ENGINEERING THE DISASTER: A DISCUSSION OF TRENDS IN NATURAL HAZARD MANAGEMENT USING CASE STUDIES OF NEW ORLEANS, LOUISIANA AND GALVESTON ISLAND, TEXAS

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<u>Abstract</u>:

Natural hazard management is the field of study that focuses on a wide variety of hazards, disasters, and how humans react to and mitigate these events. The main goals of hazard management include damage mitigation, disaster prevention, and ensuring the safety of those at risk. Humans tend to develop communities where resources are rich, but the surrounding environment can pose many hazards unknown to or under-heeded by these settlers. In response to unsustainable development, extensive engineering has been done to the surrounding landscape. This engineering can mitigate the effects of storm surge, extensive flooding, and subsidence, but often at the cost of the surrounding ecosystem. Furthermore, these technological fixes are rarely permanent solutions, and require more extensive engineering measures as cities expand and risk increases. This study uses case studies of New Orleans, Louisiana and Galveston, Texas to examine how their structural mitigation impacted their vulnerability and resilience in the event of natural disasters– primarily major hurricanes. New Orleans constructed an extensive levee system that failed during Hurricane Katrina and led to widespread flooding and deaths, while Galveston constructed a seawall in response to the hurricane of 1900 that has increased the barrier islands vulnerability to disasters in the future. This research concluded that these engineered structures are short term solutions to complex environmental problems, and a multi-pronged and environmentally conscious approach would potentially benefit both cities.

Key Words: natural disaster, natural hazard, engineering, mitigation, hurricane

Introduction to Natural Hazards:

Scale is a necessary tool that geographers utilize to conceptualize and categorize our environment and its actions and can be thought of as the extent, reach, or magnitude of a phenomenon. Scale is an essential consideration in a variety of geographical fields, including: geographic information systems (GIS), remote sensing, environmental management, and especially natural hazards studies. The scale at which a natural disaster occurs can drastically change the outcome: for example, a tropical storm that grazes the tip of Florida will impact a much smaller scale of people and property than a larger Category 5 hurricane that hits the panhandle.

The approach we use to study natural disasters and hazards has shifted in recent years. Historically, humans have tended to focus solely on the disaster itself and either avoid the hazard entirely, or make temporary repairs to reoccurring problems (Smith and Petley 2009). Now, instead of relocating to less hazardous areas, humans engage in extensive engineering projects to raise cities, bind or divert rivers, and prevent flooding. These alterations to the landscape often come at the expense of local ecological functions and aesthetic qualities and can exacerbate the very problems the structures are attempting to remedy. It is common thought in natural hazards that every engineered solution fixes one problem but causes another.

The focus of this research will be on two cities that demonstrate the complexities of unsustainable development and human engineering in response to natural hazards. New Orleans, Louisiana and Galveston Island, Texas have both been extensively engineered to mitigate the effects of natural hazards, and are facing new challenges with their historic decisions to build seawalls and levees instead of relocating in their founding years when the hazards of the location were identified. New Orleans's hazard mitigation structures worked to increase the destruction associated with Hurricane Katrina when many of the levees failed and the Mississippi River inundated large portions of the city. In Galveston, the seawall has successfully prevented storm surge inundation for nearly a century, but a proposal to extend the seawall after damages from Hurricane Ike may lead to consequences similar to those seen in New Orleans after Hurricane Katrina. An extensive case study between the two cities comparing their development and structural protections can demonstrate some of the potential impacts of extensive engineering against natural disasters.

Definitions and Concepts:

Natural hazards and natural disasters are intertwined. The study of natural hazards focuses on the potential risk involved with humans living in range of the natural processes required for Earth to function. A natural hazard can be defined as a naturally occurring or human-induced process with the potential to create loss, or a general source for future disaster (Smith and Petley 2009). It is important to note that hazards are human based. Flood plains, earthquakes, hurricanes, and volcanoes only become "hazards" once humans live on or interact with these features.

Many aspects of our environment that we may consider benign can quickly shift into hazards once they act outside of our predictions. Flood plains are resources utilized by farmers for their fertile soil until an unusually heavy flood destroys farms, and nearby houses and towns. Forest fires naturally refresh an ecosystem and allow new vegetation to reproduce and grow, but can also ignite nearby residential areas. Coastal property allows communities to create shipping ports and utilize marine resources until completely washed away by a hurricane. The risk involved with living near these hazards is perceived differently by every community.

Related to risk is the study of risk perception, or how humans interpret the environment and the natural hazards around them. Risk perception is based on the individual: it mainly stems from personal experience and anecdotal theories (Burton, Kates, and White 2005; Smith and Petley 2009; Davis et al. 2013; Hector et al. 2016; Henrich, McClure, and Doyle 2018). Risk perception studies help hazard managers to understand what their community regards as an actual risk and allows for better mitigation techniques and management strategies. If a community does not regard a hazard as a risk it is difficult to establish effective preventative measures against the hazard, and the risk to a community increases greatly.

The importance of risk perception can be demonstrated through the consideration of disaster outcomes. For instance, prior to the Galveston hurricane of 1900, the Galveston residents did not perceive how severe the risk of hurricanes were to the island. The residents were aware of the risk for milder tropical storms or smaller, slower hurricanes, but not of the risk for intense, severe hurricanes like that of the hurricane of 1900s scale. It was not until after the hurricane left more than 3,600 homes destroyed and between 8,000 – 12,000 people dead that the residents realized the true risk of hurricanes to the island and took preventative measures. These measures included the erection of a 16ft seawall and artificially raising the city 17ft above sea level to mitigate their risk and decrease their vulnerability in the future (McElreath et al. 2017)

Vulnerability in natural hazards refers to the capacity of a population to cope with conditions, events, or situations that threaten to overwhelm infrastructure, individual people, or social systems. Different populations face different levels of vulnerability based on economic, social, and environmental factors (Cutter 1996; Blaikie, Wisner, and Cannon 2003; Burton, Kates and White 2005; Parsons et al. 2006; Coles and Quintero-Angel 2018). Although related to risk, the vulnerability of a community is reflected more in resilience and recovery rather than total losses or damage capabilities. The vulnerability of a community directly relates to natural and social factors.

People who are economically disadvantaged are more likely to live in areas with greater risk, thus increasing their vulnerability (Blaikie, Wisner, and Cannon 2003; Comfort et al. 2011; Coles and Quintero-Angel 2018). Socioeconomic standing often forces people to live in regions that are more likely to be affected by natural hazards and increases their vulnerability to disasters (Blaikie, Wisner, and Cannon 2003). Furthermore, the vulnerability and risk experienced by less developed countries (LDC) is much different than the types of vulnerability and risk experienced by more developed countries (MDC). An LDC can expect high mortality rates after a natural disaster, mainly because warning systems, shelters, and evacuation options are not as developed as those expected in an MDC, where the main losses are in property and economic forms. (Smith and Petley 2009; Blaikie, Wisner and Cannon 2003).

Finally, this thesis will discuss two major hurricanes and use descriptions including categorical placements on the Saffir-Simpson scale. This scale was introduced to help communities understand what type of damages to expect from a hurricane. Though earlier versions of the scale included factors such as storm surge and rainfall estimates, but their lack of accuracy lead to their removal in 2009. The most updated scale is the Saffir-Simpson Hurricane Wind Scale which is demonstrated in Table 1.

Table 1. *The Saffir-Simpson Hurricane Wind Scale adapted from NHC.*

Category	**Sustained Wind Speed**	**Expected Damages Due to Hurricane Winds**
1	74-95 mph 119-153 km/h	Some damage: minor roof damage, small trees toppled, power may be out for several days.
2	96-110 mph 154-177 km/h	Extensive damage: major roof damage, shallowly planted trees uprooted and fallen, near total power loss for days or weeks.
3 (major)	111-129 mph 178-208 km/h	Devastating damage: severe roof damage, many trees snapped or uprooted, power and water loss for days or weeks.
4 (major)	130-156 mph 209-251 km/h	Catastrophic damage: roofs may be removed and exterior walls may be damaged, most trees uprooted or downed, total power loss for weeks or months. Uninhabitable.
5 (major)	157 mph or higher 252 km/h or higher	Catastrophic damage: many framed homes will be destroyed, fallen trees will block roads, power loss for weeks or months. Uninhabitable.

Source: National Hurricane Center

History of Natural Hazard Management:

Natural hazard management is constantly changing the scale and focus of management plans to continuously minimize risk and vulnerability while increasing a community's resilience. Table 1. adapted from Smith and Petley (2009) briefly explains the different paradigm shifts that natural hazards studies have taken and what ideas emerged to progress this evolution. It is important to understand the different paradigms, as they create a strong foundation that modern-day hazard management systems are built upon, and begin to introduce why we use the trends seen in hazard management today.

Table 2. *The evolution of Environmental Hazard Paradigms adapted from Smith and Petley 2009*

Period	Paradigm Name	Main Issues	Main Responses
Pre-1950	Engineering	Where are natural disasters occurring and what can we build to prevent them?	Use the latest technology to engineer structures to prevent natural disasters.
1950-1970	Behavioral	Why do natural disasters occur and how are human decisions impacting disasters?	Encourage less development in hazardous areas to prevent natural disasters.
1970-1990	Development	How are people with lower socioeconomic standing affected by natural disasters?	Increased awareness in vulnerability of people with lower socioeconomic standing.
1990-Present	Complexity	How can we mitigate against natural hazards in sustainable and environmentally conscious ways?	Greater understanding of ecological functions with reduced dependence on engineering mitigation.

Source: Smith and Petley 2009.

The Engineering Paradigm (Pre-1950)

Historically, hurricanes, volcanic eruptions, and earthquakes were thought to be 'Acts of God', and were to be avoided when at all possible. There was little understanding of natural hazards in this paradigm, and instead of scientific study many cultures depended on religious interpretation to explain the world around them (Donner 2007). A lack of scientific understanding and a belief that natural disasters occurred at the whims of a deity helps explain why civilizations were developed in floodplains, on fault lines, and even atop active volcanoes. During this time, humans focused on engineering solutions to natural hazards and used the latest technology to develop structural responses to natural disasters (Smith and Petley 2009) The concept of a 'technological fix' was introduced, and examples of its effectiveness are seen in modern dams, buildings that can withstand earthquakes, and in places like Galveston, TX, and New Orleans, LA, where extensive engineering is required to keep the cities functioning and out of flood waters.

Though the engineering paradigm allowed communities to continue to develop and minimized the risk of frequent, minor disasters involved with living in these areas, the technological developments increased the risk for major catastrophe should those engineered structures fail. For example, when constructing a dam to mitigate against flooding along a river, the risk for floods decreases because the river is now theoretically controlled. However, if the dam were to break or be overwhelmed by uncharacteristically high levels of rainfall, the resulting flooding to an unprepared community downstream could be catastrophic. In addition, the areas upstream that may have been inhabited are now completely inundated by the dammed reservoir.

Although it has been discovered that while these fixes can effectively mitigate against one risk, it often does so at the expense of local ecological functions. Large seawalls interrupt natural sand dune patterns, allowing the natural beach to erode (Fletcher 2011; Beuzen et al. 2018). The technology that allowed the city of New Orleans to be built at the delta of the Mississippi River cannot stop the city from subsiding into the wetlands that are being washed away without sediment replenishment (Dokka 2011). Though we are seeing the ramifications of utilizing engineering and technology to fix an environmental hazard, these approaches are still used today to protect property and minimize economic loss (Larson and Plasencia 2011; Smith and Petley 2009; Fletcher 2011).

Behavioral Paradigm (1950-1970)

Gilbert White is regarded as the father of floodplain management and introduced the idea that unsustainable development leads to natural disasters (White 1945, Kates and Burton 2008). While other research at this time focused on preventative techniques, White was the first to link humans to natural hazards. In the 1930's, White famously said, "Floods are acts of God, but flood losses are largely acts of man. Human encroachment upon the flood plains of rivers account for the high annual total of flood losses" (White 1945; Kates and Burton 2008). In his 1945 thesis, *Human adjustment to floods: a geographical approach to the flood problem in the United States*, White introduced eight types of human adjustment, or adaptive management strategies, for public policymakers to consider: elevating land, abating floods by land treatment, protecting against floods by levees and dams, providing emergency warning and evacuation, making structural changes in buildings and transportation, changing land use to reduce vulnerability, distributing relief, and taking out insurance. Mainly, White wanted policy makers to consider a wide range of options and for policy makers to weigh the social costs and benefits to any approach (Kates and Burton 2008).

White introduced the connection between hazards and humans, and how decisions humans make can impact the disasters they face (White 1945; Smith and Petley 2009; Macdonald et al. 2011). White's ideas are still very relevant in hazards management today, notably in the decreasing of development in extremely hazardous areas. His research also gave rise to an even more human-based and complex paradigm, the developmental paradigm.

Developmental Paradigm (1970-1990)

The developmental paradigm explored the connection between socio-economic vulnerability and hazards. Essentially, people who are more vulnerable to economic or societal risks also face a greater vulnerability to risks associated with natural hazards (Blaikie, Wisner, and Cannon 2003). The example of the 1974 Guatemalan earthquake, locally known as the 'class-quake,' demonstrates this idea. The economically disadvantaged communities in this region lived on steeper slopes, were less situated, and had homes made of weaker material than the neighboring middle-class neighborhoods. When the earthquake struck, the highest rates of mortality were found in the poorer communities, and the lack of protection or means of improvement left them more vulnerable to another disaster (Blaikie, Wisner, and Cannon 2003).

The developmental paradigm was fundamental in expanding our understanding of disasters globally. Studies of LDC's furthered our understandings of the limitation of technology and how technology can worsen a problem by allowing more people to occupy hazardous areas (Burton, Kates, White 2005). Furthermore, the developmental paradigm called for more public action and reform to public policy in response to natural disasters (Comfort et al. 2011). People in vulnerable situations face greater adversity in the face of natural disasters, and the demands for change while creating sustainable solutions lead to the complexity paradigm.

Complexity Paradigm (1990-Present)

The complexity paradigm blends the previous paradigms together into one comprehensive and adaptable management plan (Li, 2000; Smith and Petley 2009; Parsons et al. 2016; Coles and Quintero-Angel 2018; Habibian and Minaie 2018; Goble, Bier, and Renn 2018). After acknowledging the human aspect of natural hazard studies, natural hazard researchers began to study how we can mitigate the effects of hazards with an emphasis on helping the least privileged communities (Smith and Petley 2009; McMillen, Ticktin, and Springer 2017; Coles and Quintero-Angel 2018). This paradigm is focused on a holistic understanding of landscapes, sustainable development, audits of current management systems, and an understanding of cultures and community dynamics (Li 2000; Coles and Quintero-Angel 2018; Goble, Bier, and Renn 2018). A more holistic understanding of the landscape and the cultures that inhabit it can minimize the amount of engineering required in cities to prevent against hazards and potentially reverse the damages to the environment caused by human interference. Though this paradigm theoretically should mean wiser decision making skills, it is still in developmental stages and is only recently being referenced to in modern publications and city plans.

The Case Studies

Two cities in particular demonstrate a pattern of unsustainable development and human engineering. New Orleans, Louisiana was built on the sediment deposits of the Mississippi River, and most of the city sits below sea level. The city has had to build multiple dams and levees, as well as install pumping stations just to keep the city from completely flooding in response to heavy rains and storm surges from hurricanes (Colten 2006). Similarly, Galveston was settled on a small barrier island off the southeastern coast of Texas. This was before the settlers knew about the severe hurricanes that can strike the Gulf Coast, and in 1900 a Category Four hurricane struck the island and caused between 8,000-12,000 deaths (McElreath et al. 2017). The citizens decided to raise the island 17ft and build a 16ft sea wall to prevent the same catastrophic danger in the future (McElreath et al. 2017).

While the engineered structures in both these cities did prevent losses originally, new issues have stemmed from these technological "fixes". Dune erosion, wetland degradation and city subsidence all stem directly from these engineering fixes and require more human intervention to resolve.

<u>New Orleans: The Sinking Crescent</u>

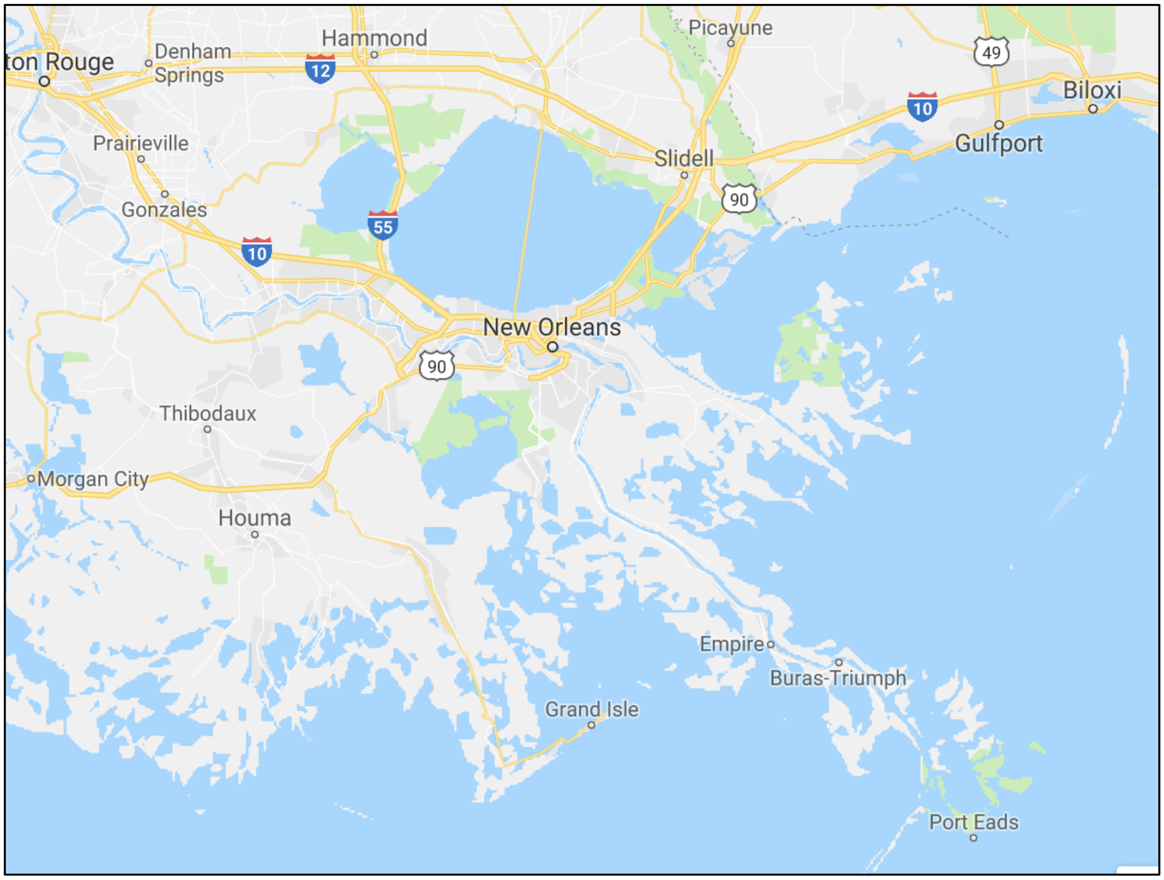

Figure 1. *The city of New Orleans, Louisiana*
Source: Google Maps

The city of New Orleans is sinking (Burkett, Zilkosi and Hart 2001; Dixon et al. 2006; Dokka 2011). This subsidence, or gradual sinking, is occurring for a variety of reasons, including pumping of groundwater; the introduction of dams and levees; and wetland barrier island degradation (Burkett, Zilkosi and Hart 2001; Dixon et al. 2006; Dokka 2011). The geography of New Orleans is important in understanding how and why these changes are making the city more vulnerable to extreme flooding.

New Orleans, Louisiana, was settled atop of a sediment load that had been built up over millions of years from fluvial deposits that were picked up in the northern river basin and deposited downstream by the Mississippi River. Soil from within the country's central drainage basin (Figure 2) gathered and traveled downstream until slowing and settling to the river floor, building up to create points of dry land between the marsh (Freudenburg et al. 2012). The French fort that founded the city was build atop a natural levee (from the French word, *lever,* "to raise") remaining from a historic route the river used to flow. Naturally, rivers like to meander and change course over time by taking the path of least resistance. This process leaves behind many natural levees like the ones New Orleans was founded upon. This relative height difference provided by the natural levees did not stop this area from flooding—rather, it was simply the area that drained the quickest (Freudenburg et al. 2012).

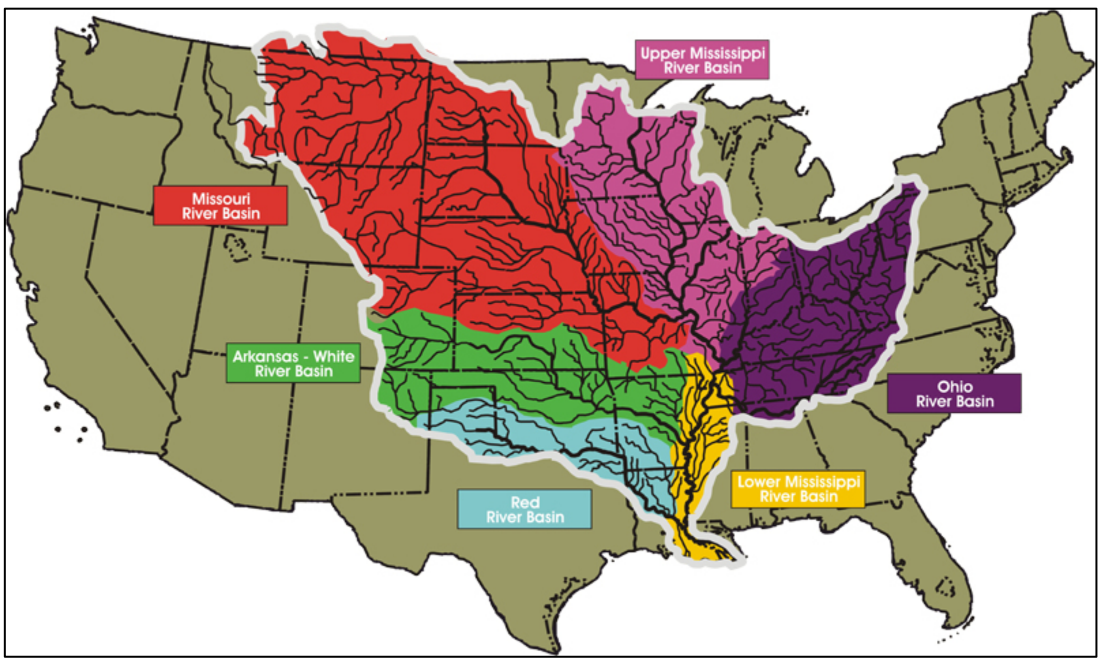

Figure 2. *The Mississippi River Basin and drainage path to New Orleans*
Source: Mississippi River Commission

The French wanted to secure this location for transport and trade, and New Orleans became an important trade city based on its location along the Mississippi River (Colten 2006). Though economically advantageous, the site introduced numerous environmental hazards, notably the lack of higher ground for expansion. The city had to expand outward from what is now Vieux Carré (Old Square) and descend in elevation into the surrounding swamp (Freudenburg et al 2012; Colten 2006). Though initial developments depended on two additional natural levees, the Metairie and Gentilly ridges, these patches of high land within the city were not sufficient for the large amounts of growth the city would experience (Colten 2006). Today, most of the city is below sea-level and stands over drained wetlands and marshes.

This urbanization required extensive draining and development atop the natural sediment load on which the city stood. However, same fluvial processes that deliver sediment to the mouth of the Mississippi also erodes the deposits out to sea, and in order for the land to remain stable the sediment load must be replenished regularly (Freudenburg et al. 2012). The development of dams and levees across the landscape drastically slowed this process, especially a series of dams along the Missouri River that decreased sediment deposits by seventy to eighty percent (Freudenburg et al. 2012). This lack of replenishment is causing the land beneath the city to be literally washed to sea, and current rates have the city subsiding at rates of about 8 millimeters per year when including the 2 millimeters per year rise in sea level (Dixon et al. 2006). This subsidence is causing roads, businesses, and homes to crumble at the foundations, and leaves them at risk for additional damages in flood events.

The subsidence is not only impacting the urban developments, but the natural ones as well. Wetland degradation is occurring at United States Geological Survey (USGS) estimates of 32 to 10.8 square miles of wetland loss per year (Couvillion et al. 2017). Though this loss is not occurring at a constant rate, if it were, it would be equal to losing a football fields' length of wetland every 34 minutes (Couvillion et al. 2017). This loss impacts the Louisiana coast in a variety of ways: loss of ecosystem for commercial fish, loss of recreation space, loss of environmental green space, and, perhaps most importantly, loss of storm surge buffering.

The wetlands act as a buffer against hurricanes and strong storms. Wetlands can reduce storm energy and absorb the storm surges that cause extensive flooding (Batker et al. 2010). The barrier islands that provide this benefit have been essentially washed away, but reinforcing the natural wetland system is still possible and highly recommended. Some studies have even placed a monetary value on the function and damage prevention of wetlands, with one hectare of wetland loss equaling about USD 33,000 increase of storm damage (Costanza et al. 2008). This values the coastal wetlands in the United States at about USD 23.2 billion per year in storm prevention services (Costanza et al. 2008). Reestablishing the wetlands would decrease sediment erosion, decrease a dependence on levees and electric-powered intercity pumps, and increase the ecosystems health and vitality (Batker et al. 2010; Day et al. 2007). In addition, these storm-prevention measures rely on natural processes instead of fossil fuels that factor into climate change and increase the rising sea levels that the city is engineering against.

The French settlers began constructing levees in 1727 (Colten 2006). Though then only 4 feet high, it demonstrates how immediately humans began to change their environment to mitigate their hazards. The levees served to prevent the Mississippi from flowing into the city, but failed to account for the flooding that may come from Lake Pontchartrain behind the city. The levees also prevented water from leaving the area, necessitating the need for more levees to now protect the rear of the city (Colton 2006). Once residents realized that when the river constrains in width it grows in height, the levees were raised to 6 feet, and eventually to around 15 feet in height. Thus, began the race of engineering against nature that remains today in New Orleans (Colten 2006)

To encourage natural drainage and increase trade, the city dug a series of canals into the heart of New Orleans (Freudenburg et al. 2012). The first of these canals, the Carondelet Canal was developed in 1794, preceding the London Avenue, 17th Street, and Industrial Canals that were dug in later years (Freudenburg et al. 2012). Then, in the early twentieth century A. Baldwin Wood designed the heavy-duty Wood Screw pump that allowed the city to have its floodwaters pumped out of it (Freudenburg et al. 2012). With this pump, the city drained the areas surrounding the canals and began to develop housing on this recently unearthed land. With these new homes came the need for even more levees and flood guards.

Figure 3. *The A. Baldwin Wood Screw Pump in Pumping Station No. 6 in New Orleans.* Photographer: Benjamin D. Maygarden for US Army Corps of Engineers

Over the past 288 years, the city of New Orleans has faced an average of one river or hurricane induced disaster every 11 years, and breeching events that occurred in 1816 and 1849 foreshadowed the flooding that came with similar levee breaches during Hurricane Katrina (Kates et al. 2006). Another notable flood occurred in 1927 when the Great Mississippi flood threatened New Orleans caused the Army Corps of Engineers to intervene and assume responsibility for all future levee development (Kates et al. 2006; Freudenburg et al. 2012).

Figure 4. *The 17th Street Canal and flood walls in New Orleans before Hurricane Katrina.* Source: The Times-Picayune

The Army Corps of Engineers constructs and maintains the levees throughout the city of New Orleans. Prior to Katrina, the corps attempted to construct higher levees throughout the canal system, but were met with resistance from residents (Freudenburg et al. 2012). Levees that are broader at the base to form a point at the peak require much more land than a simple flood wall, and residents were hesitant to give property up for the city. Floodwalls do not have the same structural support as levees, and instead are simply concrete walls supported by steel that are driven into ground (Freudenburg et al. 2012). They are less effective than levees, but take up less private land from homeowners (Freudenburg et al. 2012). When Katrina made landfall in 2005, much of the flooding stemmed from areas that were protected with these flood walls that failed under the immense stress of the storm surge.

Figure 5. *The 17th Street Canal and floodwalls in New Orleans after Hurricane Katrina*

Hurricane Katrina was the disaster bound to happen based on the unsustainable development and human engineering of New Orleans. Hurricane Katrina was the 1st largest in terms of total size and 3rd strongest hurricane to hit the United States. Though originally a Category 5 storm, Katrina weakened to a Category 3 just before making landfall in August 2005. Hurricane Katrina caused 1,570 deaths of Louisiana residents and USD 40-50 billion in monetary losses (Kates et al. 2006). Many of these deaths resulted from the heavy flooding that occurred, especially those in Lower Ninth Ward who lived near the Industrial Canal. Here the canal was supported with floodwalls instead of higher levees, and once the flood waters breached the floodwall, a trough of water was dug behind the supporting walls (Freudenburg et al. 2012). With the supporting soil washing away, the surmounting pressure eventually lead the wall to topple and be pushed 170 feet east of its original location (Freudenburg et al 2012). Not only was the entire area flooded with a wall of water, but the wall itself caused catastrophic damage as it tore through the community and hit homes, cars, and other debris in its path.

Figure 5. *The Industrial Canal spilling into Lower Ninth Ward in New Orleans, Louisiana after a flood wall failed during Hurricane Katrina*
Source: National Public Radio

The levees not only failed because of a miscalculation in design, but also because modern levee plans fail to account for the widespread subsidence occurring within the city (Burkett, Zilkoski, and Hart 2001). According to the Army Corps of Engineers, modern levee design heights are adequate for protection against a Category 3 hurricane, or about 4.5-6 meters above mean sea level (Burkett, Zilkoski, and Hart 2001). However, when accounting for subsidence and sea-level rising, many of these levees are below designated heights (Figure 3). In some instances, subsidence has lowered some of these floodwalls by up to 2 feet (Freudenburg et al. 2012).

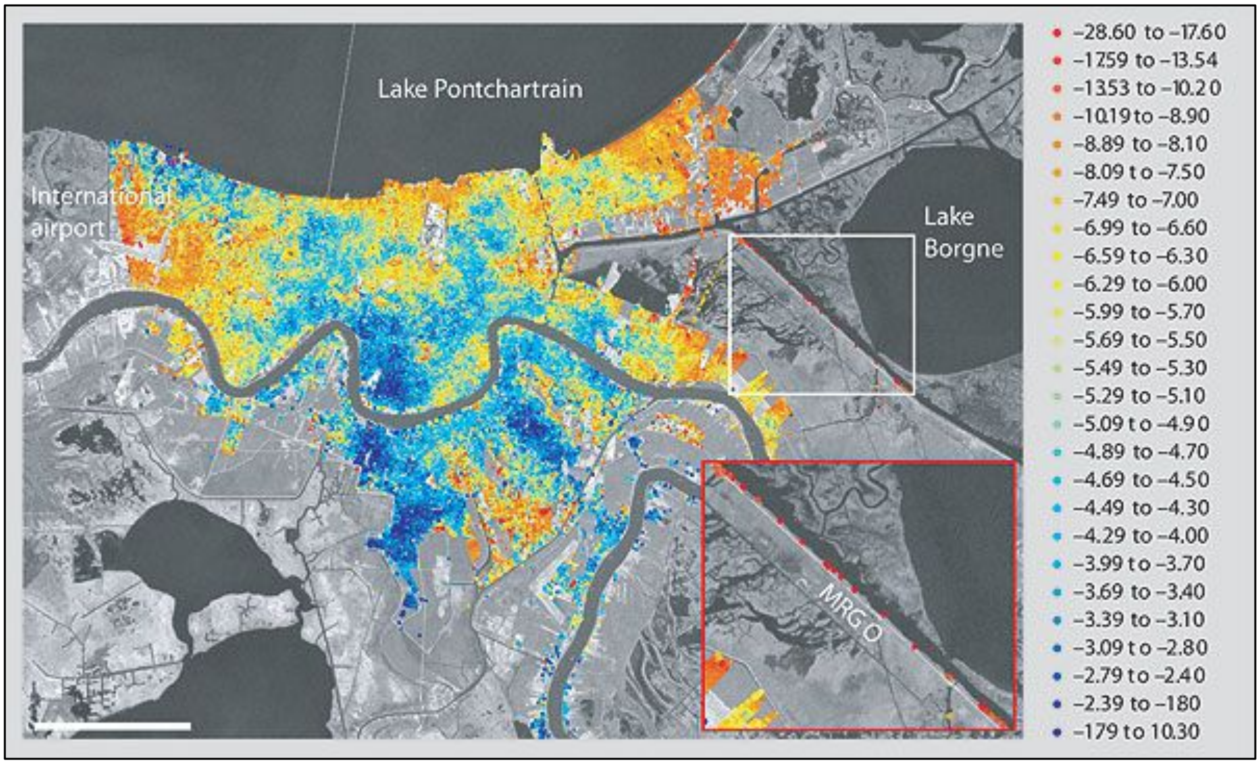

Figure 6. *Map showing rate of subsidence in New Orleans. Velocity values are given in millimeters per year as range change in the direction of radar illumination. Negative values indicate motion away from the satellite, consistent with subsidence. Many floodwall failures occurred along the MRGO canal.*
Source: Dixon et al. 2006

Figure 6. demonstrates how subsidence and levee failure may be related. The color-coded ranges next to the map indicate levels of subsidence over one year. The areas along the Mississippi River-Gulf Outlet (MRGO) canal (in red) have subsided over more

than 20mm within a year, meaning without constant rebuilding and improvements the levees lose their effectiveness with each passing year.

The factors that led to disaster in New Orleans can be traced back through years and years of policy and structural decisions. The installation of the original levees eventually lead to a development of more levees, then a pumping system to distribute the water built up in the city from the levees. The canals that were intended to incite trade and drain water out of the city have inundated communities and allowed the natural wetland barrier to be eroded away into the sea. As noted earlier, the practices that are meant to lower the hazard of an area can greatly increase its risk of greater disaster. As seen in the case of New Orleans, unsustainable development coupled with human engineering can at times lead to catastrophic disaster, and this is not the only city that deals with these consequences of its environment.

Galveston: The Raised Island

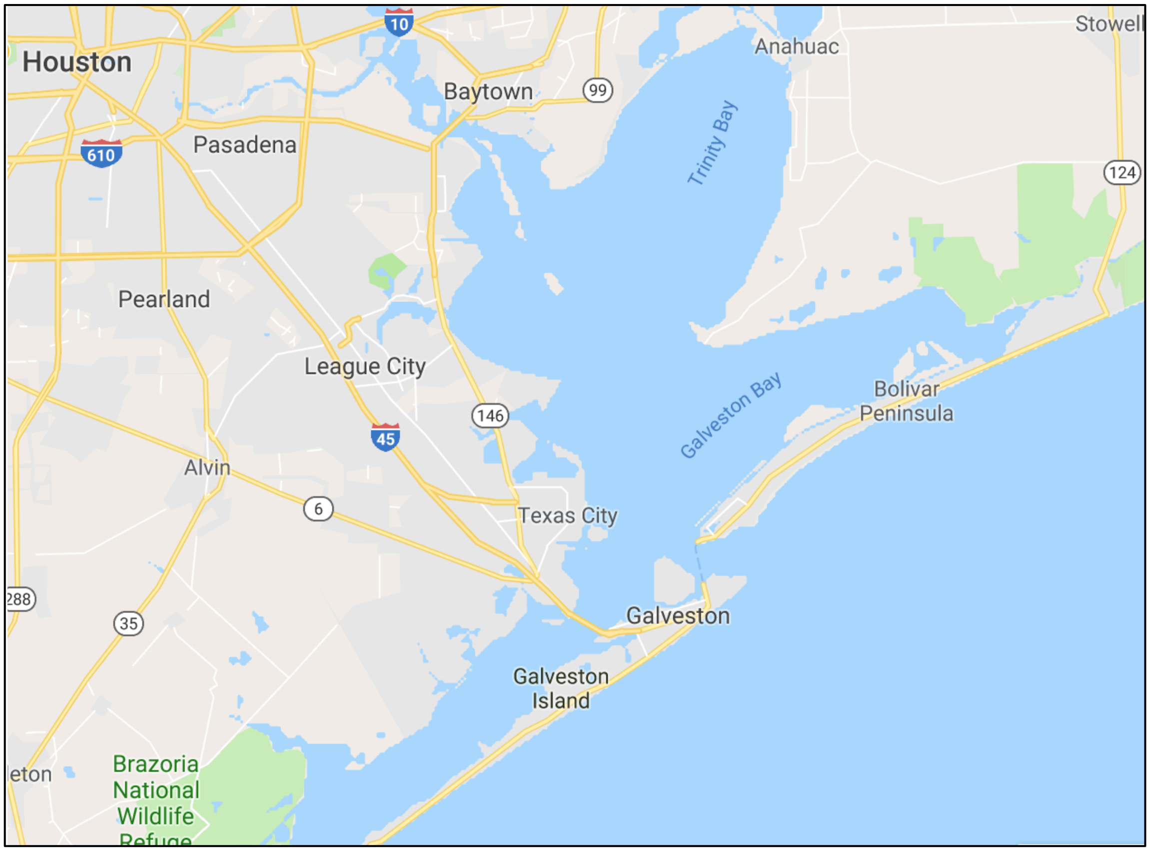

Figure 7. *Galveston Island, Texas*
Source: Google Maps

The city of Galveston has a prominent history in Texas. First occupied by the Karankawa as early as 1400, the island was never truly settled until after Texas declared its independence from Mexico in the early 1800's (Cartwright 1998; Bixel and Turner 2000). Named by Mexican soldiers in 1785, the island was called "Bahia de Galveztown" for the viceroy of Mexico Don Bernardo de Gálvez (Bixel and Turner 2000). When Stephen F. Austin brought Texan settlers into Mexican territory in 1825, the island was designated as an official port of entry for Mexico, and once Texas gained its independence in 1836 the area flooded with immigrants and new settlers (Bixel and

Turner 2000; McComb 2000). According to the U.S. census, in 1880 the island was home to 22,000 inhabitants.

Known as a safe harbor for militaries and shipping industries, Galveston quickly became an important port city in the mid-nineteenth century. Galveston ports exported cotton, hides, sugar, molasses, honey, cattle, and pecans to New Orleans, New York, and Great Britain, and imported goods such as cloth, boots, iron, coffee, books, gunpowder, bullets, and guns for local farmers and plantation owners (McComb 2000). Large cargo ships could not maneuver through the shallow Galveston bay, so outside the harbor goods were transferred to small steamboats to ferry the goods to Galveston port (McComb 2000).

The same processes that built Galveston Island are simultaneously trying to wash it away. Galveston is a sandbar formed from sediment deposits carried through the inland drainage basin into the bay. The tide similarly washes and pushes this sand down the beach front, and eventually either accumulating in sand bars in the bay or developing along human made structures. The people of Galveston quickly realized this process of sedimentation when the Galveston harbor entrance became blocked by developing sandbars (Bixel and Turner 2000; McComb 2000; Antrobus 2005).

Galvestonians were concerned over the developing sediment because in 1880 Houston had emerged as a potential economic rival and cargo ships could sail directly to Houston instead of waiting in the harbor as steamboats carried their goods to the railyards (Bixel and Turner 2000). The sand bars could potentially cause ships to run aground and posed a huge safety concern to the shipping industry. In 1881, the Committee on Deep

Water formed and decided to build twin five-mile long jetties: a southern one extending from east Galveston, and a northern one extending from west Bolivar.

Jetties work to prevent the sand from washing down the beach and into the harbor channel by creating a barrier that allows the sediment to accumulate. The jetties do not allow sand to travel naturally down the shoreline and while they do keep sediment out of the harbor system they also starve the beaches that depend on replenishment from tidal processes (Cartwright 1998). As figure 4 illustrates, an installation of jetties will often necessitate the need for more groins—jetties come in pairs are used when aiding navigation, groins are singular structures but with the purpose of limiting sand erosion– to allow accumulation on the now starved beaches and the cycle will continue down the inhabited coast line.

Jetties also compress the current into a smaller area. As seen in Louisiana with the confining of the Mississippi River this compression increases the velocity of the current and allows for greater scouring effects. In Galveston, the installation of the sandstone jetties kept the harbor clear and allowed for greater trade, and even deepened the harbor over many years. In 1895, amid construction the scouring effect already deepened the harbor from 12 feet to 17 feet, and completely washed away an inner sandbar which deepened the harbor from 9 feet to 24 feet (Baker 1986). By 1900, the depth of the harbor was between 25 feet and 28 feet, demonstrating the massive impact these engineered structures had on the Galveston coastline and surrounding environment (Baker, 1986). The success of the jetties led the people of Galveston to rely on engineered structures to alter the landscape instead of assessing the risks and hazards associated with living on a sandbar. This false sense of security given by the jetties would bleed into hazard management decisions well into the future, most notably after the unnamed 1900 Hurricane.

Figure 8. *The groins along the seawall in Galveston Island, Texas*
Source: The Texas General Land Office

Before the Galveston Hurricane of 1900, the people of Galveston knew of hurricanes that could strike the island but were relatively unaware of the severity of the storms. On September 8th 1900, the Category 4 hurricane swept across Galveston Island with wind speeds of 120 miles-per-hour and a 15-20 -foot storm surge (Cartwright 1998;

McComb 2000; Antrobus 2005; McElreath 2017). At the time, the highest point of Galveston Island was about 8 feet, but this slight elevation did not provide much safety as the entire island was submerged under water. It has been estimated between 6,000 to 12,000 people died in the storm making it the worst natural disaster in United States history (Cartwright 1998; McComb 2000; Antrobus 2005; McElreath 2017). An official count was difficult to retrieve because of the immediate need to dispose of bodies and confusion over relief tactics (McElreath 2017). Inconsistencies in counting came from bodies being washed back to shore after being washed to sea during the storm, people being trapped and lost under debris, and from purposefully throwing bodies to sea only to have them wash back to shore days later (Cartwright 1998; McComb 2000; Antrobus 2005; McElreath 2017). Many of these people were recounted or never counted at all, leading to the wide discrepancy of total deaths.

The hurricane of 1900 was catastrophic for a variety of reasons. For one, the geography of the location made it very susceptible to disaster. The island community was established atop a sandbar with the Gulf of Mexico in front; Galveston Bay behind. Galveston Bay separated the island from the mainland by approximately 25 miles, and once the storm surge began to wash in the people of Galveston were completely stranded (Cartwright 1998; McElreath 2017). This lack of evacuation route vastly increased the hazard and risk of living on the island, and lead to many otherwise preventable deaths. It also made it difficult for aide to reach the island immediately following the disaster, leaving people trapped, injured, and hungry for days after the storm (McElreath 2017).

As the hurricane neared the island, only meteorologist Isaac Cline understood the rapid incoming tide as a warning. As the tide rose, some people took to the streets to wade in the waters, watch the waves crash against roads and buildings, and children played in the streets in front of their homes (Cartwright 1998). With adequate education and warning systems, it is possible people could have been evacuated or moved to higher ground before the surge completely overtook the island. Along with education comes communication. As the storm surge flooded the island the telegraph lines were destroyed, completely cutting off contact with the outside world to alert them to the ruin that Galveston was in (McElreath 2017).

Like Louisiana following Katrina, the lack of a natural barrier on Galveston Island increased the damages that occurred in result of the storm. Before the development of the island for trade and commerce and the engineering of the jetties, the Gulf shore of the island was bordered by 12-15-foot-high sand dunes, offering a level of protection that was washed away as development increased (Antrobus 2005). Again, the engineering of a landscape eventually had consequences that led to increased devastation after a major natural event and allowed for increased unsustainable developments along the coast line. Though now it is easy to see how engineering and unsustainable development played a role in the devastation following the hurricane of 1900, the people of Galveston had just faced a traumatizing catastrophe following the success of an engineering work to protect the harbor. Their actions following the 1900s hurricane were intended only to save lives in the event of another hurricane, and in this area, they succeeded.

Immediately after the hurricane of 1900, the Deep Water Committee that was responsible for forming the jetties that protected the harbor overtook the previous government of Galveston Island (McComb 2000; Hansen 2007). Their first act was to assign a team of engineers to develop a plan to keep the city safe from future disaster.

The resulting plan included constructing a 3-mile-long and 17-foot-high seawall along the Gulf shore of the island (Hansen 2007). In addition, the engineers recommended raising the island by 17 feet to match the height of the newly constructed seawall (Hansen 2007).

The raising of the island was a massive engineering endeavor that required extensive dredging for sand to fill the underneath of houses, businesses, and roads. In this instance, the engineers had the foresight to understand that where they dredged for this material could have impacts on the island in future years. At first, it was thought that dredging the seaward side of the island would be most efficient, but engineers foresaw that extensive dredging in front of the seawall may cause scouring around the seawall (Hansen 2007). They eventually decided to dredge between the jetties at the entrance of Galveston's harbor—dredging here would allow the engineers to get all the sediment required while also deepening the harbor to encourage more trade from larger vessels (Hansen 2007).

The construction of the seawall proved its worth in 1915 when another hurricane hit the island and dramatically reduced the loss of life—from 6,000-12,000 deaths down to 275 (Hansen 2007). In subsequent years, the seawall was extended to protect more of the island and today stretches 10.3 miles. In addition, an all-weather causeway was constructed in 1912 to allow access from the island to Houston (McComb 2000). Clearly, the island had learned the consequences of living on a sandbar surrounded by hazard but the actions taken to mitigate their risk may leave them more vulnerable to disaster in the future.

Since the construction of the seawall the beach in front of it has vastly eroded. In 1904, the seawall had 300 feet of beach in front of it but after the hurricane in 1915 much of the beach had been washed away (Antrobus 2005). The fluvial processes that shifted the sand into the harbor now met a seawall that pushed the waves down against the shore, quickly eroding all the sand beneath it. By 1930, most of the shoreline before the seawall had been eroded away, so multiple groins were constructed from the seawall into the gulf to keep the sediment from washing away (Antrobus 2005). This erosion is detrimental to the safety and ecology of the island.

As discussed earlier, wetlands and sand bars act as natural buffers against hurricanes and provide many important ecological services (Batker et al. 2010; Day et al. 2007; Entwistle, Mora and Knight 2017). These wetlands and estuaries serve as fish and bird breeding grounds, storm buffers, and even commercial centers (Batker et al. 2010; Day et al. 2007; Entwistle, Mora, and Knight 2017). In Texas, more than a third of the state's population and 70% of its industry, commerce, and jobs are located within 100 miles of the coastline (Entwistle, Mora, and Knight 2017). Wetland loss puts many of these people at risk for greater damages following hurricane or flood events, and a current engineering proposal may place them at greater risk for catastrophe in the future.

Hurricane Ike hit the Texas Coast on September 13, 2008 as a Category 2 hurricane. With wind speeds of 110 miles-per-hour, the storm tore through downtown Houston and blew out the windows from the skyscrapers, causing extensive damage to the city's economic center (Merrell et al. 2010; Bedient et al. 2012). Though the hurricane winds did structural damage to the city, the rainfall brought by the storm was relatively low. However, Hurricane Ike had a 17.8-foot storm surge that nearly washed away the Bolivar Peninsula, and changed how the National Oceanic and Atmosphere Association (NOAA) categorizes hurricanes in future events (Merrell et al. 2010; Bedient et al. 2012).

The storm surge began to swell along Galveston Island 24 hours before Ike made landfall. The flooding not only happened along the gulf-side of the island, but also to areas within the bay and along Bolivar Peninsula (Bedient et al. 2012). The storm surge inundated the Bolivar Peninsula, picking up debris as it flooded in and using the same debris to cause more damage as the flood waters washed out to sea. Damage to Bolivar Island was catastrophic, and the very shorefront that the homes and businesses were built on was eroded away during the storm.

Environmentally, Hurricane Ike was a disaster. As discussed before, sand erosion and subsidence is a large problem in areas that are heavily dependent on both sediment loads and engineering structures (Dixon et al. 2006; Costanza 2008; Bedient et al. 2012; Freudenburg et al. 2012; Couvillion et al. 2017). Approximately 300 feet of beach was eroded to sea during Hurricane Ike, clearing the shore of its ability to form protective sand dunes (Bedient et al. 2012). This erosion is notable for the citizens of Houston. A Finite-Volume Coastal Ocean Model (FVCOM) conducted in 2010 demonstrated that if Bolivar Peninsula were reduced in height or volume by 45% the barrier island would have the same levels of protection as a barrier island of 0.05 meters above sea level (Rego and Li 2010). Essentially, if the Bolivar Peninsula is eroded away, Galveston Bay and the Houston area could be exposed to dangerously high water levels in subsequent hurricane events (Rego and Li 2010). In addition to the beach erosion, the saltwater intrusion from the storm surge turned the brackish, or mixed water, estuaries within

Galveston Bay into saltwater estuaries, killing many species and preventing the ecosystem from a recovering quickly (Bedient et al. 2012). Thousands of live oak trees died and 60 percent of the oyster beds in Galveston bay were lost (Bedient et al. 2012).

The only areas along the Galveston coast that did not suffer major damage were the areas protected by the 17-foot seawall (Bedient et al. 2012). This realization led the public to call for more extensive protective barriers to be put in place to protect the people living on the island, but also to protect Galveston Bay and the Houston Ship Channel from damage in the case of another Hurricane Ike-level storm surge. The widespread belief that the seawall only protected the island instead of contributing to the beach front erosion and the unsustainable development along the coast gave people the false assumption that more engineering mitigation would lessen their risk for hazard in the future.

The "Ike Dike"

The proposed "Ike Dike" came in response to the catastrophic storm surge caused by Hurricane Ike. The Ike Dike concept was created by Dr. William J. Merrell at the A&M University at Galveston. The structure proposed is "a coastal spine which would keep the Gulf surge out of Galveston Bay" (Merrell et al. 2010, pg. 698). The argument is since Galveston Bay is home to the largest and most biologically productive estuary in Texas, and to the expensive Houston Ship Channel, that storm surge needs to be completely prevented from entering the bay. This could be accomplished by extending the seawall westward from Galveston to San Luis pass, and eastward from Galveston to the Bolivar Peninsula (Merrell et al. 2010). As seen in Figure 5, the Ike Dike would stretch across all of the shoreline and act as a concrete barrier against incoming storm surge.

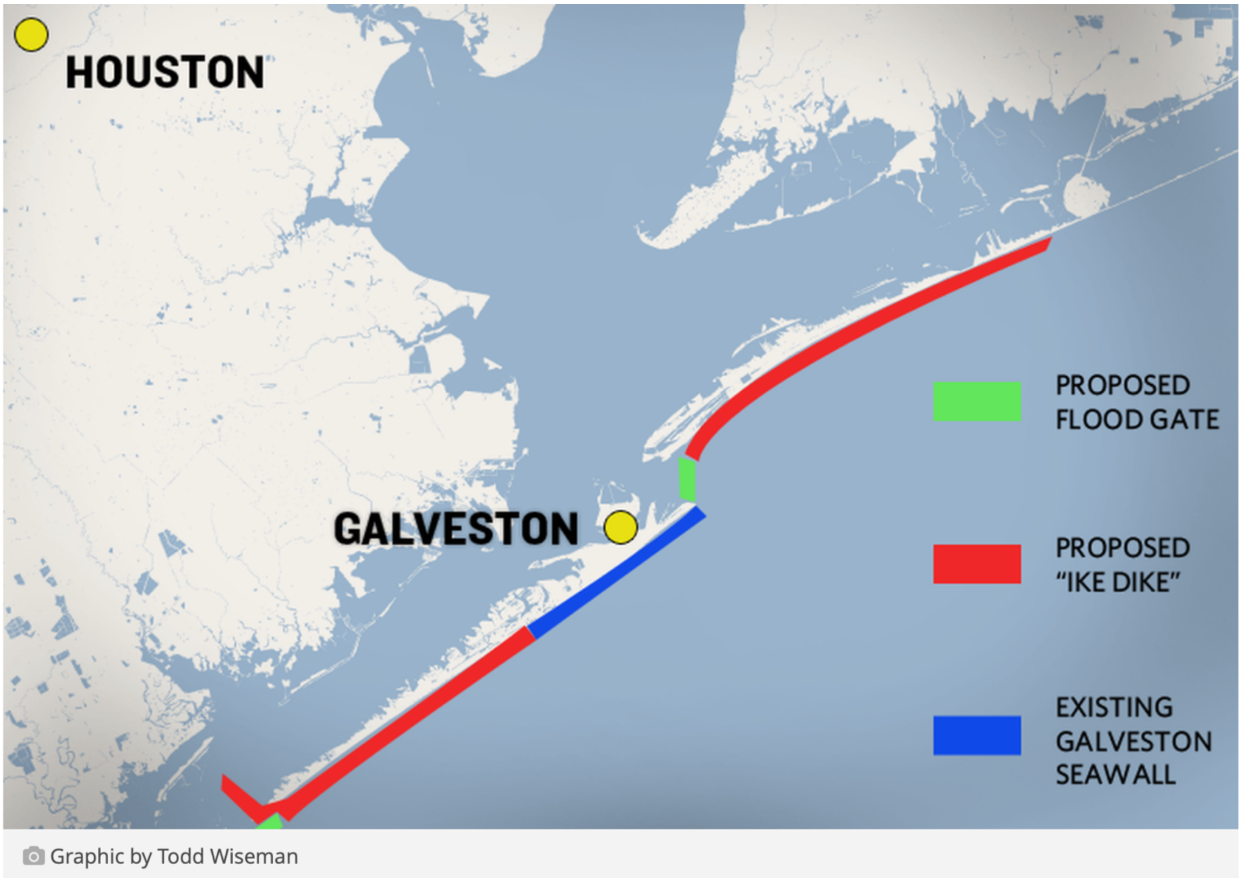

Figure 9. *The "Ike Dike" proposed by William J. Merrell of A&M at Galveston*
Source: TexasTribune.org

The concept of the Ike Dike comes from observations of the Dutch Delta Works in the Netherlands and of the levee systems in New Orleans, Louisiana. The proposed floodgate between Galveston and Bolivar Island can open to allow access for shipping, and close when needed to prevent storm surge from flooding internal waters (Merrell et al. 2010, Stoeten 2012).

The Netherlands, where the inspiration of this concept originated, is geographically similar to New Orleans with regards to a dependence on sedimentation, its location below sea level, and a dependence on waterways (Kabat et al. 2009). Sixty-five percent of the gross country's natural product comes from this region, necessitating its protection (Kabat et al. 2009). This protection comes in the form of riverine dikes, levees, and the Maeslantkering. The Maeslantkering is a moving floodgate that can open and close as needed to protect the Rotterdam Harbor from storm surge (Kawdijk et al. 2010).

Figure 10. *The Maeslantkering on Rotterdam in South Holland, Netherlands*
Source: Port of Rotterdam

It is important to note that the Maeslantkering is only a piece of the comprehensive Delta Works plan, which incorporates different levels of dams, levees, dikes, and other flood prevention engineering with preservation of ecological and natural functions. Recent trends in the Netherlands flooding prevention involve the utilization of natural resources, in what they call "building with nature" and "room for the river" (Kabat et al. 2009). Many of these strategies call for removing engineered structures and replacing them with natural alternatives such as beach nourishment where available

(Kabat et al. 2009). It should be noted that nourishment comes with its own set of drawbacks, such as the need to dredge coastlines for sand to place elsewhere, but does allow more natural processes to occur than an engineered seawall would allow. Furthermore, the Netherlands call for more rigorous floodplain management instead of high water management, meaning limiting the use of areas within the flooding range instead of preparing to protect against flooding in these areas (Pilarczyk 2006).

These differences in application and design seem to contrast the ideals presented with the Ike Dike proposal. The Ike Dike proposal is entirely dependent on engineering mitigation that has proven faulty in past extreme events like Hurricane Katrina. The Netherlands are not dependent on these engineering structures but use engineering to supplement their natural defense mechanisms, as well as attempt to minimize the number of people exposed to the hazard (Pilarczyk 2006). Even more notably, the Netherlands attempt to factor human error into their mitigation plans, resulting in multilayered flood defensive mechanisms and many contingency plans to minimize risk and hazard (Pilarczyk 2006).

Concerns about the impacts of the Ike Dike have surfaced from environmentalists and modern natural hazard scholars. One main concern is the Ike Dike's limitation of flow into the bay (Rujis 2011). The Ike Dike would limit flow through the inlets by 40-60% when open, meaning a permanent change in hydrology and sedimentation flows within the bay (Rujis 2011). These changes could result in a loss of habitat and disturb local ecology, further weakening the already declining wetland systems and their protection services (Rujis 2011; Entwistle, Mora, and Knight 2018). Instead of incorporating the multi-pronged aspect of Delta Works and similar flood management programs that work to maintain wetlands, sand dunes, and other natural structures, the Ike Dike reverts back to the engineering paradigm used before the 1950's.

A proposal that attempts to remedy these issues comes from the Rice University's Severe Storm Prediction, Education, and Evacuation from Disasters (SSPEED) Center. This proposal is known as the Houston-Galveston Area Protection System, or H-GAP (SSPEED 2017). The H-GAP plan calls for more localized engineering instead of constructing the entire coastal spine. The most notable difference between the two plans is the In-Bay System of levees and berms along the Houston Ship Channel. This system also calls for raising the Texas City levees, and building a ring levee around the city of Galveston (SSPEED 2017). The plan argues for a targeted approach instead of a wide-spread application, and allows for more natural supplements like beach and wetland restoration.

The H-GAP plan more accurately follows the Multiple Lines of Defense system demonstrated in the Netherlands (SSPEED 2017). These are the types of plans that should be invested in in the future, and Galveston would be missing on a great opportunity to lead the way in complex natural hazard management systems. The H-GAP plan aligns with the goals and ideals of the complexity paradigm, and allow for growth and adaptation for an ever-changing environment. While both plans come with faults and drawbacks, specifically in encouraging more unsustainable development in hazardous regions, the H-GAP plan does so with less ecological downfalls, a decreased reliance on engineering structures, and a more comprehensive plan that can be adapted for the future.

Discussion:

Humans will continue to change and engineer their landscape so long as we find these locations advantageous to our economies, cultures, or societies. Humans continue to populate wetland and coastal regions due to their abundance of resources and because of these developments a need for floodplain management and hazard management will be mandatory for informed planning for the future. While the most academic course of action would be to end population growths in these areas, pragmatically it is impossible to ask these residents to give up their lifestyles, cultures, properties, and homes in the sake of hazard mitigation. Instead, hazard managers must keep these areas as safe as possible for growing populations.

Natural hazards will always surround human development. The complexity paradigm insists that instead of engineering our environment to work in our advantage, that we instead use the naturally occurring landscape to mitigate our risks. This means stricter regulations on development within floodplains, limitations on landscape degradation, and a minimization of the structural mitigation that encourages unsustainable development.

New Orleans committed itself to the engineering paradigm at its founding. The city simply cannot survive now without its extensive levees and pumping stations. Hazard managers in the future can implement more wetland restoration plans to decrease its dependence on the pumps and levees, but each time the levees fall the sinking Crescent City will need to have them rebuilt again. This cyclical pattern of engineering for unsustainable developments that require more engineering will be present in the city as long as it stands, but the same is not true for Galveston Island.

Galveston has an opportunity to free itself from the hazards cycle of engineering dependence. Following the H-GAP method instead of the Ike Dike would allow the city more flexibility, more layers of defense, and less of an environmental footprint than the dependence on engineering will require. Once the Ike Dike is built, it would be near impossible to revert to a natural pre-engineering state. The seawall will lead to extensive coastal erosion, and the surrounding environment will change in response to the concrete barrier we place in the sea. As seen in the aftermath of Hurricane Katrina, the same engineering feats we develop to protect us may instead increase our risks and potential for catastrophe. Instead of engineering against the disaster, Galveston should take this opportunity to engineering an ecologically thriving landscape that supplements smaller engineering projects to maximize ecological potential with commercial and cultural endeavors.

Conclusions:

The case studies of New Orleans, Louisiana and Galveston Island, Texas examined their dependence on engineered works to mitigate the impacts of natural disasters. In New Orleans, the city has expanded around dependence on engineered pumps and levees to keep the city from inundation– pumps and levees that can fail and leave the city vulnerable to the catastrophic damage that was seen in Hurricane Katrina. In Galveston, the decision to build a 17-foot seawall and raise the island 17-feet to match did reduce damages to property and reduce to total loss of life after a major hurricane. However, expanding the seawall and increasing the islands dependence on structural mitigation may lead to environmental damages and more vulnerabilities in the future.

A dependence on engineered structures to prevent natural disasters can make the city more vulnerable to major catastrophe when these structures fail. In Hurricane Katrina, the floodwall designed to keep water out of neighborhoods collapsed and caused more damage to the surrounding community as it broke apart, demonstrating how these technological fixes often come with drawback that reduce their effectiveness. Though the Galveston seawall does not currently have major structural weaknesses like the floodwalls, an expansion of the seawall across the entire island would cause beach erosion and possible wetland degradation, reducing the islands ability to rely on anything but engineered structures during a natural disaster.

Case studies such as this provide evidence of the engineered solutions effectiveness. They can evaluate the advantages of flood prevention and water management against the disadvantages of environmental impacts and technological dependence in real world situations that are facing the ramifications. As scientists learn more about our environment and how it is changing, case studies such as this will be invaluable in comparing different solutions to natural hazard management and the developing off the advantages of each.

More research needs to be dedicated to the multilayered approaches to hazard management. These may come in the form of studying wetland buffering effects, limiting coastal engineering concepts, studying current hazard prevention infrastructure, or in running more models and programs to calculate exactly what hazards we are defending against. The "technological fix" that is present in many schools of modern scientific thought negates the inherent value of nature, our dependence on our environment, and creates hazards that may have been preventable with more environmentally conscious solutions. Progress is currently being made against this school of thought and as more environmental and hazard management teams accept the complexity paradigm, the further we go from engineering our own disasters.

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