Examining Hazardousness of Place in Houston, Texas: A Holistic View of Four Major Natural Disasters from the Past Two Decades of the 21st Century

by

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CHAPTER I. INTRODUCTION

To understand the reason the city of Houston faces yearly natural disasters of every scale, we must understand that it is the geographical location, and growing human activities that expose the city to natural forces. In other words, the *potential* interaction between humans – Houstonians - and extreme natural events, otherwise known as Natural Hazard, makes the City of Houston non-exempt from the threat of a natural hazard (Montz, Tobin, and Hagelman, 2017). As one of the largest metropolitan cities in the State of Texas, Houston residents are known for their experiences in dealing with major natural hazard/disaster occurrences of various types, magnitudes, durations, and frequencies since record-keeping began in the late 19th century. Still, its residents have shown resiliency in surviving all these disturbances. (Understanding Houston, 2021)

The Hazardousness of Houston

Houston was founded August 30th, 1836, on land near the banks of Buffalo Bayou in the southeast quadrant of the city at the elevation of 105' feet and area size of 665 square miles. It is the fourth most populous city in the nation with a population size of over 2.3 million and a metropolitan area of over 7.2 million which includes the city limits as well as the surrounding cities (Figure 1) (City of Houston, n.d.). The major natural disasters that have occurred in Houston have caught the attention of many scholars for conducting investigations leading to important discoveries about the hazardousness of the area and increased scientific understanding of the threat from natural hazards as well as their physical, social, and environmental consequences.

Hazards may be natural and inevitable, however, disasters can and should be preventable as elucidated by Dr. Iain Stewart in his keynote address to the 2009 Geographical Association stating that, "hazards emerge from nature, but disasters are made in society" (Stewarts, 2). Due to the diligent work and research of dedicated professionals who have studied and documented the impacts of natural disasters, the residents of the city of Houston who have endured these disasters have increased their awareness and learned from officials, the government and private entities. Leaders and emergency managers have reached out to the public and created platforms of information to inform and educate residents on how to save their lives and properties. Furthermore, Houston's leaders have been able to implement effective policies to provide a quicker and more efficient response/recovery efforts after each disaster as well as providing information about preparing and mitigating against future disasters in the Houston area. In general, studies and reports consist of articles, documentaries, and materials, and review only an

individual disaster occurrence and its impact to the area; only a few studies compare more than three (3) main events. Over the past forty (40) years, Houston residents have experienced twenty-five (25) federally declared disasters of various intensities (Understanding Houston, 2021). After each disaster, news stories, reports, and general information are disseminated to the public on the occurrence in question; however, there have been so many disasters in this region of Texas due to its proximity to the Gulf Coast, that it is hard to see similarities and differences making it difficult to learn from these events.

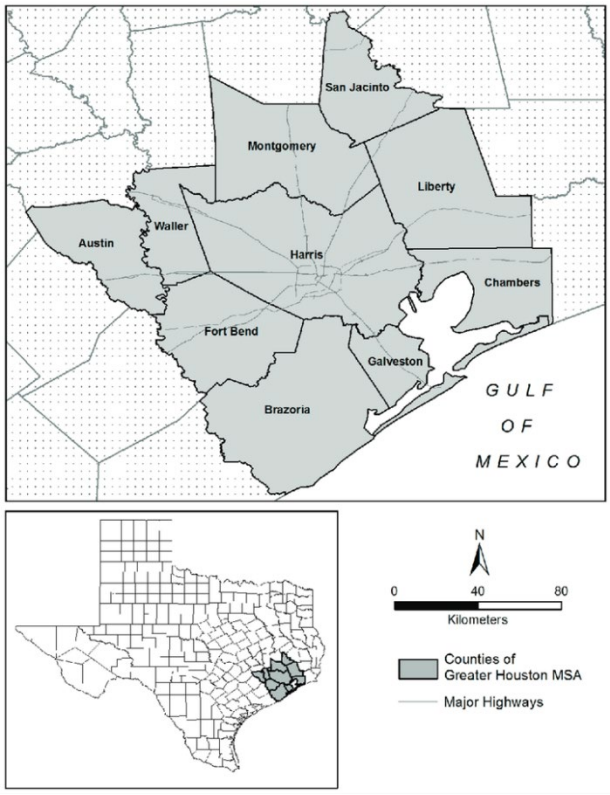


Figure 1. Study Area: Greater Houston Metropolitan Statistical Area (MSA), 2011, Texas, USA. Source: (Chakraborty, Jayajit and Collins, Timothy and Grineski, Sara and Maldonado, Alejandra 2017)

Problem Statement and Goal of the Research

This directed research investigates four major natural disasters that have happened in Houston, TX since the turn of the 21st century - Allison (2001), Ike (2008), Harvey (2017) and Imelda (2019) – with the goal of producing a holistic view of the physical geography and human impact from natural disasters

throughout the Houston area in the phases, before, during, and after each event. This research then examines the commonalities and discusses the uniqueness of hurricane and storm disasters, such as, plans for recovery, and the preparation strategies developed immediately after each storm against future hazards. Finally, this study identifies lessons learned so that emergency management professionals and city leaders might continue to develop successful responses, evaluate mistakes and mishaps for improvements, and develop preparedness plans and procedures to guard against future disaster-related destruction.

This study will be guided by the following questions:

1. What are the differences and similarities between the four major natural disasters?
2. What are the physical and meteorological characteristics of each disaster occurrence as well as the human impact from these major disasters?
3. How have these hurricane/storm disasters affected the local economy?
4. What are the lessons learned by Houston officials, planners, and emergency managers to help mitigate against natural disasters and prepare the city for future disasters?

The goal for this research is to provide a clear understanding to the readers with information and knowledge about: 1) why Houston is so prone to flooding, especially as the result of hurricanes and tropical storms, 2) how safe it is to live within the city of Houston metropolitan area, and 3) how are the city's leaders and managers dealing with the hurricane and tropical storm hazard and other natural hazards.

The reminder of this paper is organized as follows: Chapter 2. History of Hurricanes and Severe Storms; Chapter 3. Physical Characteristics and Comparative Matrix of the Four Major Disasters; Chapter 4. Comparative Analyses of the Human Impact Caused in the Region from These Four Natural Disasters; and Chapter 5. A Brief Discussion of the Lessons Learned. This final chapter addresses the research questions with the intent to improve reader's awareness of Houston geographic position of areas to live and policy makers intervention to make the Houston Metropolitan area a safe and better to live.

CHAPTER II. HISTORICAL BACKGROUND

Natural Hazards in Houston Due to Land Use and Land Cover

Since 2010, the Houston metropolitan area has seen a population increase from 5.8 million people in 2010 to 7.2 million in 2021. A Texas A&M AgriLife Extension service has conducted a study which predicted an addition of 3.5 million to the population Houston by 2035, see figure 2. In terms of land use, human usage of a particular territory has various reasons such as, economic, residential, recreational, conservational, and governmental. Given the vigorous growth in the region, Hampshire and Sipes have projected that by 2045, there will be an additional "five hundred square miles of developed area, including an estimated six million parking spaces, seven hundred eighty million square feet of non-residential uses, and three and a half billion square feet of residential use" (2019, 1). Unlike other cities in the States that apply land use models containing zones to display different functions when it comes to development of an area, Houston developments are governed by ordinance codes that address how land can be used as regulated by the city's Department of Planning and Development, therefore, the city does not have any zoning.

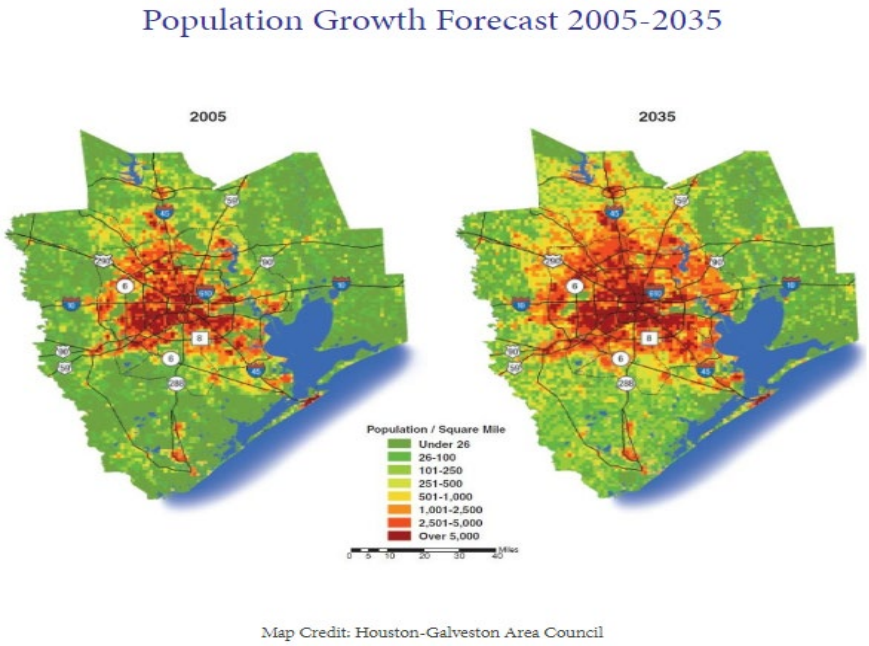


Figure 2. Population Growth Forecast 2005-2035. Source: Texas A&E AgriLife Extension

The same way, information regarding Houston's land cover and its extraterritorial Jurisdiction is managed by the department of Planning and Development. As Gregorio and Jansen would define, the land cover reflects the biological/physical dimension of the Earth's surface and corresponds in some

regard to the notion of ecosystems (2000). A much simpler way to understand and view the land use and land cover is to look at dynamic maps; for this particular study the ArcGIS web map was used to review in a detailed level of use within specific areas of the city, see figure 3 and maps originated from the Houston-Galveston Area Council illustrate the transitions within land cover over time between 2002 and 2008, see figure 4 and 5.

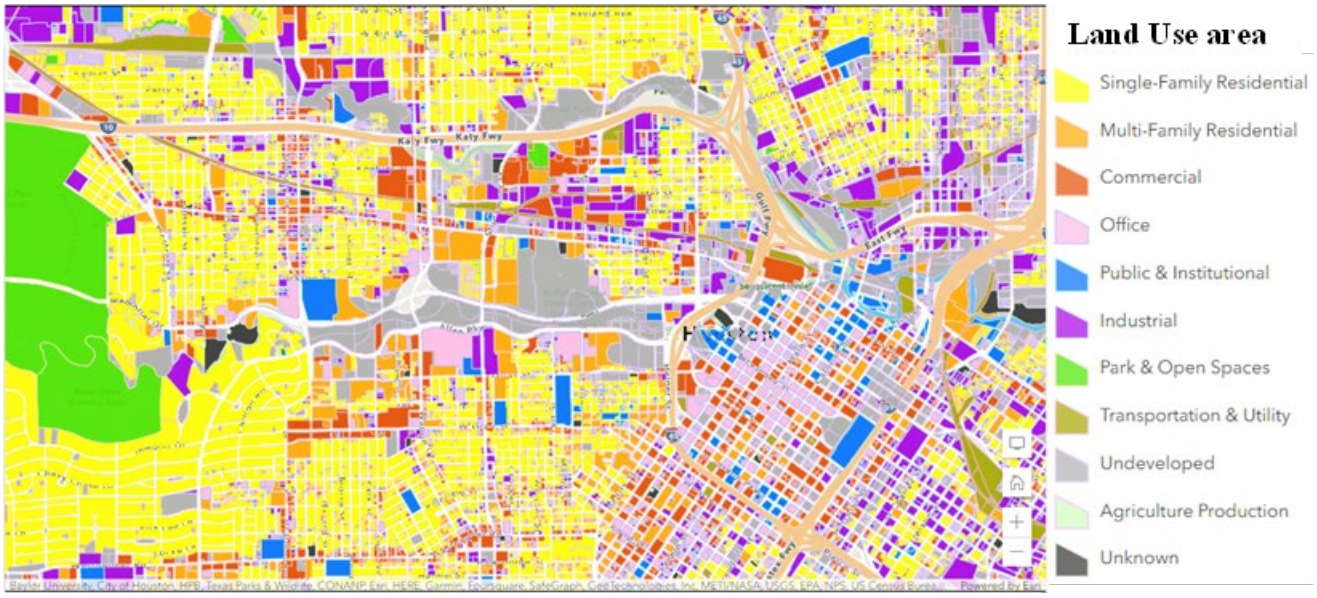


Figure 3. Land Use map of Central West Houston area generated in Geoplanner for ArcGis with GIS data from the City of Houston. Source: ArcGis Mapviewer

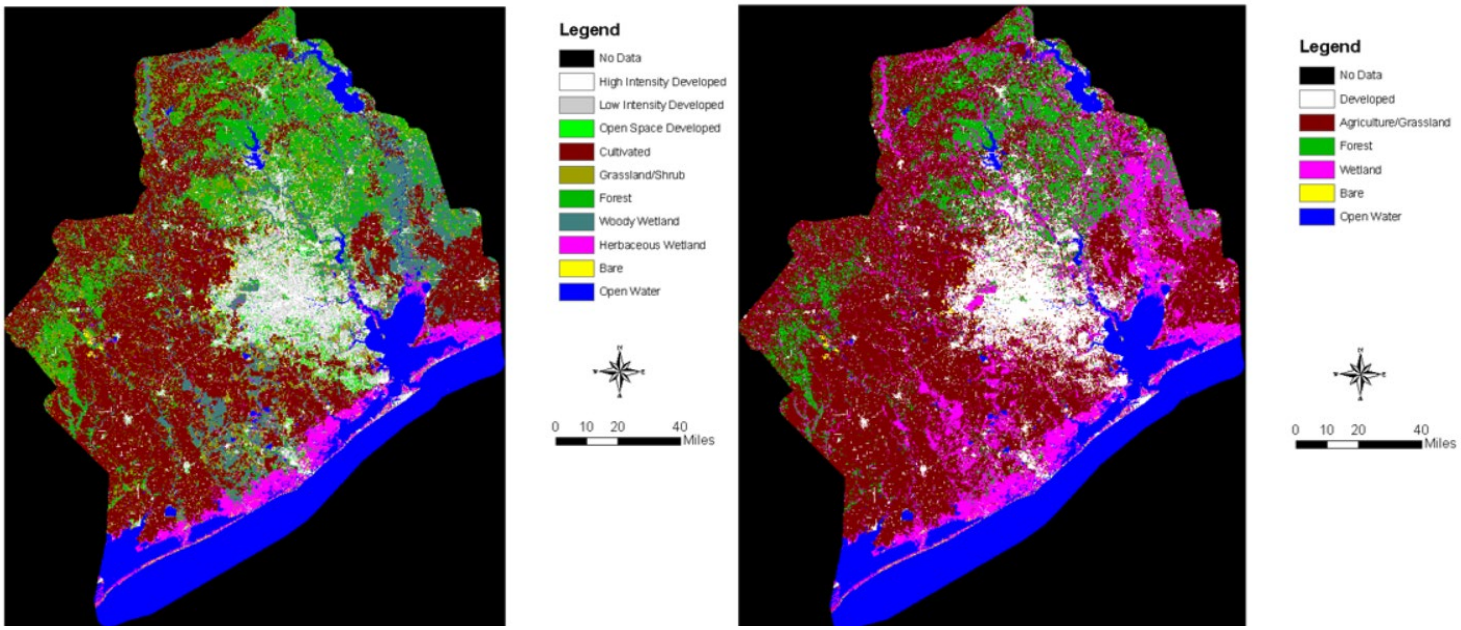


Figure 4. 2008 Land Cover Classification of the City of Houston. Left side map shows 11 category classification vs the recompressed map to the right. Source: HGAC

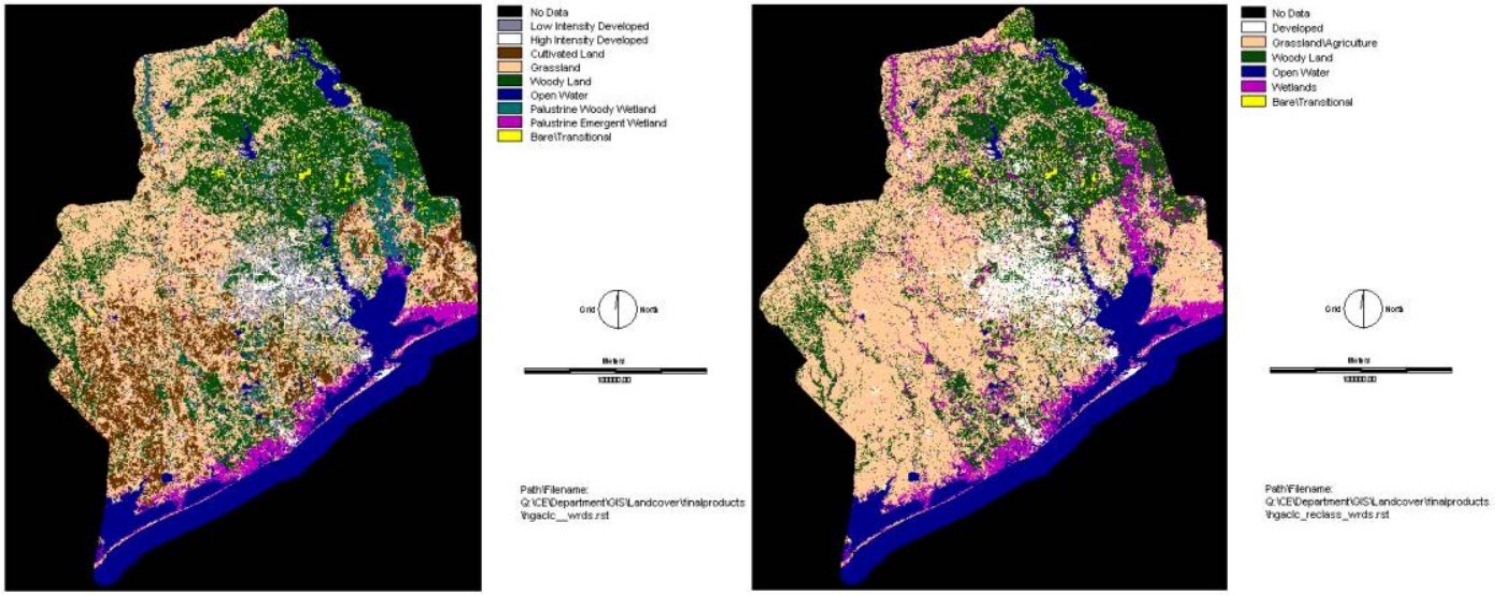


Figure 5. 2002 Land Cover Classification of the City of Houston. Left side map shows 11 category classification vs the recompressed map to the right. Source: HGAC

The city of Houston's fast development started back in the 1920s due to the discovery of crude oil in and around the area. The city grew around the confluence of White Oak Bayou and Buffalo Bayou, which served as a natural turning basin--a wider body of water, either located at the end of a ship canal or in a port to allow cargo ships to turn and reverse their direction of travel, or to enable long narrow barges in a canal to turn a sharp corner (Hampshire and Sipes, 2019).

Since 1837, the city of Houston has recorded nearly 200 floods of various intensities, making them Houston's major form of natural disaster (Hampshire and Sipes, 2019). This can be attributed to the fact that the city is founded on the banks and grew around the concourse of the White Oak Bayou and Buffalo Bayou, it's low-flat terrain, and clay soil that slows the storm water drainage process.

In sum, the city of Houston's land cover average is around twenty seven percent (27%) developed and populated. Since the city does not apply the different land use categories, the region developed areas have a blend of residential land uses, intermixed with office, commercial, public/institutional, and industrial development. The fast development of physical features, geomorphic processes and human activities in the region allegedly have caused Houston to undergo over 200 floods, fifty which were devastating, since its settlement in the 1830s (Hampshire and Sipes, 2019).

Historical Background of the Natural Disasters

The city of Houston has experienced several types of disasters such as, hurricanes, tropical cyclones, and typhoons, all of which may be referred to as tropical storms. This term defines the critical development stage "of a fledgling Hurricane, Typhon, Or Cyclone, when the storm becomes better organized, more intense, and considerably more dangerous" (Longshore, 2008, 399). In this section, these natural hazard/disaster terms will be used interchangeably to provide clarity on its historical background, but still, the focus will be on the types of this research which are reviewing hurricanes and tropical storms.

Defining Hurricane & Tropical Storm.

The term, *hurricane* is the regional name given to mature tropical cyclones, that originate over the North Atlantic and eastern North Pacific Oceans (Longshore, 2008, 243). It is a strong storm system that is characterized by winds rotating in counterclockwise direction in the Northern Hemisphere in an area with low air pressure that forms over tropical waters with winds speeds exceeding 74mph (119 km/h) (Allaby, 2003, vii). The term *hurricane* is commonly used in the United States instead of tropical cyclone (Kirkland 2010a, 115) and the symbol used to designate a hurricane on the weather and tracking arts is as pictured below with the twin convex vanes on either side of the circle indicating the counterclockwise motion of the hurricane's winds while the circle solid center signifies a storm of mature strength (See Figure 6).

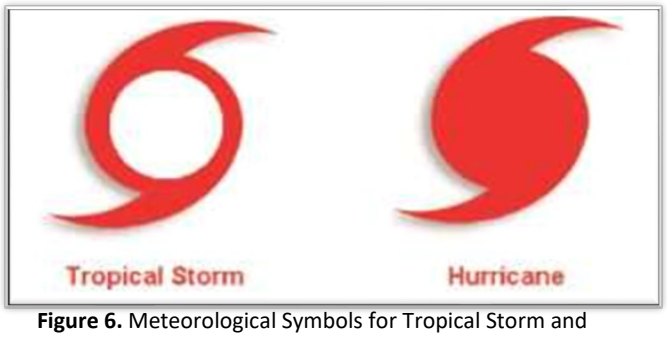


Figure 6. Meteorological Symbols for Tropical Storm and Hurricane | Source: ***WYFF News***

Like a hurricane, a tropical storm is also a tropical cyclone whose wind speeds measure between 39 and 73 mph (63-118 km/h) (Longshore, 2008, 399). On average, a tropical storm is smaller and weaker than a mature tropical cyclone. Yet, still, it manages to initiate severe flooding emergencies causing great damage to properties and human lives wherever it happens.

The Start, Occurrence, and End of Hurricane Season

There is a yearly season for which hurricanes and tropical storms happen. In the United States for instance, it happens within a six-month period ranging from June, when the Atlantic Ocean is generally warm, until November. A hurricane, as Kirkland states in *Weather and Climate: Notable Research and Discoveries*, "is a kind of heat engine – it converts the energy of warm water into wind" (2010a, 114). A hurricane originates over the warm waters with a sea-surface temperature of at least 80-86ºF (26.7 - 27ºC) in the North Atlantic Ocean "(including the Caribbean Sea and Gulf of Mexico)" and eastern North Pacific Ocean (Longshore, 2008, 243). According to article, *Earth Science for Kids: Weather - Hurricanes (Tropical Cyclones)* from Ducksters, hurricanes have three main parts, the eye found at the center with very low air pressure, the eyewall – outer part of the eye where the winds and rains are the strongest, and the rainbands which are large spirally bands that spin out from the center and give the storm its size (2018).

Hurricanes are often classified by meteorologists into categories from one to five based on the Saffir-Simpson Hurricane Wind Scale. This scale details the most salient highlights of hurricane generation and origination (Longshore, 2008, 243).

A tropical storm begins "when a loosely originated tropical depression starts to gather its strength in the warm tropical waters of the North Atlantic, North and South Pacific or Indian Oceans" (Longshore, 2008, 400). It creates a loosely defined eye that draws low-level, moisture-laden air toward it which intensifies the burgeoning convective process of rising warm air and cooling condensation. The tropical storm generally contains enormous quantities of precipitation that continue to gather until the storm either reaches hurricane force or makes landfall.

On an average, in each season, six to ten tropical storms are developed in the North Atlantic with five to six of them reaching hurricane status (Allaby, 2003, 80) see figure 7. As violent and energetic as they can be, hurricanes do not survive for long. Both hurricanes and tropical storms end in a very similar manner by making landfall where the storm begins to lose strength, and within two to three days they dissipate over cooler water (Kirkland, 2010a, 121).

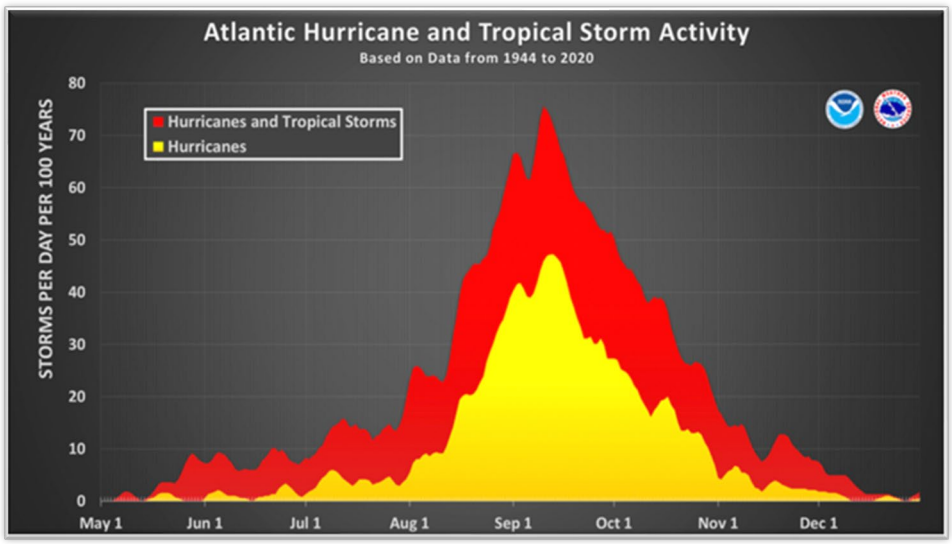


Figure 7. Atlantic hurricane and Tropical Storm Activity | Source: ***Royal Meteorological Society***

The Origin of Hurricane Names

Early in the 1900s, meteorologists have made several attempts to create a naming system for the many hurricanes formed throughout the Oceans in a way that each will be uniquely identified. Not until 1979, during the North Atlantic hurricane season, meteorologists and the public approved the naming system ordered alphabetically from A-Z and alternating between male and female names for each storm that occurred. The North Atlantic storms are named by the U.S. National Hurricane Center (NHC) (Royal Meteorological Society, 2020). Since 1979, there have been six lists of names used. Although no formal application is made for a formal removal of names, they can be retired if there is any confusion between storms of the same name. Lastly, a name is only assigned when "the air around a disturbance starts rotating counterclockwise in the Northern Hemisphere and its winds exceed 39 mph (63 km/h). At this state stage it has become a tropical storm, and until it intensifies into a hurricane the name is prefixed with TS. Once it has grown into a hurricane the prefix is dropped and it is known simply by its name, but it keeps the same name" (Allaby, 2003, 142).

Damage Prediction

When a tropical storm or a hurricane occurs, immense destruction often ensues over the impacted land area. Hurricanes are graded according to their eye pressure, wind speeds, and height of their storm surges, usually on the Saffir/Simpson Hurricane Wind Scale of 1 to 5. When a category of the hurricane is determined, the precautionary measures are taken before it arrives. On the other hand, a tropical storm is measured based on the wind speed because it can turn into a hurricane. Damages are far greater over highly settled land and densely populated areas than rural areas. Although no monetary value is attached to the damage predictions, it has been determined that the total average cost for evacuation per family can be as much as $5000 USD (CRC Insurance Service, Inc., 2020). Since the prediction of tropical storm and hurricane behavior is inexact due to sudden unexpected change in their courses, meteorologists try not to exaggerate the risk when issuing warnings.

In more recent times, predicting the damage that a tropical storm is likely to cause in a region has become more of an exact science due to the creation of the Texas Hurricane Center for Innovative Technology (THC-IT) at the University of Houston's Cullen College of Engineering and other research institutions such as, the Engineering School of Sustainable Infrastructure & Environment at the University of Florida's Herbert Wertheim College of Engineering, and the Office of Naval Research (ESSIE). Prior to the establishment of these research institutions, damages could only be determined after a storm had passed with valuations made by insurance companies. The THC-IT has been "developed in an effort to research ways to prepare for and mitigate disaster caused by hurricanes. The Hurricane Center strives to be a world class testing and research facility for developing hurricane protection products and systems, and repairing technologies to mitigate the losses, both onshore and offshore." The center will also serve as an educational forum for preparedness, and emergency planning and response, as well as develop innovative approaches for industries, businesses and communities to recover rapidly after the wake of a disaster (University of Houston, n.d.). The ESSIE has been granted a $1M project for a four-year period by the Naval Research to develop a computational framework to accurately predict the impacts the different types of damages that will be caused by the imminent landfall of hurricanes along the eastern U.S. seaboard and the Gulf of Mexico. Surely, the benefits derived from the research conducted to develop a program that can elucidate Officials on the form of damage a particular hazard could cause to the area if it made land fall, will generate more incentives to expand the studies that can improve the quality and accuracy of damage prevention efforts.

Protection and Safety

When deciding to live in an area that experiences hurricanes, it is important to know how to prepare for the impact in advance. Tropical storms and hurricanes occur throughout the tropics and territories in a low latitude, and the Gulf coast residents are especially at risk. The Gulf is the ninth-largest body of water in the world with some 3,400 miles of shoreline and covering 940,000 square miles (Houston Wilderness, n.d.). Although the city of Houston is not directly adjacent to the Gulf of Mexico, it is within 62 miles by car to Galveston, a city located along the shoreline of the Gulf coast, see figure 8. Hence, wherever one decides to live, it is always best to take precautions and be alert to the warnings and instructions from authorities before, during and after the storm.

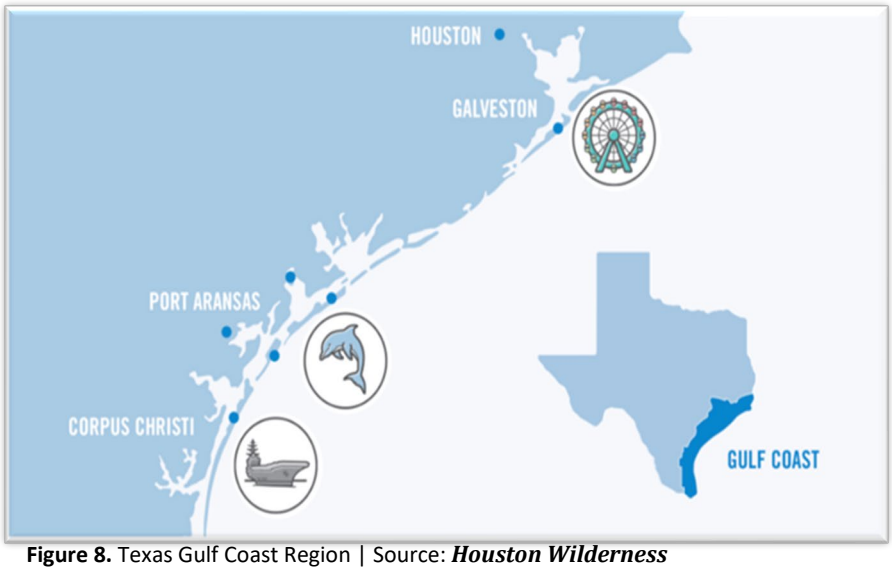


Figure 8. Texas Gulf Coast Region | Source: ***Houston Wilderness***

So, what is to be prepared for a storm? A quick answer is to be aware and alert that the area you live is prone to occurrence of natural hazardous, such as tropical storm and hurricane, and when it is about to happen warnings from authorities, weather and radio stations provide guidance to the population on how to be safe from the storm.

Allaby (2003) provides some insightful information on protection and safety. He starts by stating that it is important to know your local geography. Know key aspects about the area surrounding your home, such as the height of your home above sea or river level, or the location of the nearest river. If you so happen to live on at ground level, find out how long will it take you to move to higher ground. Furthermore, it is crucial to know ahead of time, in the event of an emergency evacuation, which shelters have been identified by authorities. Next, know how to prepare your home and family. A yearly

family meeting, especially close to the hurricane season, will help elucidate all household members about the safest area of the house and how to quickly grab the necessary items needed throughout the storm. To prepare your home you need to board up windows, secure external doors, have flashlights and a reliable battery-operated radio, as well as a camping stove for cooking, fuel, a cooler box, a first aid kit and water, dry or canned food. In normal times, one should maintain the overall state of the house and gardening, so that there are no loose roof tiles and trees or shrubs that can damage the house or lead to flying debris during the storm (Allaby, 2003, 161).

Again, as the storm approaches, authorities and stations will issue a warning within 24 hours or less from when it is expected to make landfall (Longshore, 2008, 252). That is when you should start to act and verify the extent to which all emergency supplies are prepared, in good condition, and where they are supposed to be. It is also important to check the car's fuel tank and have it full in case it is needed for evacuation. Finally, seek Emergency shelter when advised by authorities; however, if living in a mobile home, seek shelter anyway because hurricanes are likely to devastate it no matter how securely it is tied down. If sheltering-in-place and/or staying home is the only option, make sure to unplug small electrical appliances, turn off the gas supply, and move to the safest part of the property – a room with no outside wall and no windows (Allaby, 2003, 164). If possible, have flashlights and a radio, and better yet, a charged cell phone.

Chapter 3. Physical Characteristics of the Events

Now that the paper has provided definitions on key terms and some level of clarity as to why Houston is a city prone to natural hazards and disasters, such as tropical storms and hurricanes. This section of the paper will perform a comparative assessment of the physical characteristics of the tropical storms and hurricanes which include the following; hurricane track, wind and pressure, rainfall and flooding, storm surge, tornadoes, and casualty and damage of the four major natural disasters selected for this study: Allison (2001), Ike (2008), Harvey (2017), and Imelda (2019) which Houston experienced over the past 21 years.

Of the four this research studies, two of them are classified as a tropical storm and the other two as hurricanes. Both tropical storms and hurricanes cause significant impacts on life and property, such as storm surge, flooding, extreme winds, tornadoes, and lighting.

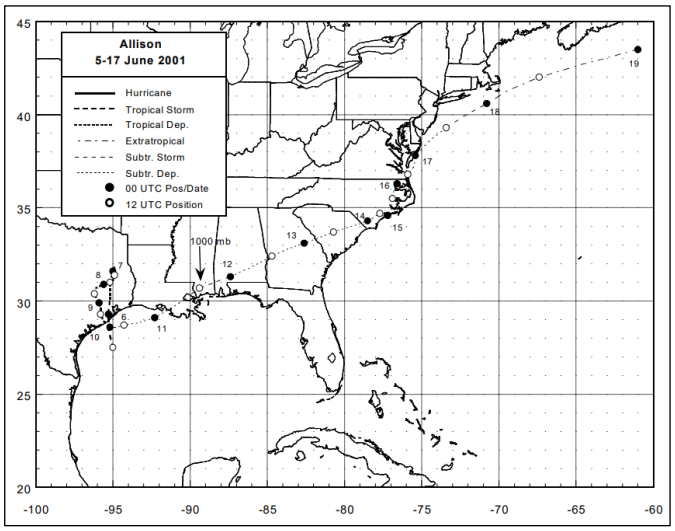
The Four Disasters—Track Summaries

While a tropical cyclone track can be traceable, the actual course of the storm is very unpredictable. In North America, the National Hurricane Center (NHC) is the responsible entity for forecasting all tropical cyclone activities in the Atlantic and Pacific basins. The tools used to track and predict a storm are satellites, reconnaissance aircraft, ships, buoys, radar, and other land-based platforms. The most common method used by forecasters for estimating the characteristics of a storm, such as location of its center, past motion (within 6-12hrs), and intensity (maximum wind speed) is by using use satellite data (Latto and Berg, 2020).

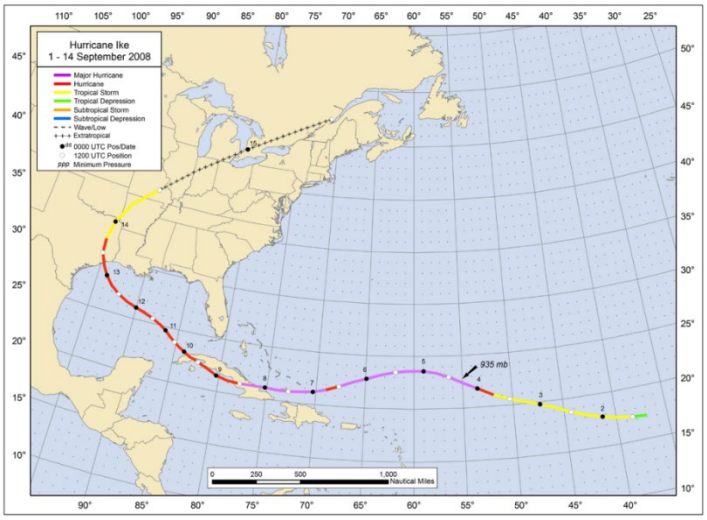
Some of the commonalities of the natural disasters being researched is that most of them formed in the West Coast of the continent of Africa, also known in the Atlantic Ocean during the North Atlantic Hurricane season. The path direction of these disaster typically begins by moving westward with the wind strength intensifying as it approaches land the speed is assessed and the storm is given a name and category.

The figure 9 below retrieved from the National Hurricane Center reports, exhibit the best track positions on each of the natural disasters. The only distinction in the track position is tropical storm Imelda (2019). It surely occurred during the North Atlantic Hurricane season of 2019, but it was not until September 17th that the NHC issued a tropical cyclone update indicating the depression had strengthened

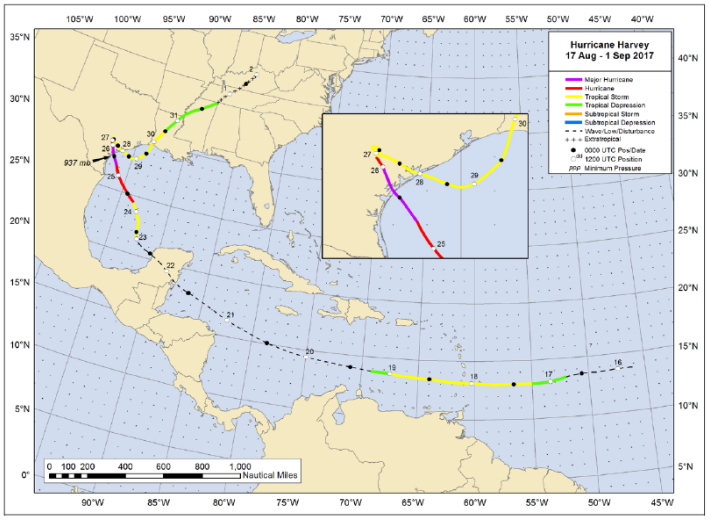
to Tropical Storm Imelda. Shortly thereafter, Imelda made landfall near Freeport, Texas at 1:30 PM CDT with maximum sustained winds of 40 mph and a minimum central pressure of 1005 millibars (29.68 inches of mercury).



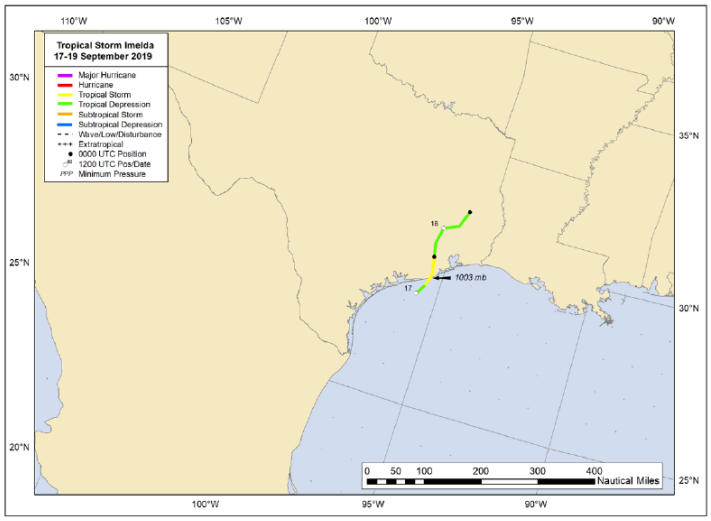
Tropical Storm: Allison (2001)



Hurricane: Ike (2008)



Hurricane: Harvey (2017)



Tropical Storm: Imelda (2019)

Figure 9: Best Track position of the four Natural Disasters that have impacted the Houston Metropolitan area (in)directly.
Source: **National Hurricane Center**

The Four Disasters: Wind and Pressure

To best determine the characteristics of a storm system is to monitor its wind speed. To categorize a particular storm to tropical storm, the wind speed must be within the range of 39-73 mph, whereas a hurricane wind speed must exceed 74 mph, as it has also been previously stated in Chapter 2. Table 1 shows the four natural disasters that have met the minimum criteria to be identified as a Tropical Storm or Hurricane. The intensity of the wind and pressure for each disaster varied throughout its trajectory based on the reports retrieved by the different weather monitoring systems.

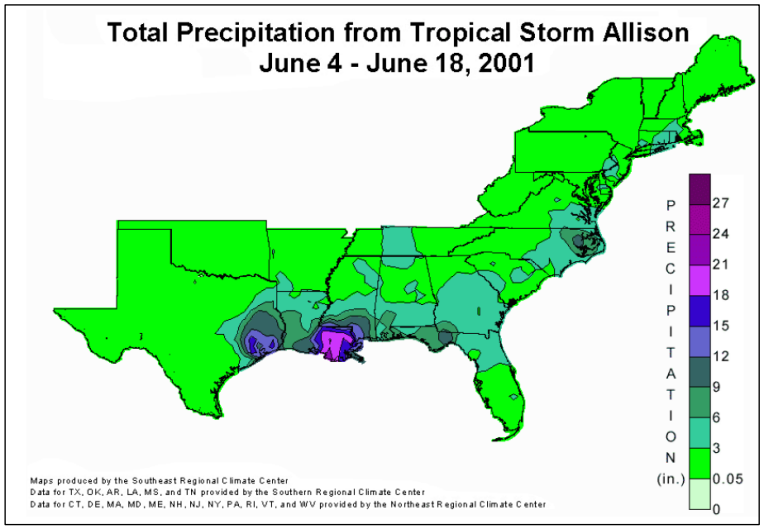
Table 1. Wind and Pressure Measurements of the Four Disasters.

	Tropical Storm Allison (2001)	Hurricane Ike (2008)	Hurricane Harvey (2017)	Tropical Storm Imelda (2019)
Wind	55 kt = 63 mph surface wind Allison's peak intensity of 50 kt = 58 mph (Stewart, 2001)	maximum sustained winds of 125 kt = 144 mph (Berg, 2009)	maximum winds of 115 = 132 mph (Murphy, 2008)	estimated peak intensity of 43 kt = 49 mph (Latto and Berg, 2020)
Pressure	1006.6 mb just west of the surface center (Gudes and Kelly Jr., 2001)	minimum central pressure of 935 mb (Berg, 2009)	estimated to be 937 mb (Murphy, 2008)	minimum surface pressure of 1003 mb (Latto and Berg, 2020)

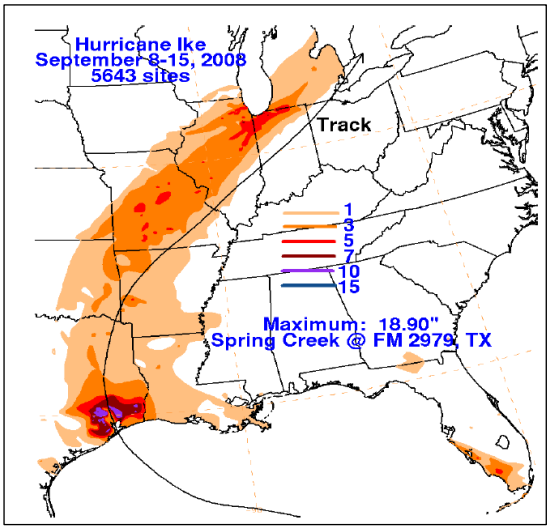
The Four Disasters: Rainfall and Flooding

With every tropical storm and hurricane, rainfall and flooding will follow. The amount of rain and flood occurrence varies by the size/proportion of each event. As seen in figure 10, the three of the four disasters reported to have caused a total rainfall of 30 inches or higher over much Eastern and Southeastern Texas. In our study area - the Greater Houston region – there was a total rainfall of 60.58

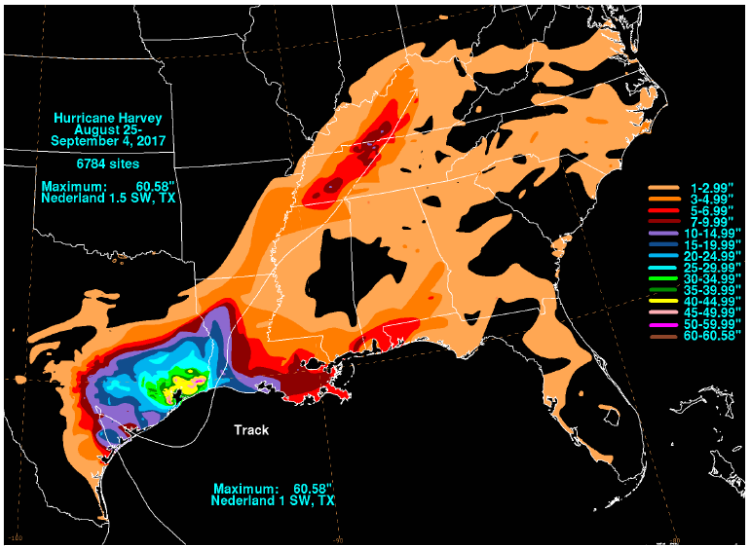
inches during Harvey which was a record high. Although hurricane Ike (2008) produced a large area of rainfall over much of Southeastern Texas the highest amount reported was 18.90 inches just north of Houston along Spring Creek at Farm Road 2979 with no flooding occurrence (Berg, 2009, 7). A widespread flooding occurred during both tropical storms "Allison (2001) and Imelda (2019), and hurricane Harvey (2017) within major Bayous and Creek areas.



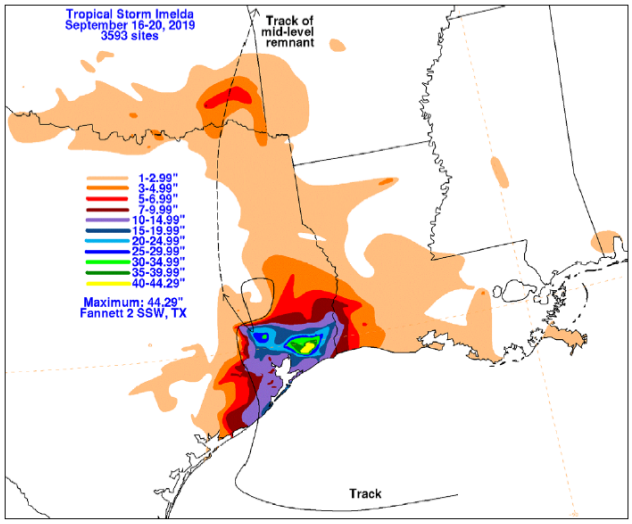
Tropical Storm: Allison (2001)



Hurricane: Ike (2008)



Hurricane: Harvey (2017)



Tropical Storm: Imelda (2019)

Figure 10: Total rainfall map in inches of the four Natural disasters. Source: **National Hurricane Center**

The Four Disasters: Storm Surge

In all four natural disasters, higher-than-normal water levels have been witnessed in every state that the event occurred. Despite the fact that hurricane Ike had the highest storm surge as shown in table 2, it is important to note that this Hurricane event did not occur within the limit of the study area, leaving hurricane Harvey (2017) as the storm with highest water levels throughout the Houston Metro area. Still, the storm surge of tropical storm Allison (2001) and Imelda (2019) were considered above the normal astronomical tide level having caused major areas and road inundation, such as the Medical Center, interstate 10, 610, and Beltway 8.

Table 2. Maximum Storm Surge Levels for Each of the Four Disasters.

	Tropical Storm Allison (2001)	Hurricane Ike (2008)	Hurricane Harvey (2017)	Tropical Storm Imelda (2019)
Height Max	3ft	12.79ft	10ft	2.35ft

The Four Disasters: Tornadoes

Due to the severe atmospheric change in a region where tropical storms and hurricanes happen, the chances of a tornado to develop are very high. That being said, the four major disasters being reviewed have indeed caused tornadoes to occur; a total of twenty-seven (27) tornadoes have formed between Harvey (2017) and Imelda (2019), see table 3, and touched down with the limits of the study area – Greater Houston. During hurricane Harvey (2017) there was one-hundred-fifty (150) tornado warning issued but most of them were relatively weak, of EF-0 and EF-1 intensity, making Hurricane Harvey a prolific tornado producer within the Houston region.

Table 3. Occurrence of Tornadoes Caused for Each of the Four Disasters.

	Tropical Storm Allison (2001)	Hurricane Ike (2008)	Hurricane Harvey (2017)	Tropical Storm Imelda (2019)
Total	23	29	52	2
Greater Houston	0	0	26	1

Overall, these natural disasters had different tracks and impacts, but all have made land fall in Texas due to its geographical location by the Gulf of Mexico.

CHAPTER 4: Socio-economic Characteristics and Human Impact

As described in previous chapters, the residents of the city of Houston suffer from disaster occurrences yearly. The city is mostly affected by the flood hazard from major storms and precipitation events, resulting in damages due to its geographical location, topography/land cover, rapid population growth, land use and development, all causing structural and environmental changes to its natural runoff and drainage patterns. This section of the paper discusses the socio-economic impacts of the four disasters being reviewed as well as the vulnerability of the areas and residents.

Natural Disaster Impact Relations

Natural disasters have a direct influence on vulnerable groups like Houstonians by causing damage to homes and businesses, physical harm and death, destruction to crops and food supply, and transportation disruptions. Due to the direct correlation between the occurrence and damages, these effects can be simply measured. Pielke, Jr. (2019) goes on to say that in addition to the immediate effects, there are also secondary effects, such as the destruction of public infrastructure, that are typically felt days or weeks after the fact. Furthermore, after a natural disaster that has detrimental knock-on effects for the region and its inhabitants, there are tertiary effects that are felt months or years afterwards. For instance, the closure of multiple businesses may lead to a drop in tourism, which would result in a reduction in sales tax revenue that would otherwise go to the local community services. This may further upset the community and the local economy. Direct impact costs frequently take the form of individual settlements, such as for the replacement of public infrastructure and the cleanup of debris. Yet, because they need calculating and are a component of an existing social activity, the costs connected with the secondary consequences are more difficult to quantify (Pielke, Jr., 2019). Due to the staggering elements, it is especially difficult to determine the costs of the tertiary effects. Figure 11 helps understand the climate related risk resulting from synergistic interaction of weather and climate hazards, vulnerability, and exposure of human and environment systems.

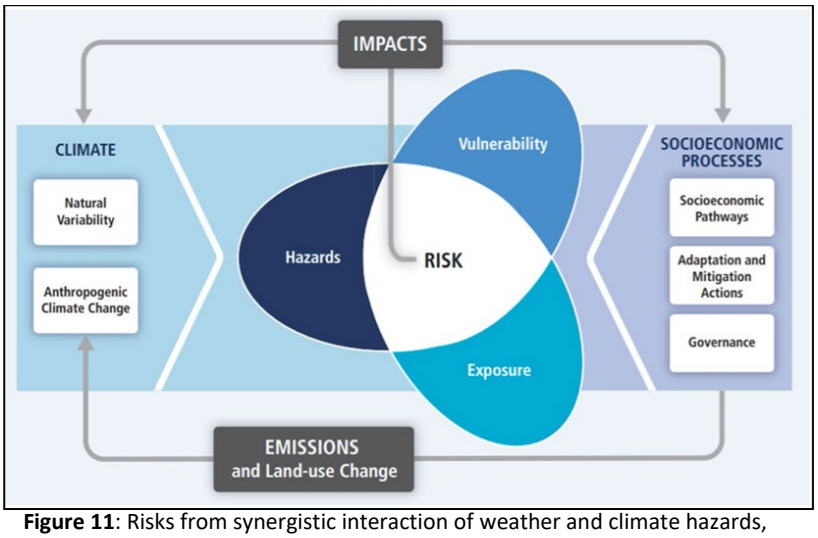


Figure 11: Risks from synergistic interaction of weather and climate hazards, vulnerability, and exposure of human and environment systems. Source IPPC 2014

Responsible Parties for the Disaster

It's vital to talk about who is responsible for a disaster before we investigate the societal effects of the four natural disasters. Two distinct studies reveal that the responsible party for the disaster is often pinpointed to being either nature or human-interference. Scholars often aim any responsibility at the decision made by policymakers while critics outside of academia say nature is the responsible party to blame for the disasters. For example, Pielke (2019) points out that less educated people tend to quickly blame nature for the damages caused by the natural hazard; whereas, scholars such as Pielke (2019) and Munoz De La Torre (2022) express that natural disasters are a consequence of human actions and decisions. Despite the argument provided by the National Oceanic and Atmospheric Administration (NOAA), that "natural disasters are typically considered acts of God, and therefore no one is held legally responsible for the damages they cause" (NOAA, n.d.), the responsibility of a disaster and its consequences can be equally attributed to governments, businesses and individuals.

An example is found with Tropical Storm Allison (2001), in which heavy rain fell for nearly five consecutive days, causing parts of Houston to receive as much as 31 inches of rain, and as a result, major bayous of the city swelled and overflowed. The existing drainage infrastructure was unable to deal with massive amounts of continuous rainfall which caused severe flooding. Allison represented a 500-year flood – a term used by the U.S. National Flood Insurance Program to describe a flood of great multitude based on 1-percent Annual Exceedance Probability (AEP) (USGS). The extent of damages may be attributed to the fact that the city has small basins, and no usage of a “Mean Areal Precipitation”

(MAP) – a tool that averages rainfall estimates and observes rainfall measurements from a radar – which would have been useful for assessing the flood risk and supplementing the analysis where gauges exist (Evans, Gudes and Kelly, 2021).

Despite all the projects developed by the local government to better manage the flood hazard, improvement efforts have been put to the test with the impact of Hurricane Harvey (2017). Not only did Harvey generate 27 trillion gallons of water throughout the State of Texas, but it also caused two flood-control reservoirs in Houston to be breached, increasing water levels throughout the Houston area to more than 50 inches of rainfall (Huber, 2018) marking between a 10,000-year to 40,000-year flood event. Physical evidence showed that the bayous' drainage systems were still not able to sustain extreme amounts of water, causing great flooding in some areas of the city.

Rarely are natural disasters completely "natural." They are more likely to be the result of a lack of political leadership, land developer ambition, poor scientific communication, and delay on the part of risk management personnel. All parties, including the city's residents must be seeking information about how to lessen, if not eliminate, the negative effects of a disaster, especially for preserving lives and protecting property.

Social Vulnerability

An at-risk population's socioeconomic situation prior to a natural disaster greatly influences how it affects that population. The groups of people who are more susceptible to the effects of a disaster and less able to cope are seen to be what constitutes vulnerability. As the Agency for Toxic Substances and Disease Registry defines, social vulnerability is the degree to which a group of people, a location, or a community can withstand external risks like natural or man-made disasters or disease epidemics (2022). The Center for Disease Control and Prevention (CDC) measures social vulnerability of a particular place using the Social Vulnerability Index (SVI) on a scale from 0 (indicating the lowest vulnerability) to 1 (highest vulnerability). In Figure 12, for example, Harris County's SVI indicates that it has the highest vulnerability risk toward negative impacts of a disaster with a SVI of 0.72 both from before and after Harvey (2017). Places that demonstrate high vulnerability levels, as reflected in high SVI index numbers, are most likely to be less resilient toward hazards and disasters, and thus, will have higher levels of human and economic suffering and loss.

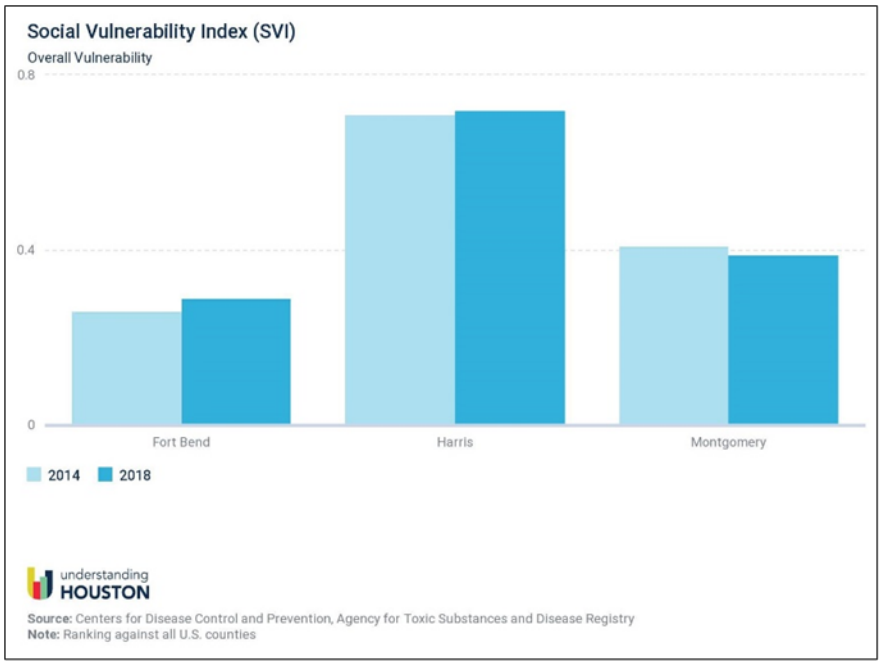


Figure 12. Social Vulnerability Index (SVI) within Greater Houston Region. Source: **Understanding Houston**

For instance, immigrant and non-white families have traits with vulnerable groups that report more severe disaster effects. This may be explained by the fact that the vast majority of these families have lower income levels and lower quality of life characteristics, such as a lack of economic and job security, unstable housing conditions, little to no access to health insurance, and inadequate financial

resources, even before a disaster. Neighborhoods are also geographically situated in low-lying locations, and they have long-standing issues with disinvestment and social problems that get worse in crisis situations (Young and Van Zandt, 2019).

In a few rare cases, people in middle- to upper-class socioeconomic groupings are able to handle and survive the effects of natural disasters. In the Houston area, it was generally noted that families with middle-to-high income levels who had good quality economic and job security, housing stability and conditions, and some type of insurance coverage were able to manage and survive the effects of Tropical Storm Allison and Hurricane Harvey. Figure 13 shows that 64% of the population in the Harris County live in a census tract that is more vulnerable than half the census tracts in the nation post-Harvey (2017) (Understanding Houston, n.d.).

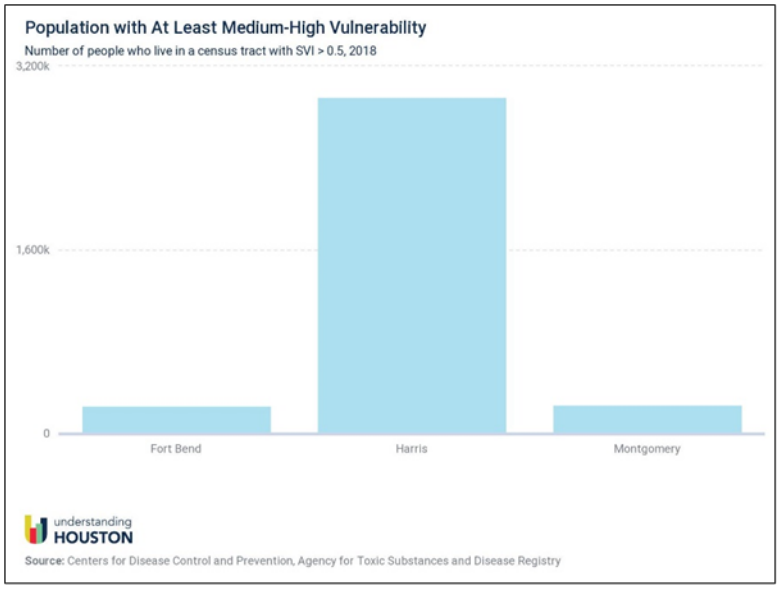


Figure 13. Population with At Least Medium-High Vulnerability. Number of people who live in a census tract with SVI > 0.5, 2018 within Greater Houston Region. Source: **Understanding Houston**

The SVI describes the characteristics and social factors of the overall vulnerability in four themes; socioeconomic status, household composition and disability, non-white status and language, and housing and transportation. Figure 14 shows how Harris County is more vulnerable than the other two counties in Houston on all four measures.

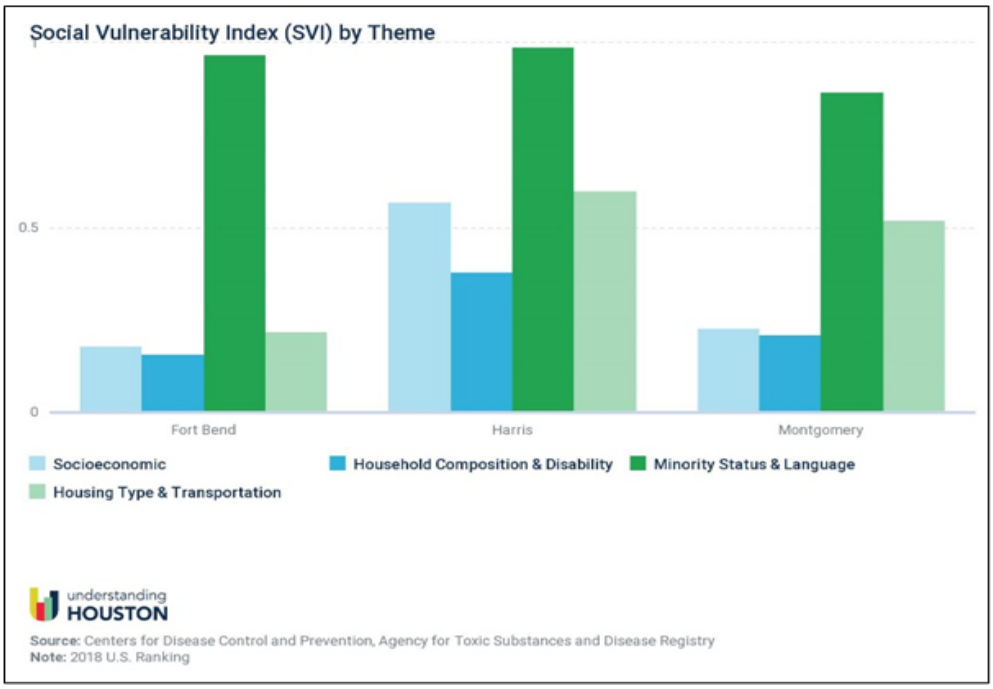


Figure 14. Social Vulnerability Index by theme within Greater Houston Region. Source: **Understanding Houston**

It is obvious that one of the key components of a community's resilience is its level of income and wealth. Low-income areas are more susceptible to the effects of catastrophes, but because of the degree of the damage to housing, transportation, and other essentials, mid-income families are also likely to experience economic insecurity.

The Four Disasters: Casualty & Damage

Table 4. Casualties and Damages Occurring to the Houston Metropolitan Area.

	Allison (2001)	**Hurricane Ike (2008)**	**Hurricane Harvey (2017)**	**Tropical Storm Imelda (2019)**
Casualties:	41 fatalities in the Houston area (Stewart, 2001)	14 fatalities occurred in the Houston area (Berg,2009)	36 fatalities occurred in Houston area (Blake and Zelinsky, 2018)	1 Fatality occurred in Houston area (Latto and Berg, 2020)
Damage:	The storm caused an estimated $5 billion in damages in the Houston area, including flooding of more than 70,000 homes and businesses (Stewart, 2001)	The storm caused an estimated $22 billion in damages in Texas, with the majority of the damage occurring in the Houston and Galveston areas (Berg, 2009)	The storm caused an estimated $125 billion in damages in Texas, with much of the damage occurring in the Houston area (Blake and Zelinsky, 2018)	The storm caused an estimated $5 billion in damages in Texas, with much of the damage occurring in the Houston area (Latto and Berg, 2020)

It has been observed during all four disasters that the greater Houston area has suffered severely from flooding which has caused significant damages to homes, businesses, and infrastructures, affecting major roads such as I-10, I-45, and US-59 as well as areas near bayous, creeks, and rivers. In addition, some areas of the greater Houston area have had power outages, mostly during Hurricane Ike (2008), as reported by the National Hurricane Center (2009).

The Four Disasters: Financial Impacts

Tropical Storm Allison (2001), Hurricane Ike (2008), Hurricane Harvey (2017), and Tropical Storm Imelda (2019) had significant financial impacts on Houston, TX. In all of them the Federal Emergency Management Administration (FEMA) provided housing vouchers or cash directly to those affected through its "Individual and Household Program" (IHP) to address urgent basic needs caused by each disaster. Figure 15 shows the disaster assistance claims to FEMA of multiple natural disasters, including, Hurricane Ike, Harvey and Tropical Storm Imelda in Harris County alone. Here are some of the key financial impacts of these events:

Table 5. Damage and Insurance Claims within the Houston Metropolitan Area.

	Tropical Storm Allison (2001)	Hurricane Ike (2008)	Hurricane Harvey (2017)	Tropical Storm Imelda (2019)
Damages claims	estimated $5 billion in damages in the Houston area (Bomgardner, 2017)	estimated $29.5 billion in damages in the Houston area (HCFCD, 2009)	estimated $125 billion in damages in the Houston area (Blake and Zelinsky, 2018)	estimated $5 billion in damages in the Houston area (Latto and Berg, 2020)
Insurance claims	in the Houston region exceeded $1 billion (Bomgardner, 2017)	in the Houston region exceeded $11 billion (HCFCD, 2009)	in the Houston region exceeded $19 billion (Blake and Zelinsky, 2018)	in the Houston region exceeded $1 billion (Latto and Berg, 2020)

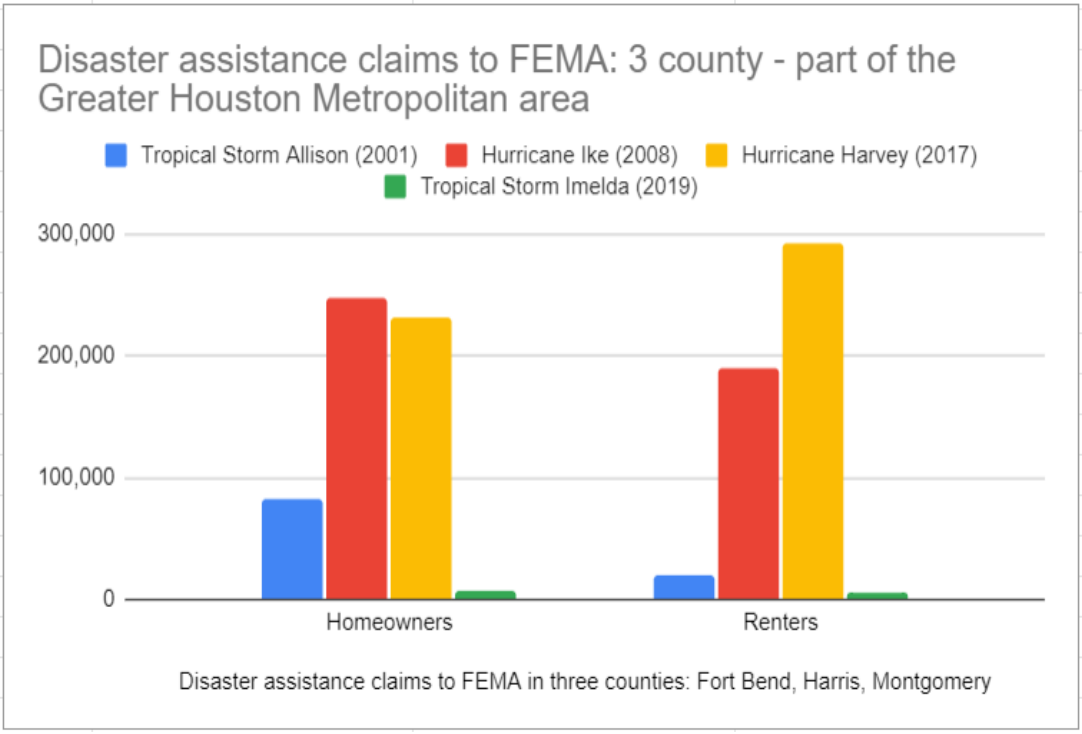


Figure 15: Three (3) County, Disaster Assistance Claims to FEMA, Number of FEMA Valid Registered Households Impacted by Claim Type by Disaster. Source: Understanding Houston and RMS (2001).

Additionally, reports show that not all homeowners and renters who have applied for FEMA were approved, figure 16 shows the dollar amount of the approval requests for both homewoners and renters in all three counties in the Greater Houston area.

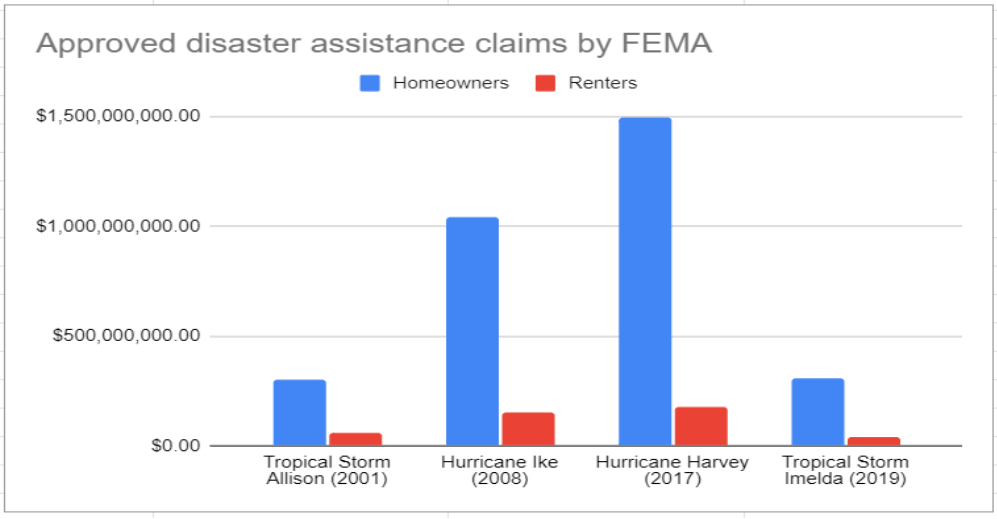


Figure 16. Dollar amount of disaster assistance claims approved by FEMA in three counties: Fort Bend, Harris, Montgomery. Source: Understanding Houston and RMS (2001).

With this data, we can clearly see that the number of claim applications after tropical storms are significantly lower than after hurricanes with homeowners. The approval rate combined for both homeowners and renters rarely rose above 50% for most disasters. Even though high-income households have the capacity to swiftly navigate through the impacts of the disaster, they are more likely to receive government assistance than low-income households since FEMA uses the home's value before the disaster to determine the level of assistance.

The Four Disasters: Housing impacts

All four disasters had significant impact on housing in the greater Houston metropolitan area. Table 6 shows the reported number of homes damaged by all of the disasters.

Table 6. Damaged Homes by all Four Disasters.

	Tropical Storm Allison (2001)	Hurricane Ike (2008)	Hurricane Harvey (2017)	Tropical Storm Imelda (2019)
Number of Homes Damaged	N/A	over 45,000	over 200,000	over 9,000

Most, if not all, of the damages caused by the disasters to homes were specifically in low-lying areas that were vulnerable to storm surge and flooding. Thousands of residents were rescued by emergency management first responders throughout the city and surrounding areas, with the majority of them being evacuated from their homes to temporary shelters. Those who returned home have reported that their living conditions were unsafe. In order to aid homeowners and towns in recovering from the storm's effects, the state and federal governments committed a large amount of funding and resources (Comptroller Texas, 2018).

The Four Disasters: Environmental Impacts

It comes as no surprise that natural disasters can have severe short- and long-term effects on public health due to the contamination of sewage, debris, and chemicals in the water and the air. With an excess of water levels, the greater Houston metropolitan area infrastructure suffered great damage. In 2001, during tropical storm Allison, rivers and streams, among other water sources, were severely

contaminated as a result of the flooding (Braun et al., 2002). Similarly, in 2008, when hurricane Ike struck, significant water source pollution, including elevated levels of bacteria and pollutants in rivers and streams, were also brought on by the flooding (Blake et al., 2011). Furthermore, flooding is seen as one of the main causes of damage to infrastructure in the Houston Metro area. Likewise, it caused significant environmental impacts during hurricane Harvey in 2017, including the release of hazardous materials and the pollution of water sources. The storm also damaged infrastructure, particularly oil and gas installations, which resulted in spills and leaks (Blake, 2018). Lastly, with the reoccurring environmental impact of water pollution, the Houston Metropolitan area faced even higher contamination than in the 2001 tropical storm Imelda with increased levels of bacteria and chemical concentrations in rivers and streams (Latto and Berg, 2020).

The Four Disasters: Health Impacts

Several factors can have a negative impact on a person's health, both physical and mental, before, during, and after a natural disaster. One of these is the combined impact of environmental risks, such as air and water pollution, and the state of mind due to the proximity to the date in which the events occur.

Inhaling contaminated air can cause respiratory diseases to develop or worsen, while consuming contaminated water will make one sick. Mold exposure, which causes dangerous respiratory conditions during cleanup procedures, is another reason for some physical health impacts, such as, respiratory illness, gastrointestinal illness, and injuries (Solomon et al. 2011).

According to the Texas Flood Registry report (2020), individuals who have experienced damages during the disaster have the tendency to have changes in behavior, depression, anxiety, sleep problems, or memory problems, as all of these are the most reported mental issue. Likewise, Cutter et al. (2003) emphasizes that damage and human dislocation results in increased mental health issues like depression and post-traumatic stress disorder (PTSD).

A study conducted by the Mental Health Association of Greater Houston found that 54% of the respondents reported experiencing moderate to severe emotional distress following the storm (Bevilacqua, 2020) after tropical storm Allison (2001). A different study conducted after Hurricane Ike (2008) by the University of Texas Medical Branch found that 49% of the respondents reported

symptoms consistent with PTSD, and 18% reported symptoms consistent with major depression (Pietrzak et al., 2012). In an effort to continue the analysis on the mental impact of individuals after a disaster, a survey conducted by the Kaiser Family Foundation and the Episcopal Health Foundation found that 45% of the respondents reported experiencing stress or emotional distress due to the hurricane Harvey (2017) (Kaiser Family Foundation and Episcopal Health Foundation 2018). The survey also found that 27% of the respondents reported experiencing problems with their mental health since the hurricane, including depression and anxiety. Lastly, after tropical storm Imelda (2019), a survey conducted by the Houston Health Department found that 39% of the respondents reported experiencing anxiety, depression, or other emotional distressors due to the storm (Bevilacqua et al, 2020). The survey also found that 25% of the respondents reported experiencing problems with their mental health since the storm.

CHAPTER 5 – CONCLUSION

As previously stated in Chapter 1, the goal of this research was to provide a clear understanding about Houston, TX; why it has a high susceptibility to flooding, which areas are the safest from flooding within Houston metropolitan area, and what strategies leaders and managers should use to deal with Hurricanes and Tropical storms. In an attempt to summarize the findings from this research, this chapter answered the following questions posed in Chapter 1 and addresses the solutions to the problems identified above.

1. What are the differences and similarities between the four major natural disasters?
2. What are the physical and meteorological characteristics of each disaster occurrence as well as the human impact from these major disasters?
3. How have these hurricane/storm disasters affected the local economy?
4. What are the lessons learned by Houston officials, planners, and emergency managers to help mitigate against natural disasters and prepare the city for future disasters?

Q. 1. What are the differences and similarities between the four major natural disasters?

All four major natural disasters significantly affected the greater Houston Metropolitan area. Some of the differences and similarities are that Tropical Storm Imelda was a weaker storm compared to the other three, reaching a maximum wind of 49mph, while Tropical Storm Allison, Hurricane Ike and Harvey have sustained wind speeds of 63mph or greater. The actual track of the storms was very different and its geographic location for land as well. The Tropical Storms Allison and Imelda made landfall in the near Freeport, TX, whereas Hurricane Ike made landfall in Galveston, TX and Hurricane Harvey made landfall on the northern end of San Jose Island about 5 mile east of Rockport, Texas. Another major difference between the four major natural disasters was the strength and period of the rainfall. Hurricane Harvey to this day is considered the wettest tropical cyclones in the State of Texas with a total rainfall of 60.58 inches near Nederland, Texas. Ranking the four major natural disasters in review, Tropical Storm Imelda (2019) is the second wettest with a total rainfall of 44.29 inches in some areas, followed by Allison (2001) with the highest recorded 35.94 inches of rainfall and Hurricane Ike (2008) with highest amount recorded of 18.90 inches. All four natural disasters have caused significant flooding due to the prolonged rainfall within many areas of the Houston Metropolitan Area which caused damage to homes, businesses, and infrastructures. It is accurate to say that, city officials have reevaluated the significance of emergency planning and response as well as the requirement for efficient flood control measures in sensitive regions after each occurrence of a natural disaster.

Q. 2 What are the physical and meteorological characteristics of each disaster occurrence as well as the human impact from these major disasters?

A mix of natural and human factors make Houston vulnerable to flooding. The majority of the city's land is at or below sea level because it is situated in a low-lying location. Moreover, the area experiences significant rainfall, especially during hurricane and tropical storm seasons, which increases the risk of flooding.

Houston is situated on a flat coastal plain with low-lying areas that are particularly prone to flooding, according to the United States Geological Survey. In addition, the city's proximity to the Gulf of Mexico increases its vulnerability to storm surge flooding during hurricanes and tropical storms. The Houston region is also highly urbanized and developed, with a lot of impermeable surfaces including buildings,

parking lots, and roadways. The risk of flooding is increased because these surfaces stop rainwater from percolating into the earth and instead cause it to rush quickly into streams and rivers.

Climate change, which has brought about more frequent and powerful extreme weather events and increased rainfall, has made Houston more susceptible to flooding in recent decades. In Houston, the chance of extreme rainfall events has increased due to human-caused climate change, according to a 2017 study that was published in the journal, *Nature*.

Like most large cities, the Houston metropolitan area is relatively safe to live in. According to the Harris County Flood Control District, some of the areas within the Houston metropolitan area that are less prone to flooding include, The Woodlands - located north of Houston, Kingwood – located northeast of Houston, Sugar Land – Located southwest of Houston, Pearland – located south of Houston, and Katy – located west of Houston. These areas have lower flood risks compared to other parts of the Houston metropolitan area. In terms of crime rate, the Property Club Report for 2022 identified nine of the safest areas to live within the Houston metropolitan area: Bunker Hill Village, Hunters Creek Village – located west of Houston, Midtown, West University Place – located downtown and the Museum District, Sugar Land – located south of Houston, Galena Park – located near the city center, Kingwood, Memorial – located west of Houston and Friendswood – located southeast of Houston because of its relatively low crime rate.

Q. 3 How have these hurricane/storm disasters affected the local economy?

The storms had a major effect on the economy of the Houston Metropolitan region, causing businesses to close, infrastructure to be devastated, and financial hardship for locals. These storms have had long-lasting consequences on the local economy. All storms have cost more than 150 billion to the city in damages which will be needed years and additional billions of dollars in rebuilding efforts. Though these disasters do not discriminate, low-income Houstonians have been disproportionately impacted by the recovery process. Due to the proximity on these events occurrences and additional flooding events that have occurred between the four major natural disasters, many Houstonians dealt with issues like homelessness, illness, financial hardship, job loss, and lack of access to education. Research conducted by Texas Organizing Project (TOP) and Dr. Wilson (2023), showed evidence that the Northeast neighborhood of Houston composed by the following zip codes: 77078, 77028 and 77016, flood

multiple times a year during major and minor storm events. Still, the area's infrastructure for drainage and flooding has experienced little to no development. With the research findings, to strengthen flood infrastructure and long-term flood prevention in low-income communities, TOP successfully petitioned Harris County to give low-income communities priority for $2.5 million in flood bonds. As resilient as locals in the Houston Metropolitan area are, they have managed to slowly recover from damages faced with support of public and private funding entities.

Q. 4 What are the lessons learned by Houston officials, planners, and emergency managers to help mitigate against natural disasters and prepare the city for future disasters?

In response to the damages caused by the natural disasters that affected the Houston Metropolitan area, the city leaders and managers implemented several changes after each of the disasters being reviewed. Such changes focused on improving emergency response, implementing flood control measures, enhancing building codes to make structures more resilient to flooding, and reducing flood risk through buyouts and home elevation. Table 7 shows a side-by-side comparison of the changes set to take place following each storm.

Table 7. Comparison of the Planned Changes After Each Disaster.

	Tropical Storm Allison (2001)	Hurricane Ike (2008)	Hurricane Harvey (2017)	Tropical Storm Imelda (2019)

Improvements in emergency response	Following the storm, Houston's leaders implemented changes to emergency response procedures, including better coordination between agencies, the establishment of an emergency operations center, and the development of a public alert system.	Following Hurricane Ike, Houston's leaders implemented changes to emergency response procedures, including the development of a more comprehensive evacuation plan, the establishment of a regional emergency operations center, and the creation of a real-time flood monitoring system.	Houston's leaders have implemented changes to emergency response procedures, including the creation of a regional emergency operations center, the development of a public alert system, and the establishment of a system for managing and coordinating volunteers.	Houston's leaders have implemented changes to emergency response procedures, including the creation of a regional emergency operations center, the establishment of a real-time flood monitoring system, and the development of a public alert system.
Enhanced building codes	The city updated its building codes to require more flood-resistant construction methods and materials, and to require that new buildings be constructed at higher elevations.	The city updated its building codes to require more flood-resistant construction methods and materials, including elevating buildings in flood-prone areas and requiring hurricane straps and reinforced roof decking.		
Implementation of flood control measures	Houston's leaders also implemented several measures to control flooding, including the construction of additional detention ponds, the installation of larger storm sewers, and the creation of new floodplain maps.			
Investment in infrastructure		The city invested in strengthening critical infrastructure, such as wastewater treatment plants and electrical	Houston's leaders have invested in strengthening critical infrastructure, such as wastewater treatment plants and	Houston's leaders have invested in strengthening critical infrastructure, such as wastewater treatment plants and electrical substations, to make

		substations, to make them more resilient to storms.	electrical substations, to make them more resilient to storms.	them more resilient to storms.
Focus on buyouts and home elevations			The city has also focused on buying out homes in flood-prone areas and elevating existing homes to reduce flood risk.	The city has also focused on elevating existing homes to reduce flood risk.

Overall, from this research project, the expectation is that readers of this paper will gain a more in-depth understanding about the Houston Metropolitan Area's disaster historical background which briefly explains the area's geographic foundation, history of hurricanes and severe storms. Additionally, readers will be apprised of the locations of physical characteristics of the area that contribute to increased risk from the four major disasters, as well as, from the analysis conducted, also be more aware of the human impact caused in the region by these four natural disasters. By understanding these prior disasters, Houstonians can better prepare themselves for the next major hazard occurrence that will, someday in the future, impact the city.

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