according to climate model projections (Knutson, Sirutis, and Zhao 2015; Knutson et al. 2010). Furthermore, the global proportion of tropical cyclones that reach the Category 4 or 5 level on the Saffir-Simpson Hurricane Wind Scale will also likely increase, but there is less confidence in the number of storms of these strengths since the global frequency of tropical cyclones is expected to decrease throughout the century (Knutson et al. 2013; Bender et al. 2010). More intense hurricanes, in turn, suggest that there is a large destructive potential in any given storm. Vecchi, Swanson, and Soden (2008), however, show that the relationship between rising sea-surface temperatures and the destructive potential of a tropical cyclones is only statistical, not physically meaningful, and convey that current measurements show long-term trends of Atlantic hurricane activity that are much more conservative. Though the global mean temperature and sea-surface temperatures in the Atlantic show statistically significant warming trends, the historical hurricane record for the basin does not have enough compelling evidence to prove that this warming will induce a long-term increase in tropical cyclones (GFDL 2018a). Vecchi and Soden (2007) suggest that vertical wind shear and upper tropospheric temperatures will increase over the western tropical Atlantic Ocean when assessing model-projected changes in large-scale environmental factors associated with variations in tropical cyclone statistics. Increased vertical wind shear and higher upper tropospheric temperatures are conditions that are unfavorable for hurricane development and intensification, while increased sea-surface temperatures have the opposite effect (GFDL 2018a).

It is difficult to predict the frequency of future intense tropical cyclones for a myriad of reasons, such as model parameter constrictions and idealized assumptions that do not reflect real-world conditions (Knutson and Tuleya 2004; Knutson et al. 2008). Using an 18-model average of climate change projections, Bender et al. (2010) estimate that the frequency of Category 4 and 5 hurricanes can increase by as much as 81% by the end of the century since observed tropical cyclones at that magnitude have increased linearly in the last 60 years. However, the confidence of these projections is low since there is little evidence to lead to that conclusion that anthropogenic climate change will lead to a large increase in the frequency of tropical cyclones in the Atlantic (GFDL 2018a).

Another factor in the difficulty in understanding how Atlantic hurricanes have changed historically is the lack of accurate records and observations from before 1965

(Vecchi and Knutson 2008). When assessing Atlantic HURDAT (Jarvinen, Neumann, and Davis 1984; McAdie et al. 2009), the hurricane database managed by the NHC, many studies have concluded that the increase in tropical cyclones in this basin since the late 19th century is most likely due to the improved monitoring from advances in technology and observation methods, such as the implementation of satellite data (Vecchi and Knutson 2008; Landsea et al. 2010; Vecchi and Knutson 2011; Villarini et al. 2011). Furthermore, Landsea et al. (2010) noticed that there has been a significant increase in the number of tropical cyclones with durations of less than two days since the 1800s. Though there is no clear indication that climate change is the cause of this, it does verify that the improvement of observational practices may be the explanation for the historical increase in tropical cyclone frequency (GFDL 2018b).

2.3.3 Storm Surge

Due to sea level rise from anthropogenic climate change, it is predicted that tropical cyclones will likely produce higher levels of storm surge (IPCC 2014). Moreover, the vulnerability of coastal regions to storm surge is also expected to increase because of the increase of commercial, residential, and infrastructural development in the most susceptible areas to tropical cyclones (GFDL 2018a). The average rate of global sea level rise has been about 3.1 mm/year since the start of satellite sea level recording in 1993 (Lindsey 2018). Throughout the 21st century, sea level rise will most likely exceed levels observed from 1971-2010 for a myriad of future carbon emission scenarios (IPCC 2014). Part of the increased risk in higher levels of storm surge are due to the rise in global sea levels (Rahmstorf 2017). Sea levels have risen about 20 cm since 1900, with the rate accelerating in the last 25 years and expected to increase further in the future (Chen et al. 2017). This is occurring because continental ice melts from global warming, which is adding water to the oceans (Rahmstorf 2017). The severity of storm surge that will happen in the future will depend on the size and intensity of the tropical cyclone, meaning that larger and more powerful storms will likely produce more storm surge (Rahmstorf 2017). With these factors expected to increase due to climate change, storm surge should also become more of a threat (Rahmstorf 2017).

2.4 Hurricanes That Have Affected Houston, Texas

Houston, Texas is vulnerable to tropical cyclones due to its geographical location along the western coast of the Gulf of Mexico. Carr (1967) calculated that a total of 32 hurricanes affected the state of Texas from 1900-1965, including the deadly Galveston hurricanes that occurred in 1900 and 1915, and had origins in the Atlantic Ocean and the Gulf of Mexico. Carr (1967) also suggested that tropical cyclones were sometimes unable to properly develop into hurricanes due to the meteorological conditions in the region, but they continued to move toward Texas as weak tropical cyclones or tropical depressions. Moreover, using HURDAT2 (Landsea, Franklin, and Beven 2015), the updated version of HURDAT, Trepanier and Tucker (2018) found that there have been 37 tropical cyclones that have impacted Houston from 1950-2017. Moreover, Islam et al. (2009) provided a comprehensive analysis of Texas hurricanes from 1851-2006 using climatological information and historical case studies and found that the Upper Texas

Coast, where Houston is located, is more prone to tropical cyclone impact that the Lower Texas Coast; that is probably due to most of these storms originating in the Gulf of Mexico. Furthermore, Islam et al. (2009) discovered that the tropical cyclones impacting that area of Texas tend to form early on the North Atlantic hurricane season, intensify rapidly, and make landfall within a few days of formation, which poses a unique threat to the ecosystems, infrastructure, and people of the coast.

An influential hurricane to impact Houston was Hurricane Ike, which made landfall on Bolivar Peninsula in early September 2008 and had an unusually long storm surge duration of 2.5 days (Kraus and Lin 2009). Thirty-four Texas counties were declared disaster areas by FEMA and 15 of them were under mandatory evacuation orders (Zane et al. 2011). Zane et al. (2011) identified 74 deaths in Texas from September 8, 2008 through October 13, 2008 that were either directly, indirectly, or possibly related to Hurricane Ike. Despite extensive and large-scale efforts for government-sponsored public education in disaster preparedness, Chen, Banerjee, and Liu (2012) discovered that the residents of the Gulf Coast showed no significant changes in preparedness and evacuation plans in a comparison of interviews conducted one month before and one year after Hurricane Ike. This emphasizes how the increase in access of information to minority groups can be beneficial for disaster resiliency and quicker recover time (Chen, Banerjee, and Liu 2012). The storm surge that affected the Houston area from Hurricane Ike also had significant consequences. Schiller (2011) used GIS to find which areas in the counties surrounding Houston would be flooded from a 2-m and 5-m storm surge and approximated that the daily wage loss can run into millions of dollars. Because of this storm surge from the hurricane, studies have examined the potential benefits of putting a levee, commonly known as the "Ike Dike," along the coastline of Galveston Island to protect the surrounding communities from this effect of major hurricanes (Subramanian et al. 2013; Pan 2015; Atoba et al. 2018).

2.5 Hurricane Harvey

Hurricane Harvey started out as a wave off the west coast of Africa on August 12, 2017, became a tropical depression east of Barbados four days later, and a tropical storm within 12 hours. It reached an initial peak intensity of 20 m/s, in the range of tropical storm classification on the Saffir-Simpson Hurricane Wind Scale, early on August 18 as the storm's center passed over Barbados and St. Vincent at 1000 UTC. Harvey regressed to a tropical wave the next day but stayed convectively active as it moved west toward the Yucatan Peninsula on August 22. A low-pressure system formed due to a burst of deep convection in the wave, which allowed Harvey to regenerate into a tropical depression the next day. Forecasters initially noted that the depression was poorly organized and had a large radius-of-maximum winds, but those conditions did not last for very long since a smaller radius-of-maximum winds formed from concentrated deep convection near the center. This was also a sign of weakening because a double eyewall was forming. Rapid intensification began on August 23 when Harvey entered an area of warm waters, light shear, and high mid-level moisture. Turning northwestward, intensity increased even further when a large mass of deep convection formed in the center of the depression and an eye was observed on August

24. Harvey became a Category 1 hurricane later that night with a well-defined eye becoming apparent in satellite imagery (Blake and Zelinsky 2018).

Almost as fast as Hurricane Harvey had sustained winds to classify it as a hurricane, the system reached major hurricane status, becoming a Category 3 hurricane by 1200 UTC on August 25. Harvey intensified to a Category 4 hurricane as it approached the Texas coast on August 26. Hurricane Harvey made landfall on the northern part of San Jose Island around 0300 UTC on August 26 with estimated sustained winds of 59 m/s and estimated minimum central pressure of 937 hPa. The hurricane made a second landfall on the Texas mainland hours later southeast of Refugio, Texas; it was slightly weaker due to land interaction with estimated sustained winds of 54 m/s and estimated minimum central pressure of 948 hPa. Once Harvey reached land, it rapidly weakened again to a tropical storm within 12 hours, but maintained sustained winds of around 18 m/s for a couple of days since the southeastern portion of the storm was still over the warm waters of the Gulf of Mexico. The storm halted in movement when it became embedded in light steering currents between a mid-tropospheric high-pressure system over the Four Corners region of the U.S. and another high-pressure system over the northern area of the Gulf of Mexico. Harvey slowly drifted east over the next several days. Though the eye passed south of the Houston area, record-setting rainfall occurred in the city and surrounding areas due to a stationary front on the north and east sides of the hurricane caused Harvey to stall. The storm finally started moving northeast late on August 29 from a strengthening ridge over the western Atlantic Ocean, but heavy rains continued to fall. Harvey made its third landfall in Louisiana early on August 30 with estimated sustained winds of 20 m/s. After this, Harvey quickly became a tropical depression again, moving northeastward and finally dissipating over northern Kentucky on September 2 (Blake and Zelinsky 2018).

Hurricane Harvey is the most recent major hurricane to impact southeast Texas. Therefore, most of the literature focuses on the storm's immediate impacts, such as the causes of fatalities during the storm (Jonkman et al. 2018). Although Texas is a vulnerable area to tropical cyclones and Houston is a rapidly growing city, social factors impacted the amount of damage this storm caused. For example, Trepanier and Tucker (2018) explain that an evacuation like that of Florida with Hurricane Irma (2017) was not conducted because of the lack of early tropical cyclone development. This resulted in over 1,000 people trapped in their homes from flooding, having to be rescued overnight. Furthermore, the Houston government also called upon those who were able to assist in the rescues with small boats and rafts in the unprecedented flooding, which put volunteer civilian lives in danger (Trepanier and Tucker 2018).

One of the notable features of Hurricane Harvey was the record-setting rainfall recorded in southeast Texas due to the storm stalling over the region for several days; it was the highest tropical cyclone rainfall event in U.S. history since official meteorological records began (Blake and Zelinsky 2018). The highest storm total rainfall report from this hurricane was 60.58 inch near Nederland, Texas, with Groves, Texas coming in a very close second place with 60.54 inches recorded (Blake and Zelinsky 2018). This rainfall was extremely unprecedented, so studies have been conducted to estimate the return period of a hurricane of similar capacity. Emanuel

(2017) found that the return period of at least 500 mm of rainfall in one event is about 100 years for the period from 1981-2000; assuming a linearly changing frequency, the return period would change for 2017 conditions to about 16 years in Texas. Moreover Oldenborgh et al. (2017) concluded that an event with rainfall similar to that of Hurricane Harvey would flood any city and that climate change has affected the probability of any given rainfall event in Texas, with intensity of rainfall increasing by 8-19% and the probability of a rainfall event equivalent to Harvey increasing by 1.5-5 times. Warming of the oceans and atmosphere that began in 1980 likely resulted in a 20% increase in accumulated event precipitation, according to a study by Wang et al. (2018) that used the Advanced Research Weather Research and Forecasting (WRF) model's downscaling simulations on Hurricane Harvey. However, Risser and Wehner (2017) note that Hurricane Harvey was a very unusual event since it stalled over Texas and can be an outlier in future precipitation studies. Trepanier and Tucker (2018) also found that Houston is at a greater risk for extreme tropical cyclone rainfall than other cities vulnerable to hurricanes, such as Miami, Florida, because of its large population, noting that geographic variability should be considered in future studies of regional tropical cyclone rainfall comparisons. Other studies note that urbanization can exacerbate the effects of the flooding caused by hurricane rainfall, which shines light on the importance of adding the component of urbanization to climatological studies when assessing the future risk of an extreme rainfall event in highly urbanized coastal areas (Kashem, Wilson, and Zandt 2016; Zhang et al. 2018).

Though studies mostly focus on the winds and precipitation that Hurricane Harvey brought to Texas, storm surge also occurred because it is one of the three hazards that make up hurricane impact. There was a combined effect of storm surge and tide that produced maximum inundation levels of 1.8-3 m above ground level north and east of Harvey's two landfalls in Texas that occurred between Port Aransas and Matagorda. The highest inundations were along the western shores of San Antonio Bay and Hynes Bay. However, a tide gauge at the Texas Coastal Ocean Observing Network site at Port Lavaca measured the highest water level of the event at 2 meters above Mean Higher High Water (MHHW). After Hurricane Harvey impacted Texas, the United States Geological Survey and the National Weather Service conducted several surveys to observe the damages of the storm. They suggested that water levels as high as 3.7 meters MHHW could have occurred between Austwell and the Aransas National Wildlife Refuge. A tide gauge at the USS Lexington in Corpus Christi measured a water level of 0.3 meters MHHW, most likely due to offshore winds on the west side of Harvey that helped to produce less flooding in that area. It is difficult to know how much storm surge occurred in every region along the coast because there are little to no tide gauge observations in some areas. Furthermore, several of the tide gauges, specifically those near Houston, Beaumont, and Port Arthur, measured peak water levels that were greatly affected by the excessive rainfall-runoff from Harvey's extreme precipitation. Therefore, some of the water levels recorded from the storm are not entirely representative of the storm surge that occurred during Hurricane Harvey (Blake and Zelinsky 2018). Because of this, there is no research that focuses specifically on

Harvey's storm surge; there are studies that look at the combined effects of rainfall-runoff and storm surge on various aspects of the Houston area (Bilskie and Hagen 2018; Aghababei, Koliou, and Paal 2018; Sreetharan, Batten, and Lawler 2018; Pan, Yan, and Archer 2018).

2.6 HAZUS-MH

The development of hazards models using GIS has become a growing topic of research in recent years. For example, by exploring the results of a hydraulic GIS model, Colby, Mulcahy, and Wang (2000) found that in the wake of Hurricane Floyd (1999), their methods showed a better representation of the flooding than FEMA's Q3 100-year and 500-year floodplain maps of the same area. However, tropical cyclones involve three hazards: extreme winds, heavy rainfall, and storm surge. Therefore, more studies are beginning to use multi-hazard models to conduct hurricane risk analyses to understand how all three phenomena affect an area at the same time, particularly in the context of economic losses. After finding the aggregated average number of tropical cyclones that have affected the Caribbean over the last 30 years, Bertinelli, Mohan, and Strobl (2016) concluded that a 50-year event could cost about $8 billion, but the risks and losses differ across the many islands in the region. Moreover, using a combination of models can create results that are in line with what was observed. Pan (2015) developed a general framework to estimate the cost of damages from Hurricane Ike using models that included direct and indirect impacts on the economy using GIS. Using this combination of models, Pan (2015) found that Ike was the third costliest hurricane to impact the U.S. at the time and the results were like what was observed in the aftermath of the storm. The use of GIS-based models can also help the user to visualize the impacts of hurricanes from maps created from model runs. Estimating hurricane-induced damage and risk to utilities in Florida, Xu and Brown (2008) presented maps developed from a probabilistic hurricane simulation model that shows peak wind gusts and, compared to the American Society of Civil Engineers 7 wind map of the state, indicated that the results are similar to what is observed in reality.

Due to the fact that tropical cyclones are associated with multiple hazards, there is a need to integrate all aspects of the coast; GIS is one of the most appropriate tools to use for this study due to its versatility (Rodríguez et al. 2009; Andrews, Gares, and Colby 2002). The Hazards U.S. Multi-Hazard (HAZUS-MH) model is multi-hazard risk assessment tool developed by FEMA and is used by local government agencies and community emergency managers to aid in mitigation, response, and recovery (Schneider and Schauer 2006). The model estimates the potential physical, economic, and social losses from many types of natural hazards and has had many successful applications in the government and private sectors (Schubert et al. 2015; Jaiswal et al. 2017; Blankenship 2009). HAZUS-MH utilizes the ArcGIS software developed by the Environmental Systems Research Institute to present the data (Schneider and Schauer 2006). The user can use HAZUS-MH as a way to analyze past storms by using historical data, hypothetical storms by creating a user-defined hurricane scenario from user-defined input, and present storms for disaster planning and response (Beckmann and Simpson 2006).

The Hurricane Wind Model within HAZUS-MH contains many different models, including a hurricane hazard model, terrain model, and wind pressure and windborne debris model, all of which are updated versions of the original models developed by Vickery et al. (2000) and Vickery, Skerlj, and Twisdale (2000). The hurricane hazard model is composed of a storm track and wind field model, as well as a hurricane rainfall model. The mean simulated rate of landfalling hurricanes has a 95% confidence interval for the observed intense hurricanes categorized by both central pressure and estimated wind speed. The hurricane rainfall model is empirical and considers the increase in rainfall rate with increasing storm intensity by deeming a factor that regards the effect of the rate of change in central pressure on rainfall rate and another factor that models the asymmetric distribution of rainfall that is a function of storm translation speed. Rainfall rates far from the storm center tended to be overestimated, but a calibration factor is used to provide reasonable estimates of rainfall rates from all areas of the storm. The terrain model considers the fact that as ground surface becomes rougher, the wind speeds near the ground decrease, but the upper level winds remain the same. However, the hurricane model yields estimates of wind speeds for open terrain conditions. In addition, there are no direct databases that describe surface roughness over regions in the U.S. Therefore, the model uses information on land use and land cover to estimate surface roughness from the National Land Cover Data compiled by the Multi-Resolution Land Characteristics Consortium (Vickery, Lin, et al. 2006).

The Wind Load Modeling included in the HAZUS-MH Hurricane Wind Model consists of Wind Induced Loads and Windborne Debris Models. The Wind Induced

Loads have an empirical modelling approach to estimate the directionally dependent wind induced pressures acting on the exterior or buildings. The Windborne Debris models consist of modelling debris from residential types of buildings, which is used to assess the window damage probabilities for buildings located within different terrains, with different building densities and missile source environments, and roof top gravel debris (Vickery, Lin, et al. 2006). The damage loss estimation model within HAZUS-MH approximates damage with an engineering-based load and resistance model (Vickery, Skerlj, et al. 2006). The costs are estimated using a combination of a cost estimated model and an empirical model developed using insurance data (Vickery, Skerlj, et al. 2006). Both models have been validated through comparisons of model and actual losses with reasonable outcomes and are acceptable to use for loss estimation (Vickery, Skerlj, et al. 2006).

HAZUS-MH is mostly used to estimate potential losses and identify risks from seismic activity, such as earthquakes (Jaiswal et al. 2017; Remo and Pinter 2012; Schmidtlein et al. 2011; Padgett, Nielson, and DesRoches 2008). In general, the studies that use HAZUS-MH that involve hurricane risk only consider one of the hazards associated with tropical cyclones: extreme winds. After using the probabilistic mode from HAZUS-MH to estimate wind speed and the deterministic mode to find the wind swath, Scheitlin et al. (2011) produced a 100-year hurricane wind gust of 58 m/s on Santa Rosa Island within a 90% confidence interval and found that at least 25% of the residential and commercial buildings would be damaged in their hypothetical simulation. The model was tested for Eglin Air Force Base in Florida, a place that is not only vulnerable to hurricanes, but also needs to act in the case of a state-wide emergency; understanding the risks for that area is essential to the safety of the entire area and results can be applied to nearby places (Scheitlin et al. 2011). Moreover, to quantify the resilience of residential buildings against a hurricane event, Tokgoz and Gheorghe (2013) formulated a methodology to create a fragility curve, which shows probabilistic numbers for an impaired structure as a function of wind speed; HAZUS-MH provided the likeliness of building type and the damage inflicted to the home. There have been few studies that also supplement the wind evaluation with storm surge, since the model combines the Hurricane Wind model and the Flood model in HAZUS-MH (Katehis 2015; Kilma et al. 2012).

CHAPTER III

DATA AND METHODS

3.1 Study Area

Located in the central south U.S., north of Mexico on the western side of the Gulf of Mexico, Texas is the second biggest state in the U.S., in both land area and population, behind Alaska and California, respectively (USCB 2018). Climatically, the study area is sub-tropical and humid with a mixture of marine prairies, marshes,

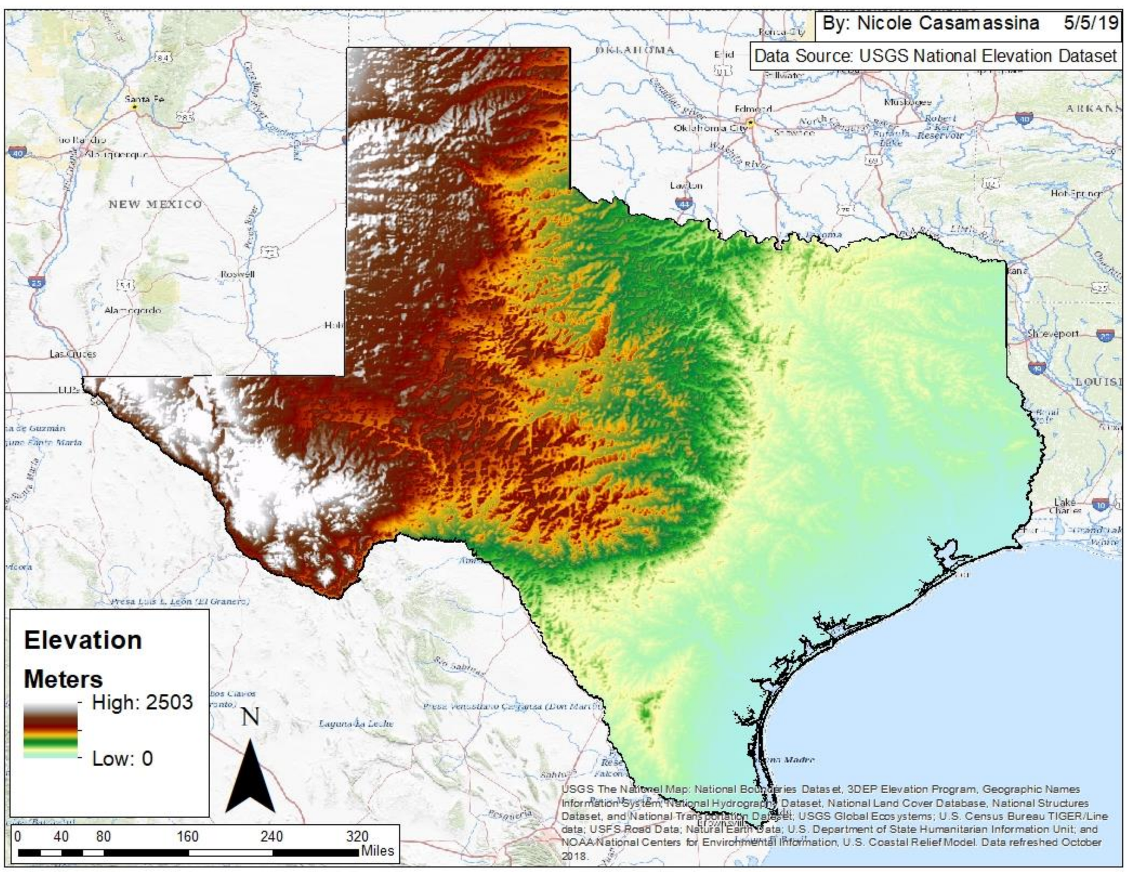

Figure 1: Map of Texas with elevation.

savanna, and woodlands (Climate of Texas 2012). Southeast Texas, specifically, has a very low elevation, especially near the coast (Rajsekhar, Mishra, and Singh 2013), and is more developed than other areas of the state (Figure 1). Houston, Texas, a major city in southeast Texas, is one of the most rapidly growing cities in the U.S., with an estimated 2017 population of over 2 million people and the expectation of it growing further to become the third most populous city in the country in the late 2020s (*About Houston: Facts and Figures* 2019). The area is also geographically vulnerable to tropical cyclones, with some of the most memorable North Atlantic tropical cyclones impacting the region, including the 1900 Galveston Hurricane, Hurricane Carla (1961), Hurricane Alicia (1983), Tropical Storm Allison (2001), Hurricane Rita (2005), Hurricane Ike (2008), and 2017's Hurricane Harvey (Roth 2010; NHC 2019a). The Greater Houston Region, which is the area including and surrounding the city, consists of nine counties: Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller (*Houston city, Texas* 2019). This nine-county region will be examined in this study because of Hurricane Harvey's great impacts on this portion of southeast Texas (Figure 2).

3.2 Datasets

This study uses a myriad of datasets, some of which are provided as the default data of HAZUS-MH, and others that are updated as part of Objective 1 of this thesis. The HAZUS-MH inventory contains hazard and boundary map data, as well as a proxy for the general building stock for the continental U.S., Hawaii, and the U.S. Territories

(FEMA 2019c). Furthermore, it consists of national data for essential facilities, high potential losses facilities, transportation systems, lifeline systems, agriculture, vehicles, and demographics, most of which are updated for the purposes of this thesis (FEMA 2019c). A full description of the databases that were not specifically updated for this study can be found at https://www.fema.gov/summary-databases-hazus-multi-hazard. A more detailed explanation of the datasets that were updated for this study is provided in Chapter IV of this thesis.

Objective 2 of this thesis will use the probabilistic mode of the HAZUS-MH Hurricane Wind Model. The storms that will be simulated for the analysis are part of the software's 100,000-year database of pre-generated peak wind gust speeds for each census tract in the U.S. The Hurricane Wind Model takes rainfall into account, so two of the three hurricane hazards will be analyzed in this part of the objective. Since the HAZUS-MH cannot estimate losses from storm surge in a probabilistic simulation, both the Hurricane Wind Model and the Flood Model will be run using the historical storm Hurricane Ike to simulate storm surge conditions in Galveston County. These data will be used to determine which areas of the Greater Houston Region are the most vulnerable to high winds, extreme rainfall, and storm surge. The developers of HAZUS-MH recently released a service package to the most recent version of the model, Version 4.2, which includes the additions of Hurricanes Sandy (2012), Harvey (2017), Irma (2017), Maria (2017), and Nate (2017) to the historical storm database (FEMA 2018b).

Objective 3 of this study will use Hurricane Harvey for the storm simulation in the Hurricane Wind Model for the wind and rainfall analysis. However, the developers

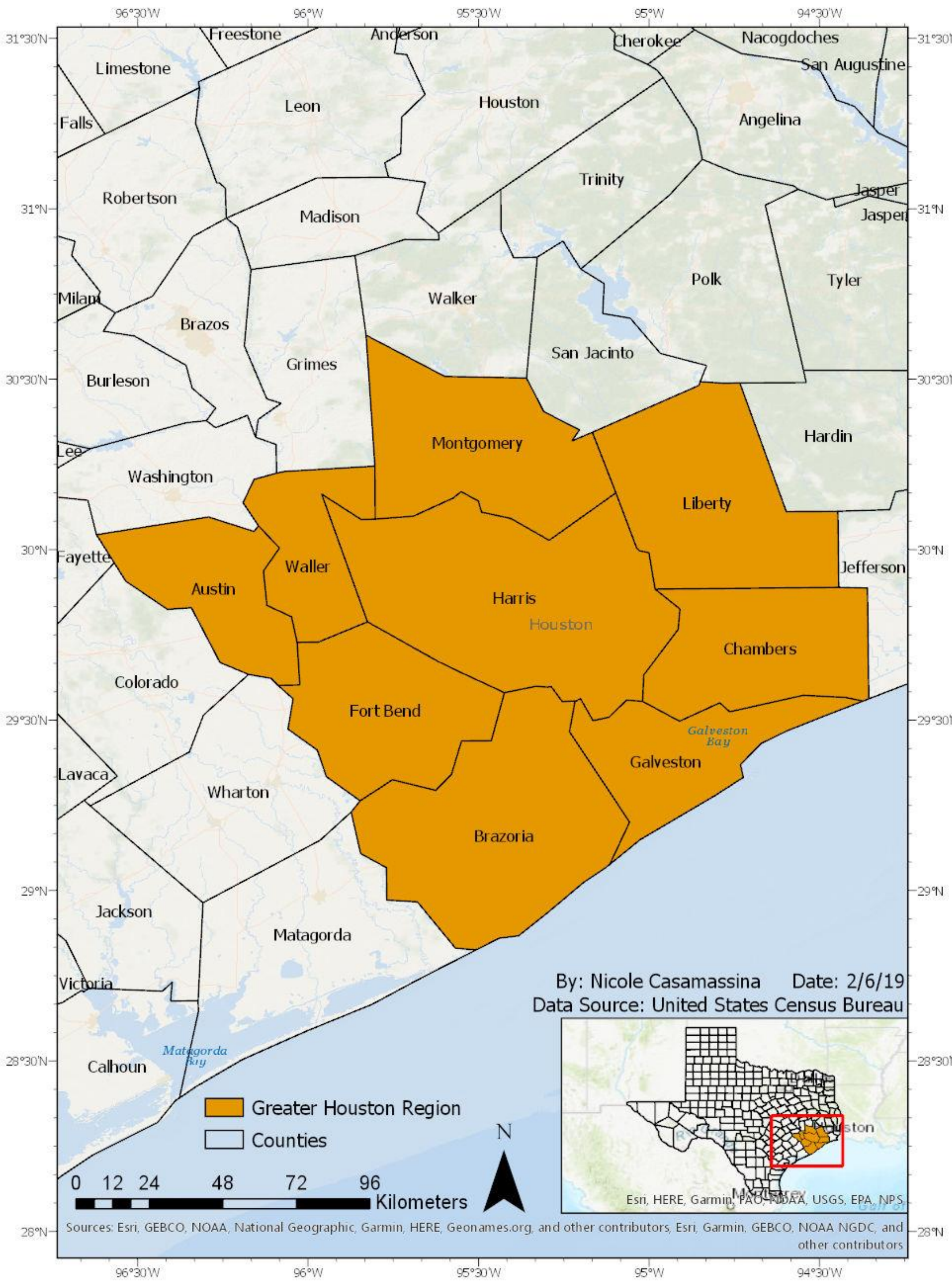

Figure 2: Map of the Greater Houston Region comprising the domain for this study.

discourage users from applying this storm to a storm surge analysis (FEMA 2018b). Therefore, the hurricane aspect of the storm surge analysis for this objective will use a storm advisory file from HURREVAC, a decision support tool of the National Hurricane Program and is administered by FEMA, the U.S. Army Corps of Engineers, and the National Hurricane Center (HURREVAC 2019). This option is included within the User-Defined Scenario option in HAZUS-MH and updated with hurricane tracks through the year 2017 (FEMA 2018d). When an existing forecast is selected, hurricane radii, and wind speeds are reduced to default factors (FEMA 2018d).

3.3 Methods

3.3.1 Objective 1: Update HAZUS-MH with more recent input variables and databases

The HAZUS-MH data inventory includes a vast amount of information for any of the hazards that can be run in this model: earthquake, flood, tsunami, and hurricane. Data that are used in all HAZUS-MH analyses include information about buildings and describes the materials that they are made from, as well as how the building is used. The material descriptions are referred to as general building types and includes descriptions such as wood, concrete, steel, masonry, and manufactured homes. Buildings can be used in many ways, such as residential, commercial, and industrial. In addition, lifelines, which are utilities that, if not available, make it difficult for normal community functioning to proceed, and replacement costs are economic factors that can be affect by hazard. For a social standpoint, demographics are common in many hazard analyses.

All the information provided in the inventory can and, where possible, should be enhanced with improved data, such as those that are up-to-date or provided by local governments. The data are verified and inputted by the CDMS, which validates that user data are compliant with the requirements for the HAZUS-MH software to work properly. The primary function of the CDMS is to allow users to query and explore the inventory and supports the transfer of data into and out of the major statewide databases (Mickey 2004). The datasets that have been updated or replaced using the CDMS are described in Tables 3, 5, 7, and 8 in Chapter IV. Using a combination of updated and default data within HAZUS-MH constitutes the study to be designated a Level 2 analysis (Table 2, adapted from the HAZUS-MH Hurricane Wind Model Technical Manual).

Parameter/Data	**Level 1 (Default Data)**	**Level 2 (Default Data)**	**Level 3 (Advanced Data)**
Wind Model	Default Probabilistic	User-Defined Scenario	
Coastal Surge Model	Default Historic	User-Defined Scenario	
Building Inventory	Default	User-Supplied	
Facilities and Building Classes	Display/Edit Locations Only – No Damage or Loss Estimates		
Terrain	Default		Expert-Supplied
Loss Functions	Default		
Damage Functions	Default		
Shelter Requirements	Default	User-Supplied Parameters	
Debris	Default	User-Supplied Tree Coverage Parameters	

Table 2: Summary of Hurricane Model Capabilities adapted from the HAZUS-MH Hurricane Wind Model Technical Manual

3.3.2 Objective 2: Identify the areas of Houston that are most vulnerable to the three hazards of extreme winds, heavy rainfall, and storm surge

Using the updated datasets provided by Objective 1, a probabilistic scenario of hurricanes will be simulated to determine the areas of the Greater Houston Region that are most vulnerable to the three hazards that are involved in the hurricane event: extreme winds, heavy rainfall, and storm surge. HAZUS-MH includes a 100,000-year database of pre-generated peak wind gusts for each census tract in the U.S. that will simulate every possible storm scenario for the study area. The hurricanes included in the database vary in size, strength, speed, and direction, providing an objective way to compare risk in different areas of the region. The probabilistic scenario option in HAZUS-MH looks at the simulated storms that intersect the study area and the total losses from those are ranked. Then, the storm that caused that loss is used to make a wind-speed map.

The HAZUS-MH Hurricane Wind Model uses several models to estimate losses in a study area. The hurricane risk model included in the overall wind model consists of three parts: a wind field model, a hurricane track model, and a rainfall model. The wind field model solves the full non-linear equations of motion of translating hurricanes and establishes parameters for a fast-running simulation. This model also accounts for storm asymmetries, changing sea surface roughness, and air-sea temperature differences. The hurricane track model simulated the entire track of a tropical storm and allows the storms to curve, as well as change speed and intensity as they move. Based on the HURDAT database, this model can show hurricane wind risk over large regions. Rainfall is one of the most difficult parameters to simulate in any hurricane model because it involves the non-linear interactions of weather fronts and topography. The rainfall model uses central pressure deficit, storm category, and storm translation speed to estimate precipitation in a hurricane. The validation of this model was done with rainfall measurements from Hurricanes Hugo (1989), Bertha (1996), Fran (1996), and Bonnie (1998) (Mickey 2004). HAZUS-MH Version 4.2 produces reasonable estimates of rainfall, but there is an expectation of significant variation with actual events due to unmodeled events (FEMA). Other models within the HAZUS-MH Hurricane Wind Model include a terrain model and a tree blow down model. A terrain model is necessary because surface roughness from buildings, trees, vegetation, and hills can slow down wind due to friction, which a hurricane model should consider for loss estimation. The tree blow down model shows the effects of trees during a wind storm. Though trees can provide shelter to structures, thus reducing wind pressure, falling trees produce a strike hazard to structures and add debris to dispose of after a storm. The tree database in HAZUS-MH includes three types of trees (deciduous, coniferous, and mixed), tree density measured in stems per acre, and tree height, distributed between three broad categories of 30-40 ft, 40-60 ft, and greater than 60 ft (Mickey 2004).

HAZUS-MH estimates physical, economic, and social losses in several ways. The model takes into consideration wind pressure, wind-borne debris, and building resistance when estimating physical losses. In HAZUS-MH, wind pressure is calculated as a function of wind speed, wind direction, and location of the wind on a building. In practice, design wind loads on buildings are determined using wind tunnel data or building code provisions based on wind tunnel data. There are two wind-borne missile models in the HAZUS-MH Hurricane Wind Model, one is for residential buildings that account for shingles, wood, and sheathing-type missiles, and the other for commercial buildings that considers gravel missiles from built-up roofing. The building debris model is based on damage states for structural and non-structural components of the HAZUS-MH model buildings and considers the typical density of that debris type. Each building type has a set of debris functions related to terrain, where rougher terrains produce less building debris. There are many ways a building can be resistant to the effects of hurricanes, such as having precautionary water resistance measures, masonry reinforcements, shuttering, improvement of roof-wall connections, and roof-deck attachments, tie downs, and roof covers. The physically based damage-to-loss model in HAZUS-MH computes direct economic losses using the explicit costing of windows, doors, sheathing, and roof covers, and the implicit costing of the estimates of volume of water entering through failed windows and doors. The estimates of the tree analysis are based on the tree coverage database, the tree blow down model, and the expected green weight of tree stems for trees greater than 30 feet tall. The eligible tree debris is an estimate made for all areas, though there may not be data for more sparsely populated areas; the volume of trees is based on 10 yd^3/ton. The terrain analysis parameters show roughness lengths where higher roughness creates more drag at the surface, which yields lower wind speeds. The direct economic impacts that are estimated in HAZUS-MH include annual gross sales, business inventory, disruption costs, restoration time, and income and wage losses. Social losses determined in this model show the need for public shelters in the aftermath of a hurricane. The parameters that are considered are age, ethnicity, income, home ownership, and the damage states of the different types of buildings (Mickey 2004).

There are several ways that HAZUS-MH presents results from a probabilistic scenario of the Hurricane Wind Model. The model can randomly select seven storms from the 100,000-year database with return periods of 10, 20, 50, 100, 200, 500, and 1,000 years, which represents the physical, economic, and social losses for each return period. The return periods are based on total direct economic losses for the entire study region. In addition, there is a full set of results provided; that contains damage, debris, shelter estimates, and dollar losses, among other results. The direct physical losses that are presented from this model include the structural damage for buildings and the extent of losses on the essential facilities. The structural damage for buildings involves the damage state probability counts and losses by occupancy and building type, while the essential facility losses show the loss of use measured in days and the damage state probability. The debris results show building debris in terms of wood and masonry, as well as steel and concrete, and the tree debris as related to building density, length of roads, and census block shapes. Trees downed near streets, highways, or buildings, make up the great majority of trees brought to curbs for collection and disposal. The direct economic losses from the general building stock include building losses, which are calculated from the structural, non-structural, content, and business inventory and interruption losses, which are estimated from wage, income, proprietor losses, and costs from rental and relocation. There is also an uncertainty analysis within the results of a HAZUS-MH Hurricane Wind Model run. The forecast uncertainties model uses statistics to forecast errors compiled from the period from 1993 to 2004 to simulate a range of possible outcomes. The results report displays the 5^{th} and 95^{th} percentiles of the simulated outcomes. HAZUS-MH can automatically save result reports and create thematic maps of results on the fly, but this can increase the analysis processing time (Mickey 2004).

When estimating the losses from storm surge in HAZUS-MH, the user must use a combination of the Hurricane Wind Model and the Flood Model. Because the model is unable to determine storm surge from a probabilistic scenario and the study area cannot be larger than one county (FEMA 2018d), the storm surge from Hurricane Ike, a historic storm in the HAZUS-MH inventory, will be simulated and analyzed to determine the potential storm surge as compared to Hurricane Harvey in Objective 3. HAZUS-MH uses three industry standard models that are used simultaneously to determine the storm surge in a study area: the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model, the Simulating Waves Nearshore (SWAN) model, and a modified version of the Wave Height Analysis for Flood Insurance Studies (WHAFIS) model (Mickey 2004). Using this combination of storm surge models allow for the estimation of economic losses to the general building stock for hurricane scenarios on coastal flood regions (Mickey 2004). Only the direct economic losses are output results from HAZUS-MH as a table or report; maps are unable to be generated in this hazard scenario, but results can be compared to flood maps from FEMA and other government agencies (Mickey 2004).

The losses that are estimated by HAZUS-MH allow for a user, government agency, or private organization in planning for emergency preparedness, response, and recovery for future tropical cyclones. This methodology considers many aspects of the built and natural environment, as well as a wide range of losses that can occur when a tropical cyclone impacts an area. The results of this objective will provide a reliable preliminary assessment of the weaknesses in the structures in the Greater Houston Region.

3.3.3 Objective 3: Assess Houston's specific losses from Hurricane Harvey

Objective 3 is like Objective 2 in that HAZUS-MH will be run for the Greater Houston Region. However, this portion of the study will have a historic storm scenario and a user-defined storm scenario for Hurricane Harvey. The results of these two scenarios will be compared to the results from Objective 2 to see if the areas that are most vulnerable to specific aspects of hurricanes were greatly affected by Harvey. The historic scenario will be used for the Hurricane Wind Model, while the storm surge will be calculated from the user-defined storm scenario. Assessing the results from Hurricane Harvey with the updated data from Objective 1 can help to evaluate current mitigation strategies in the Greater Houston Region and to understand how Harvey was unique in comparison to the probabilistic scenario.

Objective 3 will differ from Objective 2 in that the HAZUS-MH Flood Model will be used to determine the full extent of losses. The Greater Houston Region was not greatly affected by the extreme winds from Hurricane Harvey; losses related to the hurricane's winds are more apparent near the location of the its first two landfalls, which are southwest of the study area. The losses in the Houston area were almost entirely determined by the flooding, which came through the combination of the hurricane stalling for several days and the amount of precipitation in the region that were observed as a result. Because of this, only Harris County, which comprises of both the riverine and coastal features, as well as contains the city of Houston, will be used for this part of Objective 2. The outcomes of the Flood Model are slightly different from the Hurricane Wind Model in that the Flood Model has influence from the National Flood Insurance Program, which pays claims to victims during the recovery period based on the depreciated value of a building (Scawthorn, Blais, et al. 2006). However, using the Flood Model can help to estimate the losses for this unique hurricane that are lacking the results of the Hurricane Wind Model run for Hurricane Harvey.

The HAZUS-MH Flood Model can help to quantify flood risks and support communities in making informed decisions in land use and determining flood-prone areas. There are two basic analytical processes that make up the methodology of this model: a flood hazard analysis and a flood loss estimation analysis. The flood hazard portion of this analysis identifies the spatial variation in flood depth and velocity for riverine and coastal flooding conditions for a user-defined study area. A flood hazard is defined by Sathorn, Blais, et al. (2006) as the relationship between the depth of flooding and the annual probability of inundation greater than that depth and can be shown in a depth-frequency curve. A Level 1 analysis is used in this study because the Flood Information Tool, provided by HAZUS-MH and similar to the CDMS, is not used to preprocess the site-specific flood hazard data or facilitate the import of these data into the Flood Model to run a further analysis of the damage and loss associated with the flooding (Scawthorn, Blais, et al. 2006). However, the data inputted into the model in Objective 1 are used for basic loss estimation.

The flood hazard analysis begins with determining the terrain of a study area through the use of a Digital Elevation Model (DEM) (Scawthorn, Blais, et al. 2006). This is determined through HAZUS-MH, which has the capability of importing the raster files directly from the USGS National Elevation Dataset based on the spatial extent of the study region; it also clips the rasters to the watersheds that intersect the study area (Scawthorn, Blais, et al. 2006; FEMA 2018c). Topographic information is necessary for a flood hazard analysis because the boundary and depth of flooding is determined by the differences between the ground and flood surfaces (Scawthorn, Blais, et al. 2006).

Because Harris County is subject to a riverine flood hazard from its many rivers, but particularly from Buffalo Bayou and the San Jacinto River, a stream network was generated to identify the river reaches in the study area (FEMA). The Flood Model processes the DEM of the study region to determine the locations of the streams (FEMA 2018c). A hydrological analysis must also be done in order to delineate the floodplain in the area (FEMA 2018c). Harris County also has coastal areas, so a coastal flood hazard also had to be run for this study. The shoreline is determined by the DEM; the 100-year still water elevation and vertical datum for each shoreline segment were found through the use of the Harris County Flood Insurance Study (FEMA 2018c, 2017a). Delineating the floodplain also had to be performed for the coastal regions (FEMA 2018c). A single return period of 200 years was selected for both the riverine and coastal analyses since

Hurricane Harvey was determined to have a return period of approximately 230 years, in terms of its winds and precipitation (Trepanier and Tucker 2018). The HAZUS-MH Flood Model analyzes the impact of both hazards on the data inventory independently so that it can compare the resulting losses to determine which hazard has the greatest impact on that structure type (FEMA 2018c).

HAZUS-MH uses a combination of flood depth estimations and depth damage functions to find direct damage that can result from flooding. The outputs of this module are the area-weighted estimations of damage as a percent of replacement cost, either at the census block level or for a specific building and are used as inputs to the induced physical damage and direct economic and social loss modules. Depth-damage functions are plots of floodwater depth versus percent damage, and can be done for a myriad of building types and occupancies, but are most reliable for predicting damage for large groups of buildings. The depth-damage curves that are used in the HAZUS-MH Flood Model are from the Federal Insurance Administration and the U.S. Army Corps of Engineers; they are used to estimate damage to the general building stock and the essential facilities. The functions that are applied to the damages to lifeline systems differ from the other depth-damage curves in that they define the potential damage to the components of the systems that are either uniquely vulnerable to inundation or are expensive to repair or replace; these components are grouped based on vulnerabilities and expected loss. The buildings types that are evaluated for damage from a flood are the same as in the Hurricane Wind Model. In the Flood Model, building type, level of design, and quality of construction do not play a big role in the loss estimation because they do not affect a building's resistance to flooding; this is very much unlike the Hurricane Wind Model. Major structural elements typically survive flooding, unless floodwaters move with an extremely high velocity, the structures and foundations become separated, or there are flood-borne debris impacting the building, but these situations are rare (Scawthorn, Flores, et al. 2006).

The direct economic losses that are estimated in the Flood Model are building repair and replacement costs, building content losses, building inventory losses, relocation expenses, income and wage losses, and rental income losses. Income losses are dependent on the necessary time to completely restore business operations, which includes the time needed for physical restoration of a building from cleaning up, repairing, getting the required inspections and permits, and the delay of contractor availability. These are indirect losses that HAZUS-MH accounts for in the loss estimation. Therefore, a flood-specific restoration model was developed to provide that estimate of time required based on occupancy type and flood depth at 4-ft increments. The total restoration time increases with flood depth until the building reaches 50% damage; after that point, the building is considered to be totally lost and it is assumed that the building will be demolished and rebuilt (Scawthorn, Flores, et al. 2006).

Social losses are estimated in the HAZUS-MH Flood Model in terms of shelter needs. The algorithm used in the Flood Model is the same as the Earthquake Model, but slightly adjusted to demonstrate the differing shelter needs; sheltering related to floods is based on the number of displaced people in inundated areas in a study area and are modified by taking into account income and age (Scawthorn, Flores, et al. 2006). This is because those who have lower income and those who are part of younger or elderly families tend to seek shelter more than those who are more financially established (Scawthorn, Flores, et al. 2006). The individuals from displaced households also are made up of people who live in areas that were evacuated from an issued warning or who cannot get to their properties because of flooded or damaged roadways, though their structure may not be damaged (Scawthorn, Flores, et al. 2006).

CHAPTER IV

UPDATING HAZUS-MH DEFAULT DATA

4.1 Updated Datasets

The categories of data that are updated as part of Objective 1 are essential facilities, high potential loss facilities, transportation systems, and utility systems. Most of the data collected had to be modified to fit the specific requirements of the model, such as filtering national data to the state of Texas, adding replacement cost, or changing fields based on character limits. Much of the data came from the U.S. Department of Homeland Security's Homeland Infrastructure Foundation Level Data (HIFLD) public domain and were changed based on the specifications HAZUS-MH. Facility or Analysis Class attributes were added to all data based on the CDMS Data Dictionary for analysis purposes (FEMA 2019a). Furthermore, the data points representing the locations of the facilities had to be within a census tract in the state of Texas; those that did not were eliminated from the dataset for inclusion in HAZUS-MH. When the replacement cost was not included in the new dataset, the average value from the default HAZUS-MH data was calculated and the inflation percentage, found using the U.S. Department of Labor's Inflation Calculator (DOL 2019), was accounted for and added since most of the default data were collected between 1999 and 2001. The names and addresses of all facilities were limited to 40 characters. Therefore, they were either cut off at the specified limit or abbreviated based on the C1 Street Suffix Abbreviations from the United States Postal Service (USPS 2019). There are some instances when a facility was not part of the default database; when possible, those were added to HAZUS-MH for a more comprehensive analysis.

4.1.1 Essential Facilities

An essential facility is a manmade structure serving the health and welfare of the whole population of an area (FEMA 2007). Table 3 describes the replacement data for the essential facilities for HAZUS-MH, which includes medical care facilities, fire stations, police stations, emergency response centers, and schools.

Essential Facility	**Original Data Source**	**New Data Source**	**Specific Modifications to Dataset**
Medical Care Facilities	American Hospital Association, 2000	HIFLD File Name: Hospitals, 2017	Eliminated facilities that were closed or had null values for number of beds. Type of Hospital field edited based on character limits.
Fire Stations	InfoUSA Inc., 2001	HIFLD File Name: Fire Stations, 2010	
Police Stations	InfoUSA Inc., 2001	HIFLD File Name: Local Law Enforcement Locations, 2018	Eliminated facilities that were not police stations.
Emergency Response Centers	InfoUSA Inc. and FEMA, 2001	HIFLD File Name: Local Emergency Operation Centers, 2018	

Table 3: Replacement Data for Essential Facilities

Essential Facility	Original Data Source	New Data Source	Specific Modifications to Dataset
Schools	U.S. Department of Education National Center for Education Statistics, 2000	HIFLD File Names: Public School, 2018; Private Schools, 2018; College and Universities, 2018; Supplemental Colleges, 2018	Combined all files together. Eliminated schools with enrollment with negative numbers, 0, or no information. Eliminated technical and trade schools. Eliminated schools with number of students exceeding 32,767. Added two attributes with University of Houston with half the number of students for the analysis.

Table 3 Continued.

For the medical care facilities, Facility Class was determined based on the size of the hospital. A small hospital has fewer than 50 beds, while a medium hospital has between 50 and 150beds, and a large hospital has more than 150 beds (FEMA 2019a). Because the type-of-hospital field was limited to 10 characters, the names were shortened to be able to be used in the model analysis (Table 4). The types of police stations that were included were included were Park Police, Police Departments, Sheriffs' Offices, State Police, and Transit Police. The types of higher education institutions that remained in the dataset are colleges, universities, professional schools, fine arts schools, and junior colleges.

HIFLD Type of Hospital	Abbreviation for HAZUS-MH
General Acute Care	General
Psychiatric	Psych
Rehabilitation	Rehab
Long Term Care	Long Term
Critical Access	Critical

Table 4: Abbreviations of Types of Hospitals for HAZUS-MH Analysis

4.1.2 High Potential Loss Facilities

A high potential loss facility is a key resource in a community that is so vital that Their incapacity or destruction would have a devastating impact on public services, security, economics, public health, or safety (FEMA 2019b). The high potential loss facilities that are included in HAZUS-MH are dams, hazardous materials sites, military facilities, and nuclear power plants (Table 5).

High Potential Loss Facility	Original Data Source	New Data Source	Specific Modifications to Dataset
Dams	None	HIFLD File Name: Dam Lines, 2009	
Hazardous Materials Sites	Environmental Protection Agency Toxic Release Inventory Database, 1999	Environmental Protection Agency Toxics Release Inventory Program, 2017	Chemical Name field changed based on character limits.
Military Facilities	None	U.S. Census Bureau TIGER/Line Shapefiles File Name: Military Installations, 2018	

Table 5: Replacement Data for High Potential Loss Facilities

High Potential Loss Facility	Original Data Source	New Data Source	Specific Modifications to Dataset
Nuclear Power Plants	U.S. Nuclear Regulatory Commission, 2000	U.S. Nuclear Regulatory Commission, 2018	

Table 5 Continued.

The Chemical Name field had to be changed because of the 25-character limit; the shortened names that were used were either the official name as designated by the International Union of Pure and Applied Chemistry or another common name for the chemical (Table 6).

Name of Chemical	Shortened Name for Model Purposes
1-(3-Chloroallyl)-3,5,7-Triaza-1-Azoniaadamantane Chloride	Quaternium-15
1,1,1,2-Tetrachloroethane 1,1,2,2-Tetrachloroethane	Tetrachloroethane
1,1,1-Trichloroethane 1,1,2-Trichloroethane	Trichloroethane
1,1-Dimethyl Hydrazine	Dimethyl Hydrazine
1,2,3-Trichloropropane	Tricholorpropane
1,2,4-Trichlorobenzene	Trichlorobenzene
1,2,4-Trimethylbenzene	Trimethylbenzene
1,2-Dichloroethylene	1,2-Dichloroethene
1,2-Diphenylhydrazine	Diphenylhydrazine
1,2-Phenylenediamine 1,3-Phenylenediamine	Benzene-1
1,3-Dichloropropylene	Dichloropropylene
1-Chloro-1,1-Difluoroethane	Chlorodifluoroethane
2,2-Dichloro-1,1,1-Trifluoroethane	HCFC-123
2,4,5-Trichlorophenol 2,4,6-Trichlorophenol	Trichlorophenol
2,4 D 2-Ethylhexyl Ester	2,4-D 2-EHE
2-Acetylaminofluorene	Acetylaminofluorine
2-Chloro-1,1,1,2-Tetrafluoroethane	HCFC-124

Table 6: Shortened Chemical Names

Name of Chemical	Shortened Name for Model Purposes
3,3’-Dichlorobenzidine	Dichlorobenzidine
3,3’-Dimethoxybenzidine	Dimethoxybenzidine
3,3’-Dimethylbenzidine	Orthotolidine
3-Chloropropionitrile	Chloropropionitrile
3-Iodo-2-Propynyl Butylcarbamate	Iodocarb
4,4’-Diaminodipheyl Ether	4,4’-Oxydianiline
4,4’-Isopropylidenediphenol	Bisphenol A
4,4’-Methylenebis(2-Chloroaniline)	Cyanaset
4,4’-Methylenedianiline	Methylenedianiline
4-Dimethylaminoazobenzene	Methyl Yellow
Aluminum (Fume Or Dust)	Aluminum
Aluminum Oxide (Fibrous Forms)	Aluminum Oxide
Bis(2-Chloro-1-Methylethyl) Ether	Nemamort
Bis(2-Chloroethyl) Ether	Chlorex
Bis(Chloromethyl) Ether	Chloromethyl Ether
C.I. Solvent Yellow 34	Auramine
Certain Glycol Ethers	Glycol Ethers
Chlorodifluoromethane	HCFC-22
Chloromethyl Methyl Ether	Chlorodimethyl Ether
Chromium Compounds(Except Chromite Ore Mined In The Transvaal Region)	Chromium Compounds
Cresol (Mixed Isomers)	Cresol
Decabromodiphenyl Oxide	BDE-209
Di(2-Ethylhexyl) Phthalate	Dioctyl Phthalate
Diaminotoluene (Mixed Isomers)	Diaminotoluene
Dichlorobenzene (Mixed Isomers)	Dichlorobenzene
Dichlorodifluoromethane	Freon-12
Dichlorotetrafluoroethane (Cfc-114)	CFC-114
Dimethylcarbamyl Chloride	DMCC
Dinitrotoluene (Mixed Isomers)	Dinitrotoluene
Dioxin And Dioxin-Like Compounds	Dioxin
Ethylenebisdithiocarbamic Acid, Salts, And Esters	Nabam
Ethylidene Dichloride	1,1-Dichloroethane
Hexachloro-1,3-Butadiene	Hexachlorobutadiene
Hexachlorocyclopentadiene	Graphlox
Hydrochloric Acid (1995 And After Acid Aerosols” Only)”	Hydrochloric Acid

Table 6 Continued.

Name of Chemical	**Shortened Name for Model Purposes**
Isopropyl Alcohol (Manufacturing,Strong-Acid Process Only,No Supplier)	Isopropyl Alcohol
Methoxone Sodium Salt	Phenoxylene
Methyl Chlorocarbonate	Methyl Chloroformate
Methyl Isobutyl Ketone	Isopropylacetone
Methyl Tert-Butyl Ether	MTBE
Monochloropentafluoroethane	Freon 115
N,N-Dimethylformamide	Dimethylformamide
Nitrilotriacetic Acid	Triglycine
N-Methyl-2-Pyrrolidone	N-Methylpyrrolidone
N-Nitrosodiphenylamine	Diphenylnitrosamine
N-Nitrosomethylvinylamine	Myna
N-Nitroso-N-Ethylurea	Ethylnitrosourea
N-Nitroso-N-Methylurea	Methylnitrosourea
O-Toluidine Hydrochloride	O-Methylaniline
Phosphorous (Yellow Or White)	Phosphorous
Polychlorinated Biphenyls	PCB
Polycyclic Aromatic Compounds	PAH
Sodium Dimethyldithiocarbamate	Carbamodithioic Acid
Sodium O-Phenylphenoxide	Sodium 2-Biphemylate
Sulfuric Acid (1994 And After Acid Aerosols" Only)"	Sulfuric Acid
Tetrabromobisphenol A	Bromdian
Titanium Tetrachloride	Tetrachlorotitanium
Toluene Diisocyanate (Mixed Isomers) Toluene-2,4-Diisocyanate Toluene-2,6-Diisocyanate	Toluene Diisocyanate
Trans-1,4-Dichloro-2-Butene	1,4-Dichlorobutene-2
Trichlorofluoromethane	Fluorochloroform
Triclopyr Triethylammonium Salt	Garlon
Vanadium (Except When Contained In An Alloy)	Vanadium
Xylene (Mixed Isomers)	Xylene

Table 6 Continued.

4.1.3 Transportation Systems

Transportation systems are important to hazard preparedness and recovery because they can help to transfer emergency relief personnel and supplies, mitigate detrimental economic impacts, and meet other societal needs (FEMA 2013). Ensuring that the transportation systems in an area are effective and do not have unnecessary restrictions is essential to the effectiveness of prevention, preparedness, response, recovery, and mitigation of any hazard in a community (FEMA 2013). Table 7 presents the updated datasets for the transportation systems in HAZUS-MH. Highway segments, highway tunnels, light rail bridges, light rail facilities, light rail track segments, light rail tunnels, and railway tunnels were not replaced because either there were none in the Greater Houston Region or the files found did not meet the specifications of the model.

Transportation System	Original Data Source	New Data Source	Specific Modifications to Dataset
Airport Facilities	U.S. Department of Transportation Bureau of Transportation Statistics and Federal Aviation Administration, 2007	HIFLD File Name: Aircraft Landing Facilities, 2018	

Table 7: Replacement Data for Transportation Systems

Transportation System	Original Data Source	New Data Source	Specific Modifications to Dataset
Airport Runways	U.S. Department of Transportation Bureau of Transportation Statistics and Federal Aviation Administration, 2007	HIFLD File Name: Runways, 2017	
Bus Facilities	InfoUSA Inc., 2001	U.S. Department of Transportation Geospatial at the Bureau of Transportation Statistics File Name: Intermodal Passenger Connectivity Database, 2018	
Ferry Facilities	Port and Waterway Facilities Database from the U.S. Army Corps of Engineers/CEIWR Navigation Data Center Port and Waterways Division	United States Geological Survey National Map Data File Name: Ferry Ports, 2014	Inflation was not calculated since year default data obtained was not listed
Highway Bridges	National Bridge Inventory Database provided by the Federal Highway Administration Office of Bridge Technology, 2001	HIFLD File Name: National Bridge Inventory Bridges, 2017	Filtered to only highway bridges

Table 7 Continued.

Transportation System	Original Data Source	New Data Source	Specific Modifications to Dataset
Port Facilities	U.S. Army Corps of Engineers/CEIWR Navigation Data Center Ports and Waterways Division, 2000	HIFLD File Name: Port Facilities, 2019	
Railway Bridges	National Bridge Inventory, 2001	HIFLD File Name: Railroad Bridges, 2009	
Railway Facilities	U.S. Department of Transportation Bureau of Transportation Statistics, 2007	HIFLD File Name: Intermodal Terminal Facilities, 2017	Filtered to heavy railway stations

Table 7 Continued.

4.1.4 Utility Systems

Utility systems provide necessary services that allow for the continuous operation of critical business and government functions and are vital to human health, safety, and economic security (NIST 2016). Distribution sewers, natural gas distribution pipelines, natural gas pipelines, oil pipelines, potable water distribution pipelines, potable water pipelines, and wastewater pipelines were not updated because either there were none in the Greater Houston Region or the files found did not meet the specifications of HAZUS-MH. Table 8 describes the replacement data for the utility systems within the model.

Utility System	Original Data Source	New Data Source	Specific Modifications to Dataset
Communication Systems	Federal Communication Commission Broadcast Auxiliary Microwave File, 2001	HIFLD File Name: Microwave Service Towers, 2017	
Electric Power Facilities	Environmental Protection Agency Envirofacts Data Warehouse Location Reference Tables Tool, 2001	HIFLD File Name: Environmental Protection Agency Facility Registry Service Power Plants, 2019	
Natural Gas Facilities	Environmental Protection Agency Envirofacts Data Warehouse Location Reference Tables Tool, 2001	HIFLD File Name: Natural Gas Compressor Stations, 2018	
Oil Facilities	Environmental Protection Agency Envirofacts Data Warehouse Location Reference Tables Tool, 2001	HIFLD File Name: Oil Refineries, 2017	
Potable Water Facilities	Environmental Protection Agency Envirofacts Data Warehouse Location Reference Tables Tool, 2001	Environmental Protection Agency Facility Registry Service File Name: Facility Interests Dataset, 2018	Filtered to Water Treatment Plants

Table 8: Replacement Data for Utility Systems

Utility System	Original Data Source	New Data Source	Specific Modifications to Dataset
Wastewater Facilities	Environmental Protection Agency Envirofacts Data Warehouse Location Reference Tables Tool, 2001	HIFLD File Name: Environmental Protection Agency Facility Registry Service Wastewater Treatment Plant, 2019	

Table 8 Continued.

CHAPTER V

IDENTIFYING VULNERABLE AREAS IN THE GREATER HOUSTON REGION

Chapter V will present the results of Objective 2 of this thesis, which is to identify the most vulnerable areas of the Greater Houston Region to the three different types of hazards that make up a hurricane: extreme winds, heavy precipitation, and storm surge. By comparing the results of the different return periods of hurricane from the probabilistic mode of the HAZUS-MH Hurricane Wind Model, there can be a better understanding of the extent of losses with each strength of storm. These results will also be used to compare to the losses estimated from Hurricane Harvey in Objective 3.

5.1 Return Periods

Using the return period of hurricane winds can help to compare to the historical record of a study area (Emanuel and Jagger 2010). An early effort to calculate hurricane return periods was based on hurricane landfalls that occurred in the U.S. from 1886 to 1970 by Simpson and Lawrence (1971), where they studied the return periods for all hurricanes within 80-kilometer coastal segments, ranging from Texas to Maine. Elsner and Kara (1999) focused on counties along the coast, finding return periods that ranged from 4 years for Monroe County, Florida to about 100 years for some counties in Georgia and Maine. By analyzing the spatiotemporal patterns of tropical cyclone strikes from 1901-2005 at 45 different locations from Brownsville, Texas, to Eastport, Maine, Keim, Muller, and Stone (2006) found that the return period of tropical storm-strength systems or greater for southeast Texas is three years, on average. The expected return period of an event similar to Hurricane Harvey, in terms of its combined wind and precipitation measurements, in Houston, Texas is estimated to be 230 years (Trepanier and Tucker 2018). For each county in the Greater Houston Region, results were calculated for each return period based on the 100,000-year database of storms included in HAZUS-MH. To compare to the results from Hurricane Harvey (see Objective 3), the 10-year, 200-year, and 1000-year return periods will be analyzed for the purpose of this objective. This allows for the examination of the events that are likely to happen most often, a storm with risk that is like Harvey, and the most extreme scenario possible in this model.

5.2 Storm Tracks

The HAZUS-MH Hurricane Wind Model probabilistic mode was used to determine the physical, economic, and social losses that can occur for a variety of storms with specific return periods. As HAZUS-MH looks through the 100,000-year database for all storm events that intersect the study region, the total losses for each storm event are ranked and used to determine a specific storm track for each chance event (FEMA 2018d). The probable storm tracks of 10, 20, 50, 100, 200, 500, and 1000-year return periods are shown in Figure 3. The types of hurricanes that occur the most often, the 10-year and 20-year storms, probably would not make a direct impact on the Greater Houston Region since they tend to track south of the area. Though the other return

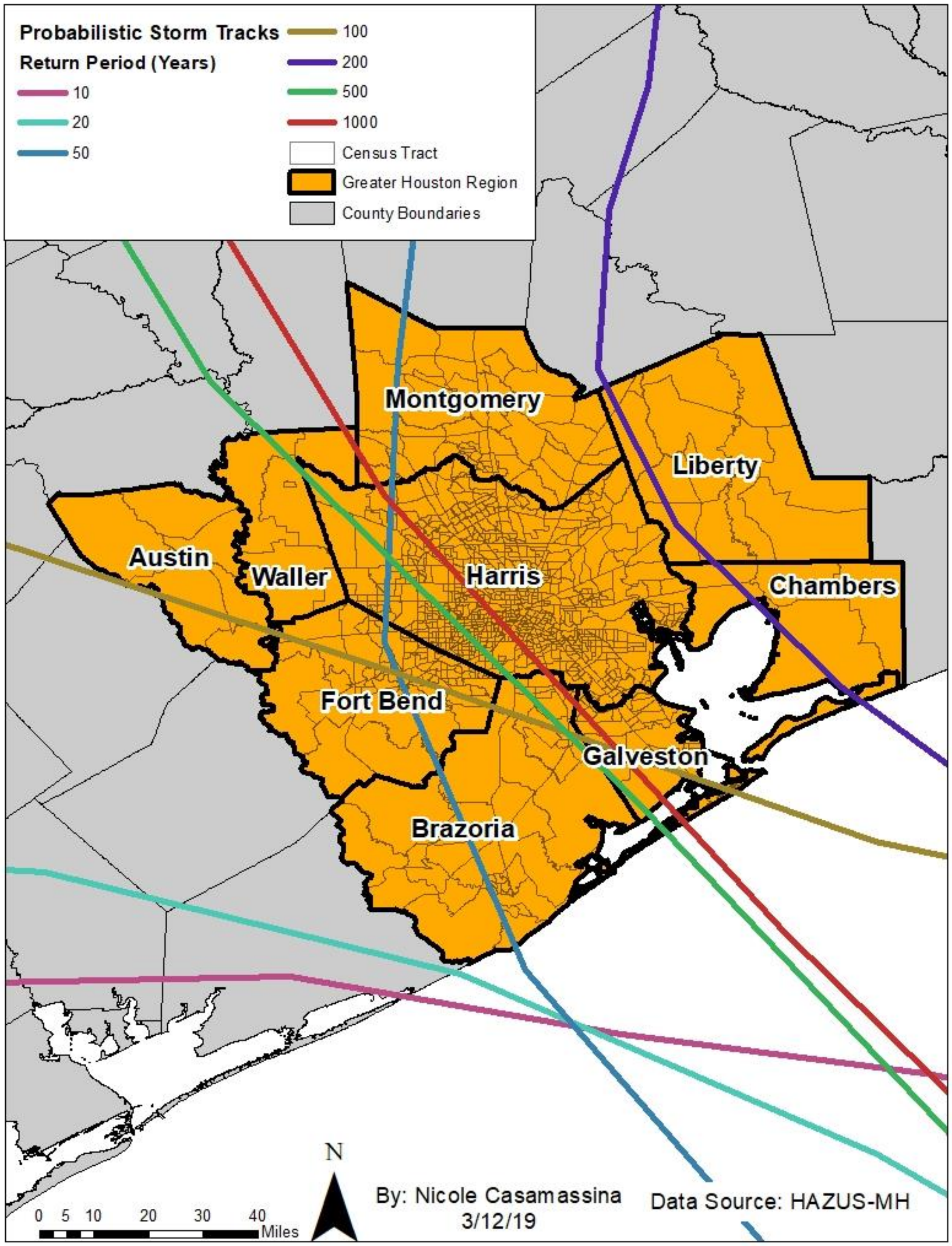

Figure 3: Probable storm tracks of the Greater Houston Region.

periods are estimated to not occur as often, they can make a direct impact on the area. These storms are usually more destructive with higher winds and the greater possibility of causing more losses.

5.3 Wind Speeds

After HAZUS-MH chooses the storm tracks for each return period, the wind speeds for the specific hurricane track are used as the basis to determine the wind speed values at the census tract level (FEMA 2018d). The wind speeds that are shown in Figure 4 are the estimated maximum 3-second gust in open terrain at 10 m above the ground at the centroid of each census tract for that specific hurricane event (FEMA 2018d). The results show that in some census tracts, there are lower wind speeds for the less frequent events. For example, on the eastern side of the Greater Houston Region in Liberty and Chambers counties, the wind speeds are higher in the 200-year return period than in the 1000-year return period. This could be due to the location of the storm track, as well as the surface roughness of the region (Figure 5).

5.4 Building Damage

The HAZUS-MH Hurricane Wind Model was run for the greater Houston Region for a total population of 5,290,416 in 1,069 census tracts with a 8,550 mi^2 area, according to 2010 U.S. Census data (FEMA 2019c). The study region contains a total of 1,848,049 buildings, of which about 92% are residential, 5.5% are commercial, and

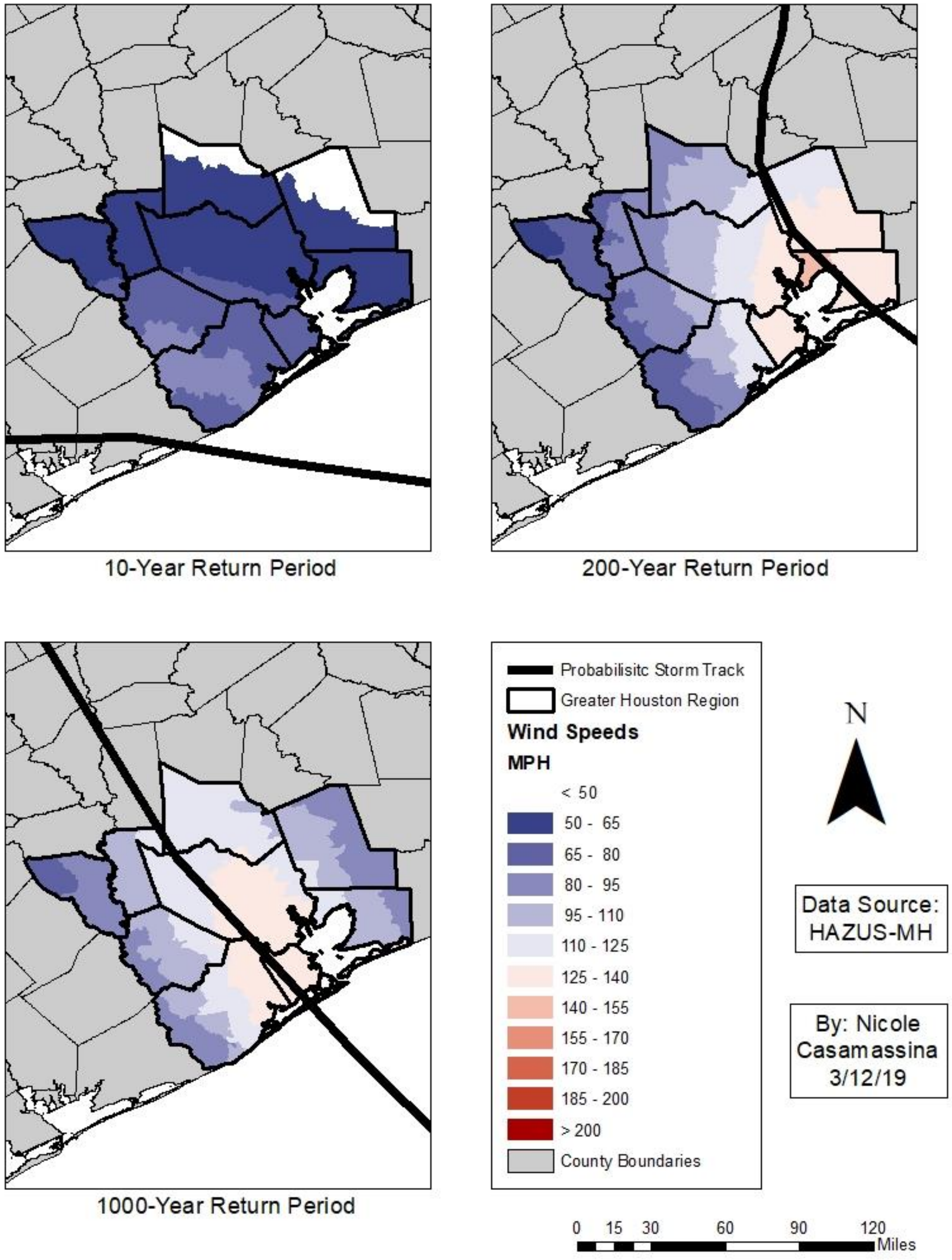

Figure 4: Wind speeds for selected hurricane return period scenarios.

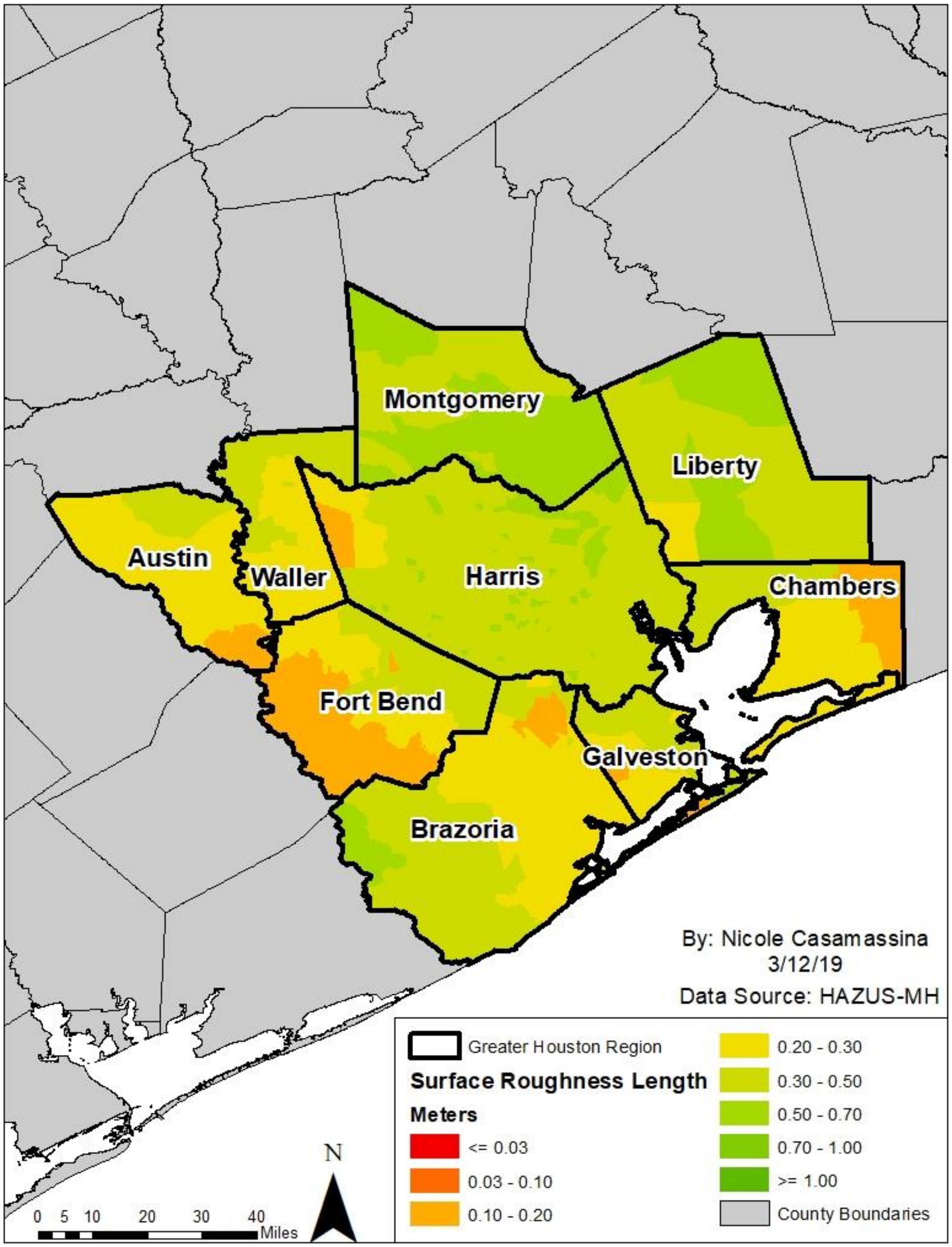

Figure 5: Surface roughness of the Greater Houston Region.

2.5% are either agricultural, industrial, religious/non-profit, governmental, or educational buildings (FEMA 2019c). The amount of structural damage on each type of building is divided into five damage state categories that range from no damage to complete destruction. For a single-family residential building, Vickery, Skerlj, et al. (2006) define no damage or very minor damage as little or no visible damage from the outside, no broken windows or failed roof deck, minimal loss of roof cover, with no or very limited water penetration. Minor damage includes a maximum of one broken window, door, or garage door, moderate roof cover loss that can be covered to prevent additional water entering the buildings, with marks or dents on walls that require painting or patching for repair. The moderate damage category is given when there is major roof cover damage, moderate window breakage, and minor roof sheathing failure, which results in damage to the interior of the building from water. Severe damage occurs when there is major window damage or roof sheathing loss, major roof cover loss, and extensive damage to the interior of the building from water. Lastly, Vickery, Skerlj, et al. (2006) describe the complete destruction designation as a complete roof failure and/or failure of wall frame and loss of more than 50% of roof sheathing. Though the definition of damage-state categories is for single-family residential buildings, they can be interpreted in a similar fashion for other types of buildings.

5.4.1 Building Damage by Occupancy Class

For all figures describing damage states by occupancy class, the number of buildings in that category is shown in terms of percent of the total number of buildings of that class. Figures 6, 7, and 8 show the building damage state by occupancy class for the 10-year, 200-year, and 1000-year hurricane return periods.

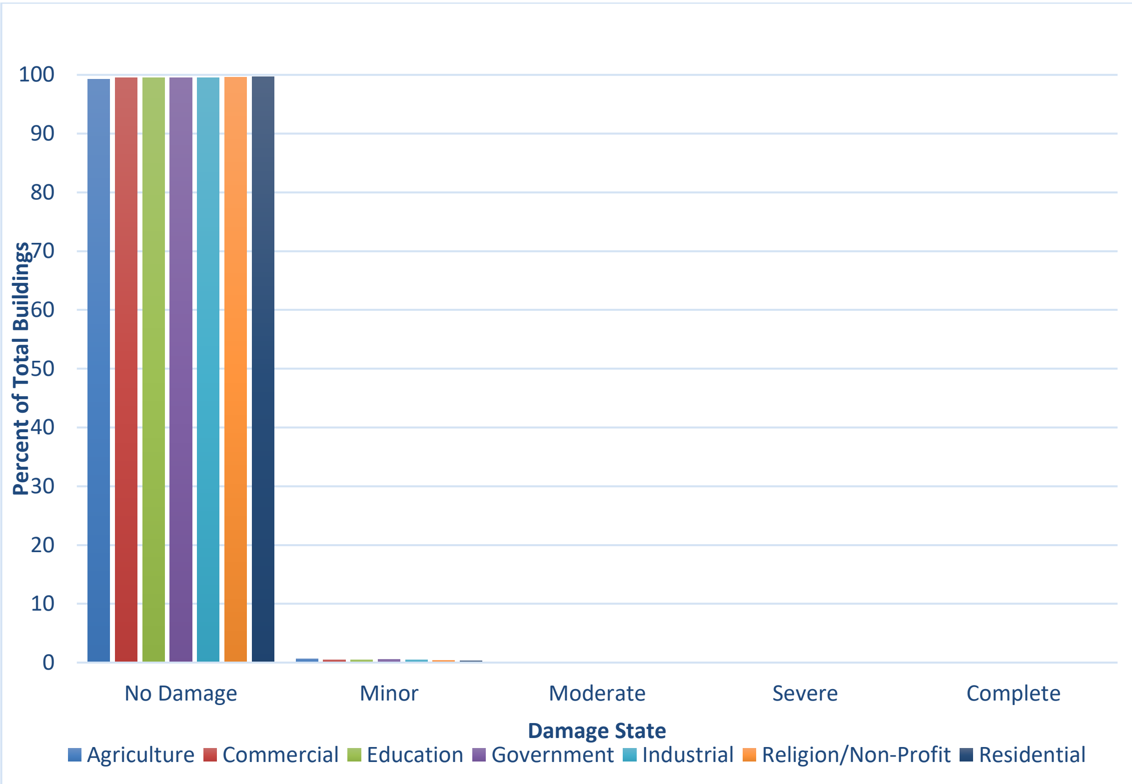

Figure 6: Building damage by occupancy class for 10-year hurricane return period.

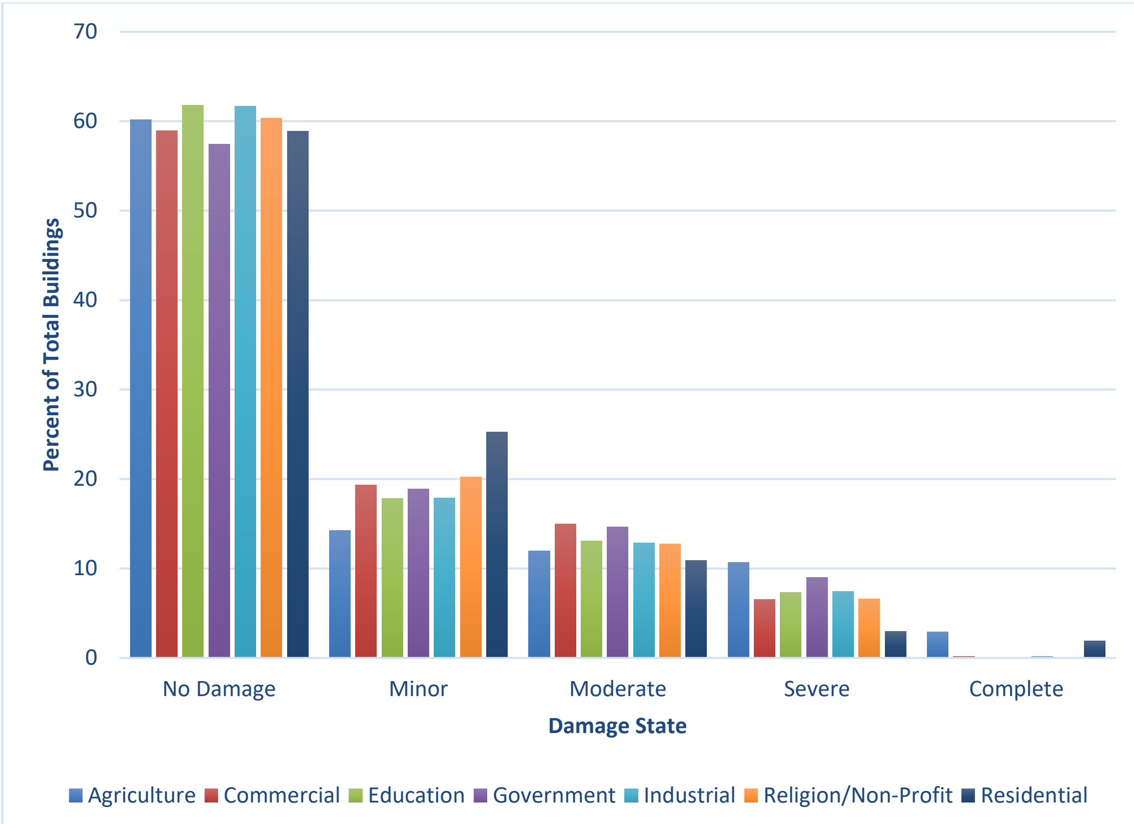

Figure 7: Building damage by occupancy class for 200-year hurricane return period

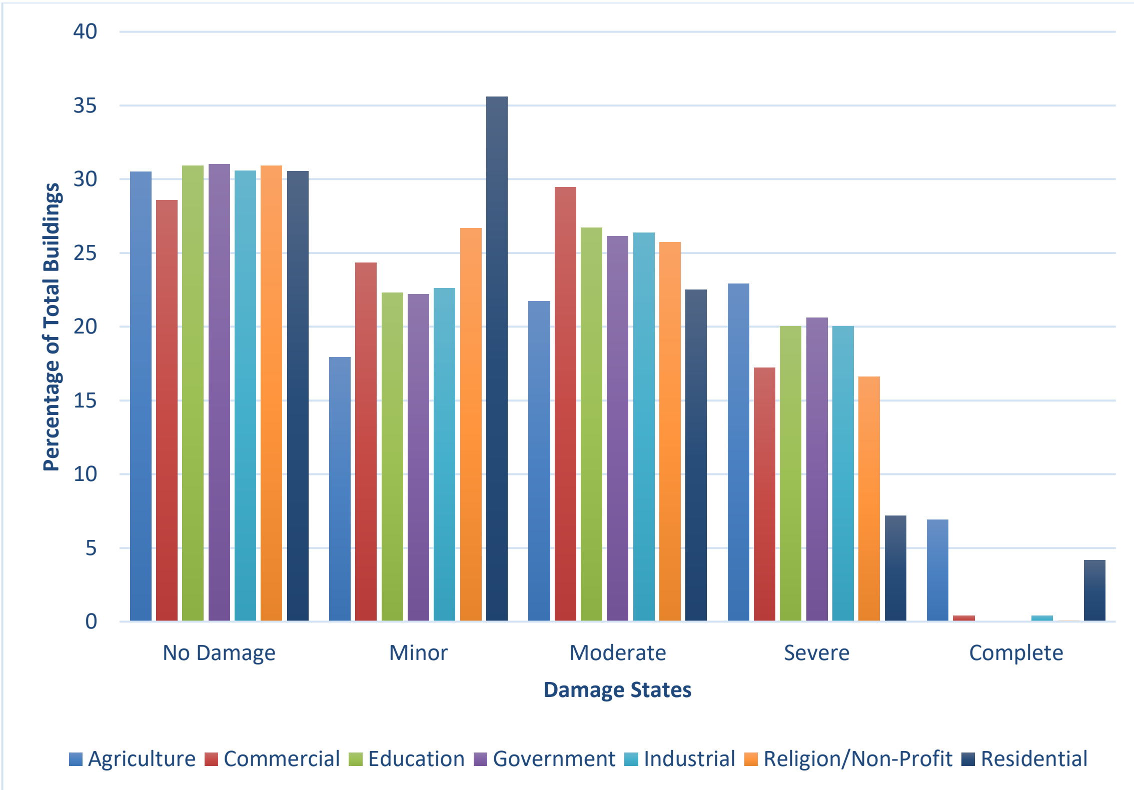

Figure 8: Building damage by occupancy class for 1000-year hurricane return period.

Almost all buildings of all occupancy classes had little to no damage in the 10-year hurricane return period scenario. This is probably because this type of storm occurs the most often of all the return periods, thus most buildings are well-prepared for such frequent events. There were little to no buildings with damage states that would greatly impair their functionality if a 10-year hurricane were to impact the Greater Houston Region. In the 200-year return period scenario, there are more buildings that will have greater damage. There are more residential buildings that are expected to have minor damage than in other occupancy classes; this could be because those types are buildings are made mater materials that are not as resilient to hurricane conditions of greater magnitude. In this scenario, agricultural and residential buildings have a small percentage in the complete destruction category, meaning that there is the potential for parts of the Greater Houston Region to have devastating results. In the 1000-year hurricane return period scenario, only about 30% of buildings will have little to no damage across all the occupancy classes. More than 35% of residential buildings can have minor damage, while the other occupancy classes are expected to have between 18% and 26% of buildings damaged. Most commercial buildings would have moderate damage, while more than 25% of agricultural buildings will fall into the severe or the complete destruction categories. A very small amount of residential buildings fall into those more serious categories in comparison to the other occupancy classes.

5.4.2 Building Damage by Building Type

Just as the results describing the building damage by occupancy class, the building damage by building type is represented in terms of percent of the total buildings of that are damaged (Figures 9, 10, and 11). Like the building damage counts by occupancy, almost no buildings are damaged in the 10-year hurricane return period scenario, with less than 1% of buildings experiencing a more severe damage state (Figure 9). In the 200-year hurricane return period scenario, more than 70% of the manufactured homes have minimal or no damage, while the other buildings types have 60% of the total with no damage. However, the manufactured homes also have the most percentage of buildings that were completely destroyed, with almost 8%. Structures made of wood are expected to have the highest percentage of buildings with minor damage in this scenario, as well. Manufactured homes have the most percentage of buildings that experience no damage in the 1000-year hurricane return period scenario, with almost 60% of the total in the Greater Houston Region. Wooden homes had the most amount of buildings with minor damage, accounting for about 38% of the total of that building type, while steel structures had more than 20% in the severe damage category. In this scenario, manufactured homes also have the most percentage of buildings in complete destruction, this time having more than 10% of the total of that building type.

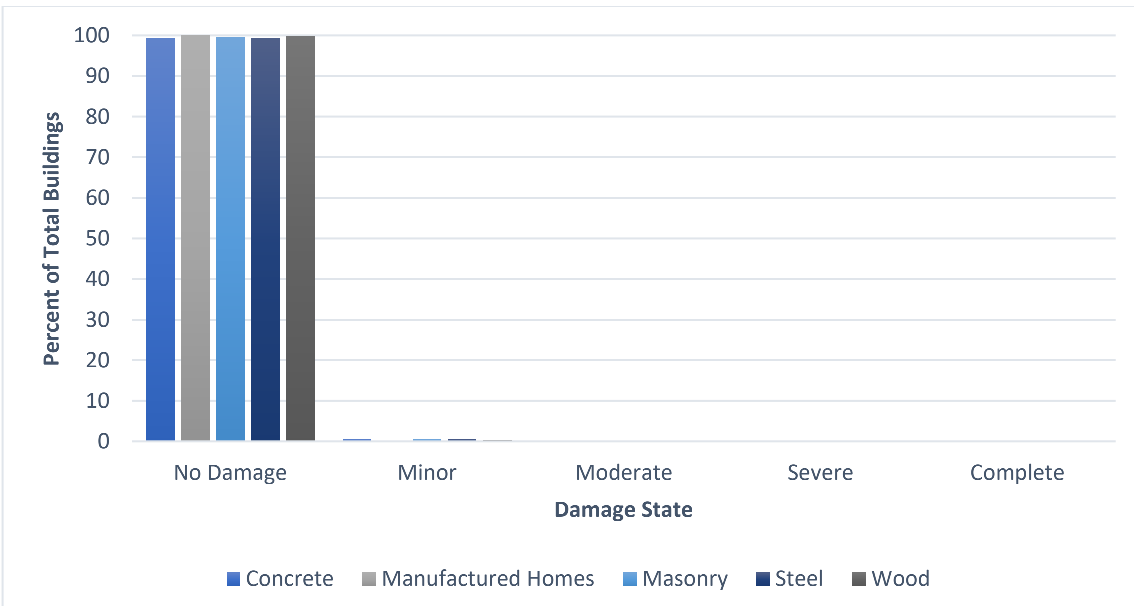

Figure 9: Building damage by building type for 10-year hurricane return period.

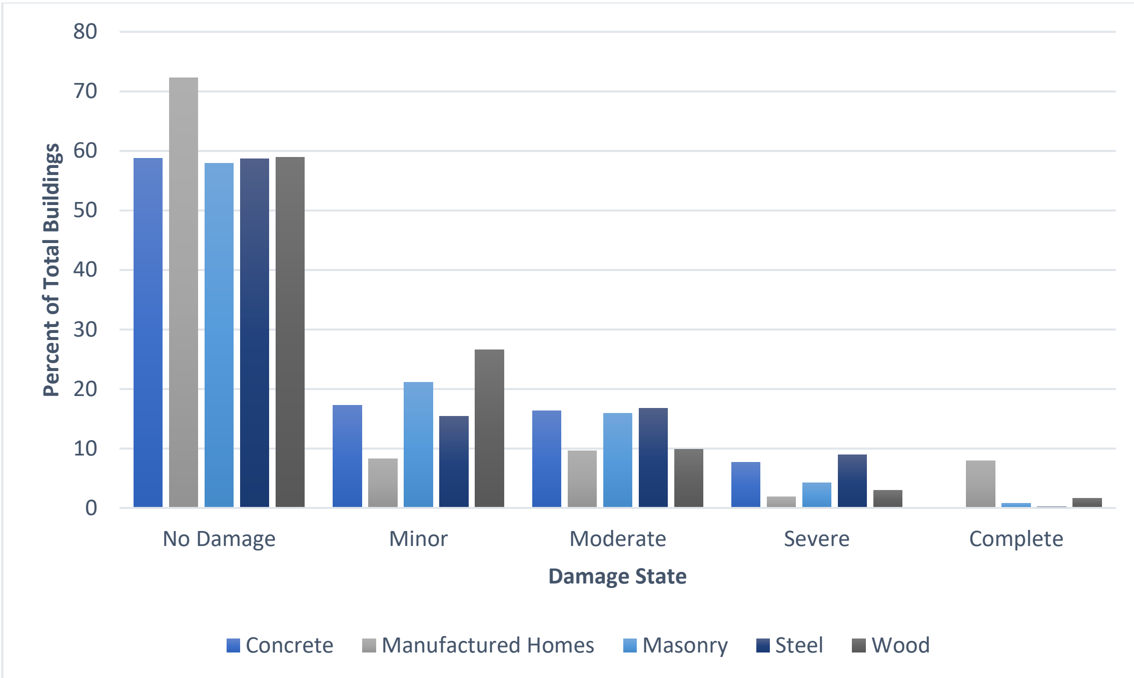

Figure 10: Building damage by building type for 200-year hurricane return period.

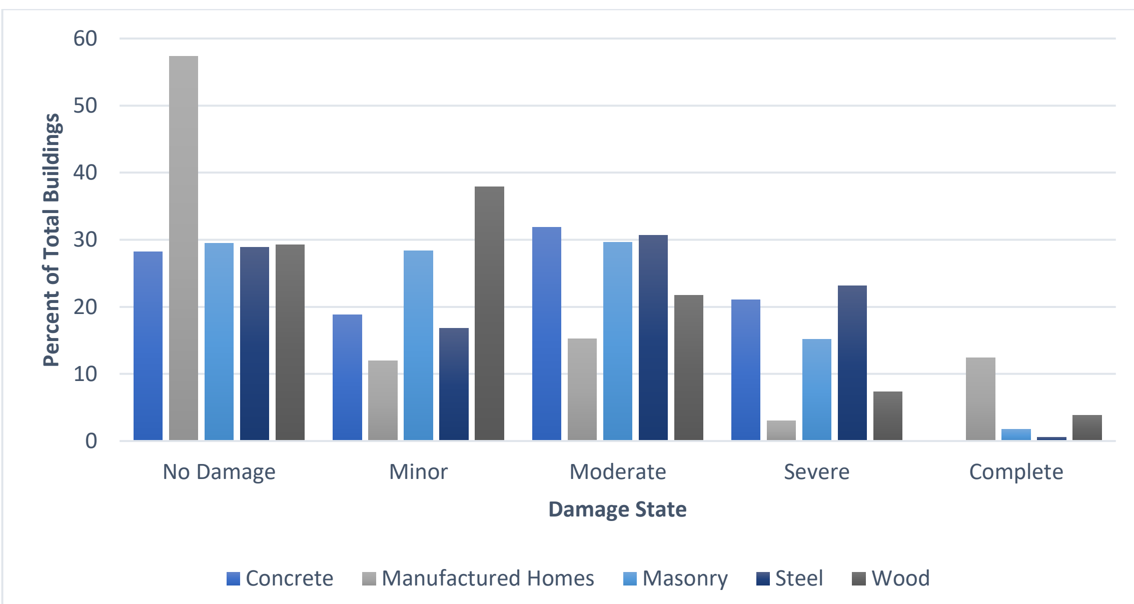

Figure 11: Building damage by building type for 1000-year hurricane return period.

5.5 Economic Losses on Building Damage

5.5.1 Direct Economic Loss

The direct economic losses that result in HAZUS-MH, based on the damages to the structures described earlier in this chapter, consider the general building stock class and the business interruption losses (Mickey 2004). The building losses include the structural and non-structural damages, the content, and the business inventory, while the business interruption losses recognize wage, income, rental, relocation, and proprietor costs (Mickey 2004). These two parameters can be broken down further into seven specific losses that will be described in this section: building, content, inventory, relocation, income, rental, and wage. All costs in this section are expressed in terms of thousands of dollars.

5.5.1.1 By Occupancy

The following tables show the direct economic losses that can occur in the Greater Houston Region from a 10-Year (Table 9), 200-Year (Table 10), and 1000-Year (Table 11) hurricane return period event for seven occupancy classes: agriculture (AGR), commercial (COM), education (EDU), government (GOV), industrial (IND), religion/non-profit (REL), and residential (RES). The resulting tables from HAZUS-MH correspond to all census tracts in the study area.

Class	Total	Building	Content	Inventory	Relocation	Income	Rental	Wage
AGR	184	138	26	3	16	0	1	0
COM	8,611	7,751	209	2	172	236	73	168
EDU	530	522	3	0	2	1	0	2
GOV	218	177	5	0	2	0	0	34
IND	1,660	1,608	37	7	6	1	0	1
REL	618	599	7	0	4	2	0	6
RES	346,210	308,791	28,846	0	4,870	0	3,703	0

Table 9: Direct Economic Losses by Occupancy Class for 10-Year Return Period

Class	Total	Building	Content	Inventory	Relocation	Income	Rental	Wage
AGR	118,255	61,449	37,988	4,676	12,059	1,123	515	445
COM	6,229,973	2,830,968	1,563,569	40,936	572,717	440,618	325,725	455,440
EDU	481,616	246,064	155,625	0	55,129	6,391	330	15,075
GOV	197,222	80,964	52,786	0	21,539	540	5,855	35,538
IND	1,786,678	860,920	698,247	110,975	67,786	15,194	11,354	22,202
REL	424,106	226,726	115,019	0	46,137	9,640	3,990	22,594
RES	47,411,770	31,486,405	10,219,471	0	4,081,762	17,916	1,564,215	42,001

Table 10: Direct Economic Losses by Occupancy Class for 200-Year Return Period

Class	Total	Building	Content	Inventory	Relocation	Income	Rental	Wage
AGR	291,450	149,954	94,979	11,684	28,993	3,278	1,262	1,300
COM	17,194,440	7,557,914	4,556,949	116,980	1,474,465	1,265,512	861,845	1,360,775
EDU	1,113,383	580,374	372,965	0	127,073	7,561	7,572	17,838
GOV	420,801	188,814	122,914	0	50,419	604	15,094	42,956
IND	4,871,251	2,295,017	1,953,680	306,634	175,607	43,568	31,073	65,672
REL	999,328	542,923	291,187	0	110,271	13,527	9,717	31,703
RES	106,997,628	69,051,237	24,607,464	0	9,606,770	45,261	3,580,819	106,078

Table 11: Direct Economic Losses by Occupancy Class for 1000-Year Return Period

The economic losses dramatically increase from the 10-year to the 1000-year hurricane return period storm. The 10-year event results in an estimated loss of over $358 million, while the 200-year event shows a $56.6 billion loss and the 1000-year event shows an estimated $131.9 billion loss. Most buildings in the study area are residential, therefore they experience the greatest economic loss. All the occupancy classes experienced a great increase in losses from the most frequent type of storm to the least likely storm scenario.

5.5.1.2 By Building Type

The direct economic losses by building type are shown in Tables 12, 13, and 14 for the three hurricane return periods. The building types are concrete (CON), manufactured homes (MH), masonry (MAS), steel (STE), and wood (WOO). Just as with the direct economic losses by occupancy class, this is also shown in terms of thousands of dollars.

Type	Total	Building	Content	Inventory	Relocation	Income	Rental	Wage
CON	1,853	1,691	19	3	31	24	62	23
MH	7,491	6,485	395	0	521	0	90	0
MAS	39,976	35,667	2,476	2	766	73	922	70
STE	3,952	3,576	156	6	60	72	22	60
WOO	294,458	263,216	24,738	1	3,694	72	2,680	57

Table 12: Direct Economic Losses by Building Type for 10-Year Return Period

Type	Total	Building	Content	Inventory	Relocation	Income	Rental	Wage
CON	1,528,346	671,911	503,429	36,583	125,129	58,347	51,751	81,196
MH	1,126,047	747,203	278,742	0	88,907	0	11,195	0
MAS	8,079,686	4,900,445	1,718,386	29,477	735,269	148,863	359,373	187,873
STE	3,379,009	1,601,071	1,067,156	74,975	223,978	142,838	106,864	162,127
WOO	42,552,610	27,879,067	9,284,870	15,552	3,683,847	141,373	1,385,800	162,101

Table 13: Direct Economic Losses by Building Type for 200-Year Return Period

Type	Total	Building	Content	Inventory	Relocation	Income	Rental	Wage
CON	4,316,522	1,865,688	1,479,799	103,267	320,601	172,373	133,600	241,194
MH	1,729,684	1,138,368	437,481	0	136,786	0	17,049	0
MAS	18,936,545	10,930,309	4,419,029	82,041	1,763,570	411,350	835,796	494,448
STE	9,114,236	4,217,813	2,979,629	208,266	570,619	403,901	282,580	451,428
WOO	97,848,382	62,243,087	22,712,255	41,723	8,782,024	391,687	3,238,358	439,250

Table 14: Direct Economic Losses by Building Type for 1000-Year Return Period

Again, direct economic losses greatly increase from the 10-year hurricane return period event to the 1000-year hurricane return period event. The losses begin at $347.7 million for the 10-year hurricane, increase for the 200-year storm to $56.6 billion, and again to $131.9 billion for the 1000-year storm. Buildings made of wood have the most economic losses of all the building types because they are the most by count. Though concrete and steel structures had the lowest loss from the 10-year event, manufactured homes had much larger losses in the 200-year and 1000-year hurricane return period scenarios.

5.5.2 Output and Employment

HAZUS-MH also estimates the loss of employee output or productivity as a direct economic loss, as well as the losses that result from lack of employees in the aftermath of a hurricane. The results are presented for the 10-year, 200-year, and 1000-year hurricane return periods are only for the occupancy classes and the costs are shown in thousands of dollars.

5.5.2.1 Employment Loss

Figure 12: Employment losses from 10-year, 200-year, and 1000-year return period hurricanes

Commercial structures experienced the most economic losses from employment for all three event scenarios (Figure 12). In comparison, the other occupancy classes do not have as significant of an impact, with losses until $2 million in each case. Government buildings have the most losses outside of the commercial building costs (Figure 12). But have much lower losses than the other occupancy classes for the other return periods. Agricultural buildings had fewer losses than expected.

5.5.2.2 Output Loss

Output losses include the costs of employees not being able to work, which is due to factors such as the employees not being able to come to work due to health risks from water damage or a tree blown down, blocking the road. HAZUS-MH produces output loss results by census tract for each occupancy class. Like the employment loss, the commercial structures experienced the most economic losses and the agricultural buildings experienced little to no losses for all three return periods (Figure 13). The residential building losses in the Greater Houston Region have a significant increase from the 10-year return period hurricane to the 1000-year return period hurricane, going from $0 to over $1 million.

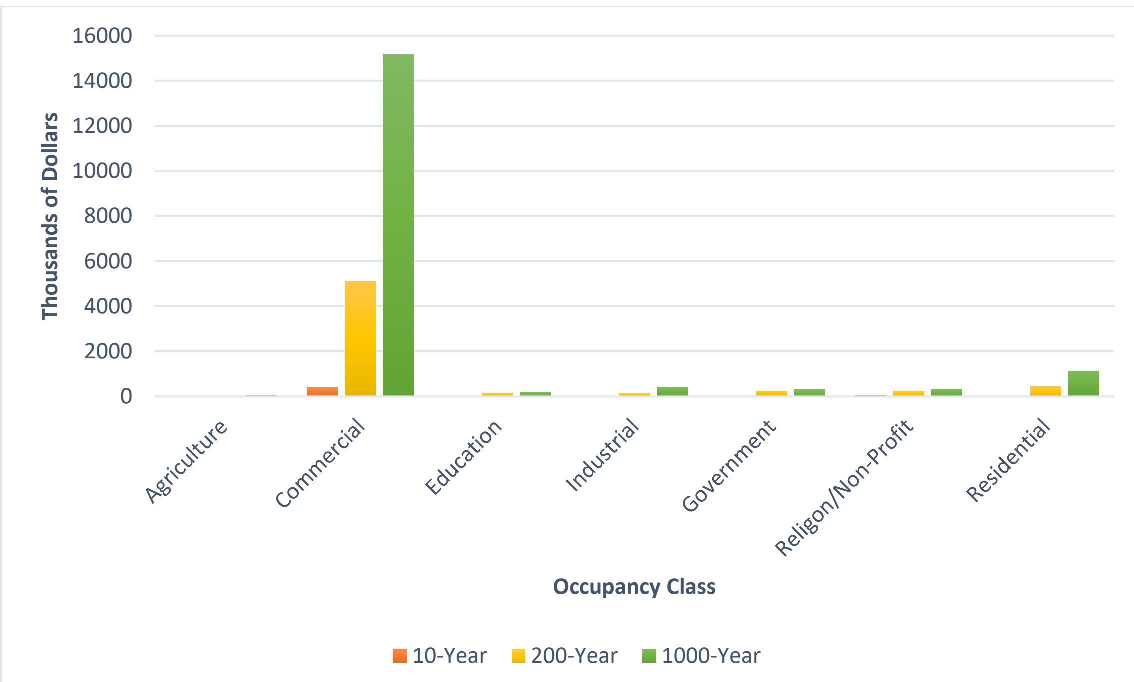

Figure 13: Output losses from 10-year, 200-year, and 1000-year return period hurricane

5.6 Essential Facilities

5.6.1 Medical Care Facilities

No medical care facilities in the study area would experience losses of use during a 10-year storm (Figure 14). During a 200-year hurricane, few of the facilities would be out of commission, with the rest having a loss of use period of less than 3 days. The areas of the Greater Houston Region with hospitals that are unable to take patients are closer to the coast and are near other facilities. There are some hospitals in the study area that would have loss of use longer than one week, with a few having more than two weeks; these facilities are also along the coast and along the pathways of the city of Houston. Only the hospitals on the outskirt areas of the Greater Houston Region would have loss of use of less than 3 days.

5.6.2 Fire Stations

For the 10-year, 200-year, and 1000-year return period hurricane events and their relation to the days lost for the fire stations in the Greater Houston Region, these facilities have zero days lost (Figure 15), meaning that they can have full use during an emergency during tropical cyclone impact and post-storm recovery efforts.

5.6.3 Police Stations

There is full use of the police stations during a 10-year hurricane event (Figure 16). Though there is mostly no loss of days in the 200-year return period scenario, the facilities that do have losses are near the coast and near the probabilistic hurricane track. However, the loss of use is only about one day. In the 1000-year hurricane, there are more police stations that are affected and have more than one day of loss of use; these facilities are primarily located in Galveston County.

5.6.4 Emergency Response Centers

Like the other essential facilities, there are little to no expected days lost for the emergency response centers. The 200-year return period and 1000-year return period maps are almost identical. The locations are affected are close to the coast and the storm track, in the areas of higher winds (Figure 17).

5.6.5 Schools

The 10-year hurricane is expected to have no days lost, just like all the other essential facilities. Some schools in the Greater Houston Region can have as many as 195 days lost in the wake of a 200-year hurricane. The facilities with the most days are located near the coast or near the probabilistic storm track. For the 1000-year hurricane return period, schools near the coast and along the probabilistic storm track have the most expected days with loss of use, the highest being 208 days. In both the 200-year and the 1000-year events, the days lost decrease as the distance from the coast or the storm track increases. The schools that are located more inland or on the edges of the study area have less loss of use (Figure 18).

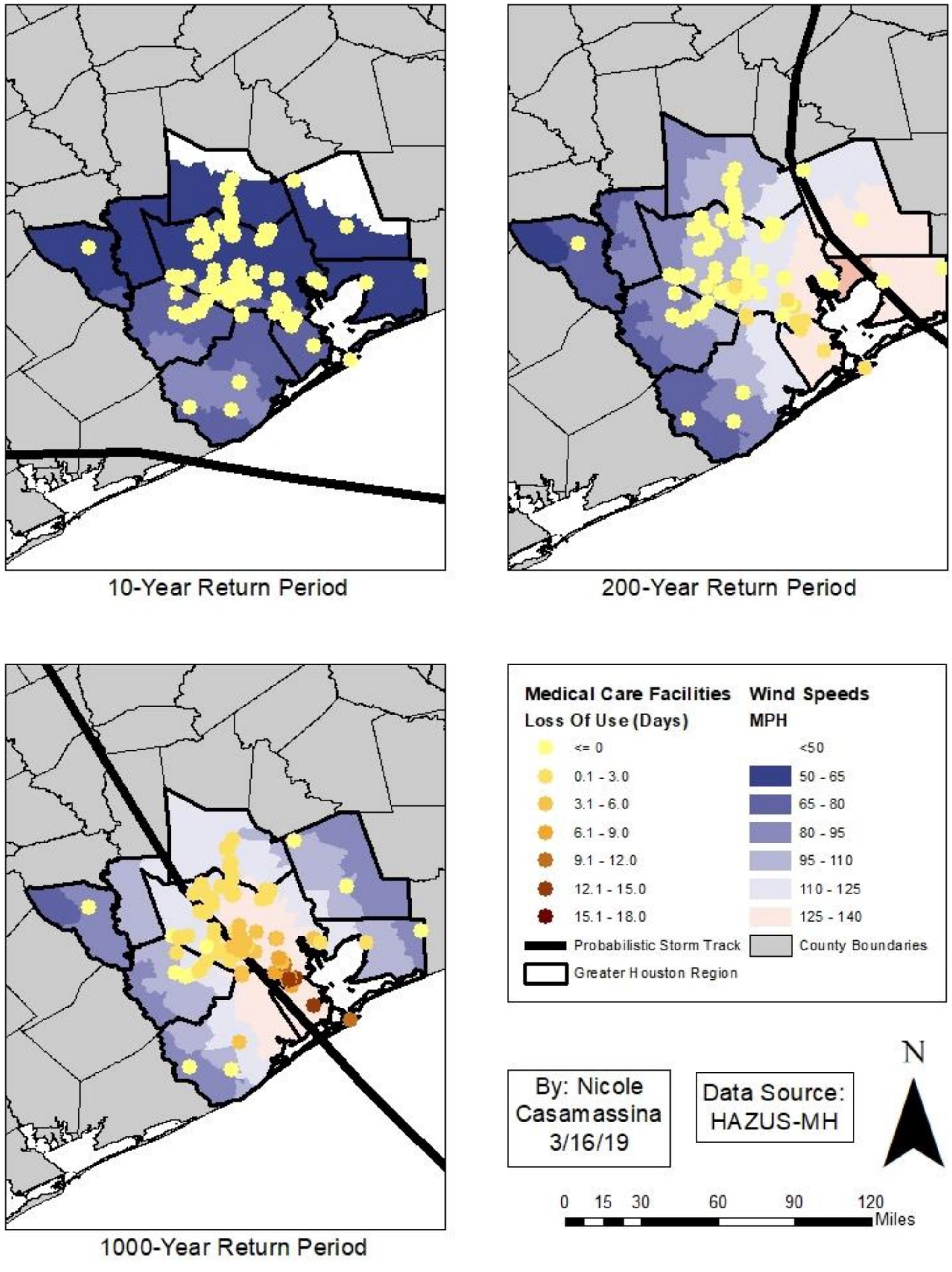

Figure 14: Locations of the medical care facilities and their loss of use

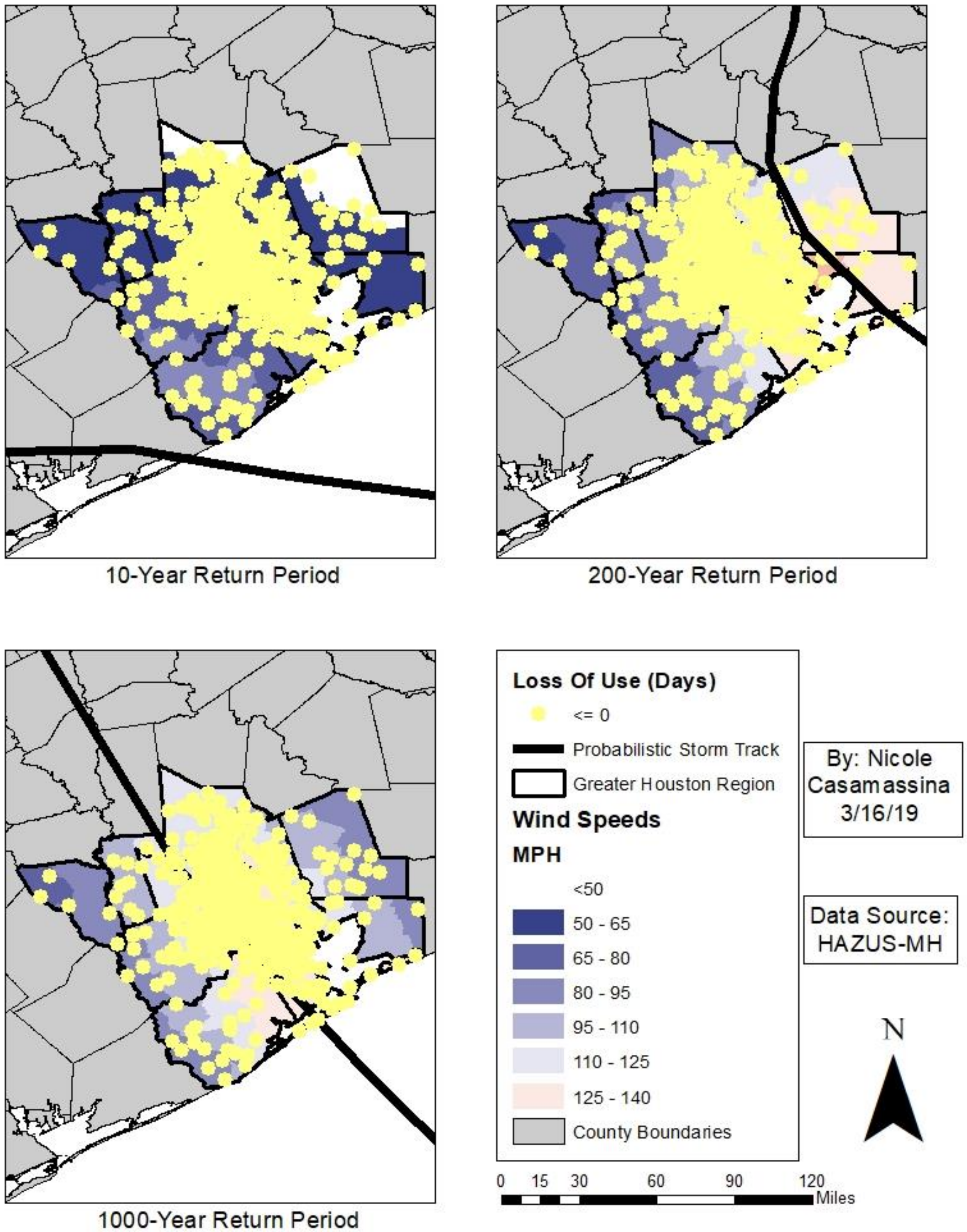

Figure 15: Locations of the fire stations and their loss of use

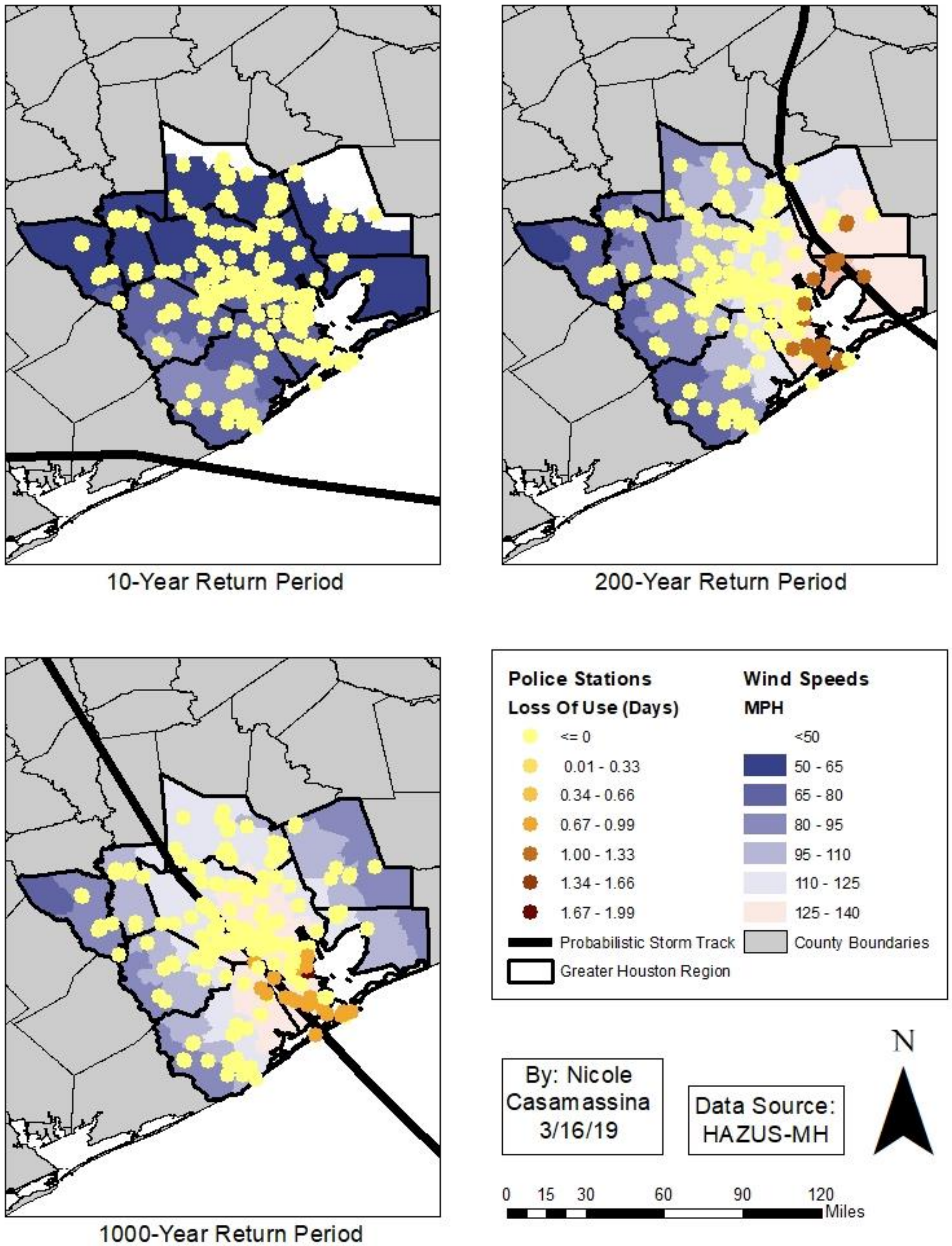

Figure 16: Locations of the police stations and their loss of use

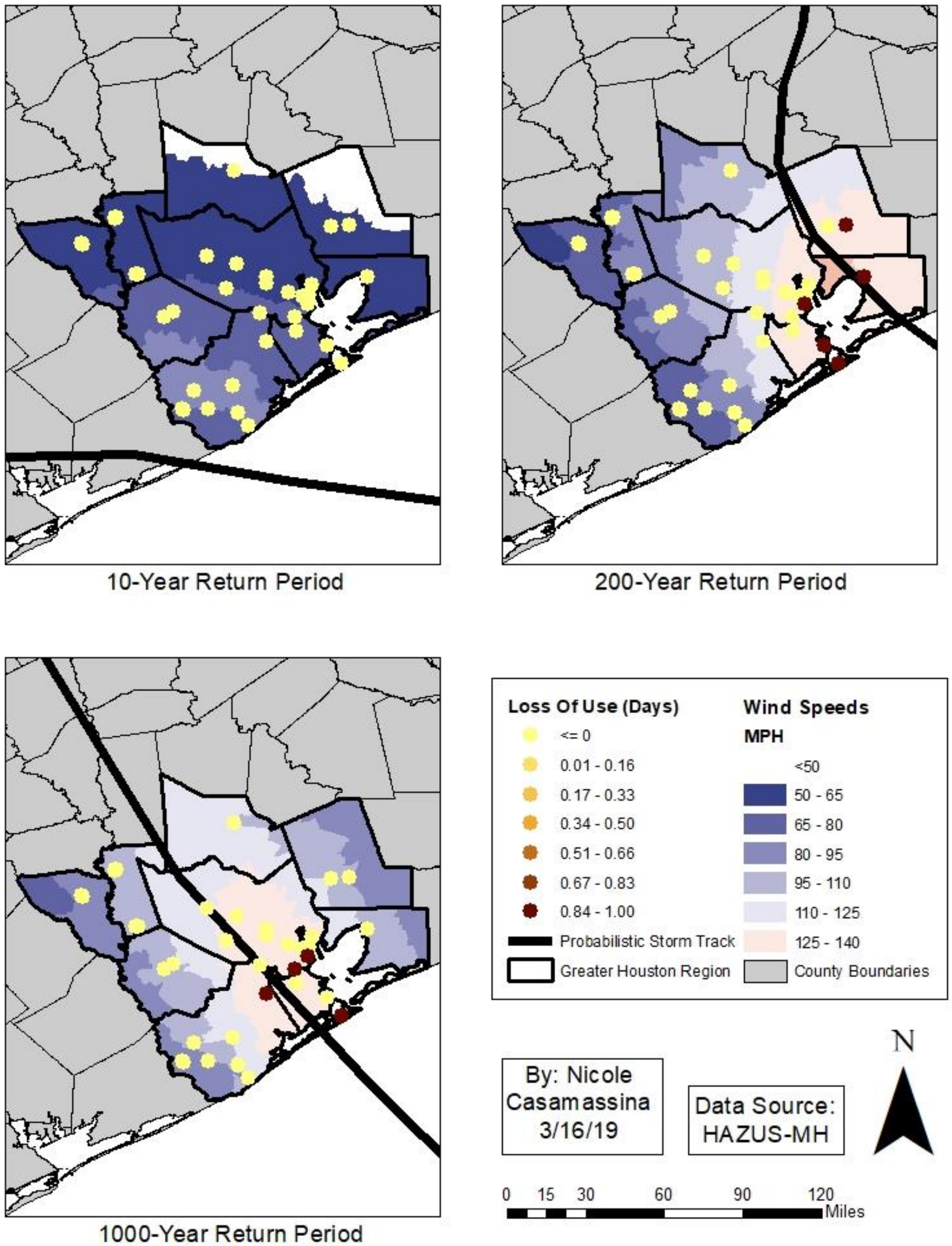

Figure 17: Locations of the emergency response centers and their loss of use

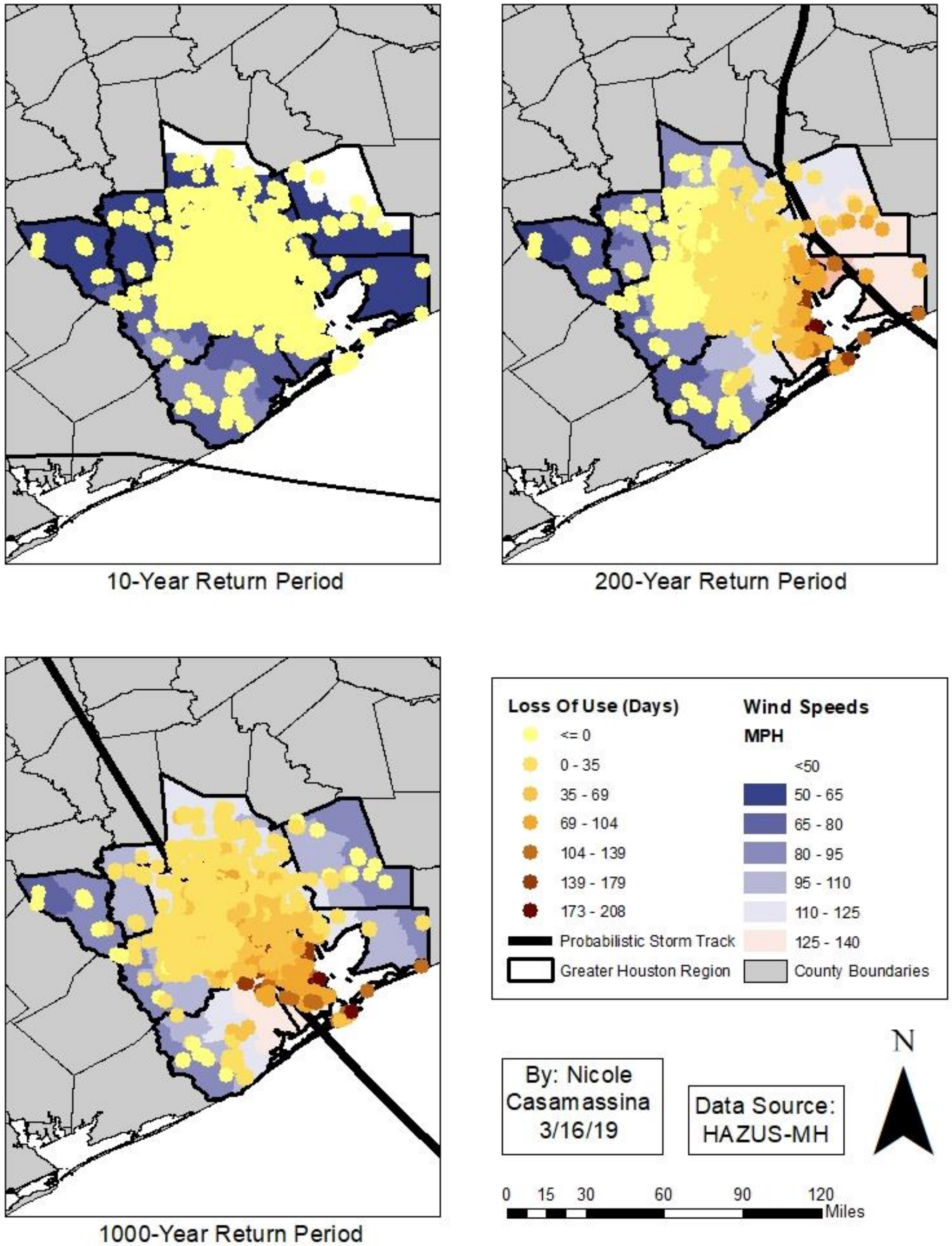

Figure 18: Locations of schools and their loss of use

5.7 Debris Analysis

The debris that HAZUS-MH analyzes is separated into four categories: brick and wood, concrete and steel, eligible trees, and trees, and is reported as the expected weight of each debris type in tons (Figure 19). Eligible trees are the downed trees that would likely be collected and disposed of at the public's expense (FEMA 2018d).

In each scenario, trees have the highest amount of debris because they are the lightest debris type. Concrete and steel, being the heaviest, are expected to produce the least debris. The eligible trees amount is lower than expected, since trees that are downed would likely need to be disposed of if they are blocked a road or on power lines. In the 1000-year hurricane event, there are be more than 60 million tons of trees that become debris in the high winds and extreme precipitation of the hurricane.

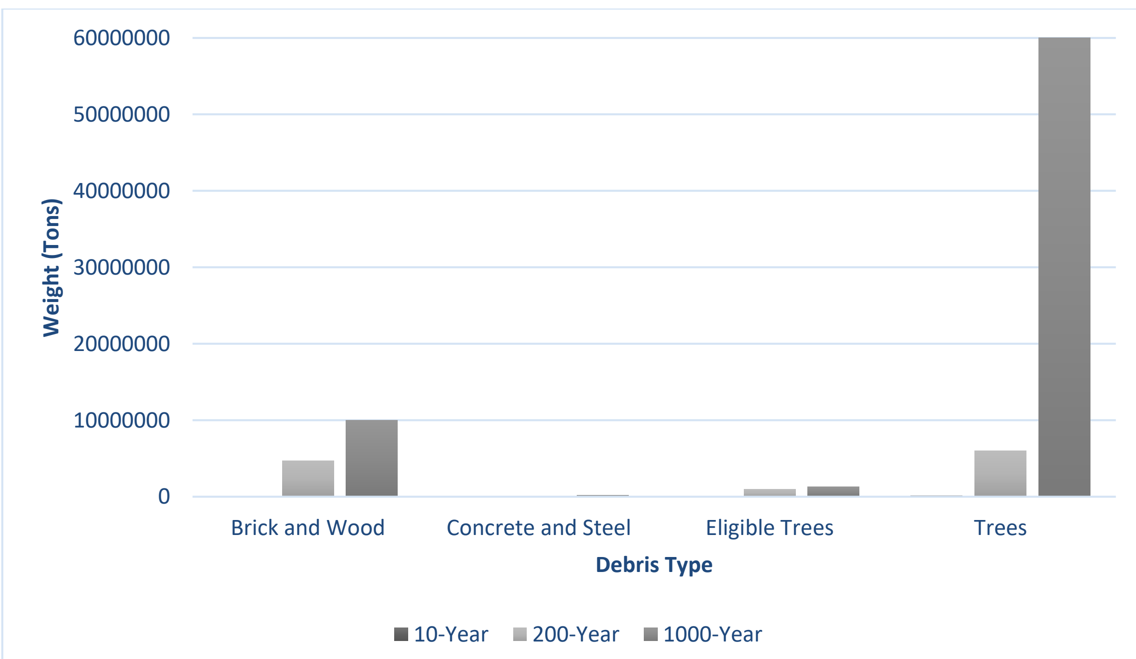

Figure 19: Debris expected from 10-year, 200-year, and 1000-year hurricanes

5.8 Shelter Analysis

5.8.1 Displaced Households

The social impacts of a hurricane can be described by the number of displaced households an area can experience, which HAZUS-MH quantifies by census tract. The probabilistic 10-year, 200-year, and 1000-year hurricane return periods and the resulting number of displaced households in the Greater Houston Region indicates that the number of census tracts with a great number of displaced households decreases from the 200-year return period to the 1000-year return period (Figure 20). This is due to the location of the storm track, which results in wind damage, as well as the census tract's proximity to the nearby waterbodies, which can be a reason for damage from flooding.

5.8.2 Short-Term Shelter Needs

Societal impacts can also be explained in terms of the short-term shelter needs. The number of shelters needed in the wake of 10-year, 200-year, and 1000-year hurricanes (Figure 21) correspond with the number of displaced households because people will need to access them quick, and at a short distance from their homes. Since there may not be shelters in all census tracts, people may need to go further and use shelters in another census tract.

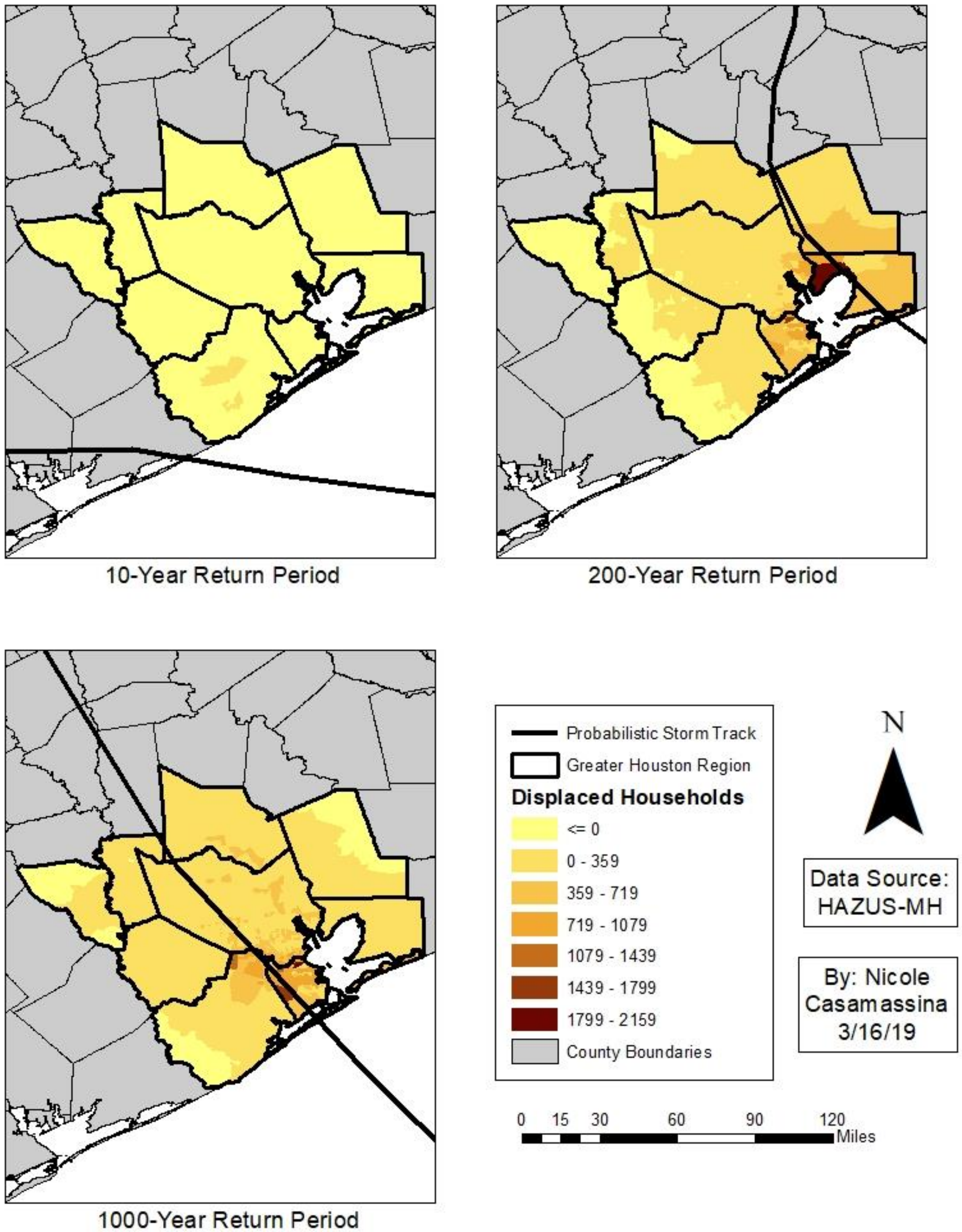

Figure 20: Displaced households by census tract

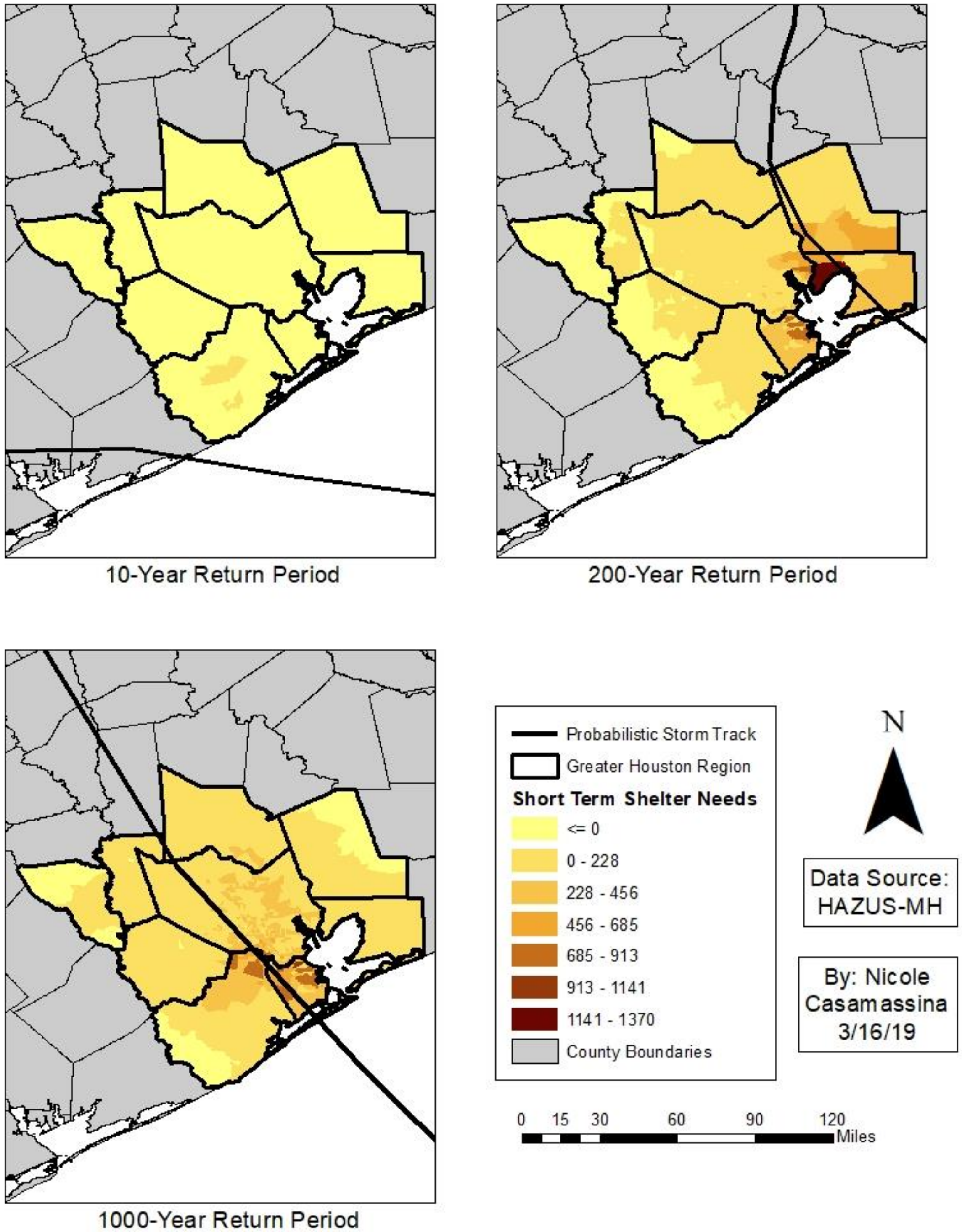

Figure 21: Short-term shelter needs by census tract

5.9 Storm Surge

To estimate the losses from storm surge, a combined hurricane and flood hazard analysis was run for Galveston County, Texas. Since HAZUS-MH is unable to produce results for a probabilistic scenario, Hurricane Ike was simulated for Galveston as a historical scenario (FEMA 2018d). This alternate study region was chose for both the hurricane and flood models because the area must be about the size of one coastal county (FEMA 2018d). The hurricane wind model is run first using the SLOSH model to produce estimates of the coastal still water elevations (FEMA 2018d). The “No Waves” option was selected for this scenario, where the SWAN model is skipped entirely and the Flood Model assumes depth-limited waves at the coastline rather than using significant wave heights produced by the SWAN model, so that the analysis could be completed with no issues (FEMA 2018d). The initial water level with respect to the North American Vertical Datum of 1988 was estimated to be 0.964 ft above sea level by using the NOAA tide forecasts and the pre-storm tide anomaly, which is the difference between the forecast and observed water levels two days before landfall at Galveston Pier 21 (NOAA 2008). This shows the water level along the coast that would have been expected in the absence of the hurricane near the center of the study region at the time of hurricane landfall. After the wind-only damage and loss calculations are completed, the hurricane coastal storm surge analysis is run with results including two sets of direct building losses: one for the wind damage by itself, and the other for the combined wind and surge damage. The Flood Model is then used to obtain the combined losses, first by running a coastal surge analysis and then calculating the combined losses. To analyze the coastal storm surge, the user must import a digital elevation model for the study region (FEMA 2018d). HAZUS-MH has a database from the United States Geological Survey's National Map at 1 arc-second and 1/3 arc-second resolutions and automatically determines which raster images are needed based on the spatial extent of the study area (FEMA 2018c). The model then needs to delineate the floodplain to output a flood depth grid, which is comprised of the SLOSH model and wave height grids (FEMA 2018d). To complete the analysis, the HAZUS-MH Flood Model is run to find the general building stock damages and losses (FEMA 2018c). The results show the combined wind and flood losses for the study region of Galveston county and they are only available for the building, content, and inventory losses, but not for the relocation, income, rental, and wage losses (FEMA 2018c). The results are divided into the losses by occupancy class and building type (FEMA 2018c).

5.9.1 By Occupancy

The direct economic losses from the combined wind and flood analysis of Galveston County by occupancy class for Hurricane Ike exceeds $63 billion, with most costs coming from the damages to residential buildings, particularly with the building replacement costs and content losses (Figure 22). Commercial buildings also had significant losses in those categories, estimated to be more than $386 million. The losses from inventory damages were very small for all occupancy classes; education, governmental, religious/non-profit, and residential buildings lost $0, while the other three classes had losses that did not surpass $8 million.

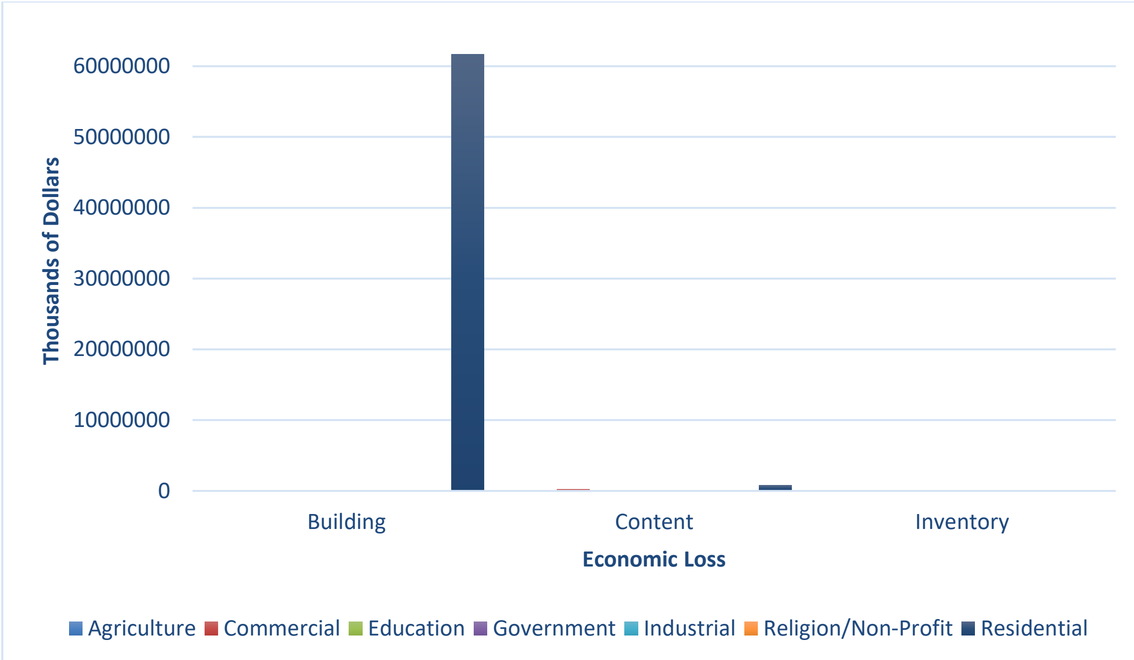

Figure 22: Direct economic losses by occupancy classes from Hurricane Ike's storm surge

5.9.2 By Building Type

The direct economic losses caused by storm surge from Hurricane Ike in Galveston County, divided by building type indicates that, like the division by occupancy class, building replacement cost and content losses dominated the losses for this county (Figure 23). Structures made of wood had the greatest losses, with costs estimated to be around $1.1 billion. Masonry also had significant losses of over $222 million and most of it was due to the building replacement costs. Losses from inventory damages only came from buildings made of masonry and wood, but only had losses of just almost $4.5 million.

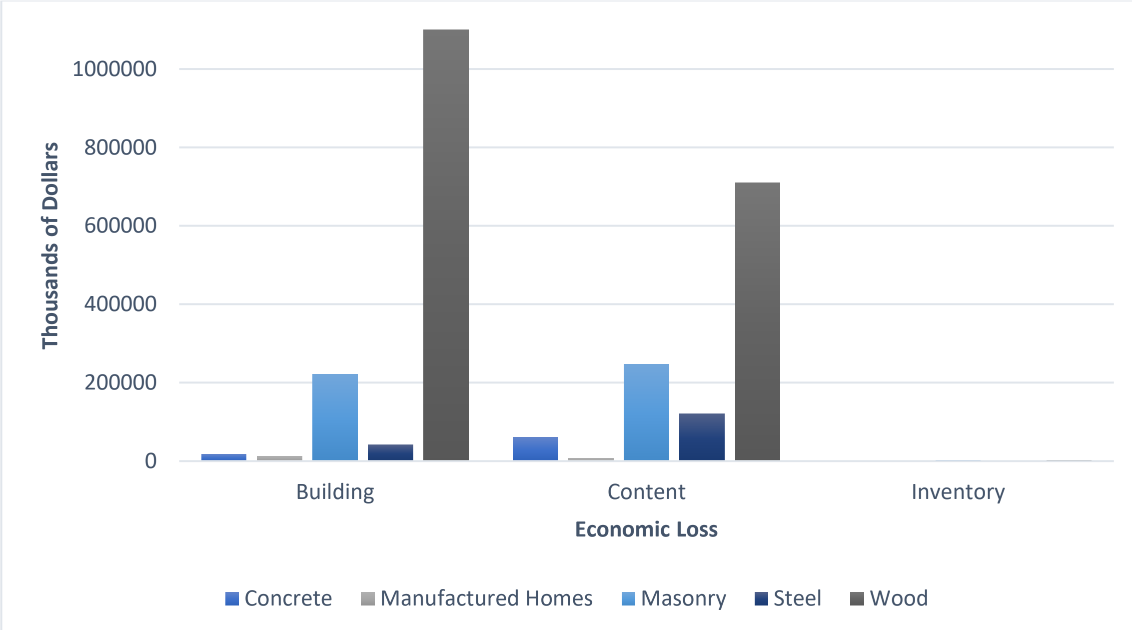

Figure 23: Direct economic losses by building type for Hurricane Ike's storm surge

5.10 Discussion

The 10-year, 200-year, and 1000-year hurricane return period probabilistic scenarios represent the potential tropical cyclones that can impact the Greater Houston Region. Using the HAZUS-MH Hurricane Wind and Flood Models, the physical, economic, and social losses were calculated from the extreme winds, heavy precipitation, and storm surge that can occur during these three hurricane scenarios for this study area. The storms that are expected to occur less frequently were also expected to have the greatest impact on the region. Based on the results presented in this chapter, it is obvious that the most vulnerable areas in the Greater Houston Region to the hazards of hurricanes are the locations of structures and facilities that are closest to the storm track or the coast. Those that are located with both conditions are even more susceptible to having large losses. The residential and wooden structures experienced more damage than any other category of building and the 1000-year hurricane return period scenario caused the most damage in the Greater Houston Region. The losses greatly increased as the return period increased; this trend could be seen in every result throughout this chapter.

The losses that come from the different hurricane scenarios show that any tropical cyclone to impact the Greater Houston Region, whether directly or indirectly, can result in billions of dollars' worth of damages. This can mean that mitigation strategies need to improve in order to reduce the impact costs, as well as recovery time in the aftermath of the storm, in this area. This is apparent with the residential and wooden buildings that are in the counties around the central Harris County, where Houston is located. Most of the people working in the city would live in the outer suburbs of the area; with many of those people affected by a tropical cyclone, the economy of this major city would also be impacted. This can have adverse effects on county, state, and federal economies, such as FEMA providing aid to those impacted and shelters being opened by the state. However, the data from the general building stock was not updated as part of Objective 1, meaning that these data are out of date (FEMA 2019c). This has an impact on the results because Houston has been undergoing an intense urban sprawl in recent years, with population increasing exponentially from 2010 to the present, and continuing to grow every year (*About Houston: Facts and Figures* 2019). If this scenario were to be done with more recent general building stock data, it is expected that the losses, especially the economic losses, would be lower since major hurricanes, such as Hurricanes Ike and Harvey, have made a major impact on the Greater Houston Region, prompting changes in building codes and other hurricane mitigation strategies.

CHAPTER VI

ASSESSING LOSSES FROM HURRICANE HARVEY

6.1 Storm Track and Wind Speeds

FEMA recently updated the HAZUS-MH hurricane model with storm information from the 2017 North Atlantic Hurricane Season, including Hurricane Harvey. Using the historical scenario in the model, Harvey was simulated to see the effects on the Greater Houston Region. The track of the tropical cyclone is south and west of the study area. This is because Harvey made its first and second landfalls southwest of Houston, though it did turn clockwise after making landfall before stalling over southeast Texas. The wind speeds that were observed in the Greater Houston Region were in tropical storm range of 39-73 mph for the entire region, but only peaked to greater than 50 mph in the southwest corner of Brazoria County (Figure 24).

6.2 Building Damage

6.2.1 By Occupancy Class

Almost 100% of all buildings had no damage from the winds of the tropical cyclone, with less than 1% expecting minor damage (Figure 25).

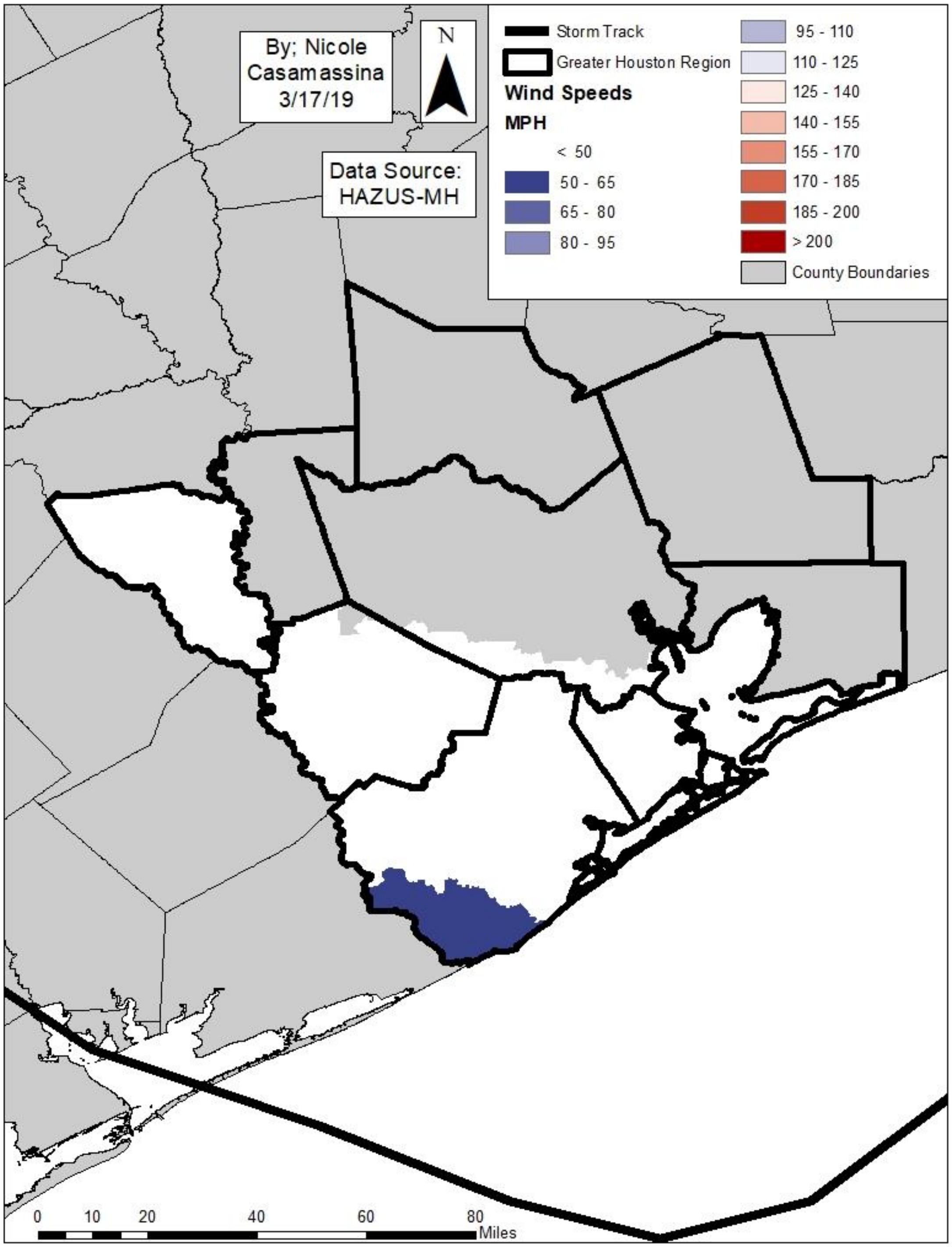

Figure 24: Hurricane Harvey storm track and estimated wind speeds in the Greater Houston Region

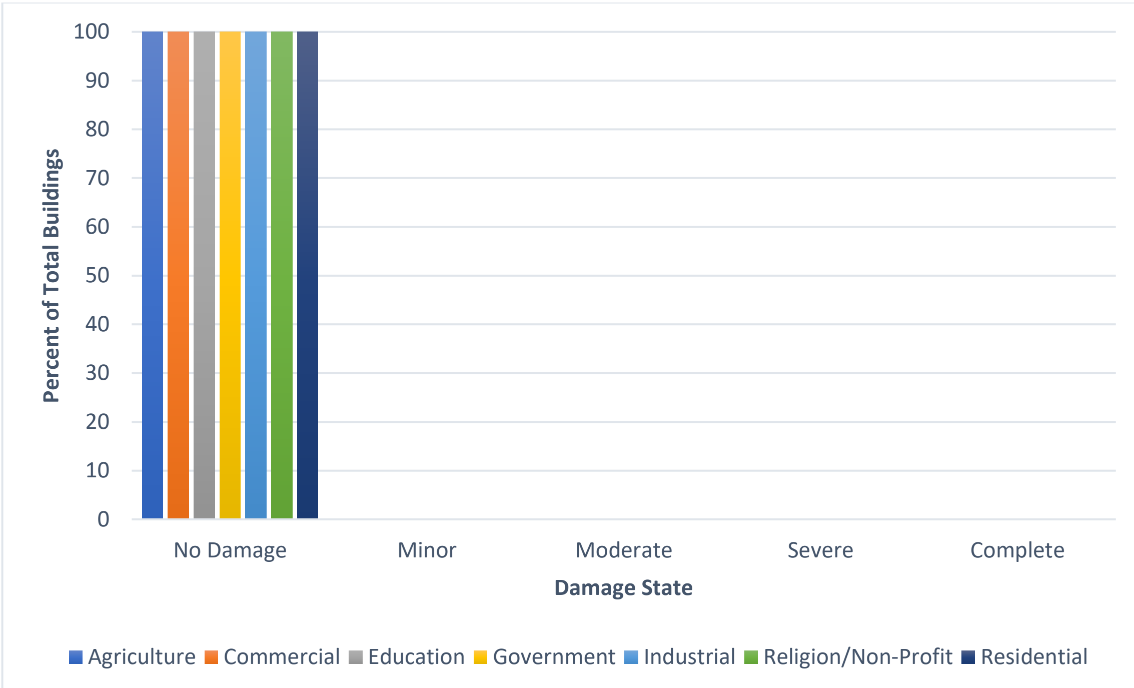

Figure 25: Building damage by occupancy class for Hurricane Harvey

6.2.2 By Building Type

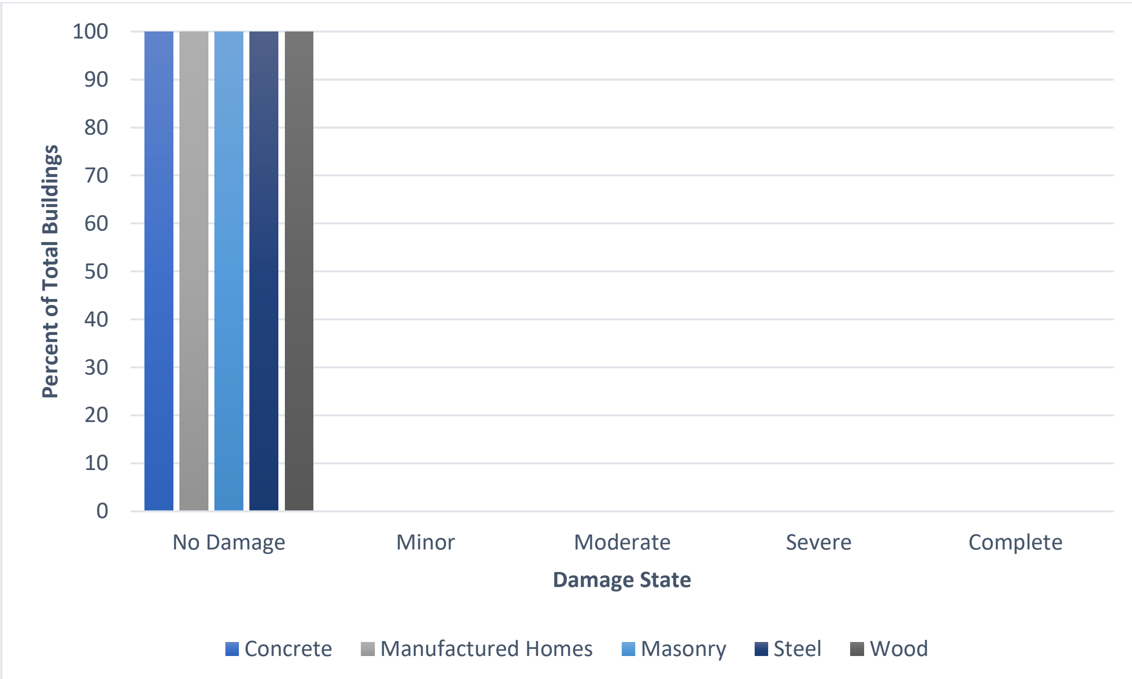

Figure 26: Building damage by building type for Hurricane Harvey

Like the division by occupancy class, all types of buildings had at or close to 100% with no damage (Figure 26). Only buildings made from concrete, masonry, and steel had less than 1% receiving minor damage due to the winds from Hurricane Harvey.

6.3 Economic Losses on Building Damage

6.3.1 Direct Economic Loss

There were no direct economic losses to the different occupancy classes of buildings from the winds of Hurricane Harvey in the Greater Houston Region.

Separated by building type, there was virtually no losses by building type; the highest economic losses came from manufactured homes of approximately $2,370.

6.3.2 Output and Employment

There were no employment or output losses from the winds produced by Hurricane Harvey in the study area.

6.4 Essential Facilities

None of the essential facilities had significant losses in the Greater Houston Region.

6.5 Debris Analysis

There was no debris caused by Hurricane Harvey's winds in this study area.

6.6 Shelter Analysis

No people needed to evacuate from their homes, therefore no short-term shelters were necessary from Hurricane Harvey's winds.

6.7 Storm Surge

The storm surge from Hurricane Harvey was simulated for Galveston County, Texas using a combination of the HAZUS-MH Hurricane Wind and Flood Models. This hurricane scenario was imported from HURREVAC into the model, with the storm track beginning at a location less than 24 hours before landfall (FEMA 2018d). All the parameters of this simulation were the same as the Hurricane Ike simulation described in Chapter V. The only exception was the initial water level with respect to the North American Vertical Datum of 1988, estimated to be 0.7 ft at Galveston Pier 21 (NOAA 2017).

6.7.1 By Occupancy

Losses were highest for residential buildings, with costs resulting to be around $17 million (Figure 27). Commercial and industrial buildings also had significant losses of less than $1 million each due to storm surge from this tropical cyclone. The only losses in inventory came from industrial buildings. Educational and government buildings had no losses from Hurricane Harvey's storm surge.

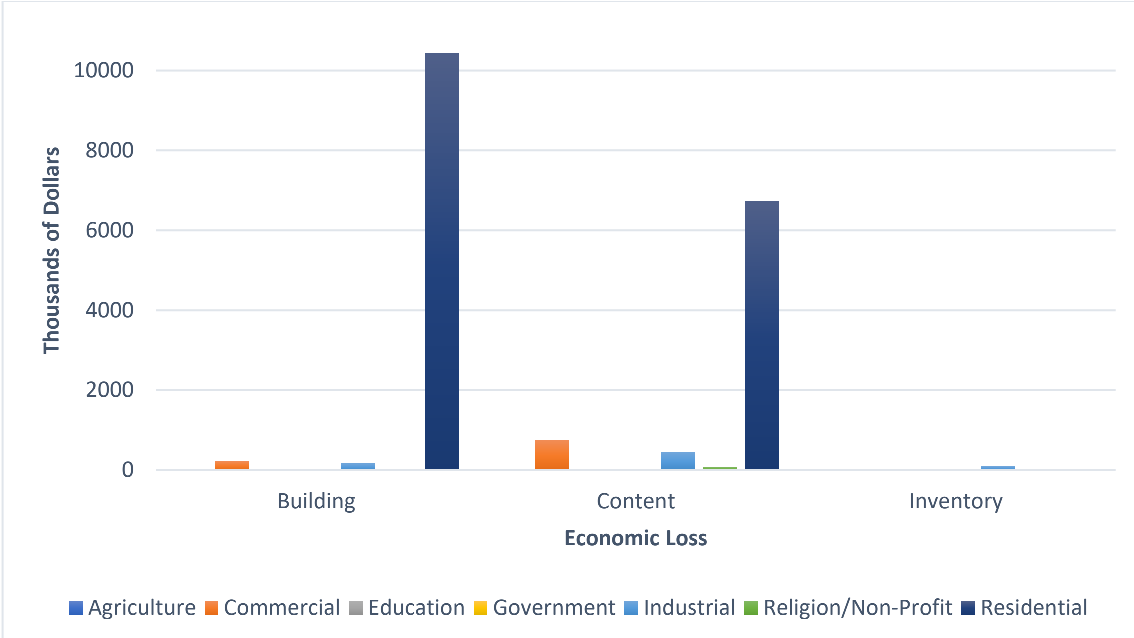

Figure 27: Direct economic losses by occupancy class from Hurricane Harvey's storm surge

6.7.2 By Building Type

The losses that resulted from wood buildings were the highest of all the categories, resulting in almost $1 million in damages (Figure 28). Inventory losses for all categories were less than $1,000, with concrete, manufactured homes, and steel structures having $0 in losses. Buildings made of concrete also had no losses in building replacement costs. Content losses in steel structures were much higher than the building replacement losses, but the total costs are much lower than the wood buildings and manufactured homes.

6.8 Losses from Flooding

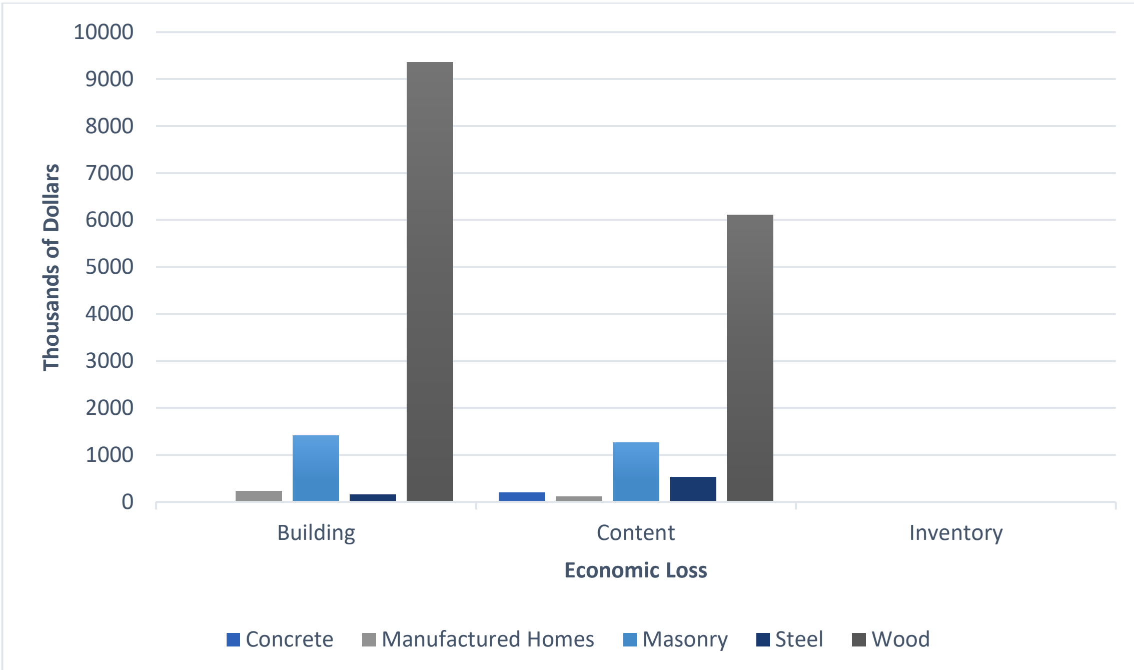

Figure 28: Direct economic losses by building type from Hurricane Harvey's storm surge

The HAZUS-MH Flood Model was run for Harris County because the wind losses described earlier in this chapter do not truly represent the total costs from Hurricane Harvey; the winds were of tropical storm strength or loss. However, flooding was the major issue for this county, therefore the results from the flood model give a clearer representation of all the physical, economic, and social losses from this storm. Both the riverine and coastal flooding analyses were conducted for a 200-year return period because the return period for Hurricane Harvey is estimated to be 230 years (Trepanier and Tucker 2018).

6.9 Riverine Flooding

Riverine flooding in Harris County for the 200-year scenario can be as high as 51 ft. particularly in the northern and eastern sides of the county (Figure 29). These depths also occur in some of the lower elevations in the study area, as well as in the downtown areas of Houston.

6.10 Coastal Flooding

The coastal flooding that can occur from a 200-year flood had a lower depth than the riverine flooding, with the maximum estimated to almost 27 ft in the areas with the lowest elevations in the county (Figure 30). These areas also include some of the most densely populated regions in the county, as well as some economic hub near the Houston Ship Channel.

6.11 Damage to General Building Stock

Damage to the general building stock is the percent of structures affected by either a riverine or coastal flood, or both, that had greater than 50% damage to the building.

6.11.1 By Occupancy

For the buildings that were affected by flooding in this scenario, 100% of the agricultural structures within the floodplain experienced damaged of more than 50% (Figure 31). Residential buildings were the most affected, with more than 50% lost, but only about 30% of the total dwellings of this category were affected in the floodplain.

6.11.2 By Building Type

Over 80% of the manufactured homes within the river and coastal floodplains experienced more than 50% damage to the buildings (Figure 32). The other building type categories had less than 30% of the structures greatly affected by the flooding of a 200-year storm. This is especially surprising that most of the wood buildings did not experience major damages, but it is possible that many of these structures had minor damages, but it is possible that many of these structures had minor damage and were not reported in these data.

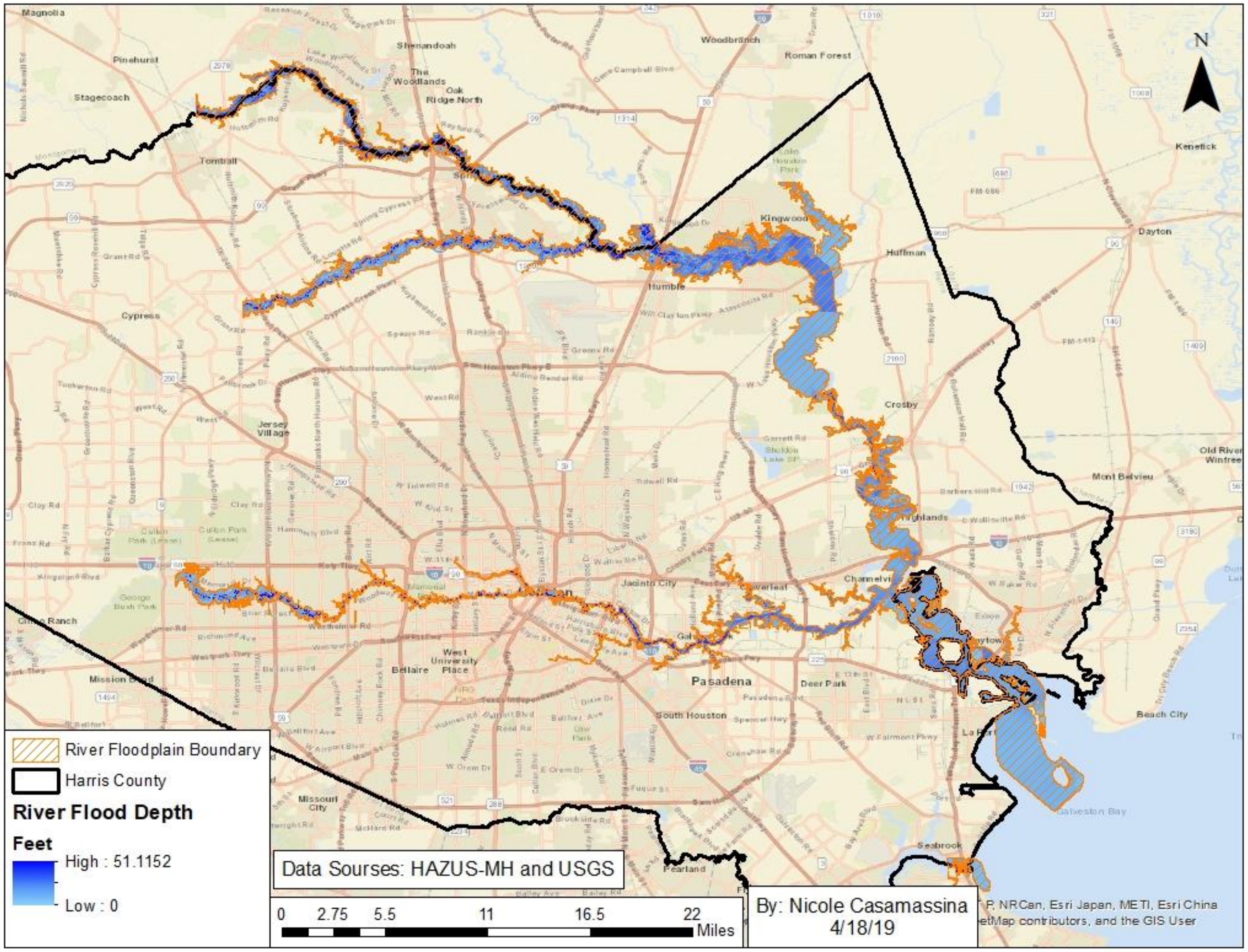

Figure 29: 200-year riverine flooding for Harris County

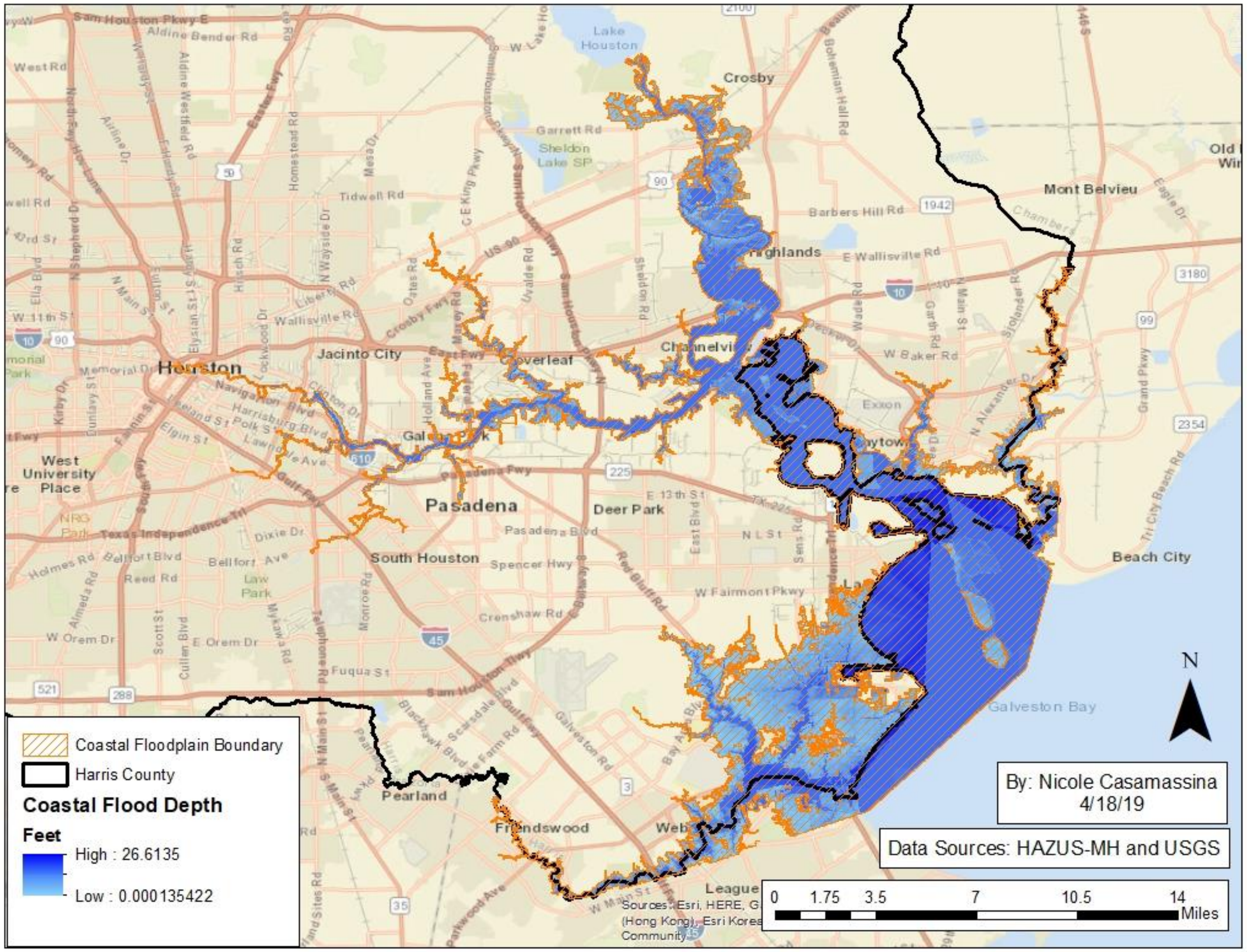

Figure 30: 200-year coastal flooding for Harris County

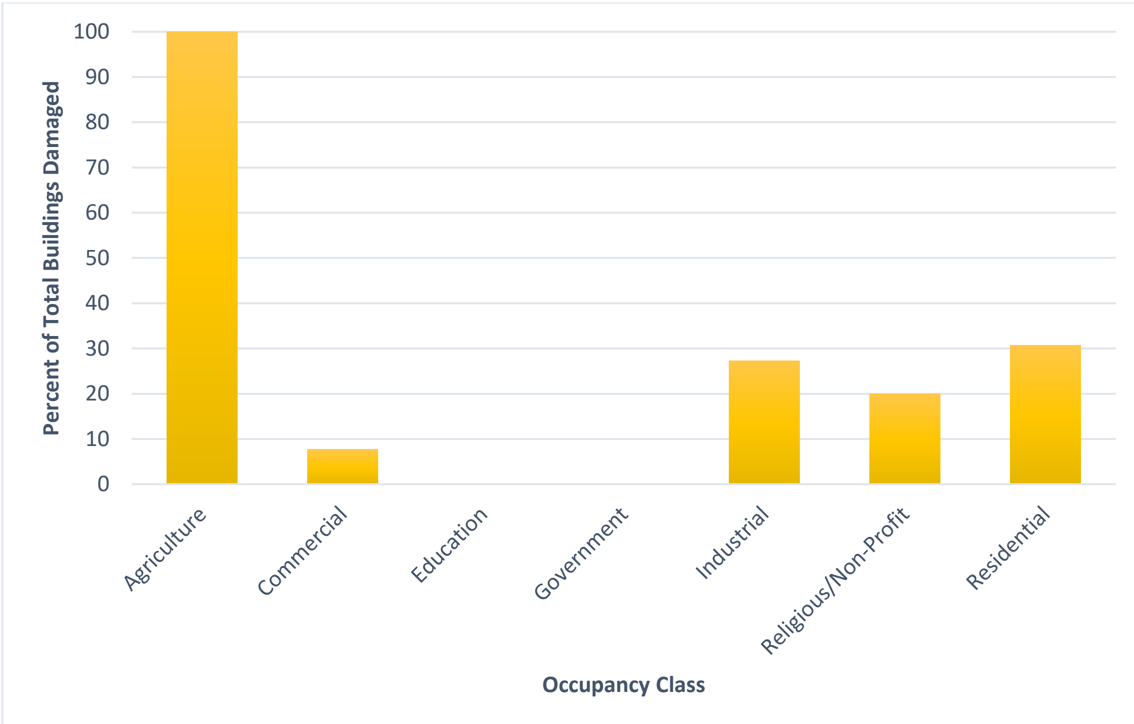

Figure 31: Building damage due to flooding by occupancy class

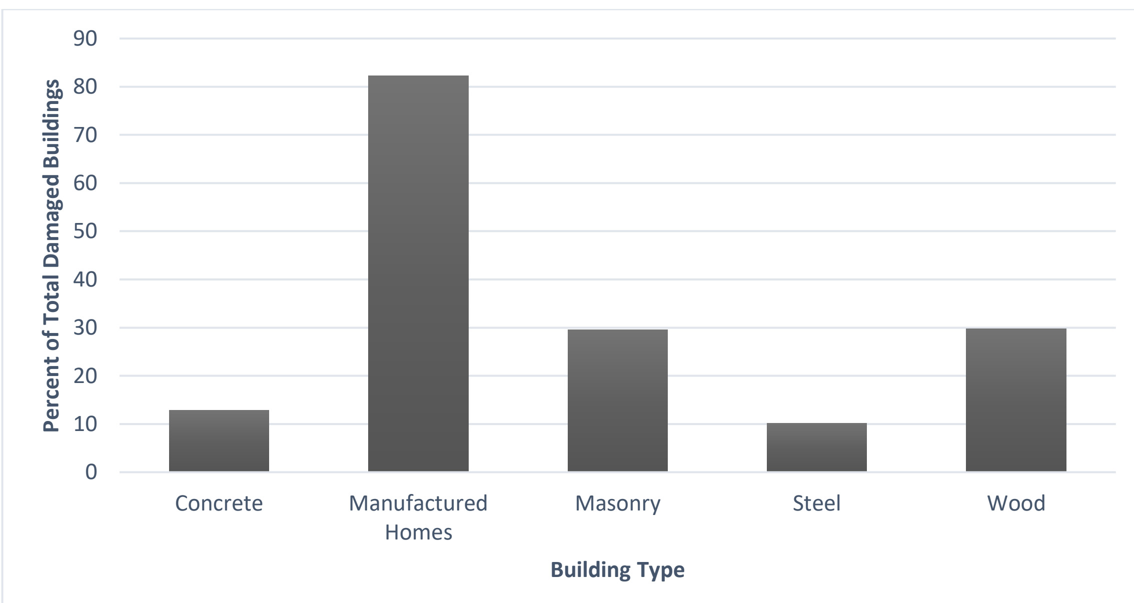

Figure 32: Building damage due to flooding by building type

6.12 Economic Losses on Building Damage

Unlike in Chapter V, the values from the HAZUS-MH Flood Model are estimated as the actual dollar amount; not in terms of thousands of dollars.

6.12.1 Direct Economic Loss

The following tables show the direct economic losses that can occur from a 200-year flood in Harris County for the seven occupancy classes and five building types, which correspond to all census blocks within the riverine and coastal floodplains.

6.12.1.1 By Occupancy

Class	Total	Building	Content	Inventory	Relocation	Income	Rental	Wage
AGR	19,818	4,871	9,475	1,481	696	2,406	8	881
COM	3,107,867	435,323	871,042	21,094	215,154	751,983	156,944	656,327
EDU	205,475	21,448	56,573	0	12,280	33,982	921	80,271
GOV	492,618	9,517	39,973	0	10,531	4,929	3,260	424,408
IND	416,472	103,028	238,381	40,306	8,724	11,207	1,971	12,855
REL	341,764	41,285	130,902	0	22,480	43,221	2,298	101,578
RES	6,083,338	3,256243	1,934,748	0	582,695	9,859	276,591	23,202

Table 15: Direct Economic Losses by Occupancy Class for 200-Year Return Period Flood

The losses that occur from a 200-year flood in Harris County can result in over $10 million in damages (Table 15). Since most buildings in this area are either residential or commercial, they experience the highest economic losses of all the occupancy classes. The building replacement costs were lower than expected and, except for residential structures, lower than the content losses.

6.12.1.2 By Building Type

Type	Total	Building	Content	Inventory	Relocation	Income	Rental	Wage
CON	667,200	106,660	231,000	10,500	30,400	90,200	19,900	178,600
MH	34,192	18,531	9,014	0	5,788	0	859	0
MAS	2,353,939	639,653	694,947	14,373	159,158	270,572	101,666	473,570
STE	1,347,923	190,376	413,806	26,137	76,579	245,224	49,760	346,041
WOO	6,203,358	2,906,319	1,920,688	7,661	572,776	241,379	263,973	290,562

Table 16: Direct Economic Losses by Occupancy Class for 200-Year Return Period Flood

Wooden structures have the most loss in this scenario, with damage costs exceeding $6 million, because they have the highest county of buildings within the floodplains (Table 16). Building replacement costs and content losses for the buildings made of masonry are also particularly high. Inventory losses for all building types were lower than expected.

6.12.2 Output and Employment

6.12.2.1 Employment Loss

The HAZUS-MH Flood Model outputs the estimated employment loss in terms of thousands of days. There were no significant employment losses in Harris County from a 200-year flood scenario.

6.12.2.2 Output Losses

Commercial structures had the most output loss, which is to be expected because that occupancy class had the most employment out of these categories (Figure 33).

Education buildings also had over $600,000 in output loss, making it the second highest loss for this scenario.

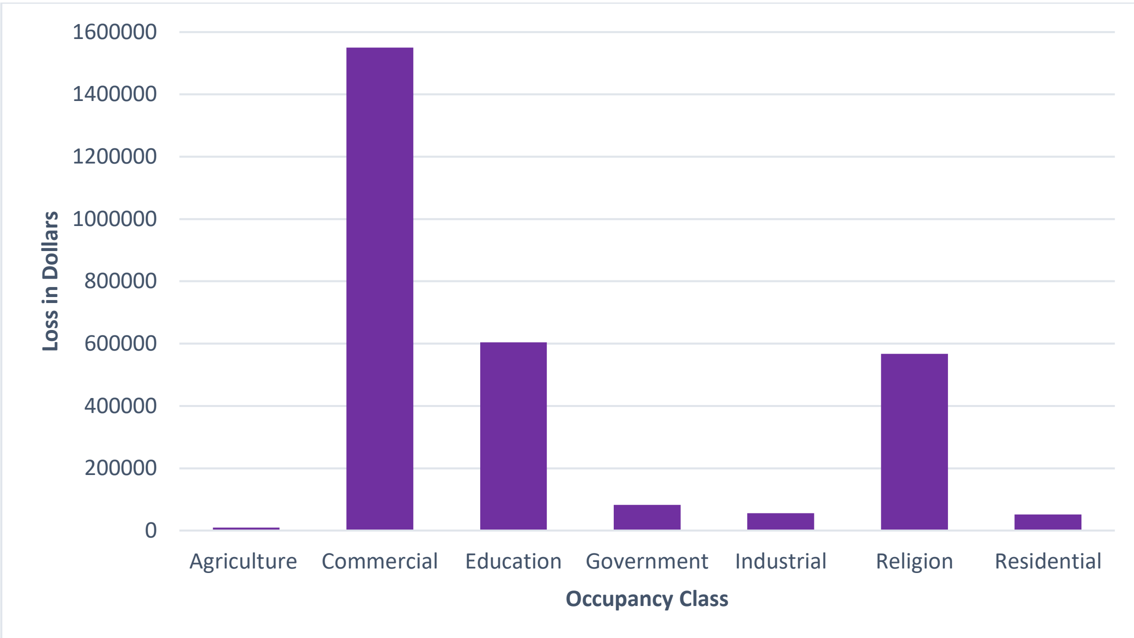

Figure 33: Output losses for 200-year return period flood

6.13 Essential Facilities

Medical care facilities, fire stations, police stations, emergency response centers, and schools are all considered to be essential facilities (Figure 34). All the essential facilities affected by the flood are also located within the floodplain. Most of the facilities that were damaged in this scenario are in the southeast corner of the study area, where both riverine and coastal floodplains are located, near the Houston Ship Channel. Outside of that area, the locations of essential facilities are isolated in different areas of Harris County.

6.14 Transportation Systems

The transportation systems that are affected by the 200-year flood in this scenario only include the highway bridges (Figure 35). The affected bridges in Harris County are mostly scattered evenly throughout the area. However, there are some bridges in the southeast corner of the county that are grouped together that are affected by both river and coastal flooding.

6.15 Utility Systems

Only two potable water facilities are affected by the flooding from the 200-year flood scenario in Harris County (Figure 36). Both locations are near the coastlines of the county, making them vulnerable to flooding more frequently. Though these specific potable water facilities receive notable damage, the other utility facilities in the county are not affected by the riverine or coastal flooding.

6.16 Debris Analysis

The debris that the HAZUS-MH Flood Model analyzes is separated into three categories: building finish, structural, and foundation; it is estimated as the expected weight of each debris type in tons (Figure 37). Building finish produced the highest amount of debris in the floodwaters, with the total estimated to be approximately 250,000 tons. The foundation and structural debris are much lower than the finish debris and are estimated to weigh around 165,000 tons.

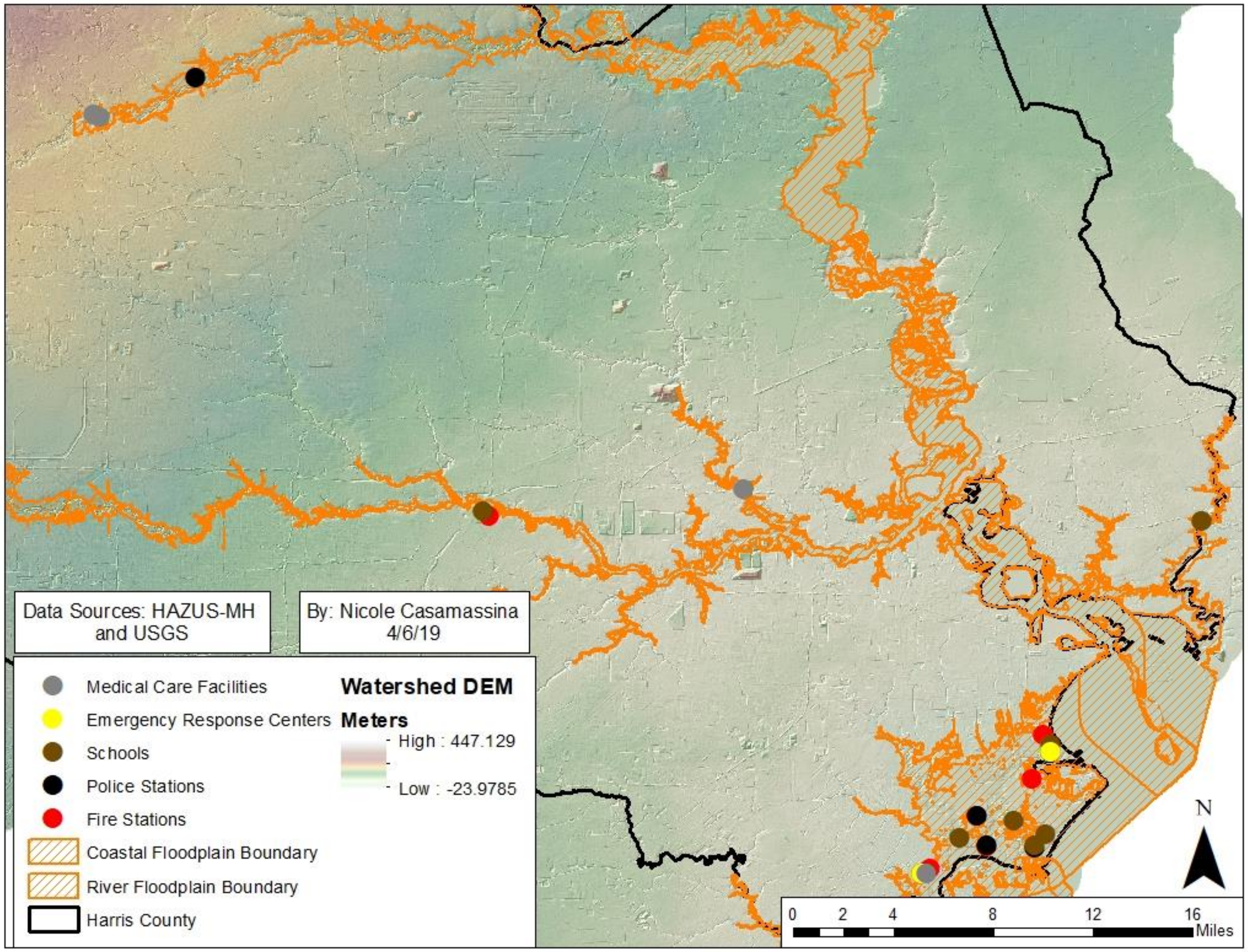

Figure 34: Locations of essential facilities in Harris County affected by a 200-year return period flood

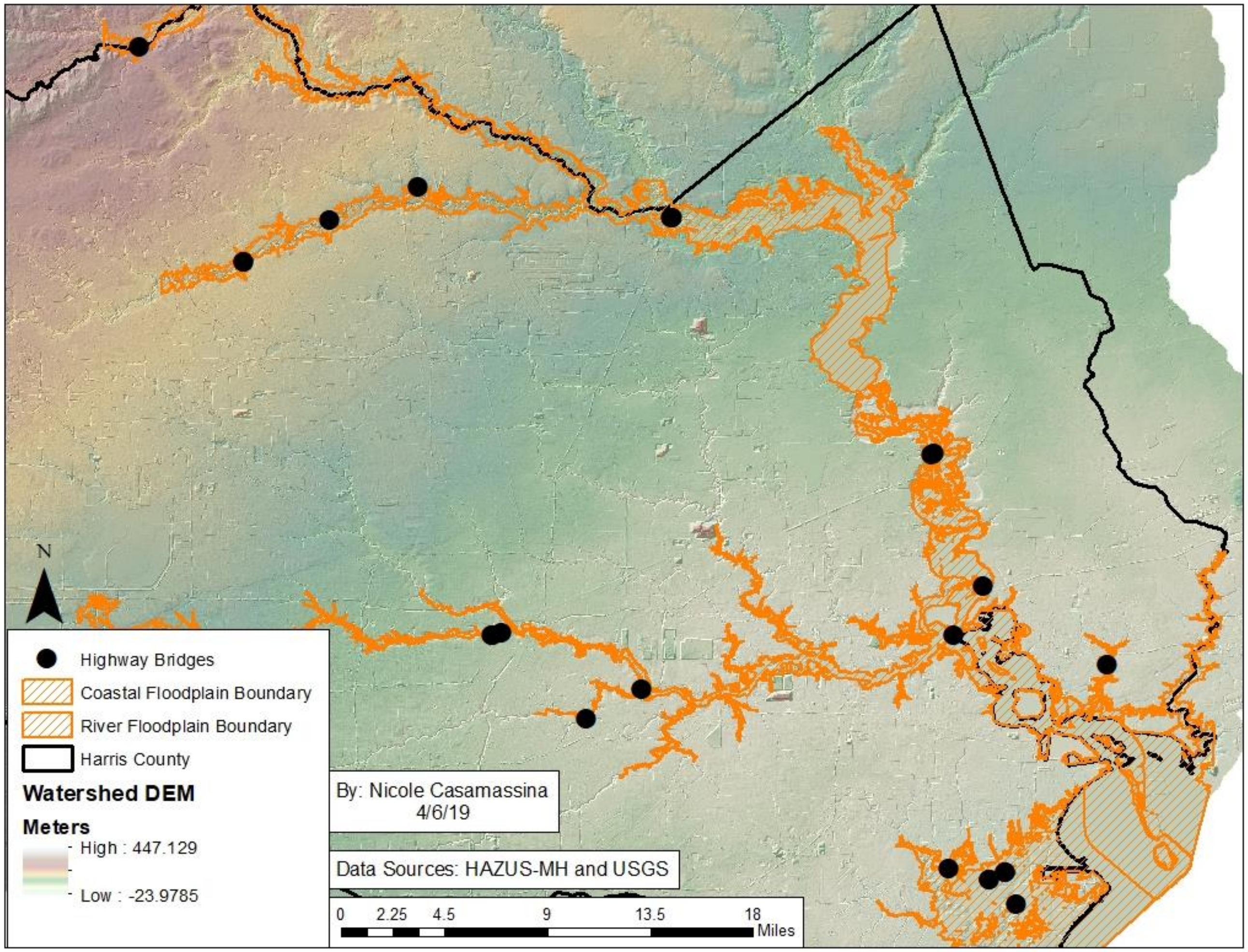

Figure 35: Locations of transportation facilities in Harris County affected by a 200-year return period flood

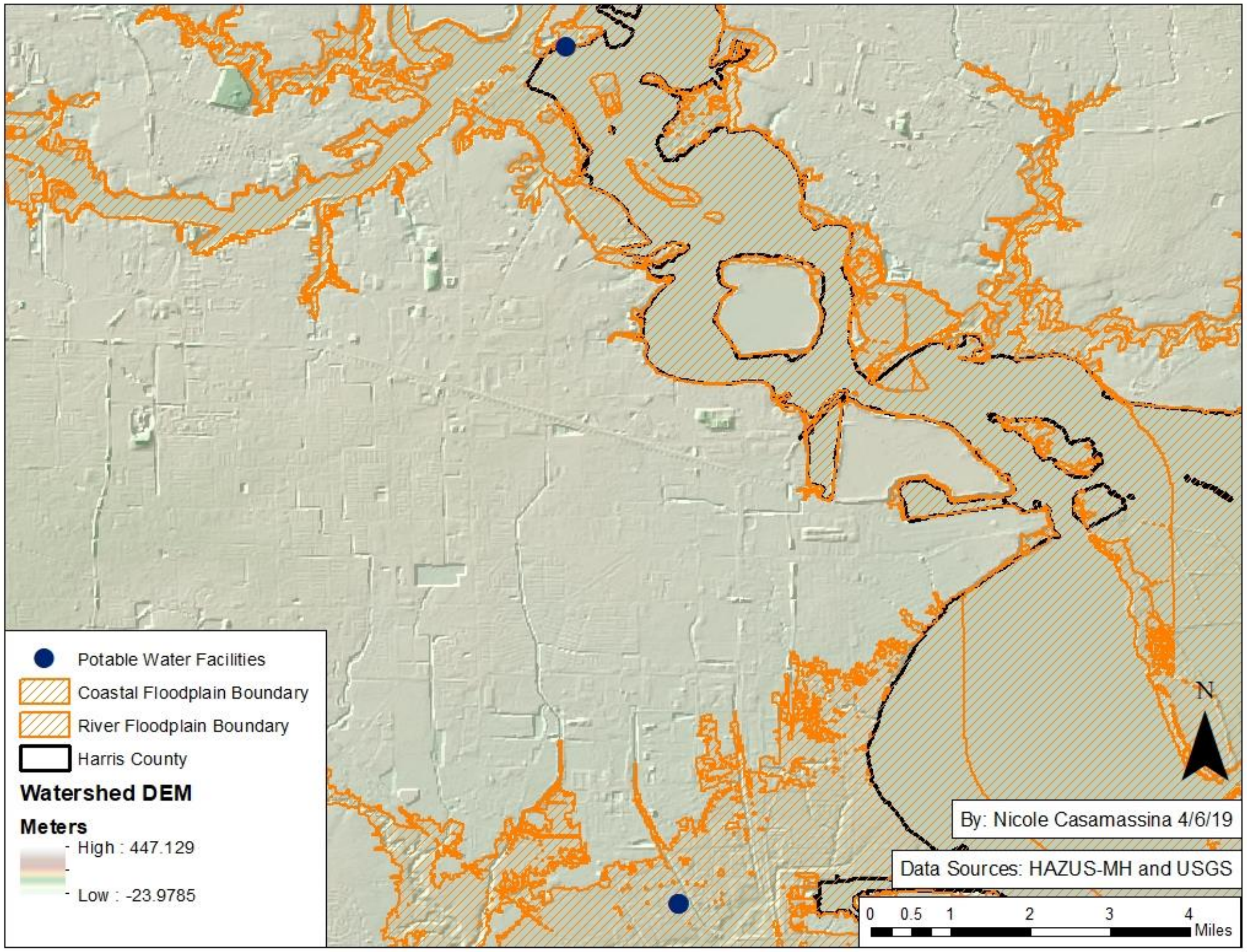

Figure 36: Locations of utility facilities in Harris County affected by a 200-year return period flood

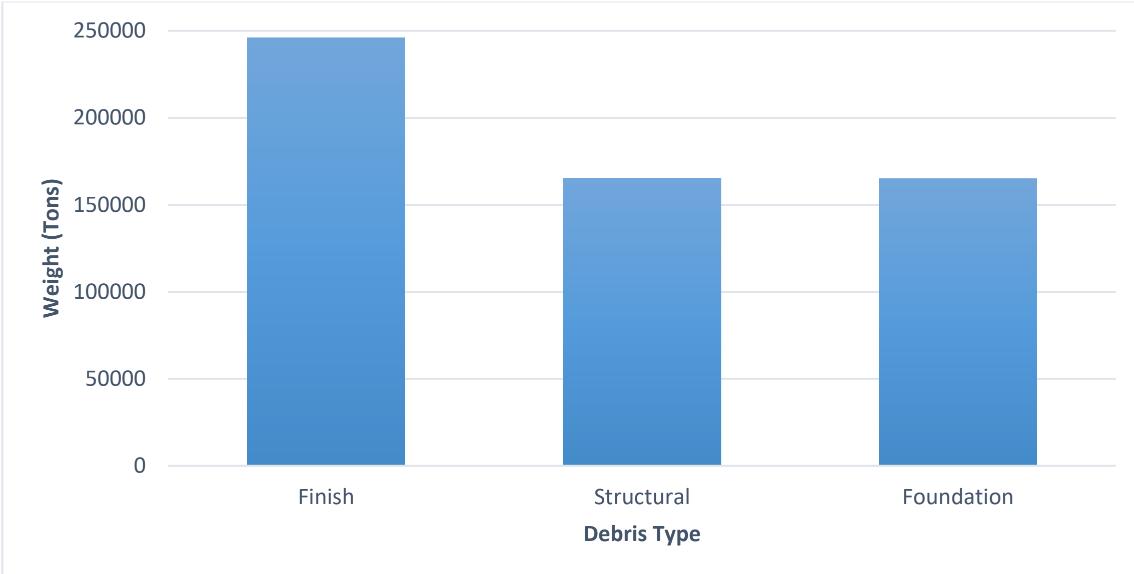

Figure 37: Weight of debris from a 200-year return period flood

6.17 Shelter Analysis

6.17.1 Displaced Population and Short-Term Shelter Needs

The displaced population due to a 200-year flood is approximately 84,000 people with the need for about 5,800 short-term shelters throughout Harris County. However, this data is based on the 2010 U.S. Census, so it may not reflect what would be needed for a present-day storm. This displaced population is also small in percentage in comparison to the entire county, which was around 4 million in 2010 (*Houston city, Texas* 2019). Nonetheless, almost 100,000 people displaced is significant and would still need to be addressed with urgency in the wake of a flood.

6.18 Discussion

The results from the Hurricane Harvey simulation from the HAZUS-MH Hurricane Wind Model and the results from the 200-year probabilistic riverine and coastal flooding from the HAZUS-MH Flood Model representing the conditions of the flooding caused by the hurricane show that this storm caused immense losses and billions of dollars in damages. Based on the results from Hurricane Wind Model, the damage was not from the winds, but rather from precipitation and the resulting flooding in the Greater Houston Region, particularly for Harris County. However, the losses that come from the buildings in the floodplain were not as high as expected, given what is known about the flooding of Hurricane Harvey.

There were no significantly damaged manufactured homes reported in the results of the HAZUS-MH Hurricane Wind Model. However, there were some losses associated with the minor damages to those structures; they were small and estimated to be $2,370. In the storm surge analysis, it was noted that the commercial and industrial buildings had high economic losses, while the educational and governmental buildings had much lower damage costs. This is most likely because the latter structures tend to be located more inland. Furthermore, manufactured homes are not located in the floodplains in this scenario since the losses are much lower in comparison to the other building types. With 51 ft in riverine flooding estimated for a 200-year flood, it is expected that the losses coming from the downtown Houston area will be much higher since the city was built around Buffalo Bayou and other rivers. The coastal flooding in Harris County is estimated to be about half of the riverine flooding at around 27 ft, but can potentially be more dangerous and devastating because of the lower elevation of the coastal area. This low and flat topography of the area can cause the floodwater to be more widespread, affecting more people and property.

Hurricane Harvey made landfall as a major hurricane well southwest of the Greater Houston Region, so the intense winds that were observed were not near this study area. The winds that were in this region were of tropical storm-strength; the buildings in this region are most likely able to withstand that force. However, it is obvious that the structures located within the riverine and/or coastal floodplains had a lot of damage from the flooding. The high floodwaters observed in Harris County were much higher than what was estimated in the HAZUS-MH Flood Model. With hundreds of thousands of tons of debris, just within Harris County, from a 200-year flood, millions of dollars of losses are expected. Not as many facilities are affected by the riverine and coastal flooding as in the results from the Hurricane Wind Model, so the losses are much less than the results from the 200-year probabilistic return period hurricane from Objective 2 of this thesis. The residential and wooden structures received the most losses in both models; results since they have the highest county of all the categories within the floodplains; this is due to more building homes in the most vulnerable areas to flooding in Harris County. However, manufactured homes are not typically located in the floodplain or just did not receive as much damage in this scenario. These data may be out of date, due to there not being any available updates with more recent data in Objective 1, therefore the losses from Hurricane Harvey were likely much larger. It is clear the flooding mitigation strategies in the study area should be changes to reduce the damages and resulting losses that can come from a storm such as Hurricane Harvey.

CHAPTER VII

CONCLUSION

7.1 Summary

In this study, the physical, economic, and social losses than can occur from probabilistic hurricane scenarios and Hurricane Harvey were analyzed from the Greater Houston Region in southeast Texas using FEMA's HAZUS-MH Model. In Objective 1, most databases included the model were replaced with available updated information from government sources to provide the most up-to-date estimates possible. This was necessary because much of the included HAZUS-MH data were collected between 1999 and 2001 and would not truly represent the losses that could occur from a hurricane in recent years. The essential facilities, high potential loss facilities, transportation systems, and utility systems were updated as part of this objective. Though there were no direct results from Objective 1 of this thesis, this comprehensive effort led to the results from Objectives 2 and 3 producing losses that were more representative of the current structure and environmental conditions of the Greater Houston Region.

Objective 2 sought to find which areas of the Greater Houston Region were the most vulnerable to the three hazards associated with tropical cyclones: high winds, extreme precipitation, and storm surge. The winds and precipitation were analyzed using the HAZUS-MH Hurricane Wind Model. The probabilistic mode was used to determine the probable storm tracks of the 10, 200, and 1000-year return periods to compare the most and less frequent hurricanes, as well as the strength of the storm that is most like the strength of Hurricane Harvey. The results of this objective showed the losses dramatically increased as the return period of the storm also increased. Furthermore, the residential and wood buildings received the most damage of all structure types in all three scenarios, meaning that more people and property, and fewer businesses, would be greatly affected by the winds of a tropical cyclone in the study area (Figures 38 and 39). The effects of storm surge were found using a combination of the HAZUS-MH Hurricane Wind and Flood Models for Hurricane Ike in Galveston County, Texas; only the direct economic losses were able to be produced. Residential and wood buildings again had the highest losses from this hurricane hazard, but the structures made of masonry also had losses estimated to be in the millions of dollars. The areas of the Greater Houston Region that are most vulnerable to the effects of hurricanes depend on the storm track and the proximity to the coast. The western part of Chambers County that shares its boundary with Galveston Bay, for example, has high losses in the 200-year return period scenario because it experiences the coastal effects of the storm, as well as the closeness to the storm track, meaning higher winds. Since higher winds are closer to the center of the storm, and therefore the storm track, those census blocks that are intersect or are near the storm track experience the most losses.

In the final objective of this thesis, the HAZUS-MH Hurricane Wind Model was run with a historical Hurricane Harvey. Though this model accounts for winds, precipitation, and size of storm, as well as many other attributes of a hurricane, the results of this model show that, in general, winds would produce a lot of damage, but this turned out to not be an issue with Harvey in the Greater Houston Region. The

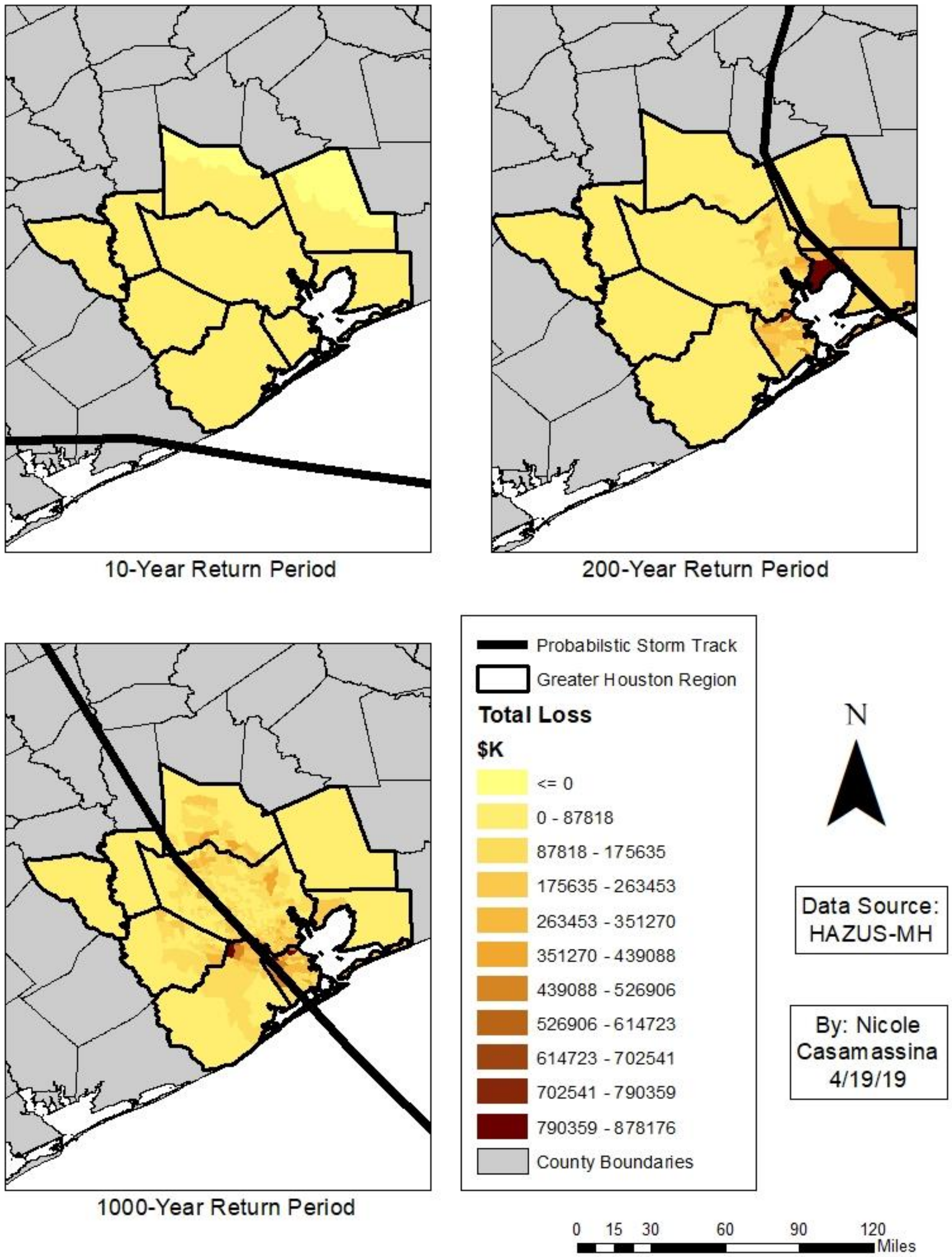

Figure 38: Total economic losses for residential buildings

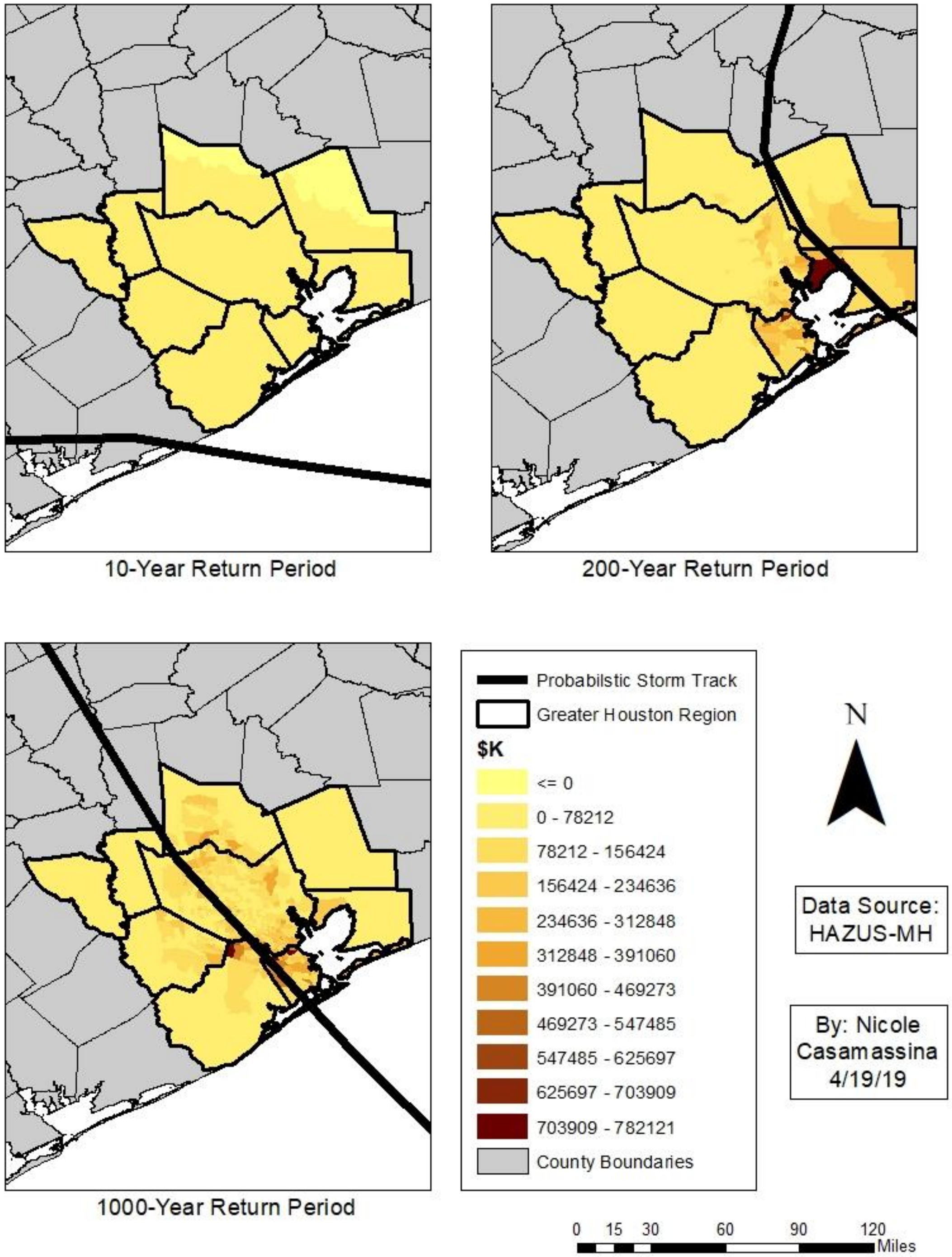

Figure 39: Total economic losses for wood buildings

results of the storm surge analysis for this hurricane in Galveston County show that the residential and wood buildings had the highest losses, but this hazard in a hurricane was not nearly as devastating as the surge from Hurricane Ike; the estimated losses were about half of what was estimated for Ike. Since the results from the hurricane and surge analysis did not give a true insight to the losses that were observed in Hurricane Harvey, the HAZUS-MH Flood Model was then also run for Harris County to get a clearer picture of the effects of flooding from this unique hurricane. Both riverine and coastal analyses were run to determine which areas of Harris County would be most affected by a 200-year flood. Based on this, it was determined that that southeast section of the county near the Houston Ship Channel is most vulnerable to both types of flooding due to the widespread coastal flooding that occurs in a 200-year flood, as well as the high flooding from the rivers. The economic losses that resulted from the flooding were more in line to what was observed during Hurricane Harvey. Residential and wooden structures had the most losses of all the building types, but manufactured homes also had surprisingly high losses from the flooding, as well.

7.2 Implications

The results of this study have various implications for other areas of the U.S. Though there is debate on exactly how climate change will affect hurricanes, there is agreement that tropical cyclones are expected to be able to produce more precipitation, though hurricanes will most likely occur less frequently and have stronger winds (Knutson et al. 2010; Knutson et al. 2013; Knutson, Sirutis, and Zhao 2015; Wright, Knutson, and Smith 2015). Hurricanes affect Texas about once every 2-3 years, but some of the most recent notable storm, such as Hurricane Ike and Hurricane Harvey, have made a lasting impact on the people of the Greater Houston Region. However, there has been an increase in development in this area of the county, making people more vulnerable to hurricane damages from wind, rainfall, and storm surge than before (Dixon and Fitzsimons 2001). Hurricane preparedness officials fear that the general public will think that large loss of life and property will diminish in future tropical cyclone events because of advanced technology and improved forecasting (Blake, Landsea, and Gibney 2011). Yet, NOAA directors and other prominent meteorologists and climatologists have stressed the importance of proper hurricane preparedness plans to be formulated, maintained, and executed in the most vulnerable areas of the U.S. so that losses can be reduced in the future (Blake, Landsea, and Gibney 2011).

The methodology used in this thesis can be applied to other areas of the U.S. and to other hurricanes for comparison. Applying the HAZUS-MH Flood Model to supplement the results of the Hurricane Wind Model can also help to understand the combined effects of hurricanes that produce more flooding effects than wind damages. Because climate change is expected to affect hurricanes, particularly with the increase in precipitation, it is important to understand all implications of hurricanes, not just the winds.

The results of this study can benefit federal, state, and local governments and organizations in understanding the significance of the damages created by a unique tropical cyclone, such as Hurricane Harvey. Recent hurricanes have caused record-setting precipitation, flooding and storm surge, and loss of homes throughout the Greater Houston Region and southeast Texas, so coordinate at all levels of government were necessary to ensure that the hazard mitigation, emergency preparedness strategies, emergency response, and the disaster recovery were as efficient as possible. For example, before Harvey made landfall, FEMA sent supplies and personnel to join the Texas Division of Emergency Management and other local agencies to respond to the devastation (FEMA 2017b). In the immediate aftermath of the hurricane, FEMA distributed $1.5 billion in federal funds, which included assistance grants, low-interest disaster loans, and flood insurance advance payments (FEMA 2017b). In the months after Harvey, FEMA conducted an after-action report to evaluate their response to the entire 2017 North Atlantic Hurricane Season and have taken the recommendations of improvement, such as supporting states in building a greater capacity to respond to and recover from disasters by maintaining financial support while correctly sizing the federal deployment footprint, and implemented them into their future strategic plans (FEMA 2018a). Having knowledge of how a hurricane can affect a certain area can provide the general public and decision makers with the necessary information to maintain and increase preparedness at all levels (Demuth et al. 2012). This can also lead to the effects of the three hazards of hurricanes being lessened (Demuth et al. 2012). Furthermore, understanding how climate change might affect hurricanes in the future and their possible effects to the environment can play a role in protecting lives and property (Demuth et al. 2012).

7.3 Limitations

One of the limitations of this study is the use of a model to estimate losses. The most apparent examples of this are the results from the HAZUS-MH Hurricane Wind Model's simulation of Hurricane Harvey for the Greater Houston Region. Although the hurricane model accounts for a myriad of hurricane features, such as rainfall rate, it did not correctly evaluate the damages that Harvey caused on the study area in terms of the flooding from by the immense precipitation. In turn, the HAZUS-MH Flood Model was run to represent that hazard. Future research utilizing this methodology will have to keep in mind that the HAZUS-MH Hurricane Wind Model is best suited for hurricanes whose winds were the biggest drivers of losses; the flood model may have to be used in order to estimate the total losses.

Another limitation was the data used in Objective 1 of this thesis. The data found from the various federal departments and organizations had to be manipulated for successful inclusion in the model. In some cases, the only the only publicly available data did not include all the necessary components for a full analysis for some facilities. For example, the data associated with highway bridges did not include a record of the year built or remodeled for all the highways in the Greater Houston Region; understanding the age and materials used to build a structure can help to estimate its vulnerability to hurricane-strength winds and floods. More comprehensive data with all the necessary attributes would be needed in future research using any of the models included in HAZUS-MH.

Statistical significance was also not able to be calculated because HAZUS-MH produced the same results every time it was run with the considered parameters in both the Hurricane Wind Model and the Flood Model. However, testing of the models and statistical analyses were performed during the development stages and can be found in the technical manuals of the models.

The Greater Houston Region in southeast Texas is an area in the U.S. that is vulnerable to tropical cyclone impacts. The effects of climate change on hurricanes were evident when Hurricane Harvey produced record-setting rainfall in this area. Though hurricane and flood models, such as those included in HAZUS-MH, can estimate the physical, economic, and social losses associated with storms such as Harvey, some caution must be taken get a clear picture of the potential impacts of future storms. Regardless, the population of this area is at risk for tropical cyclone impact, which will continue to increase if actions far beyond the current efforts are not taken to mitigate these hazards.

REFERENCES

About Houston: Facts and Figures. 2019. City of Houston 2019 [cited 2019].

Aghababei, M., M. Koliou, and S. G. Paal. 2018. Performance Assessment of Building Infrastructure Impacted by the 2017 Hurricane Harvey in the Port Aransas Region. *Journal of Performance on Constructed Facilities* 32 (5).

Andrews, B. D., P. A. Gares, and J. D. Colby. 2002. Techniques for GIS modeling of coastal dunes. *Geomorphology* 48 (1-3).

Atoba, K. O., S. D. Brody, W. E. Highfield, and W. J. Merrell. 2018. Estimating Residential Property Loss Reduction from a Proposed Coastal Barrier System in the Houston-Galveston Region. *Natural Hazards Review* 19 (3).

Beckmann, H., and D. M. Simpson. 2006. Risk assessment and GIS in natural hazards: issues in the application of HAZUS. *International Journal of Risk Assessment and Management* 6 (4):408-422.

Bender, M. A., T. R. Knutson, R. E. Tuleya, J. J. Sirutis, G. A. Vecchi, S. T. Garner, and I. M. Held. 2010. Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. *Science* 327:454-458.

Bertinelli, L., P. Mohan, and E. Strobl. 2016. Hurricane damage risk assessment in the Caribbean: An analysis using synthetic hurricane events and nightlight imagery. *Ecological Economics* 124:135-144.

Bilskie, M. V., and S. C. Hagen. 2018. Defining Flood Zone Transitions in Low-Gradient Coastal Regions. *Geophysical Research Letters* 45 (6):2761-2770.

Blake, E. S., C. W. Landsea, and E. J. Gibney. 2011. The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2010 (And Other Frequently Requested Hurricane Facts), ed. Commerce. Miami, Florida: NOAA.

Blake, E. S., and D. A. Zelinsky. 2018. Tropical Cyclone Report: Hurricane Harvey: National Hurricane Center.

Blankenship, R. 2009. Hospitals Get a Jolt of Reality with HAZUS-MH Earthquake Analysis Results. *Esri Healthy GIS Newsletter*.

Burton, C. G. 2010. Social Vulnerability and Hurricane Impact Modeling. *Natural Hazards Review* 11 (2):58-68.

Carr, J. T. 1967. Hurricanes Affecting The Texas Gulf Coast. Austin, TX: Texas Water Development Board.

Chen, V., D. Banerjee, and L. Liu. 2012. Do People Become Better Prepared in the Aftermath of a Natural Disaster? The Hurricane Ike Experience in Houston, Texas. *Journal of Public Health Management and Practice* 18 (3):241-249.

Chen, X., X. Zhang, J. A. Chruch, C. S. Watson, M. A. King, D. Monselesan, B. Legresy, and C. Harig. 2017. The increasing rate of global mean sea-level rise during 1993-2014. *Nature Climate Change* 7:492-495.

Climate of Texas. 2012. In *Water For Texas 2012 State Water Plan*, 144-155. Austin, TX: Texas Water Development Board.

Colby, J. D., K. A. Mulcahy, and Y. Wang. 2000. Modeling flooding extent from Hurricane Floyd in the coastal plains of North Carolina. *Global Environmental Change Part B: Environmental Hazards* 2 (4):157-168.

Demuth, J. L., R. E. Morss, B. H. Morrow, and J. K. Lazo. 2012. Creation and Communication of Hurricane Risk Information. *Bulletin of the American Meteorological Society* 93:1133-1145.

Dixon, R. W., and D. E. Fitzsimons. 2001. Toward a Quantified Hurricane Vulnerability Assessment for Texas Coastal Counties. *Texas Journal of Science* 53 (4):345-352.

DOL. 2019. *Inflation and Consumer Spending: Inflation Calculator* 2019 [cited 2019].

Elsner, J. B., and B. Kara. 1999. *Hurricanes of the North Atlantic: Climate and Society*: Oxford Universiy Press.

Emanuel, K. 2017. Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Sciences of the United States of America* 114 (48):12681-12684.

Emanuel, K., and T. Jagger. 2010. On Estimating Hurricane Return Periods. *Journal of Applied Meteorology and Climatology* 49:837-844.

Emanuel, K. A. 2005. *Divine Wind: The history and science of hurricanes*. New York, New York: Oxford University Press.

FEMA. Flood Model Hazus-MH Technical Manual, ed. H. Security. Washington, D.C.

———. HAZUS-MH 2.1 Technical Manual, ed. H. Security, 1-59. Washington D.C.

———. 2007. Design Guide for Improving Critical Facility Safety from Flooding and High Winds: Providing Protection to People and Buildings, ed. H. Security: FEMA.
———. 2013. Emergency Support Function #1 - Transportation, ed. H. Security, 6.
———. 2017a. Flood Insurance Study Harris County, Texas and Incorporated Areas, ed. H. Security.
———. 2017b. Historic Disaster Response to Hurricane Harvey in Texas.
———. 2018a. 2017 Hurricane Season FEMA After-Action Report, ed. H. Security.
———. 2018b. Hazus 4.2 SP1 User Release Notes, ed. H. Security, 13.
———. 2018c. Hazus Flood Model User Guidance, ed. H. Security: FEMA.
———. 2018d. Hazus Hurricane Model User Guidance, ed. H. Security.
———. 2019a. Comprehensive Data Management System (CDMS) Data Dictionary For Use with Hazus-MH Version 2.1, ed. H. Security, 115. Washington, D.C.: Federal Emergency Management Agency Mitigation Division.
———. 2019. *Introduction to Hazard Mitigation* 2019b [cited 2019].
———. 2019. *Summary of Databases in Hazus*. Deartment of Homeland Security, August 28, 2018 2019c [cited March 5, 2019 2019].

GFDL. *Global Warming and Hurricanes: An Overview of Current Research Results*. NOAA, September 20, 2018 2018a [cited.
———. 2018. *Historical Changes in Atlantic Hurricane and Tropical Storms*. NOAA 2018b [cited 2018].

Houston city, Texas. 2019. United States Census Bureau 2019 [cited 2019].

HURREVAC. *HURREVAC* 2019 [cited.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 151. Geneva, Switzerland: IPCC.

Islam, T., W. Merrel, W. Seitz, and R. Harriss. 2009. Origin, Distribution, and Timing of Texas Hurricanes: 1851-2006. *Natural Hazards Review* 10 (4):136-144.

Jaiswal, K., D. Bausch, J. Rozelle, J. Holub, and S. McGowan. 2017. Hazus Estimated Annualized Earthquake Losses for the United States, 78: Federal Emergency Management Agency.

Jarvinen, B. R., C. J. Neumann, and M. A. S. Davis. 1984. A tropical cyclone data tape for the North Atlantic Basin, 1886-1983: Contents, limitations and uses. *NOAA Technical Memo* NWS NHC 22.

Jonkman, S. N., M. Godfroy, A. Sebastian, and B. Kolen. 2018. Brief communication: Loss of life due to Hurricane Harvey. *Natural Hazards and Earth System Sciences* 18:1073-1078.

Kashem, S. B., B. Wilson, and S. V. Zandt. 2016. Planning for Climate Adaptation: Evaluating the Changing Patterns of Social Vulnerability and Adaptation Challenges in Three Coastal Cities. *Journal of Planning Education and Research* 36 (3):304-318.

Katehis, S. 2015. Validating the HAZUS Coastal Surge Model for Superstorm Sandy, Geographic Information Science and Technology, University of Southern California.

Keim, B. D., R. A. Muller, and G. W. Stone. 2006. Spatiotemporal Patterns and Return Periods of Tropical Storm and Hurricne Strikes from Texas to Maine. *Journal of Climate* 20:3498-3509.

Kilma, K., N. Lin, K. Emanuel, M. G. Morgan, and I. Grossman. 2012. Hurricane Modification and Adaptation in Miami-Dade County, Florida. *Environmental Science & Technology* 46 (2):636-642.

Klotzbach, P. J., S. G. Bowen, R. Pielke, and M. Bell. 2018. Continental U.S. Hurricane Landfall Frequency and Associated Damage: Observations and Future Risks. *Bulletin of the American Meteorological Society* 99:1359-1377.

Knight, D. B., and R. E. Davis. 2007. Climatology of tropical cyclone rainfall in the southeastern United States. *Physical Geography* 28 (2):126-147.
———. 2009. Contribution of tropical cyclones to extreme rainfall events in the southeastern United States. *Journal of Geophysical Research: Atmospheres* 114 (23).

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Augi. 2010. Tropical cyclones and climate change. *Nature Geoscience* 3:157-163.

Knutson, T. R., J. J. Sirutis, S. T. Garner, G. A. Vecchi, and I. M. Held. 2008. Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions. *Nature Geoscience* 1:359-364.

Knutson, T. R., J. J. Sirutis, G. A. Vecchi, S. Garner, M. Zhao, H.-S. Kim, M. Bender, R. E. Tuleya, I. M. Held, and G. Villarini. 2013. Dynamical Downscaling Projections of Twenty-First-Century Atlantic Hurricane Activity: CMIP3 and CMIP5 Model-Based Scenarios. *Journal of Climate* 26:6591-6617.

Knutson, T. R., J. J. Sirutis, and M. Zhao. 2015. Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios. *Journal of Climate* 28:7203-7224.

Knutson, T. R., and R. E. Tuleya. 2004. Impact of CO2-Induced Warming on Simulated Hurricane Intensity and Precipitation: Sensitivity to the Choice of Climate Model and Convective Parameterization. *Journal of Climate* 17 (3477-3495).

Kraus, N. C., and L. Lin. 2009. Hurricane Ike along the upper Texas coast: An introduction. *Shore and Beach* 77 (1):3-8.

Landsea, C., J. Franklin, and J. Beven. 2015. The Revised Atlantic Hurricane Database (HURDAT2), ed. N. H. Center. Miami, FL, USA.

Landsea, C. W., G. A. Vecchi, L. Bengtsson, and T. R. Knutson. 2010. Impact of Duration Thresholds on Atlantic Tropical Cyclone Counts. *Journal of Climate* 23:2508-2519.

Lindsey, R. 2018. Climate Change: Global Sea Level. *ClimateWatch Magazine*.

McAdie, C. J., C. W. Landsea, C. J. Neumann, J. E. David, E. S. Blake, and G. R. Hammer. 2009. Tropical Cyclones of the North Atlantic Ocean, 1851-2006 (with 2007 and 2008 track maps included), ed. N. C. D. Center, 238. Asheville, North Carolina: NOAA.

Mickey, K. 2004. An Overview of HAZUS - Multi-Hazard: FEMA's GIS-Based, Multi-hazard Risk Assessment Program for Analyzing Potential Losses. In *Mid - Atlantic Regional Workshop for Historically Black Colleges and Universities (HBCUs) and Local Communities: Partnering through Emergency Management and Mitigation*. Indianapolis, Indiana.

Montgomery, M. T., and B. F. Farrell. 1993. Tropical Cyclone Formation. *Journal of Atmospheric Sciences* 50:285-310.

NHC. 2019. *Hurricanes in History*. National Hurricane Center 2019a [cited 2019].
———. 2019. *Storm Surge Overview*. NOAA 2019b [cited 2019].

NIST. 2016. Critical Assessment of Lifeline System Performance: Understanding Society Needs in Disaster Recovery, ed. Commerce. Redwood City, CA: National Institute of Standards and Technology Engineering Laboratory.

NOAA. 2019. *NOAA/NOS/CO-OPS Observed Water Levels at 8771450, Galveston Pier 21 TX From 2008/09/09 00:00 GMT to 2008/09/15 23:59 GMT* 2008 [cited 2019]. Available from https://tidesandcurrents.noaa.gov/waterlevels.html?id=8771450&units=standard&bdate=20080909&edate=20080915&timezone=GMT&datum=NAVD&interval=6&action=.

———. 2019. *NOAA/NOS/CO-OPS Observed Water Levels at 8771450, Galveston Pier 21 TX From 2017/08/22 00:00 GMT to 2017/08/28 2017 23:59 GMT* 2017 [cited 2019]. Available from https://tidesandcurrents.noaa.gov/waterlevels.html?id=8771450&units=standard&bdate=20170822&edate=20170828&timezone=GMT&datum=NAVD&interval=6&action=.

———. 2019. *Hurricane Costs*. NOAA Office For Coastal Management 2019 [cited 2019].

Oldenborgh, G. J. v., K. v. d. Wiel, A. Sebastian, R. Singh, J. Arrighi, F. Otto, K. Haustein, S. Li, G. Vecchi, and H. Cullen. 2017. Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters* 12.

Padgett, J. E., B. G. Nielson, and R. DesRoches. 2008. Selection of optimal intensity measures in probabilistic seismic deman models of highway bridge portfolios. *Earthquake Engineering & Structural Dynamics* 37 (5):711-725.

Pan, Q. 2015. Estimating the Economic Losses of Hurricane Ike in the Greater Houston Region. *Natural Hazards Review* 16 (1).

Pan, Y., C. Yan, and C. L. Archer. 2018. Precipitation reduction during Hurricane Harvey with simulated offshore wind farms. *Environmental Research Letters* 13 (8).

Paul, S. H., and H. O. Sharif. 2018. Analysis of Damage Caused by Hydrometeorological Disasters in Texas, 1960-2016. *Geosciences* 8 (10).

Rahmstorf, S. 2017. Rising hazard of storm-surge flooding. *Proceedings of the National Academy of Sciences of the United States of America*.

Rajsekhar, D., A. K. Mishra, and V. P. Singh. 2013. Regionalization of Drought Characteristics Using an Entropy Approach. *Journal of Hydrologic Engineering* 18:870-887.

Remo, J. W. F., and N. Pinter. 2012. Hazus-MH earthquake modeling in the central USA. *Natural Hazards* 63 (2):1055-1081.

Risser, M. D., and M. F. Wehner. 2017. Attributable Human-Induced Changes in the Likelihood and Magnitude of the Observed Extreme Precipitation during Hurricane Harvey. *Geophysical Research Letters* 44 (12):12,457-12,464.

Rodríguez, I., I. Montoya, M. J. Sánchez, and F. Carreño. 2009. Geographic Information Systems applied to Integrated Coastal Zone Management. *Geomorphology* 107 (1-2).

Roth, D. 2010. Texas Hurricane History, ed. N. W. Service. Camp Springs, MD.

Saffir, H. S. 1973. Hurricane Wind and Storm Surge. *The Military Engineer* 65 (423):4-5.

Scawthorn, C., N. Blais, H. Seligson, E. Tate, E. Mifflin, W. Thomas, J. Murphy, and C. Jones. 2006. HAZUS-MH Flood Loss Estimation Methodology. I: Overview and Flood Hazard Characterization. *Natural Hazards Review* 7 (2):60-71.

Scawthorn, C., P. Flores, N. Blais, H. Seligson, E. Tate, S. Chang, E. Mifflin, W. Thomas, J. Murphy, C. Jones, and M. Lawrence. 2006. HAZUS-MH Flood Loss Estimation Methodology. II. Damage and Loss Assessment. *Natural Hazards Review* 7 (2):72-81.

Scheitlin, K. N., J. B. Elsner, S. W. Lewers, J. C. Malmstadt, and T. H. Jagger. 2011. Risk assessment of hurricane winds for Eglin air force base in northwestern Florida, USA. *Theoretical and Applied Climatology* 105 (3-4):287-296.

Schiller, A. R. 2011. The impact of a storm surge on business establishments in Houston MSA. *Natural Hazards* 56:331-346.

Schmidtlein, M. C., J. M. Shafer, M. Berry, and S. L. Cutter. 2011. Modeled earthquake losses and social vulmerability in Charleston, South Carolina. *Applied Geography* 31 (1):269-281.

Schneider, P. J., and B. A. Schauer. 2006. HAZUS- Its Development and Its Future. *Natural Hazards Review* 7 (2):40-44.

Schott, T., C. Landsea, G. Hafele, J. Lorens, A. Taylor, H. Thurm, B. Ward, M. Willis, and W. Zaleski. 2012. The Saffir-Simpson Hurricane Wind Scale, ed. N. H. Center: NOAA.

Schubert, C. E., R. J. Busciolano, P. P. H. Jr., A. N. Rahav, R. Behrens, J. S. Finkelstein, J. M. Jr., and A. E. Simonson. 2015. Analysis of storm-tide impacts from Hurricane Sandy in New York: USGS Scientific Investigations Report 2015-5036, 75.

Simpson, R. H. 1974. The Hurricane Disaster Potential Scale. *Weatherwise* 27 (169):169-186.

Simpson, R. H., and M. Lawrence. 1971. Atlantic hurricane frequencies along the United States Coastline, ed. Commerce, 14.

Sreetharan, M., B. Batten, and S. Lawler. 2018. Challenges and Options for Analyzing Combined Occurrences of Storm Surge and Rainfall Runoff. In *18th Annual World Environmental and Water Resources Congress of the Enivornmental-and-Water-Resources-Institute*, 520-531. Minneapolis, MN.

Subramanian, D., J. Salazar, L. Duenas-Osorio, and R. Stein. 2013. Constructing and validating geographically refined HAZUS-MH4 hurricane wind risk models: a machine learning approach. In *ATC & SEI Conference on Advances in Hurricane Engineering 2012*, 1056-1066.

Tokgoz, B. E., and A. V. Gheorghe. 2013. Resilience Quantification and Its Application to a Residential Building Subject to Hurricane Winds. *International Journal of Disaster Risk Science* 4 (3):105-114.

Torres, J. M., B. Bass, N. Irza, Z. Fang, J. Proft, C. Dawson, M. Kiani, and P. Bedient. 2015. Characterizing the hydraulic interactions of hurricane storm surge and rainfall-runoff for the Houston-Galveston region. *Coastal Engineering* 106:7-19.

Trepanier, J. C., H. F. Needham, J. B. Elsner, and T. H. Jagger. 2015. Combining Storm Surge and Wind Risk from Hurricanes Using a Copula Model: An Example from Galveston, Texas. *The Professional Geographer* 67 (1):52-61.

Trepanier, J. C., and C. S. Tucker. 2018. Event-Based Climatology of Tropical Cyclone Rainfall in Houston, Texas and Miami, Florida. *Atmosphere* 9 (5).

USCB. 2018. State Population Totals and Components of Change: 2010-2017, ed. U. S. C. Bureau.

USPS. 2019. *C1 Street Suffix Abbreviations*. United States Postal Service 2019 [cited 2019].

Vecchi, G. A., and T. R. Knutson. 2008. On Estimates of Historical North Atlantic Tropical Cyclone Activity. *Journal of Climate* 21:3580-3600.
———. 2011. Estimating Annual Numbers of Atlantic Hurricanes Missing from the HURDAT Database (1878-1965) Using Ship Track Density. *Journal of Climate* 24:1736-1746.

Vecchi, G. A., and B. J. Soden. 2007. Increased tropical Atlantic wind shear in model projections of global warming. *Geophysical Research Letters* 34 (8).

Vecchi, G. A., K. L. Swanson, and B. J. Soden. 2008. Whither Hurricane Activity? *Science* 322 (5902):687-689.

Vickery, P. J., J. Lin, P. F. Skerlj, L. A. T. Jr., and K. Huang. 2006. HAZUS-MH Hurricane Model Methodology. I: Hurricane Hazard, Terrain, and Wind Load Modeling. *Natural Hazards Review* 7 (2):82-93.

Vickery, P. J., P. F. Skerlj, J. Lin, L. A. T. Jr., M. A. Young, and F. M. Lavelle. 2006. HAZUS-MH Hurricane Model Methodology. II: Damage and Loss Estimation. *Natural Hazards Review* 7 (2):94-103.

Vickery, P. J., P. F. Skerlj, A. C. Steckley, and L. A. Twisdale. 2000. Hurricane wind field model for use in hurricane simulations. *Journal of Structural Engineering* 126 (10):1203-1221.

Vickery, P. J., P. F. Skerlj, and L. A. Twisdale. 2000. Simulation of Hurricane Risk in the U.S. Using Empirical Track Model. *Journal of Structural Engineering* 126 (10):1222-1237.

Villarini, G., G. A. Vecchi, T. R. Knutson, and J. A. Smith. 2011. Is the recorded increase in short-duration North Atlantic tropical storms spurious? *Journal of Geophysical Research: Atmospheres* 116 (D10).

Wang, C., X. Wang, R. H. Weisberg, and M. L. Black. 2017. Variability of tropical cyclone rapid intensification in the North Atlantic and its relationship with climate variations. *Climate Dynamics* 49 (11-12):3627-3645.

Wright, D. B., T. R. Knutson, and J. A. Smith. 2015. Regional climate model projections of rainfall from U.S. landfalling tropical cyclones. *Climate Dynamics* 45 (11-12):3365-3379.

Xu, L., and R. E. Brown. 2008. A Hurricane Simulation Method for Florida Utility Damage and Risk Assessment. In *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century 2008 IEEE*, 1-7.

Zane, D. F., T. M. Bayleyegn, J. Hellsten, R. Beal, C. Beasley, T. Haywood, D. Waltz-Beckham, and A. F. Wolkin. 2011. Tracking Deaths Related to Hurricane Ike, Texas, 2008. *Disaster Medicine and Public Health Awareness* 5 (1):23-28.

Zhang, W., G. Villarini, G. A. Vecchi, and J. A. Smith. 2018. Urbanization exacerbated the rainfall and flooding caused by hurricane Harvey in Houston. *Nature* 563:384-389.

Zhu, L., and S. M. Quiring. 2013. Variations in tropical cyclone precipitation in Texas (1950 to 2009). *Journal of Geophysical Research: Atmospheres* 118:3085-3096.