HURRICANE STORM SURGE SEDIMENTATION ON EAST TEXAS GULF COAST MARSHES: SPATIAL VARIATIONS IN SEDIMENT DISTRIBUTION IN THE RIGHT-FRONT QUADRANT OF HURRICANE IKE

by

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DEDICATION

This dissertation is dedicated to several close family members who have loved and supported me throughout my life and who support my love of geography. To the departed, but not forgotten, John Kveton (great uncle). To my uncle and aunt, James and Margaret Hodge (who planted the geography seed in my life), to my parents, Jon and Mary Hodge, to my maternal grandparents, George and Rose Krupala, and to my sisters and brother, Kimberly Hodge, Cynthia Hodge, and Michael Hodge.

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ABSTRACT

Hurricanes are well known for producing catastrophic devastation to both natural and human environments along the northern Gulf of Mexico coastline. Hurricane Ike made landfall on the eastern tip of Galveston Island, Texas, on 13 September 2008, and the region in the right-front quadrant of the storm experienced catastrophic storm surge flooding. This study investigates spatial variations in sediment distribution on McFaddin National Wildlife Refuge, which is located in the geographic region that was impacted by the right-front quadrant of Hurricane Ike. Fieldwork conducted in summer 2017 and summer 2018 involved digging shallow pits on four transects between Sabine Pass, Texas, and High Island, Texas. Eight pit sites were established on Transect 1, the easternmost transect, and six pit sites each were established on Transects 2, 3, and 4, with Transect 4 located farthest west. All four transects extend 880-1630 meters, with pit sites beginning near the coastline and extending landward. Elevations were measured at each pit site along all four transects using a telescopic level and stadia rod. Results obtained in the field indicate that the Hurricane Ike sediment deposit has been found on all four transects, and that the deposits decrease in thickness moving landward along each transect. On Transect 1, at Pit Site 1, the thickness of the Hurricane Ike deposit was 61 centimeters; this same deposit gradually tapers down to a thickness of 4 centimeters at Pit Site 8. On Transect 4, Pit Site 1 had a sediment thickness of 53 centimeters, whereas at Pit Site 6 the deposit was 5 centimeters thick. Additionally, there is evidence that

sedimentation has been impacted by the presence of man-made levees that lie perpendicular to the Gulf Coast at Transects 2, 3, and 4.

Furthermore, the observational results of this study were used in Regression Analyses to model hurricane storm surge sediment deposit thickness based on pit site distance inland, pit site elevation, and distance from the landfall of Hurricane Ike. Moreover, Analysis of Variance revealed whether distance inland, distance from landfall location, and the interaction between distance inland and distance from landfall location had any significant effect on storm surge deposit thickness. Actual sediment deposit thicknesses measured in the field were compared to the Regression and Analysis of Variance results. Results show that the Power Law Curve from the Regression Analyses was the most robust predictor of pit site sediment thickness based on distance inland, with an R^2 value of 0.538. Additionally, the Regression and Analysis of Variance results revealed that transect distance from the landfall location of Hurricane Ike was the only independent variable that could not predict or explain storm surge deposit thickness.

The goal of this study was to discover spatial variations in storm surge sedimentation in the geographic region impacted by the right-front quadrant of Hurricane Ike. The findings of this study provide improved understanding of the spatial relationship between storm surge sedimentation and storm surge heights, valuable knowledge about the sedimentary response of coastal marshes subject to storm surge deposition, and useful guidance to public policy aimed at combating the effects of sea-level rise on coastal marshes along the northern Gulf of Mexico coastline.

1. INTRODUCTION

1.1 Overview

Coastal marshes along the northern Gulf of Mexico coastline provide several important functions, such as serving as habitat for a variety of flora and fauna, sequestering carbon, and protecting urban and industrially developed locations farther inland by acting as a buffer to hurricanes. Coastal marshes along the Gulf of Mexico coastline act as sponges and absorb much of the wave energy and flooding rains from these powerful storms. However, present rates of relative sea-level rise on the East Texas Gulf Coast are around 5-7 mm per year (Kennish 2001). Relative sea-level rise at Sabine Pass, Texas, has averaged 5.66 mm per year during the past three decades (Thatcher, Brock, and Pendleton 2013). Sea-level rise along the northern Gulf of Mexico is primarily caused by thermal expansion of seawater due to increasing global water temperatures, regional subsidence due to groundwater and mineral extraction, and lack of riverine sediment to fill growing accommodation space. These conditions threaten to convert coastal marshes to open water with the consequent loss of valuable marsh functions (DeLaune, Nyman, and Patrick 1994; Kennish 2001; Gedan, Silliman, and Bertness 2009; Glick et al. 2013; Kent and Dokka 2013). Rates of northern Gulf of Mexico marsh loss have been dramatic – between 1955 and 1978, the loss of marshes was 127 km^2 per year – equivalent to the area of Rhode Island every 21 years (Turner 1997). These trends all point to a need to develop more accurate and robust methods for assessing coastal marsh dynamics, particularly under the impacts of natural hazard events such as hurricanes and floods.

One way the detrimental effect of rising sea level is countered is via natural aggradation of marsh surfaces by sedimentation processes. Whereas many studies have documented the destructive force of hurricane storm surges; such as beach and dune erosion, (Hayes 1967; Fitzgerald, van Heteren, and Montello 1994; Dingler and Reiss 1995; Stone et al. 1997; Wang et al. 2006; Doran et al. 2009; Watson 2009) research shows they are also a natural source of sediment for marsh surface accretion (Turner et al. 2006; Williams and Flanigan 2009; Williams and Denlinger 2013; Liu et al. 2015; Hodge and Williams 2016; Yao, Liu, and Ryu 2018). A storm surge is a rise of sea level generated by a strong cyclonic storm, above predicted astronomical tides. Hurricanes are the main cause of storm surges because of the combination of their very low pressures and high winds. The low atmospheric pressure causes ocean water to bulge up under the hurricane while the hurricane-force onshore winds push ocean water landward, creating a localized area of higher sea level, known as a storm surge. If a storm surge occurs during high tide, the conditions are exacerbated due to the normal storm surge being in the area of Earth within a tidal bulge; this condition is known as the storm tide (Figure 1.1). In the northern hemisphere, the area of greatest storm surge is located along the right-front quadrant of a landfalling hurricane. For example, Jefferson County, Texas, the location of McFaddin National Wildlife Refuge (NWR), was in the right-front quadrant of landfalling Hurricane Ike in September 2008. The counter-clockwise circulation of winds in the storm caused the greatest buildup of water along shorelines in this quadrant (see Figures 1.2 and 1.3).

Many factors determine whether or not a storm surge inundates nearshore terrestrial environments and the resulting depth of storm surge flooding. These factors include the magnitude of the storm, the speed at which the storm advances, the nearshore bathymetry, the coastal morphology, the nearshore topography and the presence and height of coastal barriers, such as foredunes (Georgiou, Fitzgerald, and Stone 2005). On the Gulf Coast, it is common for intense hurricanes to generate storm surges several meters in height that flood nearshore environments many kilometers inland. Hurricane storm surges commonly transport sediment inland from bays, the nearshore seafloor, beaches, and dunes thereby forming storm surge deposits in nearshore terrestrial environments, including marshes and woodlands. The sediments deposited by storm surges can extend a considerable distance inland. For example, Hurricane Ike’s storm surge deposit extended over 3500 meters inland, just east of High Island, Texas (Williams 2010). Near the shoreline, storm surge deposits are typically thicker and sandier, and commonly form washover fans and terraces (Williams 2011; also see Figure 1.4). Farther inland, deposits become thinner and finer-grained. This thinning and fining of the deposit is due to the sediment having been deposited from suspension (Hodge and Williams 2016). The smaller particles, such as clay and silt, weigh less and remain in the storm surge’s water column for a longer period of time, therefore traveling farther inland than larger particles, such as sand and pebbles.

1.2 Purpose Statement

In recent decades, researchers have focused on the role of hurricane storm surge sedimentation as a mechanism of aggradation in salt and brackish marshes bordering the Gulf of Mexico (Cahoon et al. 1995; Cahoon 2006; Turner et al. 2006; Williams 2009; Hodge and Williams 2016). Anomalous sand beds, deposited by hurricane storm surges, are known to be preserved in the subsurface of coastal marshes, and, if identified, can provide a time marker horizon that can be used to assess local sedimentation rates (Turner et al. 2007; Williams 2009; Hodge and Williams 2016). A number of studies, many that involve hurricane storm surge sediment deposits, have aimed at measuring vertical accretion on coastal marshes to determine if marsh accretion can keep pace with projected sea-level rise (Cahoon 2006; Turner et al. 2006; Williams 2003, 2009, 2010, 2012; Williams and Denlinger 2013; Hodge and Williams 2016; Walters and Kirwan 2016; Yao, Liu, and Ryu 2018).

The purpose of this research is to determine the spatial extent of the Hurricane Ike (2008) storm surge sediment deposit that is likely preserved on East Texas Gulf Coast marshes. This study will build upon recent research at McFaddin NWR by Hodge and Williams (2016) by digging shallow pits and identifying the likely Hurricane Ike storm surge sediment deposit at multiple coastal marsh transects between High Island, Texas, and Sabine Pass, Texas. The deposit is expected to be near the surface and should be composed of sand (with coarser sand closer to the coastline and finer grained sand farther inland) separated by darker organic-rich sediment above and below the sand-rich deposit (Hodge and Williams 2016). This project should provide improved understanding of how hurricane sediment deposits are preserved temporally in the low-lying marshes of the Gulf of Mexico coastline, as well as how storm surge deposits are preserved at varying distances from a hurricane’s landfall location. The information contributed from this project should also serve as an aid to coastal management agencies trying to combat rapid conversion of marshes to open water due to a combination of regional subsidence and sea-level rise.

1.3 Research Objectives

The uncertainty over the magnitude, distribution and significance of hurricane sediment inputs into coastal marshes, highlights the need for more research on hurricane sedimentation and the potential importance of incorporating the contribution of hurricanes to coastal marsh aggradation into coastal management plans. Relatively few quantitative studies have been done assessing hurricane contributions to coastal marsh aggradation. Better understanding of hurricane sediment inputs could have important consequences for coastal management entities that build and maintain seawalls, levees, and dams which could inhibit sediment accretion on coastal marshes. If more information is found that supports the positive impacts of these coastal marsh accretion events, then the findings could influence policy makers in order to allow storm surges to inundate certain areas of the coast to permit the maximum amount of possible sediment deposition.

Direct anthropogenic impacts on sedimentation include those that result from the physical alteration and immediate loss of habitat during construction of bulk-heads, dikes, weirs, levees, piers, docks, pipelines, and other hard structures, as well as the excavation of canals, ditches, and oil drill sites (Deegan, Kennedy, and Neil 1984; Sasser et al. 1986; Swenson and Turner 1987; DeLaune et al. 1989; Turner 1990; White and Morton 1997; Bryant and Chabreck 1998; Kennish 2001). Historically, the modification of coastal marshes for agricultural purposes, such as draining and filling, and their reclamation for domestic and industrial development have substantially reduced viable wetland habitat area during the past century (Adam 1990; Anderson et al. 1992; Kennish 2001).

Longer term, indirect impacts are also associated with some of these habitat disturbances. For example, the construction of impoundment dikes, water-control embankments, levees, dams for flood control, as well as canals and their associated spoil banks invariably alter the hydrology of these wetland systems, often interfering with normal tidal flooding and drainage, modifying overland water flow, decreasing sediment supply to the marsh surface, and arresting vertical accretion (Kennish 2001). Additionally, riverine sediment deficits and the use of prescribed burns on coastal marshes are two more complex issues that affect the geomorphic health of coastal marshes (Henton et al. 2013).

This project encompasses several important objectives. First, field work was conducted in a series of four coastal marsh transects between High Island, Texas, and Sabine Pass, Texas, in order to discover the spatial extent and variability of the Hurricane Ike storm surge sediment deposit that likely exists in this region. Second, the spatial extent and thickness of the storm surge deposit was compared to the landfall location of Hurricane Ike. It was expected that the thickest and most extensive storm surge deposits are in the right-front quadrant of a landfalling hurricane. The entire study region was within the right-front quadrant of where Hurricane Ike made landfall, and it was very likely that the storm surge deposit exists along all four transects. Documenting how the sediment deposits differed amongst all four transects was an important aspect of this study as well. Third, the results of this study were used in regression analyses in order to model hurricane storm surge sediment deposit thickness based on pit site distance inland, pit site elevation, and location from the landfall of Hurricane Ike. Fourth, Analysis of Variance (ANOVA) revealed whether distance inland, distance from landfall location, and the interaction between distance inland and distance from landfall location had any significant effect on storm surge deposit thickness. Actual sediment deposit thicknesses measured in the field were compared to the regression and ANOVA results. Finally, the results of this project should be of interest and provide useful guidance to coastal management agencies aimed at combating the effects of sea-level rise on coastal marshes along the northern Gulf of Mexico coastline.

1.4 Chapter One Figures

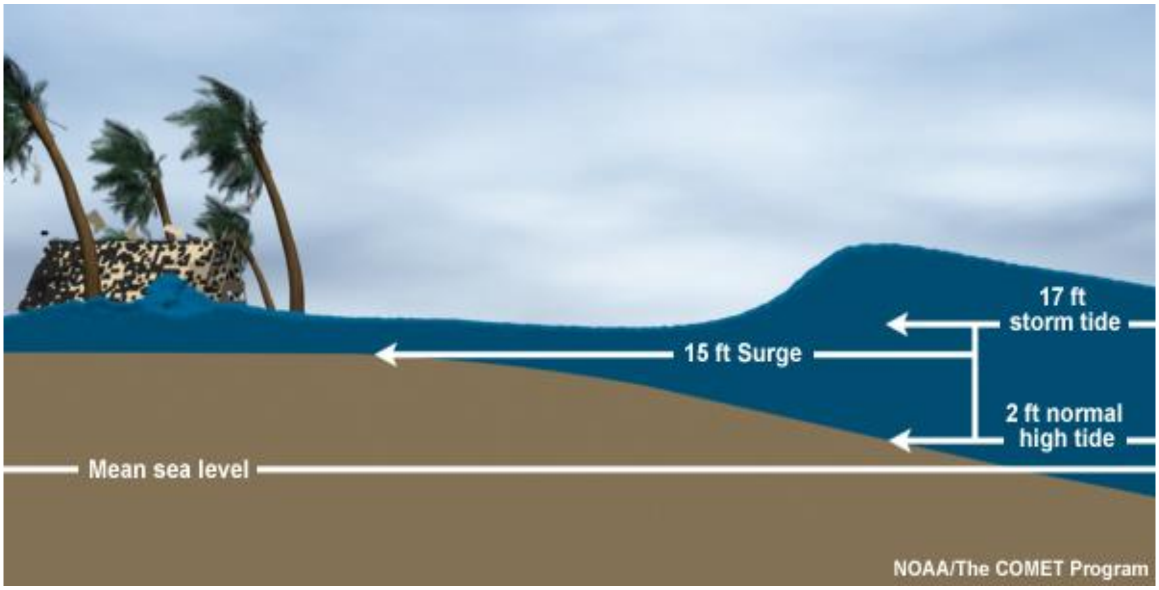

Figure 1.1. Illustration of the relationship between mean sea level and normal tide (non-storm conditions), and a storm surge during high tide (NOAA 2018).

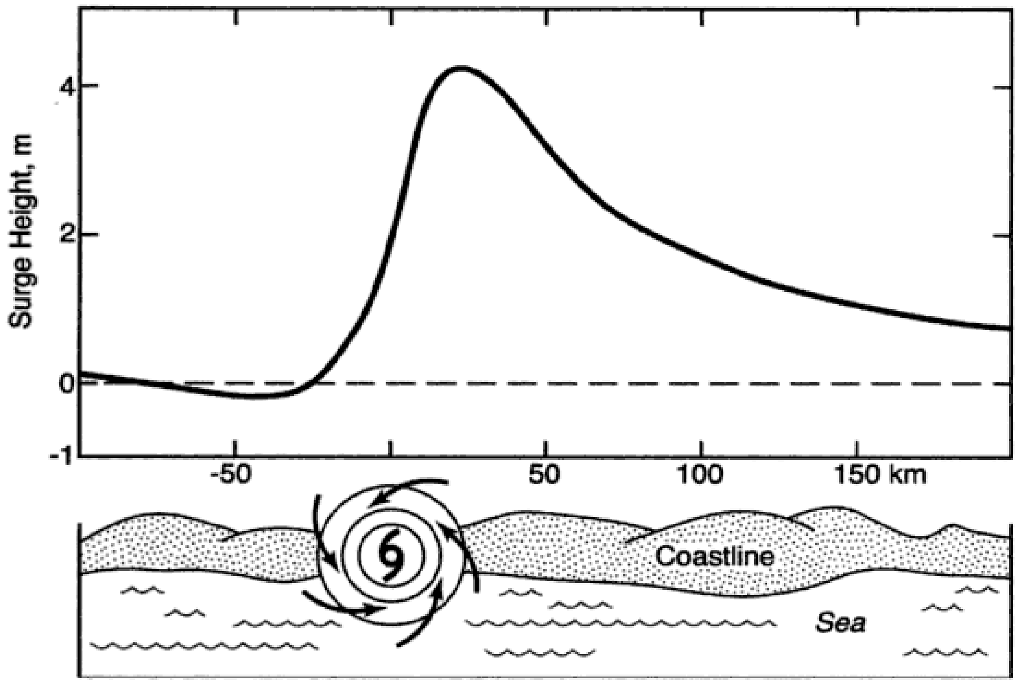

Figure 1.2. Typical hurricane storm surge and wind directions (Liu 2004).

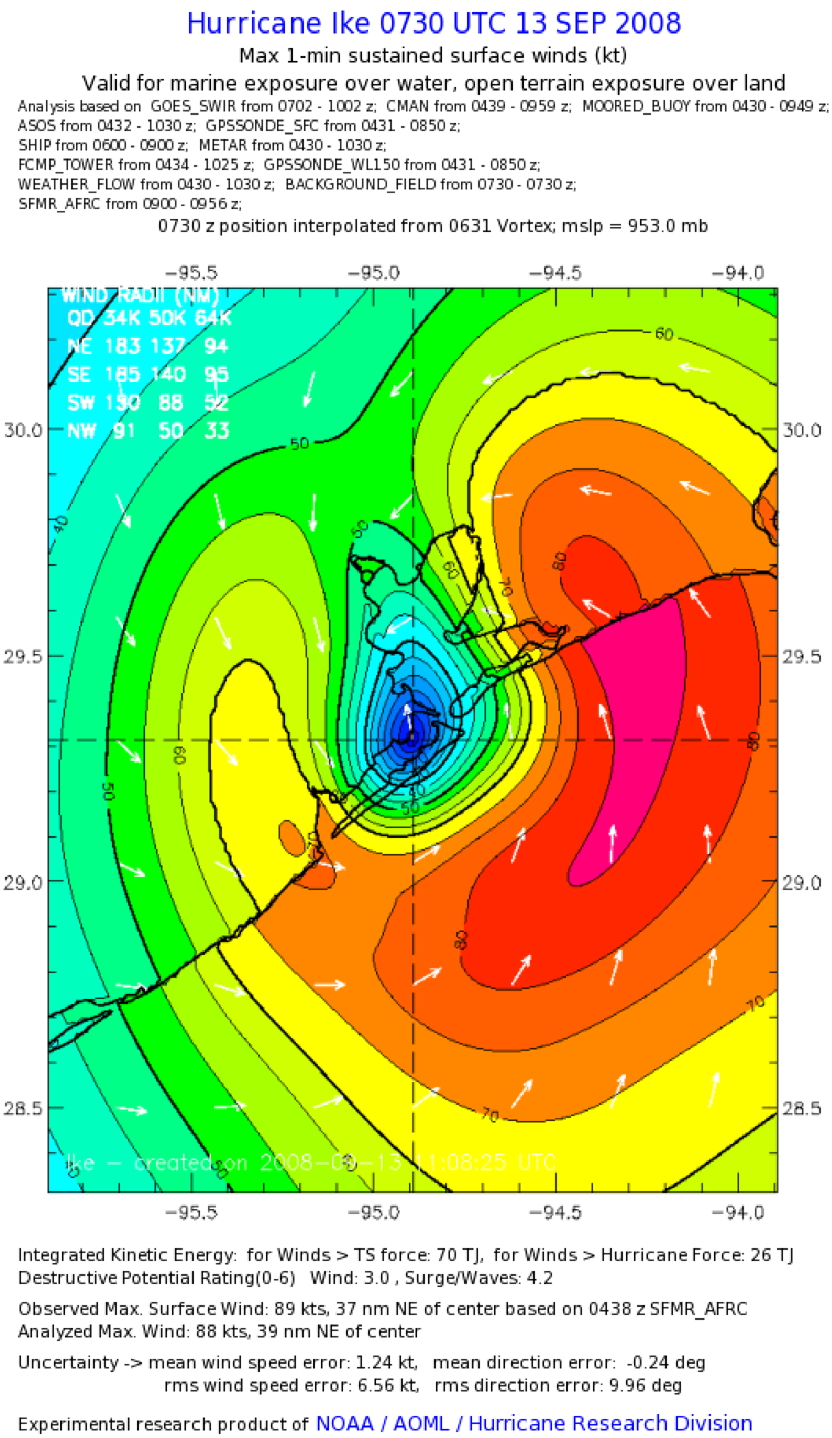

Figure 1.3. The surface winds of Hurricane Ike as it made landfall at 0730 UTC on 13 September 2008 (NOAA 2009).

Figure 1.4. McFaddin NWR shortly after Hurricane Ike made landfall. The image shows washover fans landward of a heavily eroded beach (modified from Google Earth 2017).

2. LITERATURE REVIEW

2.1 Pioneering research in hurricane sedimentation

It has been well known for several hundred years that powerful hurricanes wreak havoc and destruction on human settlements in North America and the Caribbean. However, it was not until the 1960s that hurricanes were first scientifically seen as geologic agents on coastal regions. Hurricanes erode and deposit sediment especially in regions where there are plentiful riverine sediment sources such as along the northern Gulf of Mexico coastline. The greatest geological effects from hurricanes are caused by wind-driven waves and storm surges. Miles Hayes performed extensive research in coastal geomorphology starting in the 1960s with his Ph.D. dissertation focused on hurricane-induced sedimentation on Padre Island, Texas (Hayes 2016). His extensive field work and research (Figure 2.1) along the Texas Gulf Coast, investigated the geological effects of Hurricanes Carla (1961) and Cindy (1963). Hayes (1967) was one of the first studies to document catastrophic storm effects in the sedimentary rock record. Most of his field work was conducted on South Padre Island, North Padre Island, and the region of the coast up to Port Aransas.

According to Hayes (1967), wave action was the dominant coastal process in the area, but hurricane sedimentation played an important role in nearshore sedimentation processes. The study involved a comparison of the before and after effects of Hurricane Carla. Following Hurricane Carla, Hayes (1967) found that areas up to 24 m in depth just offshore from Padre Island picked up mollusk shells, rock fragments, coral blocks and other materials and deposited them onto the barrier island. This showed how the wave action of strong hurricanes can have an effect on sea bottoms at those depths. Hayes also documented how finer sediment particles were deposited by the “return flow” of the storm surge. Initially, the strong currents of the storm surge cut “hurricane channels” into narrower zones of the barrier island (Figure 2.2), which then connected the Gulf of Mexico with the lagoons on the west side of Padre Island. After the storm passed, the return flow deposited a thin layer of fine sand; as well as a graded layer of fine sand, silt and clay on the offshore shelf (Hayes 1967). Some important conclusions of his work include how hurricanes can mix environment-sensitive faunas from a variety of environments into a single sedimentary deposit; and that hurricanes can play a primary role in sediment transport in nearshore environments.

Ball, Shinn, and Stockman (1967) conducted a significant study in the late 1960s that involved research of the geological impacts of Hurricane Donna (1960) across South Florida as it traversed from the Northern Caribbean Sea into the Gulf of Mexico. The geology of the region was already detailed prior to the impact of Hurricane Donna, so it was possible to contrast the “before and after” effects of the storm. The main effects of the storm were caused by the high storm surge (up to 4.3 m in some parts of the Florida Keys) and large breaking waves (Ball, Shinn, and Stockman 1967). The Florida Keys are composed of a carbonate reef platform, so all of the sedimentary deposits resulting from the effects of Hurricane Donna were limestone-rich. The purpose of the investigation was to determine: A. the geologic work of a hurricane, B. how this work differed from that done by day-to-day geologic processes, and C. the geologic record of this work (Ball, Shinn, and Stockman 1967). Methodologies for determining the pre-Hurricane Donna geologic conditions included the use of photographs, cores, maps, and bottom markers (which were provided by the Shell Oil Company). These materials were excellent for determining pre-Donna sea floor conditions (Ball, Shinn, and Stockman 1967). By comparing photographs and cores taken before and after the hurricane, the researchers were able to observe its effects and to weigh them against those of day-to-day processes.

Field investigations after the storm included documenting erosion and deposition of various sediment particle sizes on the reef tract, outside reef zone (such as Key Largo Dry Rocks), patch reefs, sand shoals behind the reefs, sediment mounds, tidal passes, lagoons, tidal flats, and “sand bordering the mudbank margin”. A few observations and conclusions reached in the study include how hurricane currents caused the formation of coarse coral rubble and that this rubble was transported to the leeward sides of the platform-edged reefs; as well as the significant deposition of lime mud on the tidal flats above normal high tide (Figure 2.3) (Ball, Shinn, and Stockman 1967). To add to this, a major finding was that muddy-sediment accumulations at the Rodriguez Bank and the banks of Florida Bay were not significantly affected by storm-wave erosion. Ball, Shinn, and Stockman (1967) states that this is noteworthy because the ancient mudstone mound structures are more resistant to erosion than the organic coral reefs. The findings by Ball, Shinn, and Stockman (1967) demonstrate catastrophic uniformitarianism such that events that are catastrophic in terms of calendar time are important and common place in terms of geologic time.

2.2 Significant studies in the 1970s and 1980s

Research on hurricane sedimentation is quite limited in the decade of the 1970s, however there is a continuation of and build-up of knowledge regarding coastal erosion and depositional processes and hurricane washover fans (Pierce 1970; Fisher and Stauble 1977). Pierce (1970) studied aerial photographs of the Outer Banks of North Carolina from the 1960s. His research discussed the conditions under which washover fans or tidal inlets formed, namely, on either the seaward side or lagoon side of a barrier island. By analyzing aerial photographs, Pierce (1970) concluded that tidal inlets in a wide barrier with extensive tidal flats are eroded from the lagoon side of the barrier island. Washover fans were the result of an attack on a barrier island from the seaward side (Pierce 1970).

Fisher and Stauble (1977) did extensive field work on Assateague Island, Virginia and Maryland. The goal of the study was to determine the role of Hurricane Belle (August 1976) on island washover fans and monitor any subsequent erosion. The results indicated that $19m^3$ of sand per meter of washover centerline was deposited at the survey site. Due to the wind direction around the storm, there was no deflation of the washover deposit as the storm subsided; however, much of the freshly deposited washover fan was eroded back onto the beach by strong offshore winds in 1977 (Fisher and Stauble 1977). The significant finding of the study was that overwash of lower intensity storms may not be significant enough to allow for long-term sediment accumulation on the barrier island (Fisher and Stauble 1977).

In the 1970s, Morton (1978) studied rhomboid bed forms developed from hurricane washover fans on the Texas Gulf Coast from Padre Island to the Matagorda Peninsula. At the time of the study, there had already been extensive research as to how storms modify and shape coastal landforms; however, there was still much to learn about the permanent contributions that infrequent hurricanes make to the geological record. Some significant conclusions of his work are that preservation of rhomboid bed forms and internal structures are optimized if: A. the total duration of high discharge is short, B. the falling stage of discharge is very rapid, C. the site is sufficiently elevated so that the sediment surface is not frequently inundated, and D. the sediment surface is protected from further modification (Morton 1978).

The decade of the 1980s saw a number of studies describing how hurricanes serve as geomorphic agents along the northern Gulf of Mexico, especially on the Louisiana coastline (Rejmanek, Sasser, and Peterson 1988; Nakashima 1989). Additionally, in a related field tied to the importance of coastal marshes, studies of marsh accretion, subsidence and erosion were occurring during this time period (DeLaune, Baumann, and Gosselink 1983; Baumann, Day, and Miller 1984). The study by Rejmanek, Sasser, and Peterson (1988) was regionally focused on the Mississippi River deltaic plain, Louisiana. It had been known in the latter half of the 20th century that the marshes forming the deltaic plain were rapidly subsiding and eroding. The study took into consideration the amount of sediment the Atchafalaya River delivered to the area, as this sediment was thought to help offset the subsidence of the marshes. The primary goal of the study was to measure sedimentation rates in marshes influenced by floodwaters from the Atchafalaya River in order to assess the rate of marsh accretion (Rejmanek, Sasser, and Peterson 1988).

The study site was located on Willow Bayou and included four distinct locations that exhibited a different marsh grass. Feldspar clay marker horizons were established to measure sedimentation rates. The study locations were visited three times in an eighteen month time span and revealed that decaying organic matter as well as sediment deposition from Hurricane Danny (1985) made a significant contribution to sediment accretion on the marsh (Rejmanek, Sasser, and Peterson 1988). The results of the study indicated that in the Willow Bayou, normal river flooding contributes very little to marsh sedimentation rates as compared to hurricane-induced sedimentation; and that the hurricane-induced sedimentation represents a partial compensation to prevailing subsidence of marshes in abandoned delta lobes (Rejmanek, Sasser, and Peterson 1988).

Nakashima (1989) focused his study on the geomorphic effects of Hurricane Bonnie on a 54 km long shoreline in southwest Louisiana, bordering on Sabine Pass at the western edge. The study outlined the impacts of the onshore winds, waves and storm surge on three different shoreline types in this region. The shoreline types studied included a natural beach system, a beach that had been scraped by a road grader, and a beach that had been artificially stabilized by a revetment (Nakashima 1989).

Data for the study were acquired by extensive field work before and after the impact of Hurricane Bonnie (1986). Eight beach profile transects were established before the storm made landfall, and were subsequently surveyed before the storm and three times over a six month period after Hurricane Bonnie made landfall. Each profile transect was surveyed to the maximum extent of wading using an automatic level and stadia rod (Nakashima 1989). The results of the study showed that Hurricane Bonnie caused net erosion across the entire study area, with the greatest losses occurring along natural shoreline and modified shoreline. The least amount of erosion occurred along the armored section.

The results of the study indicated that the net volumetric change for the natural and modified beaches had a persistent recovery, and in many places, the pre-storm sediment volume had been surpassed. This showed that natural accretion was occurring on these beaches to offset the considerable wave erosion caused by Hurricane Bonnie. The situation was different in the artificially stabilized beach. Erosion continued to dominate this section of the study area throughout the entire six month monitoring period (Nakashima 1989). The results suggested that for this region, a totally natural or slightly modified beach system consisting of a dune, wide backbeach, and gentle foreshore slope withstands storms more effectively than a revetment. Nakashima (1989) concluded with the argument that anthropogenic barriers to sedimentation are detrimental to the natural recovery of beaches after a hurricane.

2.3 Advances in the 1990s

The 1990s saw significant advancement of hurricane sedimentation studies along the Gulf of Mexico Coastline. The impact of Hurricane Andrew (1992) on coastal marsh sedimentation was documented by several teams of researchers (Cahoon et al. 1995; Nyman, Crozier, and DeLaune 1995; Risi et al. 1995). Additionally, these studies focused mainly on the impact of marsh sedimentation, as opposed to beach morphology which was more frequent in earlier decades (Ball, Shinn, and Stockman 1967; Hayes 1967). Hurricane Andrew was a very rare category five storm that crossed southern Florida, entered the Gulf of Mexico and then made a second landfall on the Louisiana coastline as a category three storm. The noteworthy study by Cahoon et al. (1995) presented data on storm tide characteristics, short-term sediment accumulation, vertical accretion, and elevation change in marshes and shallow water-bottoms associated with the passage of Hurricane Andrew. Only a small portion of the sedimentation measurements were taken specifically to study Hurricane Andrew; however, the broad spatial and temporal coverage of the datasets provided a more comprehensive view of storm impacts than was previously studied (Cahoon et al. 1995).

The influence of Hurricane Andrew on sediment distribution was determined from field plots established prior to the passage of the storm by a variety of measuring techniques which integrate different time scales (Cahoon et al. 1995). The extent and temporal patterns of sediment deposition were determined from sediment traps, sediment cores extracted from marshes (Figure 2.4), marker horizons and benchmarks associated with other studies by D. Cahoon. These data were collected from eleven different sites west of the Mississippi River in southeast Louisiana (Cahoon et al. 1995). Additionally, storm tide data, and storm wind data were used in the study, as those forces were known to redistribute sediment on coastal marshes (Hayes 1967).

Cahoon et al. (1995) found that there was a strong direct increase in short-term sediment deposition associated with the passage of the Hurricane Andrew storm tide. The increased rates of short-term sediment deposition remained high until the first major winter cold front when water levels were lowered long enough to enhance the consolidation of and removal of the readily re-suspended storm sediments from the coastal marshes (Cahoon et al. 1995). Sediment dynamics were variable as sediment was introduced from outside the coastal marsh system in some areas, whereas in other areas sediment was redistributed as the marsh substrate eroded during storm passage. Hurricane Andrew generated more vertical accretion in one storm than an entire season of cold fronts in both the year before and after the storm (Cahoon et al. 1995). The results suggested that hurricanes play an important role in coastal marsh survival and that coastal and marsh management agencies should implement ways which help facilitate natural marsh accretion from hurricane sediment deposition (Cahoon et al. 1995).

2.4 Advancements in the 21st Century

Entering the 21st century there is a dramatic increase in hurricane sedimentation studies along the Gulf of Mexico coastline. These studies are increasingly important, especially as sea-level rise and regional subsidence continue to threaten much of the region, especially the Louisiana coastline (Baumann, Day and Miller 1984; DeLaune, Nyman, and Patrick 1994; Cahoon 2006; Tweel and Turner 2014; Walters and Kirwan 2016). A study by Liu et al. (2014) documented sediment deposition from Hurricane Isaac near Frenier, Louisiana. Prior to the study, sedimentary signatures of hurricane deposits were documented in several different coastal environments along the northern Gulf coast (Cahoon et al. 1995; Turner et al. 2006; Williams and Flanagan 2009; Williams and Denlinger 2013), yet no studies were undertaken to analyze storm surge deposition in wetlands adjacent to large, inland brackish water bodies (such as Lake Pontchartrain). The study by Liu et al. (2014) presented results documenting the distribution and characteristics of storm surge deposits derived from Hurricane Isaac (2012) in a wetland on the western shore of Lake Pontchartrain, Louisiana (Figure 2.5).

Other significant research, specifically from 2008-2016, has been conducted by Harry Williams along the Texas and Louisiana Gulf Coasts. Field work documenting the Hurricane Rita storm surge deposit was conducted shortly after the storm made landfall in November 2005, in southwest Louisiana (Williams 2009). Results indicated that the storm surge deposit was up to 0.5 m thick and extended at least 500 m inland. Analysis of the deposit indicated two distinct sedimentary layers: a thin layer of finer sand and mud and an overlying thicker layer of coarser sand. The findings from Williams (2009) suggested that the deposition from suspension of finer sand and mud was an early stage of storm surge inundation, and that the coarser sand was a traction load deposit, formed at a later stage of storm surge inundation.

Following the landfall of Hurricane Ike, Williams (2010) documented the storm surge deposit on McFaddin NWR on the Southeast Texas Gulf Coast in January 2009. A series of pits were dug along a transect extending from 90 to 1230 m inland from the coastline. Samples were obtained in order to document the texture, and were especially focused on areas directly above and below the sand-rich layer, in order to investigate the possibility of offshore foraminifers in the deposit. Results indicated that the storm surge deposit thinned and fined inland and was distinguished from the underlying marsh by coarser texture, lower organic content, and abundant offshore foraminifers (Williams 2010). An important implication of the study was that it could form the basis for paleotempestological studies if foraminifers are preserved over long periods of time.

Hodge and Williams (2016) conducted a follow up study on McFaddin NWR in August 2014. The original purpose of the follow up research was to identify and document the Hurricane Ike sediment deposit, and any possible storm surge deposits located beneath the Ike deposit. Extensive field and laboratory work revealed that the hurricane sediment deposits of Hurricanes' Audrey (1957), Carla (1961), Rita (2005) and Ike (2008) were preserved on the marsh. Some conclusions of the study were that the marsh dynamics were controlled by hurricane activity (such as storm surge overwash), flood-derived and organic sedimentation, changes in marsh surface elevation and degree of compaction. Hurricane sedimentation was an important contributor of marsh aggradation since 1957 and helped to counteract the effects of sea-level rise on marsh elevation. The results of the study were significant because they provided improved understanding of the sedimentary response of coastal marshes subject to storm surge deposition and added support to other studies that encouraged coastal management agencies to consider reducing physical barriers to storm surge sedimentation (Hodge and Williams 2016).

Research on the geomorphic impacts of hurricanes in coastal regions has been increasing rapidly in recent decades and is likely to continue throughout the 21st century. Another very relevant area of research that evolved from the pioneering work of Hayes is paleotempestology. Paleotempestology is the study of past hurricane activity by using geological proxies (Liu, 2004). Research done by Donnelly et al. (2001), Liu and Fearn (2002), Liu (2004), and Donnelly (2005) are several examples of recent paleotempestological studies in the United States. Work by Chris Houser has focused on dune morphology and their recovery after storms, and much of his research takes place on Padre Island (Houser, Hapke, and Hamilton 2008; Houser, Hobbs, and Saari 2008; Houser et al. 2015). Hurricane Harvey (2017) produced similar impacts to the storms documented by Houser, Hapke, and Hamilton (2008), Houser, Hobbs, and Saari (2008), and Houser et al. (2015), by eroding and breaching the foredunes on Padre Island (Figure 2.6).

2.5 Chapter Two Figures

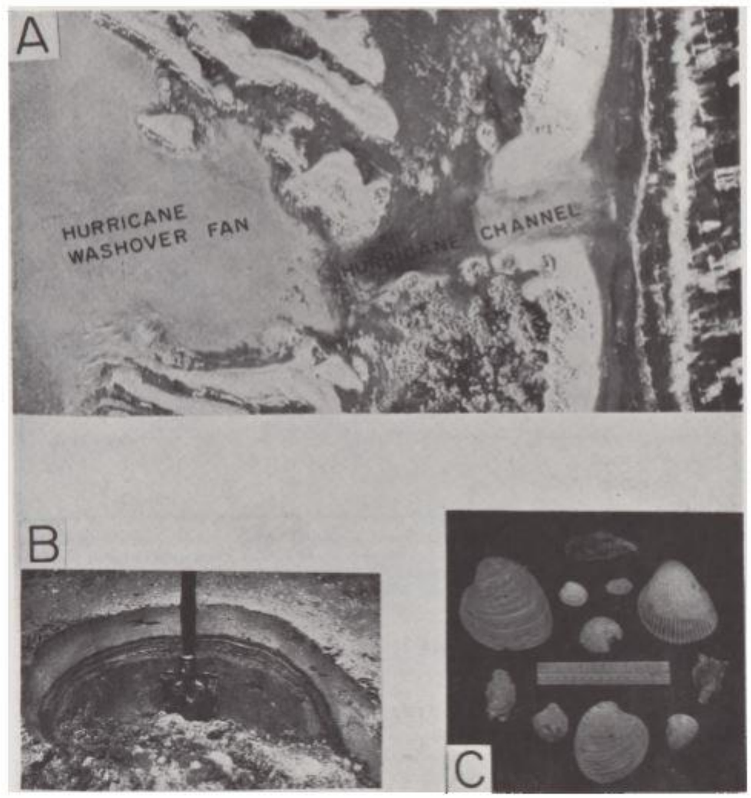

Figure 2.1. A small sample of research conducted in the 1960s. **A**. Washover fan from Hurricane Carla on central Padre Island, **B**. pit dug on Padre Island revealing stratigraphy, and **C**. assortment of mollusk shells deposited by storm surge of Hurricane Carla (Hayes 1967).

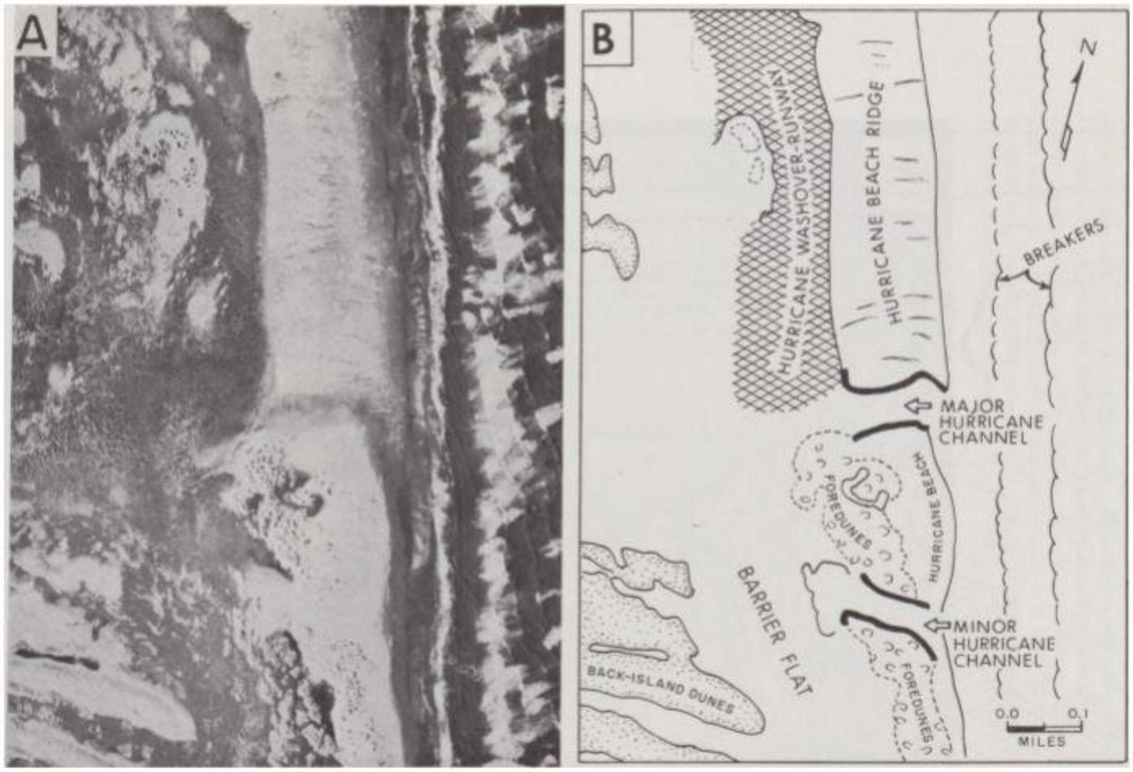

Figure 2.2. Some imagery of Padre Island from the 1960s. **A**. Aerial image of Padre Island showing geomorphic impacts from Hurricane Carla and **B**. Map of Padre Island showing hurricane channels, beach ridges, and other barrier island landforms (Hayes 1967).

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Figure 2.3. Two-inch-thick layer of lime mud stranded on Crane Key by the hurricane ebb tide. The dark surface under the new mud is the pre-hurricane algal mat (Ball, Shinn, and Stockman 1967).

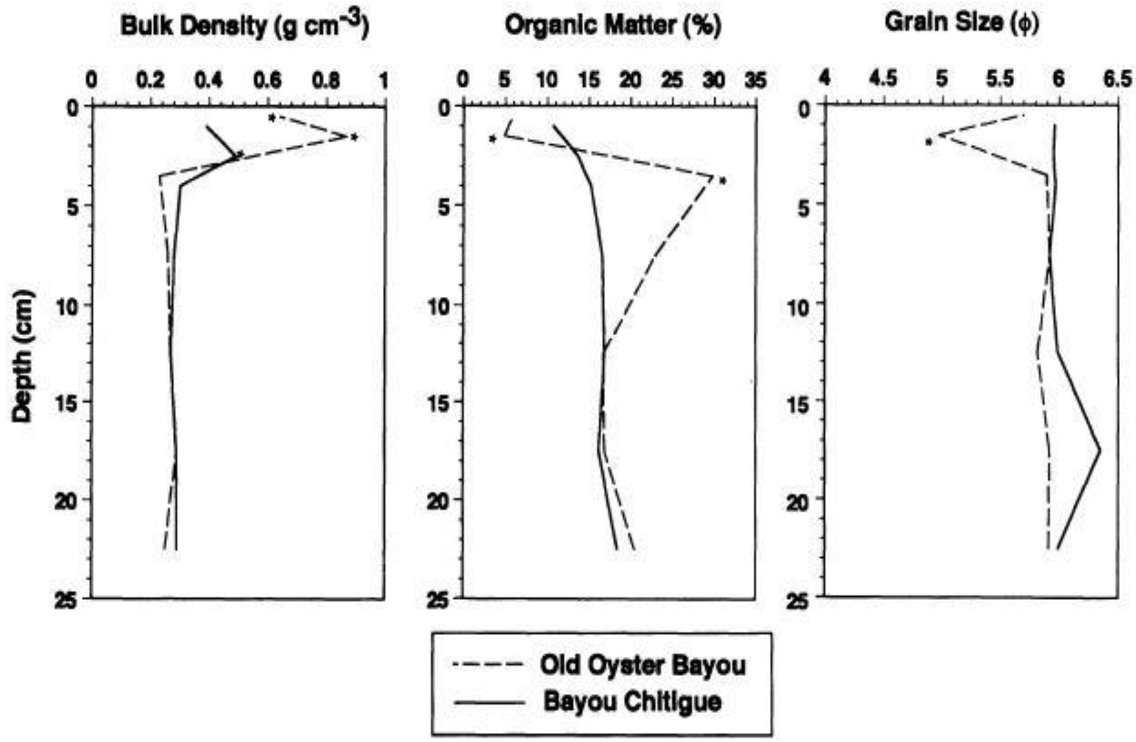

Figure 2.4. Soil profiles following the landfall of Hurricane Andrew. These soil profiles were sampled at two different locations three-four months after the landfall of Hurricane Andrew. These data show the average of seven cores (Cahoon et al. 1995).

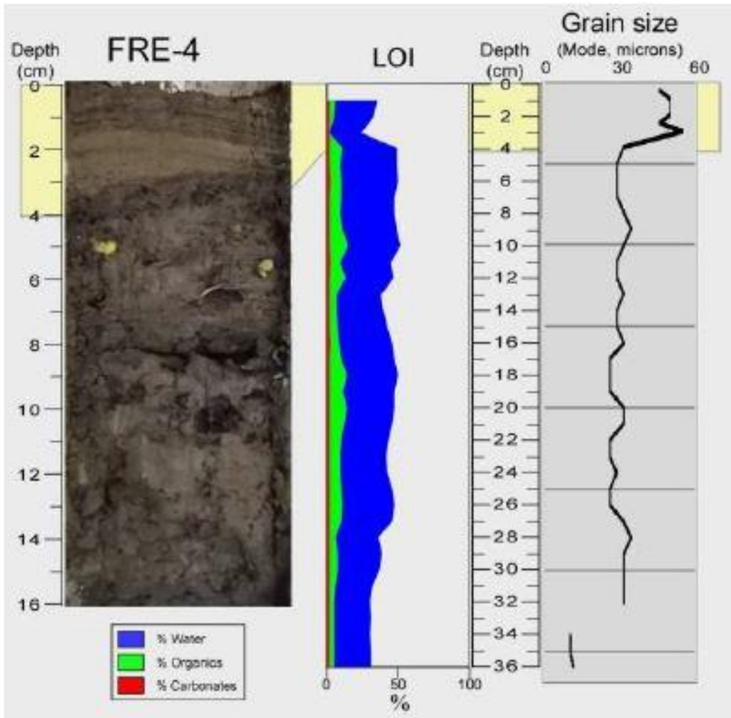

Figure 2.5. Loss-on-ignition curves for a sediment core extracted near Frenier, Louisiana. The hurricane sediment deposit is coarse in grain size and is shown in the top four centimeters (Liu et al. 2014).

Figure 2.6. A breach in the foredunes on Padre Island, Texas. This breach was caused by the storm surge of Hurricane Harvey which made landfall 67 km northeast of this location (Hodge, Anzah, and Dixon 2018).

3. RESEARCH METHODS

3.1 Study Site

McFaddin NWR is a 23,820 hectare tract of coastal marshes and brackish lakes located in Jefferson County in the far southeast corner of Texas, approximately 20 km southwest of Sabine Pass. A wide sandy beach backed by low (1-2 m) discontinuous foredunes forms the ca. 35-km boundary between the refuge and the Gulf of Mexico. Inland, the refuge contains palustrine emergent marsh that is categorized as temporarily, seasonally, or semipermanently flooded, depending on subtle variations in elevation (Williams 2010). McFaddin NWR includes one of the largest remaining freshwater marshes on the Texas Gulf Coast, as well as thousands of hectares of intermediate to brackish marsh. It is an important feeding and resting habitat for waterfowl, such as geese. A considerable number of ditches in the marsh are home to alligators, and feral hogs inhabit the area as well. The region surrounding the study area in Jefferson County, Texas, is mostly made of marshlands and brackish lakes, and is home to a number of wildlife management areas. The Gulf Intracoastal Waterway is also an important nearby feature; it is a navigable channel mostly used by recreational boats and barges. Important economic activities of the region include petroleum production, petroleum refining, shipping, ranching, and land management by the federal government.

The geology of the region surrounding McFaddin NWR is composed of recent Holocene-aged alluvium as well as barrier-island deposits. The alluvium consists of clay, silt, sand, and abundant organic deposits whereas the barrier-island deposits are largely composed of sand, with well-pronounced cheniers near Sabine Pass. The soils of the region mostly consist of beaches, fine sandy loams, silty clay loams, and mucky peat on the marshes, with sediment particle sizes decreasing and organic matter increasing moving landward from the Gulf Coast. The sandier soils have a high runoff, whereas the mucky peat is poorly drained, floods frequently, and has slopes of 0 to 1 percent (USDA 2019). The climate of the region is humid subtropical (Koppen Cfa), warm and humid most of the year, with mean annual precipitation of 1270-1520 mm and temperatures of 21-22°C (Larkin and Bomar 1983).

Hodge and Williams (2016) originally chose McFaddin NWR as a research site to investigate the storm surge sediment bed deposited by Hurricane Ike because the refuge was in the right-front quadrant of the landfalling hurricane and it was known that a storm tide of > 4 m occurred in the region (Berg 2009). The storm made landfall on 13 September 2008 at 0700 UTC at 29.3°N, 97.4°W; which is located at the northeastern tip of Galveston Island (Berg 2009; see Figure 3.1). Additionally, Hurricane Rita made landfall approximately 30 km east of Clam Lake (on McFaddin NWR) on 24 September 2005. Storm surge deposits from Hurricane Rita were also found at Texas Point National Wildlife Refuge (NWR), which is approximately 18 km east of Clam Lake Road (on McFaddin NWR) in Jefferson County, Texas (Crosby and Reese 2009; also see Figure 3.1). Cores obtained at Texas Point NWR in November 2006 revealed a sandy Hurricane Rita storm surge deposit at the surface of the marsh. The deposit varied from 2 to 15 cm in thickness and, in places, was capped by silt and clay, presumably deposited from suspension in standing flood waters (Crosby and Reese 2009).

The study region is located between High Island, Texas, and Sabine Pass, Texas, and is composed of four different marsh transects: Transect 1 (T1), Transect 2 (T2), Transect 3 (T3), and Transect 4 (T4). The transects extend from near the coastline to roughly 1,200 m inland (see Figure 3.1). Prior to this study, there was a significant geographical gap of around 30 km between High Island, Texas, and Clam Lake on McFaddin NWR that had yet to be explored for hurricane sediment deposits, and an extensive literature search failed to find any articles regarding research in the large gap between High Island and Clam Lake. Texas State Highway 87 formerly ran through this region but it has been closed since 1989 due to coastal erosion; primarily from the impacts of tropical storms and hurricanes in the latter half of the 20th century (Moore, Myers, and Rappl 2008; also see Figure 3.2). This aspect makes access to this region challenging, and an All-Terrain Vehicle (ATV) was necessary to safely traverse the beach in order to then have access to the marshes in this region. A permit was issued by McFaddin NWR, good for three years (and renewable) in order for field work to legally be conducted (see Appendix). Additionally, a U.S. Government key, which opens any gate on McFaddin NWR, was lent to allow access to the transect locations. Research grants were utilized to provide financial assistance for truck rentals (in order to transport an ATV to the study site). The ATV was necessary to move about the marsh transects (Figure 3.3). Most transects (T2, T3, and T4) were accessed and established by driving on levees that run perpendicular to the coastline. A number of these levees are utilized by hunters during the waterfowl hunting season (see Figure 3.4A), and some of them access the Gulf Intracoastal Waterway (GIWW; see Figure 3.4B). A field assistant was also available to assist with the field work that took place in summer 2017 and summer 2018. All field work took place within the boundaries of McFaddin NWR.

3.2 Methods and Data Analysis

Six to eight pit sites (designated by Transect and Pit Site; e.g. T1-1 is Transect 1, Pit Site 1) were located on each transect at McFaddin NWR in Jefferson County, Texas. The pit site locations were lined up linearly at each transect extending from 142 to 1630 m inland from the Gulf coast. The transects were aligned with the storm surge direction to allow sampling of the deposit from near the shoreline to progressively farther inland locations. The geographic coordinates of each pit site were recorded using a Garmin eTrex 20 Global Positioning System (GPS) with a reported accuracy of ± 10 m (Garmin 2011). The topographical relief of each site (along each transect) was measured by a telescopic level and stadia rod (Figure 3.5A, B). The telescopic level and stadia rod were set up at different places along each transect and tied in with either a known nearby United States Geological Survey (USGS) benchmark or the mean sea level mark on the beach. On the transects too far to tie into a known USGS benchmark, the elevation was measured from the mean sea level mark (on the Gulf coast shoreline) close to the times mid-way between the high and low tides. Up to four leveling sites (where the telescopic level was set up) were required to cover transects > 1000 m.

Utilizing a similar methodology to Williams (2010, 2018) and Williams and Denlinger (2013), the pit sites were dug with a shovel and spade along each transect; this method allows for visually confirming the lithology of each pit without causing compaction errors (Williams 2018). The linear spacing of pits were weighted towards the coastline, with site one closest to the coastline and site eight furthest from the coastline Pit sites near the coastline were located closer together, whereas the pit sites farther inland were spaced farther apart. This spatial orientation of the pit sites was utilized because thicker sediment deposits were expected closer to the coastline, whereas sediment thickness substantially decreases farther inland (Hodge and Williams 2016). The depth of each pit site and any identifiable hurricane sediment deposits were measured with a meter stick and measuring tape (Figure 3.6). Photographs of the pit lithology, soil profiles extracted from the pit, and the surrounding environment were taken and descriptions of the soil/lithology of each pit site were also documented. Soil texture was evaluated by feel, which helped determine the extent of sediment layers in each pit (Gardiner and Dackombe 1982).

After the thickness of the Hurricane Ike storm surge sediment deposit was calculated (from every pit site on all four transects), Multiple Regression Analyses and Simple Linear Regression Analyses were run in order to model storm surge deposit thickness. Multiple Linear Regression allows the prediction of one variable from several other variables; whereas Simple Linear Regression allows the prediction of one variable from another (Cronk 2008). The prediction equation for multiple regression is $Y' = B_0 + B_1X_1 + B_2X_2 + \ldots\ldots BzXz$. In the prediction equation just mentioned: Y' is the dependent variable to be predicted, B_0 is the y-intercept; and B_1 and B_2 are slopes for each respective independent variable (X). In this study, two different multiple regression analyses were run as well as three separate simple linear regression analyses. The first multiple regression analysis included one dependent variable and two independent variables. The dependent variable was storm surge deposit thickness in centimeters. The two independent variables included distance inland from the coastline (X_1, numerical variable) and elevation above sea level (X_2, numerical variable) in meters. The variable explained was storm surge deposit thickness. The two independent variables (explanatory variables) were tested to see how well they model storm surge deposit thickness.

The second multiple regression analysis included one dependent variable and three independent variables. The dependent variable was storm surge deposit thickness. The three independent variables included distance inland from the coastline in meters (X_1, numerical variable), distance from the landfall longitude of Hurricane Ike in kilometers (X_2, numerical variable), and elevation above sea level in meters (X_3, numerical variable). The variable explained was storm surge deposit thickness. The three independent variables (explanatory variables) were tested to see how well they model storm surge deposit thickness. Additionally, three simple linear regression analyses were run. The prediction equation for simple linear regression is $Y' = a + bX$. Y' is the dependent variable to be predicted, a is the y-intercept, and X is the independent variable. The first simple linear regression was conducted in order to determine if radial distance from landfall (independent variable) could predict storm surge deposit thickness (dependent variable). The second simple linear regression analysis was run in order to determine if pit site distance inland (independent variable) could predict storm surge deposit thickness. Curve Fits were also included for the second simple linear regression analysis. The third simple linear regression analysis was run in order to determine if pit site elevation (independent variable) could predict storm surge deposit thickness.

To add to the quantitative methods being utilized for this study, a Hierarchical Cluster Analysis was computed in SPSS in order to group the pit sites based on distance inland (for the ANOVA procedures). Following this, two separate one-way ANOVA's and a single two-way factorial ANOVA were run in SPSS. The ANOVA is a procedure that determines the proportion of variability attributed to each of several components. It is one of the most useful and adaptable statistical techniques available (Cronk 2008). The one-way ANOVA compares the means of two or more independent groups to see if there are any significant differences between them. In the first one-way ANOVA, the sediment thickness (dependent variable) was compared to the distance inland (independent variable). In the second one-way ANOVA, the sediment thickness (dependent variable) was compared to the distance from landfall. The two-way factorial ANOVA tests the effect of two independent variables on a dependent variable. The dependent variable for the two-way factorial ANOVA was storm surge deposit thickness. The independent variables included distance inland and distance from the landfall of Hurricane Ike. There were three sub-hypotheses of the two-way factorial ANOVA procedure. These included: A null hypothesis (H_0) of no effect on distance inland on storm surge deposit thickness, a H_0 of no effect on distance from landfall on storm surge deposit thickness, and a H_0 of no interaction of distance inland and distance from landfall on storm surge deposit thickness.

3.3 Chapter Three Figures

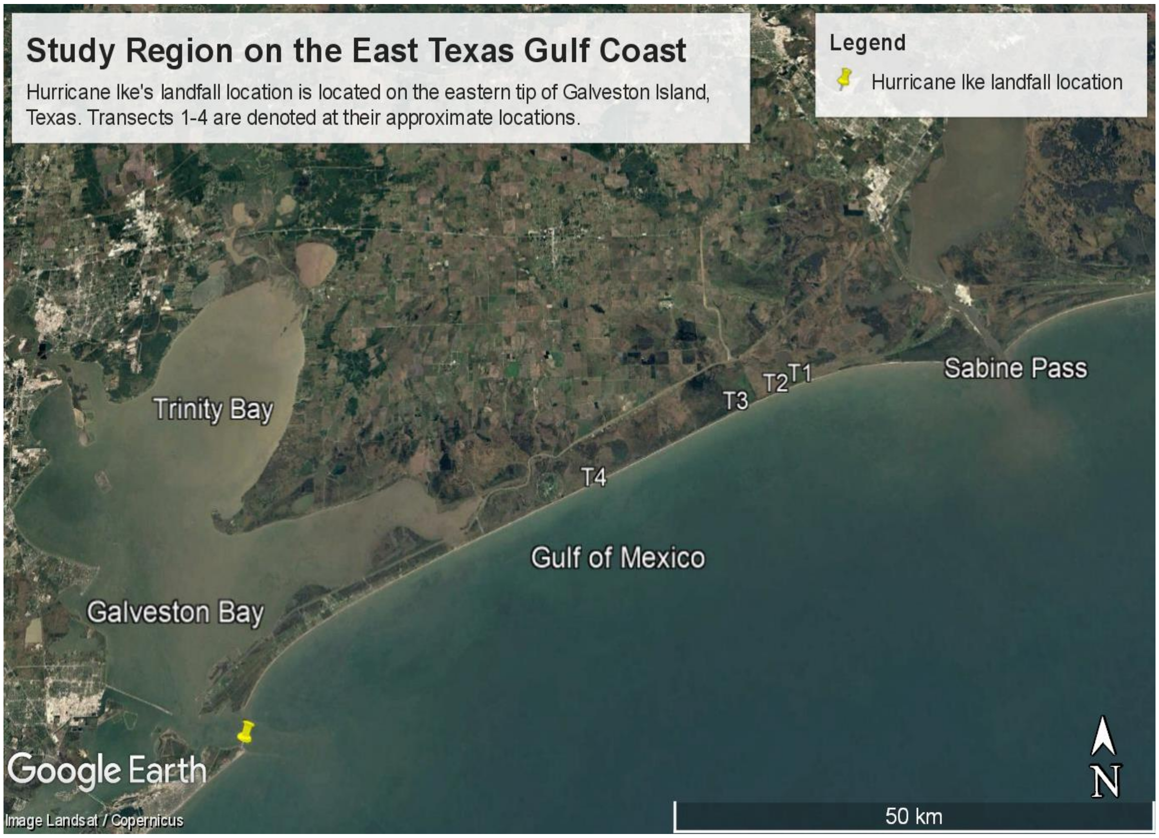

Figure 3.1. The study region spans from near High Island, Texas, in the southwest to Sabine Pass, Texas, near the Louisiana border. The location of where Hurricane Ike made landfall on 13 September 2008 is denoted by a yellow pin. T1, T2, and T3 are the farthest northeast, whereas T4 is 4 km east of the town of High Island (modified from Google Earth 2017).

Figure 3.2. Texas State Highway 87 has been closed since 1989. Hurricane Jerry (October 1989) was the “nail in the coffin” for this 33 km stretch of road between the Clam Lake Road intersection and High Island. Photo taken from near the Clam Lake Road intersection on McFaddin NWR. Photo by author.

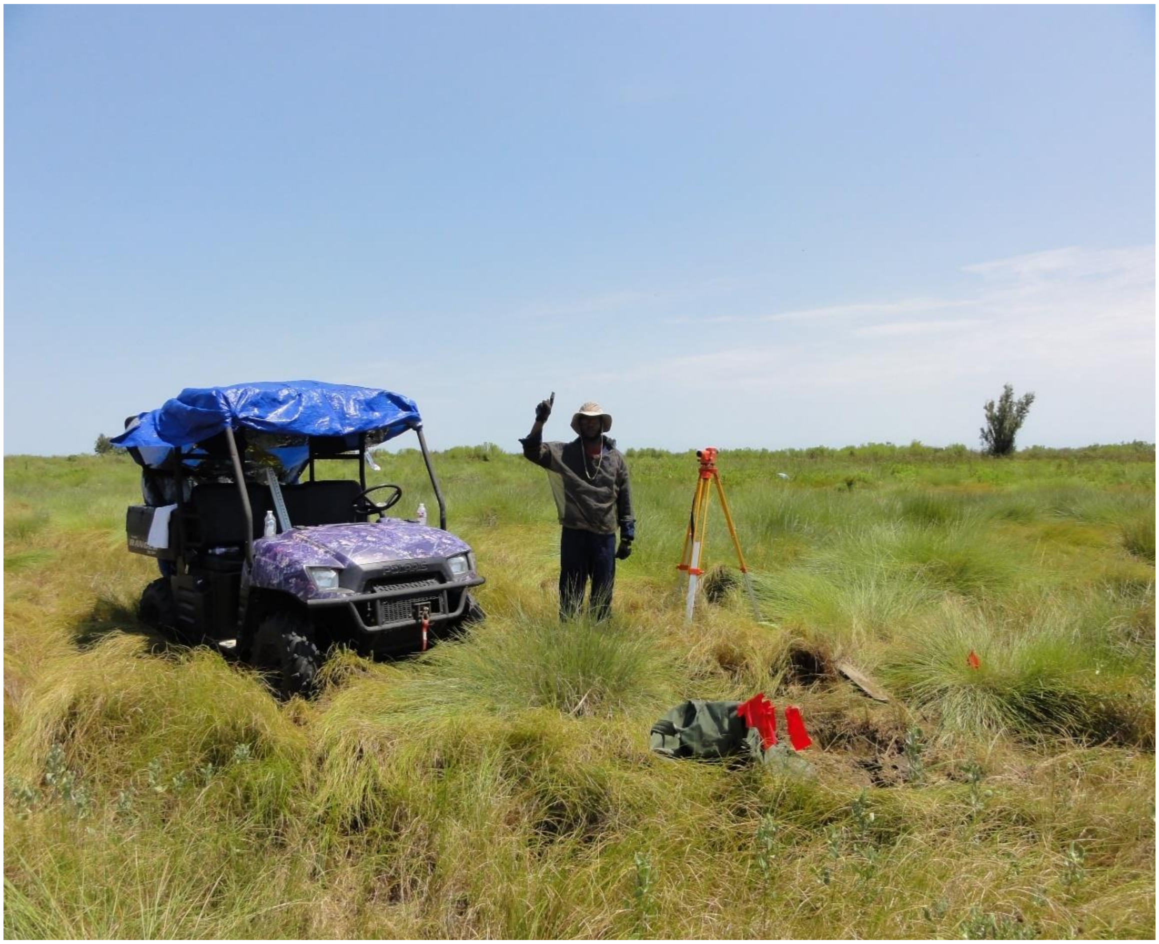

Figure 3.3. An ATV was used to safely traverse the study region. Photograph shows T2-1. Photo by author.

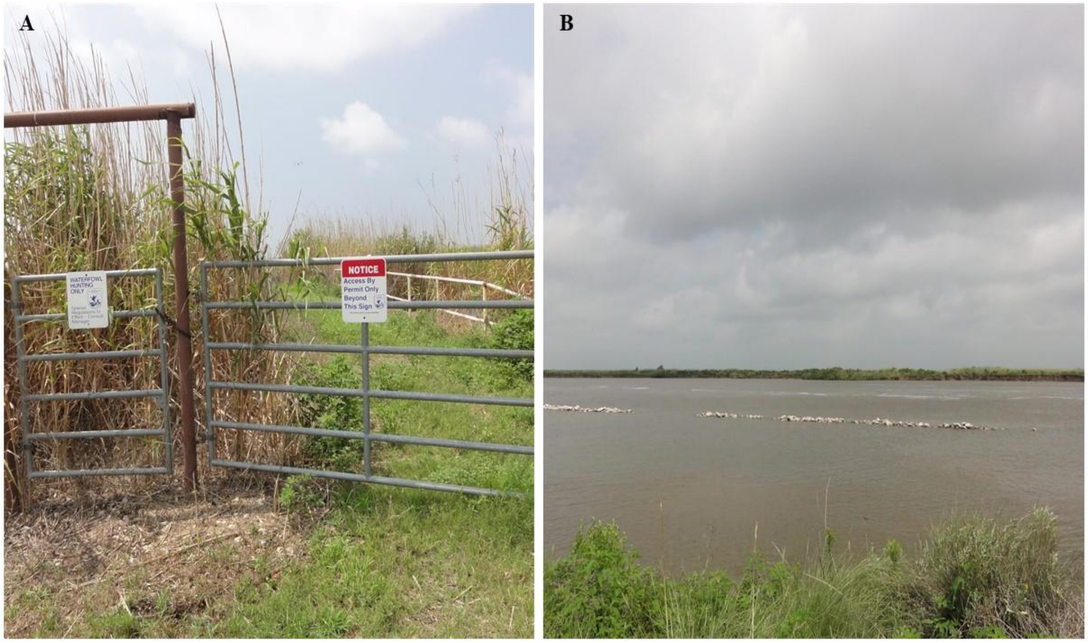

Figure 3.4. Levee and GIWW near Clam Lake. **A**. Hunters and others with permits can utilize the levees on the refuge. Photo by author. **B**. The GIWW cuts through McFaddin NWR and is landward of all the study transects. Photo by author.

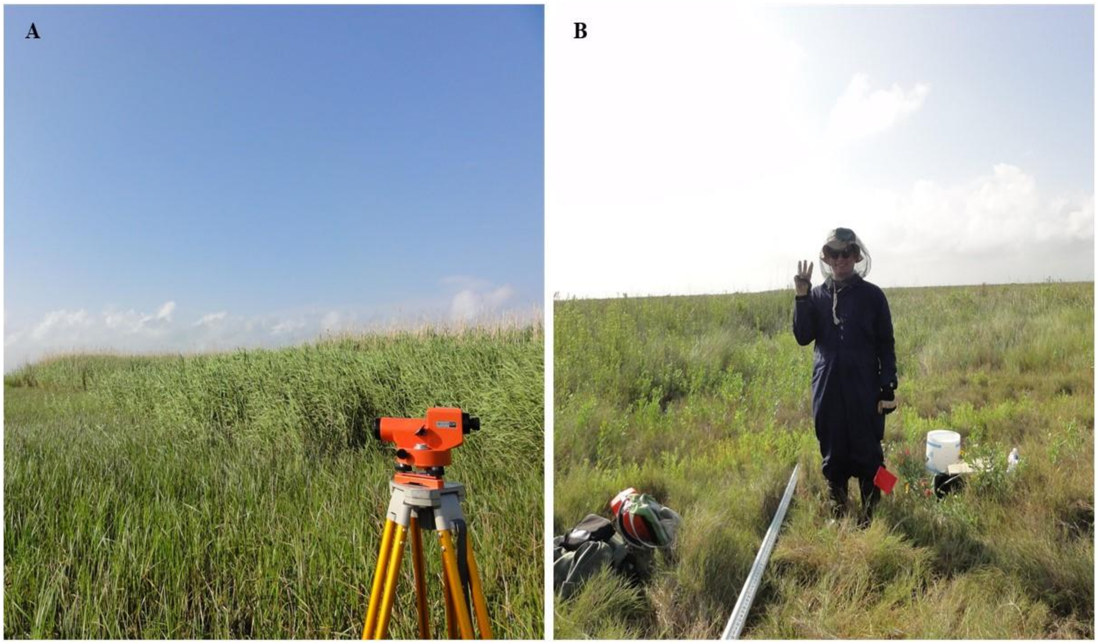

Figure 3.5. Pit site elevations were measured with a telescopic level and stadia rod. **A**. A telescopic level is in the foreground, and in the background is *Spartina alterniflora* surrounding Wiseman Lake, near T1-3. Photo by author. **B**. The terrain looking landward at T1-3; stadia rod is visible in the foreground. Photo by author.

Figure 3.6. A shovel and a spade were used to dig shallow pits along each transect. In this image, at T1-6, a light-colored sand-rich deposit is visible near the surface, to the right of the measuring tape. The organic-rich marsh deposits are the dark-colored layers immediately above and below the sand-rich deposit. Measuring tape for scale. Photo by author.

4. RESULTS

4.1 Field Work

A sand-rich deposit was visually apparent on all four transects, was located at or near the surface, and was identified at almost all pit site locations in the study region. Field work on T1 began in summer 2017 and was completed in summer 2018. A series of eight pit sites were dug that stretch from T1-1 to T1-8 (Figure 4.1). T1 is near Clam Lake on McFaddin NWR and lies 73 km northeast of where Hurricane Ike made landfall (Figure 3.1). All elevations on T1 were tied to a USGS benchmark a few meters north of Highway 87 in the vicinity of the study area (Benchmark Designation E1015, elevation 1.54 m, NAVD88; personal communication, Robert Josey, Texas Department of Transportation, August 14, 2015). The elevation at the benchmark was then tied to a known point closer to T1 with an identical height of Highway 87 (1.47 m). Since Highway 87 was mostly still intact (in the vicinity of T1) after Hurricane Ike struck the region, the telescopic level and stadia rod were used to obtain elevations along the entirety of T1 which was tied to USGS Benchmark E1015. Elevations along this transect range from 1.63 m at T1-1 to 0.1 m at T1-8 (see Table 4.1). A sand-rich washover fan exists on the most seaward portion of the transect (T1-1 to T1-3). T1-1 is located on the center of the washover fan and the deposit is approximately 60 cm thick there. The deposit extends from the surface, and correspondingly lacks a surface marsh deposit, as the elevation here is too high for flood derived sediment from tides and heavy rains. Below the sand-rich deposit was a darker colored layer; presumably of higher organic content.

T1-2 is located 221 m inland, has an elevation of 0.84 m, and is landward of the center of a washover fan that T1-1 is on. T1-2 is about 50 m west of Wiseman Lake (a small, brackish lake on the marsh). A predominantly organic-rich marsh deposit of 2 cm (mixed with some sand) extends from the surface; whereas immediately below this lies a sand-rich deposit of roughly 39 cm. This site is in a low area that drains into Wiseman Lake, and a considerable amount of the surficial deposit here has been accreted due to floodwaters from heavy rains.

T1-3 is only 25 m landward than T1-2; its nearby location was chosen due to it being landward of the low spot that drains Wiseman Lake (in order to assess what lithologic differences may exist between these two pit sites that are in close proximity to each other). T1-3 is located 246 m inland, has an elevation of 0.9 m and contains an organic-rich marsh deposit of 5 cm which extends from the surface down to the top of the sand-rich deposit. The sand-rich deposit here is 23 cm thick. T1-4 is located 384 m inland, has an elevation of 0.99 m and has an organic-rich marsh deposit that extends from the surface down to a depth of 7 cm. Below this lies a sand-rich deposit of 8 cm; much thinner than T1-1 to T1-3. Below the sand-rich layer, an organic clay deposit was found (7 cm thick), with another layer of sand below that (5 cm thick).

Moving farther inland, T1-5, which is located next to a small marsh pond, is 505 m inland, with an elevation of 0.84 m (Figure 4.2). An organic-rich marsh deposit extends from the surface down to a depth of 6 cm. Directly beneath this lies a sand-rich deposit 5 cm thick. Continuing landward, T1-6 is 757 m inland, has an elevation of 0.47 m and has a largely organic-rich layer in the uppermost 1 cm. There is a sand-rich deposit of roughly 7.6 cm that exists directly beneath the top organic-rich layer. Beneath the sand-rich deposit there is a marsh deposit 13 cm thick. A second sand bed; presumably older than the uppermost sand bed, is 3.8 cm thick. T1-7 is 1,100 m inland, sits at just 0.25 m above sea level, and has a dark, organic-rich marsh deposit at the uppermost 5 cm of the pit. There is a sand-rich deposit 6 cm thick, immediately below the marsh deposit. Finally, T1-8 is 1,385 m inland, sits just above sea level at 0.1 m and has a dark organic-rich marsh deposit that extends from the surface down to a depth of 5 cm. The sand-rich layer lies immediately below and has a thickness of roughly 2.5 cm. T1-7 and T1-8 are the most landward sites on T1 and are also the lowest elevation. Floodwaters from Clam Lake frequently flood this area, and the water table is high as well. During field work conducted in July 2018, a high water table was encountered while digging the pits for T1-7 and T1-8. Soil profiles were extracted and allowed to dry for a few days. Upon reassessment, a dark, moist, organic-rich marsh deposit was confirmed at both pit sites, as well as the sharp lithologic contrast against the underlying sand bed. The sand-rich deposit generally decreases in thickness moving inland along the transect (Figure 4.3).

Field work on T2 was conducted in July and August 2018. A series of six pit sites were dug that stretch from T2-1 to T2-6 (Figure 4.4). T2 is on McFaddin NWR and lies 71 km northeast of where Hurricane Ike made landfall, and about 2 km west of T1. As opposed to T1, T2 does not contain any washover fan deposits, yet a sand-rich layer was still found at all pit sites investigated (Table 4.2). Due to the complete destruction of Highway 87 in the vicinity of T2, the elevations from T1 were not tied to T2. The elevations along T2 were tied to mean sea level at the coastline, seaward of T2-1. T2-1 is located 175 m inland, has an elevation of 1.23 m, and has a 2.5 cm thick surficial deposit largely devoid of sand. Immediately below this lies a sand-rich deposit 13 cm thick. T2-2, located 325 m inland, has an elevation of 0.61 m, with the top 1.3 cm composed of a dark organic-rich layer. Immediately below this lies a sand-rich deposit 4 cm in thickness. T2-3 is located 570 m inland, has an elevation of 0.57 m, and has a very thin organic-rich surficial layer 0.6 cm thick. A sand-rich deposit roughly 3.8 cm thick lies immediately below the organic-rich surface layer. It is notable that T2-1 to T2-3 all contain a second sand layer; presumably derived from Hurricane Rita. This is not surprising, as T2 is only 2 km west of T1, where deposits from Hurricane Rita have been previously found in that vicinity (Hodge and Williams 2016). T2-4 is located 825 m inland, has an elevation of 0.4 m and has a 2.5 cm organic-rich marsh deposit at the surface. A sand-rich deposit of 10 cm lies directly beneath the marsh deposit. T2-5 is 1,087 m inland, lies at an elevation of 0.27 m, and contains a surficial organic-rich marsh deposit approximately 2.5 cm thick. The sand-rich deposit lies immediately below the organic-rich deposit and is roughly 3.9 cm thick. Lastly, T2-6 is 1,266 m inland, has an elevation of 0.19 m and has a surficial marsh deposit 2.5 cm thick. Immediately below this lies a sand-rich deposit 3.5 cm thick. Similar to T1, the sand-rich deposit predominantly decreases in thickness farther inland (Figure 4.5).

Field work on T3 was conducted in August 2018. A series of six pit sites were dug that stretch from T3-1 to T3-6 (see Table 4.3). T3 is on McFaddin NWR and lies 67 km northeast of where Hurricane Ike made landfall (Figure 4.6). Like T2, T3 does not contain any washover fan deposits. Due to a lack of USGS benchmarks in the vicinity, the elevations along T3 were measured from mean sea level, seaward of T3-1. T3-1 is located 295 m inland, landward of an earthen levee and sits at an elevation of 0.51 m. A 36 cm pit was dug in which the top 10 cm contains a dark clay-rich muddy deposit. The layer directly beneath that is a sand-rich deposit 5 cm thick. No other sand-rich layers were visually apparent in the pit (Figure 4.7).

T3-2, located 452 m inland, and 0.49 m above sea level, has a thin organic-rich deposit at the top 3 cm of the surface. Immediately below this lies a sand-rich deposit of 6.3 cm. T3-3 is located 696 m inland, is 0.4 m in elevation, and is completely devoid of a sand-rich deposit in the 33 cm pit that was dug. A uniformly dark, organic-rich marsh deposit extends the entire depth of the pit. T3-3 is noteworthy of being the first pit site in the research area (regarding the chronologic manner field work was conducted) that is completely devoid of a sand-rich layer (Figure 4.8). T3-4 is located 1,018 m inland, sits at an elevation of 0.2 m and has a thin surficial marsh deposit of 3.2 cm. Immediately below this lies a sandy deposit roughly 1.3 cm thick. The sandy deposit was very spotty in the vicinity of T3-4, and the thickness of the sand-rich deposit was determined from a soil profile extracted from the pit. T3-5 is 1,316 m inland, has a very low elevation of 0.11 m, and has a thin surficial organic layer at the uppermost 2.5 cm of the pit. Directly beneath the organic-rich layer lies a sandy deposit only 0.6 cm thick; this deposit is spotty in nature in the pit and in the vicinity of T3-5. Lastly, T3-6 is 1,630 m inland, has a very low elevation of 0.1 m and is completely devoid of a sand-rich deposit. Like T1 and T2, T3 shows a decrease in the sand-rich deposit with increasing distance inland (Figure 4.9).

Field work on T4 was conducted in August 2018. A series of six pit sites were dug that stretch from T4-1 to T4-6 (see Table 4.4). T4 is on the western edge of McFaddin NWR, is 5 km east of the small town of High Island and lies 46 km northeast of where Hurricane Ike made landfall (Figure 4.10). Similar to T1, T4 has thicker sand-rich deposits than the lesser amounts seen along T2 and T3. Due to lack of USGS benchmarks in the vicinity, elevations along T4 were tied in with mean sea level on the coastline, seaward of T4-1. T4-1 is located 142 m inland, is 0.61 m in elevation, and has a surficial organic-rich deposit at the uppermost 5 cm of the pit. Immediately below the organic-rich deposit lies a layer of sand 53 cm thick. T4-2 is located 231 m inland, is 0.55 m in elevation and has a 5 cm dark-colored surficial deposit (composed of a mixture of sand, clay and organics). A sand-rich deposit 58 cm thick is directly underneath the surface layer. T4-3 is located 303 m inland, is 0.69 m in elevation and has a 10 cm thick root mat at the surface. Beneath this lies a sand-rich deposit 15 cm thick. T4-4 is located 405 m inland, is 0.58 m in elevation and has a thin sandy deposit of 10 cm. The sandy deposit began at the surface; thus, there was a lack of a darker, more organic-rich layer. T4-5 is 570 m inland, is 0.51 m in elevation, and has a thin organic-rich layer at the uppermost 2.5 cm of the pit. Beneath this lies a sandy deposit approximately 5.6 cm thick. Lastly, T4-6 is 880 m inland, is 0.48 m in elevation, and has a mostly organic-rich root mat in the uppermost 5 cm of the pit. Directly beneath the root mat lies a sand-rich deposit 5 cm thick (Figure 4.11). T4 is similar to the other three transects because the sand-rich deposit generally decreases with distance inland (Figure 4.12).

4.2 Regression Analyses

The prediction equation for multiple regression is $Y' = B_0 + B_1X_1 + B_2X_2 + \ldots\ldots BzXz$. In the prediction equation just mentioned: Y' is the dependent variable to be predicted, B_0 is the y-intercept; and B_1 and B_2 are slopes for each respective independent variable (X). Two multiple regression analyses were performed in Microsoft Excel in order to model storm surge deposit thickness based on distance inland, distance from landfall, and pit site elevation. The first multiple regression analysis (Equation

4.2.1) was performed in order to model storm surge deposit thickness (*Y'*) based on distance inland (X_1) and pit site elevation (X_2); utilizing this equation: $Y' = B_0+B_1X_1+ B_2X_2$. A significant regression result was found:

Thickness = 16.220 - 0.016(Distance Inland) + 13.311(Elevation) (4.2.1)

F (2, 23) = 6.796

P-value = 0.005

$R^2 = 0.371$

The H_0 that there is no explanatory power in the independent variables was rejected. These results mean that the sediment deposit thickness decreases 0.016 cm for each meter farther inland, and that the sediment deposit thickness increases 13.311 cm for each meter increase in elevation. The results state the direction (decrease), strength (0.371), value (6.796), degrees of freedom (2, 23), and significance level (0.005) of the regression. These results are significant since the *p* value is < 0.05 (Table 4.5). The predicted change in sediment thickness farther landward is in line with the empirical results obtained in the field.

The second multiple regression analysis (Equation 4.2.2) was performed in order to model storm surge deposit thickness (*Y'*) based on distance inland (X_1), distance from the landfall location (X_2) of Hurricane Ike, and elevation (X_3) of each pit site location; utilizing this equation: $Y' = B_0+B_1X_1+ B_2X_2 + B_3X_3$. A significant regression result was found:

Thickness = 34.163 - 0.007(Distance Inland) - 0.447(Distance Landfall) + 22.798(Elevation) (4.2.2)

F (3,22) = 5.432

P-value = 0.006

$R^2 = 0.426$

The H_0 that there is no explanatory power in the independent variables was rejected. These results mean that the sediment deposit thickness decreases 0.007 cm for each meter farther inland, decreases 0.447 cm for each kilometer away from the landfall location, and increases 22.798 cm for each meter rise in elevation. The results state the direction (decrease), strength (0.371), value (5.432), degrees of freedom (2, 23), and significance level (0.006) of the regression. These results are significant since the p value is < 0.05 (Table 4.6). The predicted change in sediment thickness farther landward is in line with the empirical results obtained in the field.

Additionally, three simple linear regressions were computed. The prediction equation for all three simple linear regressions is $Y' = a + bX$. Y' is the dependent variable to be predicted, a is the y-intercept, and X is the independent variable. The first simple linear regression (Equation 4.2.3) was performed in order to predict sediment thickness (Y') based on radial distance (X) from landfall. The regression equation was not significant:

$$F\,(1,24) = 2.09 \tag{4.2.3}$$

P-value = 0.161

$R^2 = 0.080$

Radial distance from landfall is not a significant predictor of sediment thickness due to a $p > 0.05$ (Table 4.7). The second simple linear regression (Equation 4.2.4) was performed in order to predict sediment thickness (Y') based on distance inland (X) from the coastline. A significant regression equation was found:

$$\text{Thickness} = 29.349 - 0.024(\text{Distance Inland}) \qquad (4.2.4)$$

$F\ (1,24) = 12.654$

P-value = 0.002

$R^2 = 0.345$

Pit site sediment thickness decreased .024 cm for each meter inland from the coastline. The results state the direction (decrease), strength (.345), value (12.654), degrees of freedom (1,24), and significance level (0.002) of the regression. These results are significant since the p value is < 0.05 (Table 4.8). Additionally, curve fits were run for Equation 4.2.4. The Linear, Logarithmic, and Power Law curve fit model parameters all show significant results for sediment thickness based on distance inland (see Table 4.9).

The third simple linear regression (Equation 4.2.5) was performed in order to predict sediment thickness (Y') based on pit site elevation above sea level (X). A significant regression equation was found:

$$\text{Thickness} = -2.24 + 28.22(\text{Elevation}) \qquad (4.2.5)$$

$F\ (1,24) = 11.256$

P-value = 0.003

$R^2 = 0.319$

Pit site sediment thickness increased 28.22 cm for each meter of elevation increase. The results state the direction (increase), strength (.319), value (11.256), degrees of freedom (1,24), and significance level (0.003) of the regression. These results are significant since the p value is < 0.05 (Table 4.10). These results are fascinating and show that multiple regression could provide a significant contribution to the body of knowledge regarding hurricane-derived sedimentation studies on the Gulf of Mexico coastline.

4.3 ANOVA Analyses

A Hierarchical Cluster Analysis was performed in SPSS in order to group the pit sites based on distance inland (this was necessary in order to perform the ANOVA analyses). The pit sites were clustered into three groups. Group 1 had a distance inland of >1000 m. Group 2 had a distance inland of between 500 m and 1000 m. Group 3 had a distance inland of <500 m (see Tables 4.1, 4.2, 4.3, and 4.4). A one-way ANOVA (Equation 4.2.6) was computed to compare sediment thickness (cm) by pit site distance inland (m) based on the groupings identified in the Hierarchical Cluster Analysis. A significant result was found:

$$F = (2,23) = 7.11 \qquad (4.2.6)$$

P-value = 0.004

Sediment thickness differs significantly based on which group a pit site was in (Table 4.11). Group 1 had a mean thickness of 2.59 cm (*sd* = 2.20 cm). Group 2 had a mean thickness of 5.49 cm (*sd* = 2.94 cm). Group 3 had a mean thickness of 26.19 cm (*sd* = 22.25 cm). Additionally, a Tamhane post hoc test was run in order to show which groups differed from one another. The results of the Tamhane post hoc test show that Groups 1 and 3 ($p = .017$) as well as Groups 2 and 3 ($p = .035$) significantly differ from each other. Groups 2 and 1 do not significantly differ ($p = 0.141$; see Table 4.12). These results show that the pit sites located >1000 m inland had significantly less sediment than the pit sites <500 m inland from the coastline (which compares Groups 1 and 3 respectively). The pit sites located between 500 m and 1000 m inland also had significantly less sediment than the pit sites located <500 m inland (which compares Groups 2 and 3 respectively). These findings support the empirical evidence collected in the field that the thickest sediment deposits were found closest to the gulf coast.

The second one-way ANOVA (Equation 4.2.7) was computed to compare sediment thickness (cm) by distance from landfall (km) along four different transects. No significant difference was found:

$$F\ (3,22) = 2.44 \tag{4.2.7}$$

P-value = 0.092

The sediment thickness did not significantly differ amongst the four transects based on transect distance from landfall. T1 had a mean thickness of 18.82 cm (*sd* = 20.70 cm). T2 had a mean thickness of 6.40 cm (*sd* = 4.08 cm). T3 had a mean thickness of 2.23 cm (*sd* = 2.80 cm). T4 had a mean thickness of 24.63 cm (*sd* = 24.51 cm). These results show that sediment thickness did not significantly differ based on transect distance from the landfall location of Hurricane Ike (Table 4.13).

A two-way factorial ANOVA (Equations 4.2.8.1, 2, 3) was computed in order to determine if there was an interaction of distance inland and distance from landfall on storm surge deposit thickness. There were three sub-hypotheses of the two-way factorial ANOVA. Equation 4.2.8.1 had a H_0 of no effect on distance inland on storm surge deposit thickness. Equation 4.2.8.2 had a H_0 of no effect on distance from landfall on storm surge deposit thickness. Equation 4.2.8.3 had a H_0 of no interaction of distance inland and distance from landfall on storm surge deposit thickness. The main effect for distance inland was not significant:

$$F = (2,15) = 2.22 \tag{4.2.8.1}$$

P-value = 0.143

The main effect for distance from landfall was also not significant:

$$F = (3,15) = 0.937 \tag{4.2.8.2}$$

P-value = 0.447

Finally, the interaction between distance inland and distance from landfall was likewise not significant:

$$F = (5,15) = 0.687 \tag{4.2.8.3}$$

P-value = 0.640

The three sub-hypotheses were all not significant due to having a p value of > 0.05. Thus, the results indicate that the interaction between distance inland and distance from landfall has no significant effect on sediment thickness (Table 4.14). There was a failure to reject the H_0 with all three sub-hypotheses.

4.4 Chapter Four Tables

Table 4.1. T1 sand-rich deposit thickness, pit site elevation, distance inland, and cluster group for each pit site.

Pit site	Thickness (cm)	Pit site elev. (m)	Distance Inland (m)	Group
T1-1	60.6	1.63	166	3
T1-2	38.7	0.84	221	3
T1-3	21.6	0.9	246	3
T1-4	8	0.99	384	3
T1-5	5.2	0.84	505	2
T1-6	7.6	0.47	757	2
T1-7	6.35	0.25	1,100	1
T1-8	2.5	0.1	1,385	1

Table 4.2. T2 sand-rich deposit thickness, pit site elevation, distance inland, and cluster group for each pit site.

Pit site	Thickness (cm)	Pit site elev. (m)	Distance Inland (m)	Group
T2-1	12.9	1.23	175	3
T2-2	4.1	0.61	325	3
T2-3	3.8	0.57	570	2
T2-4	10.2	0.4	825	2
T2-5	3.9	0.27	1,087	1
T2-6	3.5	0.19	1,266	1

Table 4.3. T3 sand-rich deposit thickness, pit site elevation, distance inland, and cluster group for each pit site.

Pit site	Thickness (cm)	Pit site elev. (m)	Distance Inland (m)	Group
T3-1	5.1	0.51	295	3
T3-2	6.4	0.49	452	2
T3-3	0	0.4	696	2
T3-4	1.3	0.2	1,018	1
T3-5	0.6	0.11	1,316	1
T3-6	0	0.05	1,630	1

Table 4.4. T4 sand-rich deposit thickness, pit site elevation, distance inland, and cluster group for each pit site.

Pit site	Thickness (cm)	Pit site elev. (m)	Distance Inland (m)	Group
T4-1	53.3	0.61	142	3
T4-2	58.4	0.55	231	3
T4-3	15.2	0.69	303	3
T4-4	10.2	0.58	405	3
T4-5	5.6	0.51	570	2
T4-6	5.1	0.48	880	2

Table 4.5. Equation 4.2.1 shows a *p* value (Significance F) of 0.005. The result is significant.

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3030.463	1515.231	6.796	0.005
Residual	23	5128.022	222.957		
Total	25	8158.485			

Table 4.6. Equation 4.2.2 shows a *p* value (Significance F) of 0.006. The result is significant.

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	3471.699	1157.232	5.432	0.006
Residual	22	4686.786	213.035		
Total	25	8158.485			

Table 4.7. Equation 4.2.3 shows a p value (Significance F) of 0.161. The result is not significant.

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	653.717	653.717	2.091	0.161
Residual	24	7504.768	312.699		
Total	25	8158.485			

Table 4.8. Equation 4.2.4 shows a *p* value (Significance F) of 0.002. The result is significant.

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2816.546	2816.546	12.654	0.002
Residual	24	5341.938	222.581		
Total	25	8158.485			

Table 4.9. Results for the Linear, Logarithmic, and Power Law equations. These results are from Equation 4.2.4 and are all significant: $p < 0.05$.

Model Summary and Parameter Estimates

Dependent Variable: sediment thickness

	Model Summary					Parameter Estimates	
Equation	R Square	F	df1	df2	Sig.	Constant	b1
Linear	0.345	12.652	1	24	0.002	0.293	0.000
Logarithmic	0.523	17.051	1	24	0.000	0.360	-0.003
Power Law	0.538	17.224	1	24	0.000	5606.855	-1.874

The independent variable is Distance from the Coastline.

Table 4.10. Equation 4.2.5 shows a p value (Significance F) of 0.003. The result is significant.

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2604.754	2604.754	11.256	0.003
Residual	24	5553.731	231.406		
Total	25	8158.485			

Table 4.11. Equation 4.2.6 results. These results compare sediment thickness to groups by distance inland. The results are significant and show a *p* value (Significance F) of 0.004.

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Between Groups	2	3117.985	1558.992	7.114	0.004
Within Groups	23	5040.500	219.152		
Total	25	8158.485			

Table 4.12. Tamhane post hoc test results showing how Groups 1 and 3 and Groups 2 and 3 significantly differ from each other ($p < 0.05$).

Multiple Comparisons

Dependent Variable: Sediment Thickness [cm]

	(I) Cat. Dist. Inland	(J) Cat. Dist. Inland	Mean Difference (I-J)	Std. Error	Sig.
Tamhane	1	2	-2.895	1.332	0.141
		3	-23.598	6.760	0.017
	2	1	2.895	1.332	0.141
		3	-20.703	6.789	0.035
	3	1	23.598	6.760	0.017
		2	20.703	6.789	0.035

Table 4.13. Equation 4.2.7 results. These results compare sediment thickness to distance from landfall location. The results (not significant) show a *p* value (Significance F) of > 0.05.

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Between Groups	3	2034.078	678.026	2.436	0.092
Within Groups	22	6124.406	278.382		
Total	25	8158.485			

Table 4.14. Equation 4.2.8 showing interaction between distance inland and distance from landfall (catdin*catdid respectively). The interaction is not significant, as the *p* value (Sig.) is > 0.05.

Tests of Between-Subjects Effects

Dependent Variable: Sediment Thickness [cm]

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4633.227[a]	10	463.323	1.971	0.114
Intercept	2381.756	1	2381.756	10.134	0.006
catdin	1044.188	2	522.094	2.222	0.143
catdid	660.813	3	220.271	0.937	0.447
catdin*catdid	807.833	5	161.567	0.687	0.640
Error	3525.258	15	235.017		
Total	12874.063	26			
Corrected Total	8158.485	25			

a. R Squared = .568 (Adjusted R Squared = .280)

4.5 Chapter Four Figures

Figure 4.1. T1 lies 73 km northeast of the landfall location of Hurricane Ike. Pit site locations are indicated by white dots. The elevation is highest at on a washover fan at T1-1 and gradually lowers to near sea level at T1-8 (modified from Google Earth, 2017).

Figure 4.2. T1-5 is about 35 cm deep and contains a visually apparent sand-rich layer near the surface. The dark-colored layer below the sandy deposit is the organic-rich marsh deposit. Photo by author.

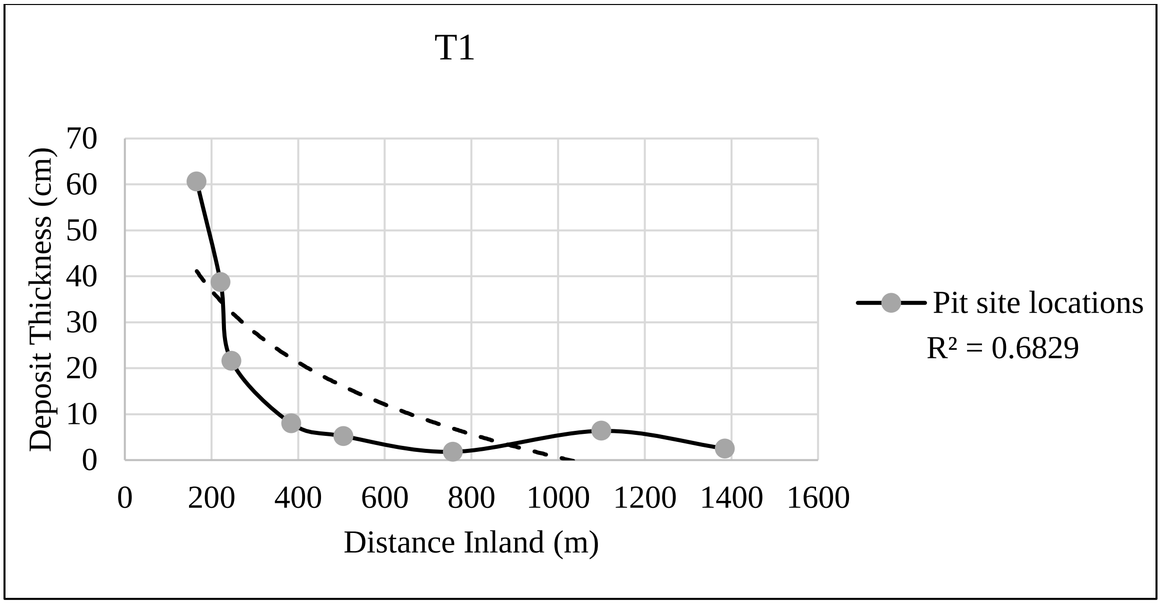

Figure 4.3. Scatter chart showing relationship between sediment deposit thickness and distance inland along T1.

Figure 4.4. T2 lies 71 km northeast of where Hurricane Ike made landfall. Pit site locations are indicated by white dots. It is about 2 km west of T1 (modified from Google Earth, 2017).

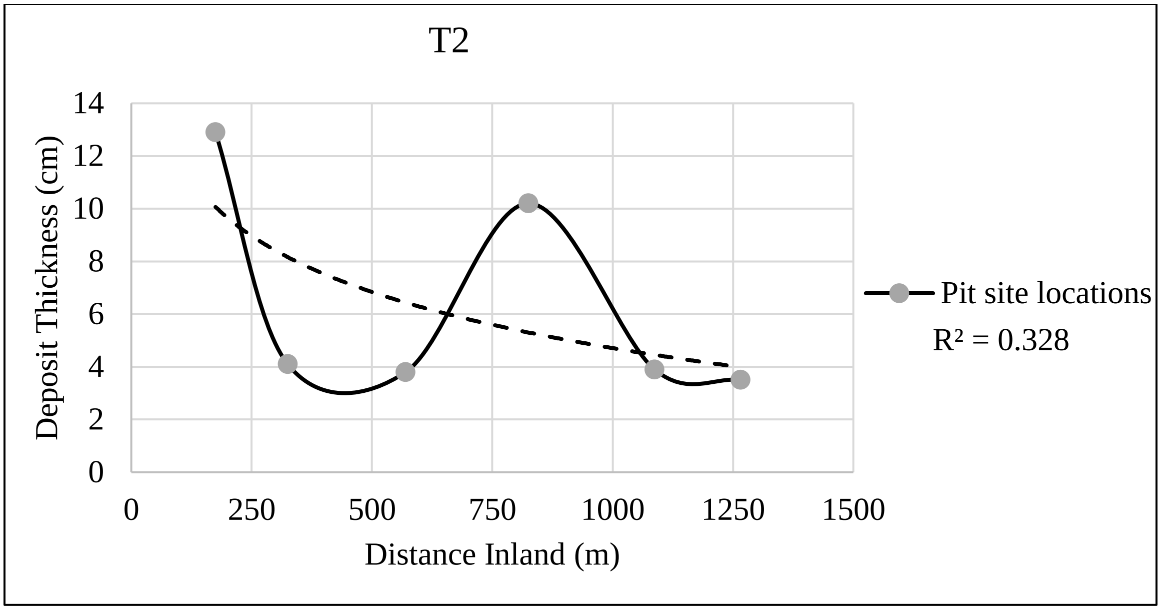

Figure 4.5. Scatter chart showing relationship between sediment deposit thickness and distance inland along T2.

Figure 4.6. T3 lies 67 km northeast of where Hurricane Ike made landfall. Additionally, T3 is about 4 km west of T2. It is notable that this transect lies immediately landward of an earthen levee (modified from Google Earth 2017).

Figure 4.7. A soil profile extracted from T3-1. Notice the prominent light-colored sand bed towards the middle of this sample. The organic-rich marsh deposits are the dark-colored layers immediately above and below the sand-rich deposit. Photo by author.

Figure 4.8. T3-3. Notice uniformly dark organic-rich deposit that extends the depth of the pit. This was the first pit site encountered in the entire study area that was completely devoid of a sandy deposit. Photo by author.

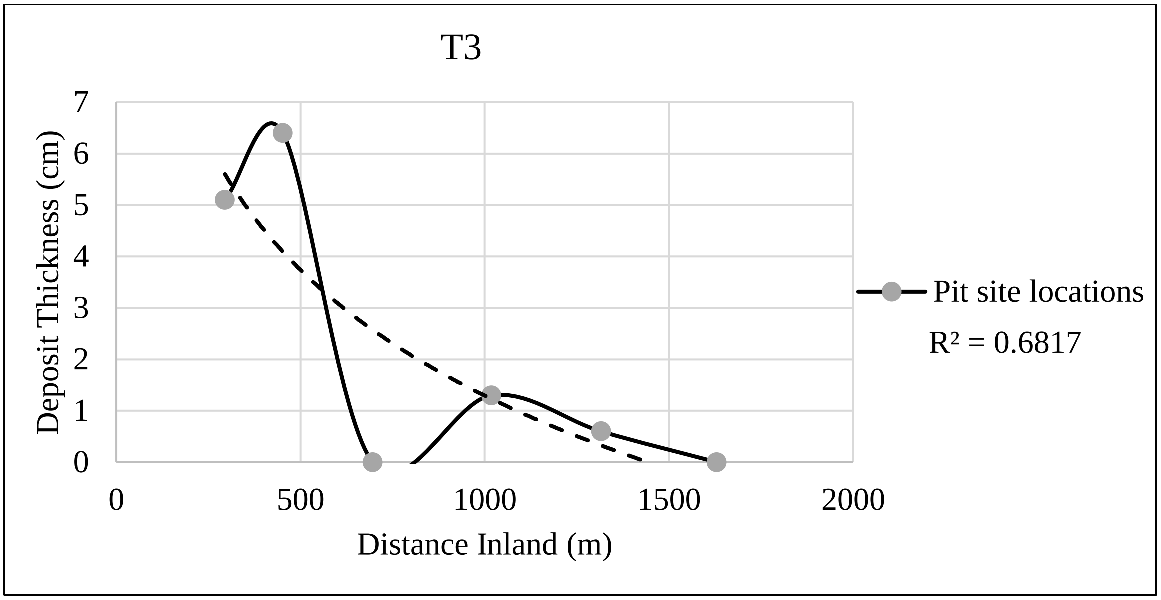

Figure 4.9. Scatter chart showing relationship between sediment deposit thickness and distance inland along T3.

Figure 4.10. T4 lies 46 km northeast of where Hurricane Ike made landfall. Like T3, an earthen levee exists in the vicinity of T4 (modified from Google Earth, 2017).

Figure 4.11. T4-6. Notice sandy deposit clearly visible to the left of the measuring tape. The organic-rich marsh deposits are the dark-colored layers immediately above and below the sand-rich deposit. Photo by author.

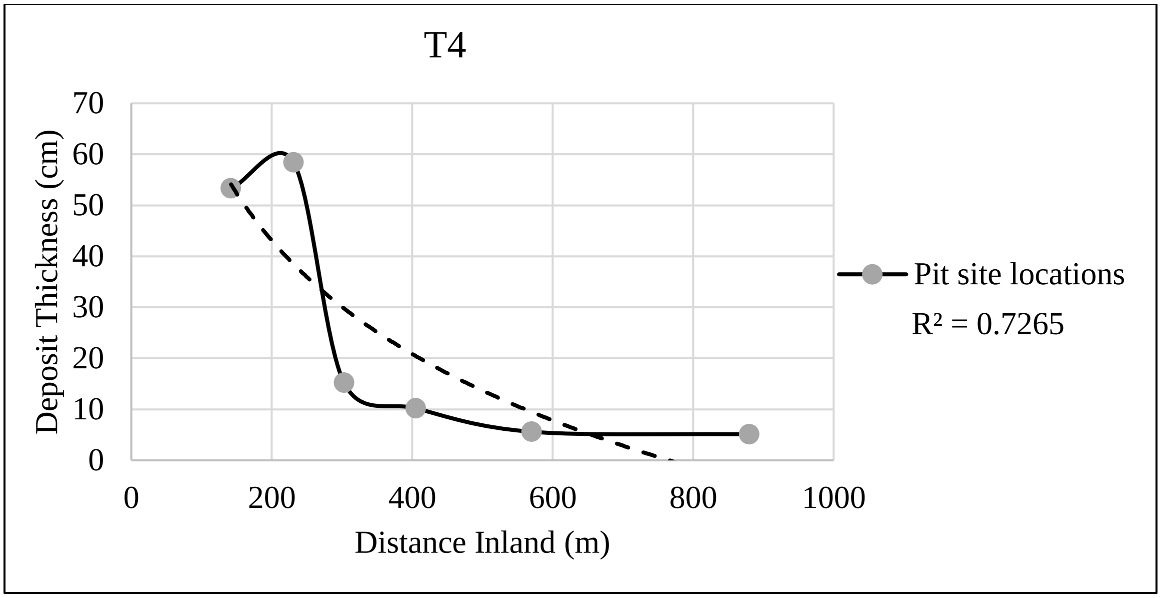

Figure 4.12. Scatter chart showing relationship between sediment deposit thickness and distance inland along T4.

5. DISCUSSION

5.1 Discussion of Field Results

A sand-rich deposit was visually apparent on all four transects, was located at or near the surface, and was identified at almost all pit site locations in the study region. Additionally, the entire study region was within the right-front quadrant of Hurricane Ike (Figure 5.1) and there was not a hurricane strong enough to deposit a sand-rich deposit after 2008 in the study region (Hodge and Williams 2016; Williams 2018; Yao, Liu, and Ryu 2018). Other studies have found this sand-rich deposit on East Texas and Southwest Louisiana Gulf Coast marshes as well; including on the Bolivar Peninsula west of High Island, Texas (Hawkes and Horton 2012; Hodge and Williams 2016; Williams 2010, 2018; Williams and Denlinger 2013; Yao, Liu, and Ryu 2018). Therefore, it is extremely likely that the sand-rich layer that exists near the surface on all four transects was deposited by Hurricane Ike in 2008. All of the transects were within the right-front quadrant of Hurricane Ike and had similar storm surge heights, with the storm surge exceeding 3 m across most of McFaddin NWR (Figure 5.2). The highest storm tide in Jefferson County occurred at the Sabine Pass tidal gauge, which measured a storm tide height of 4.42 m (Berg 2009).

A layer of sand was visible near the surface along all four transects. This sand layer was light-colored, and was visually distinct from the darker, more organic-rich underlying marsh deposits. Some pit site locations had a dark, organic-rich layer above this sandy deposit as well (see Figure 4.8). The marsh deposits in contact with the surface are composed of a litter layer, peat, and are often mixed with clay. They are frequently inundated by tidal floodwaters and are dark colored as well (Hodge and Williams 2016).

T1 contains eight pit sites and lies approximately 700 m west of a previous study by Hodge and Williams (2016). Along T1, a thick sandy washover fan exists from near the coastline to the vicinity of T1-3; this washover fan was thick enough to bury marsh vegetation and was clearly visible for several months after Hurricane Ike's landfall (Figure 5.3). The thickness of the sand deposit decreases substantially from T1-1 to T1-3 as the washover fan decreases in thickness and ends in between T1-3 and T1-4. T1-4 is completely landward of the washover fan and has a sand-rich deposit more similar to T1-5 to T1-8 (see Table 4.1). The elevations on the transect are the highest on the washover fan but has a decreasing elevation trend towards T1-8. A notable exception is the vicinity of T1-2 and T1-3. There is a naturally occurring low spot that was likely a tidal connection with Wiseman Lake in the recent past. Wiseman Lake is dominated by a thicket of *Spartina alterniflora*, (see Figure 3.4) but seems to be largely cut off from a tidal connection to the Gulf of Mexico. T1-2 is in the center of this low-lying area, whereas a bit farther landward, T1-3 is 0.06 m higher in elevation despite the fact that it has a thinner sand-rich sediment deposit (Table 4.1). The reason that the sand-rich deposit thickness is so similar between T1-4 to T1-8 is because they are all landward of the edge of the washover fan.

Beginning at T1-4, the elevation continually decreases, reaching sea level (landward of T1-8) at Clam Lake; the sand-rich deposit continues to decrease as well, with a thickness of only 2.5 cm at T1-8.Very similar trends in elevation and deposit thicknesses were documented by Hodge and Williams (2016) on a transect about 700 m to the east of T1. Though not the focus of this study, it is very likely that the Hurricane Rita deposit was identified at some of the pit sites on T1 (e.g. T1-4). This would not be surprising, as the Hurricane Rita deposit was identified on a transect 700 m east of T1 by Hodge and Williams (2016). Prior research studies focusing on the Hurricane Rita sediment deposit also found that sand-rich deposits generally thin out farther inland (Crosby and Reece 2009; Williams and Flanagan 2009). It is notable that the T1 washover fans are presently not visible on the surface, as they are obscured by vegetation (Figure 5.4).

T2 lies about 1.6 km west of T1 and has six pit sites. T2 does not contain a washover fan and has a much thinner sand-rich deposit at the most seaward pit sites (see Figure 5.5). T2-1 has a sand-rich deposit of only 12.9 cm; this is much less than the seaward most pit sites on T1. The sand-rich deposit does decrease landward of T2-1 and drops to 4.1 and 3.8 cm respectively at T2-2 and T2-3. However, T2-4 is anomalous due to a sand-rich deposit of 10.2 cm. It is quite likely that an obstruction in the area of T2-4 caused the sand-rich deposit to be thicker than T2-2 and T2-3. During the time of sediment deposition there could have been an anomaly on the marsh surface (such as a tall bunch of grass or a feral hog wallow) that caused the sandy deposit to be thicker at T2-4. Subtle variations in the marsh topography prior to the sand-rich layer being deposited could have influenced sand deposition as well. It is also worth noting that the sand-rich layer in the vicinity of T2-4 was spotty and uneven. T2-5 and T2-6 had sand-rich deposits of to 3.9 and 3.5 cm respectively.

The elevation along T2 gradually decreased from a high of 1.23 m (at T2-1), to a low of 0.19 m (at T2-6). It is very likely that the sand-rich deposit extends landward of T2-6. Another difference between T1 and T2 is that T1 lies in an area of largely undisturbed marsh. The closest anthropogenically altered terrain (to T1) is along Clam

Lake Road, located 900 m east of T1. Also, the remnant of Texas State Highway 87 lies about 60 m seaward of T1-1, but this remnant road does not appear to impact sedimentation, as extensive washover fans were easily deposited landward (see Figure 1.4). T2 lies along an old road that existed prior to the creation of the wildlife refuge (Sean Reed, U.S. Fish and Wildlife Service, 10 June 2019, e-mail) and it is possible that this anthropogenic modification has impacted the deposition of the sand-rich deposit. There are also no washover fans in the vicinity of T2: this is likely due to shorter foredune heights and extents which would have resulted in a reduced volume of sand available to be transported inland with a storm surge. It is also possible that the nearshore and foreshore environments were less extensive around T2, which would have resulted in a reduced availability of sediment. Recently, anthropogenic levees have been built in the vicinity of T2 (Figure 5.6) and this will likely alter storm surge overwash dynamics when future storms impact the refuge (Rogers et al. 2015; Williams 2018). The earthen levees were built by the U.S. Fish and Wildlife Service and are parallel to the coastline in order to protect marshes from storm surge inundation (Sean Reed, U.S. Fish and Wildlife Service, 10 June 2019, e-mail).

T3 lies about 4 km west of T2 and has six pit sites. Like T2, T3 does not contain a washover fan and has the lowest mean sediment thickness of any transect (see Table 4.3). T3-1 has a sand rich-deposit of only 5.1 cm; this is the thinnest sand-rich deposit on any of the most seaward pit sites amongst all four transects. T3-2 had only a slightly thicker deposit of 6.4 cm, whereas T3-3 had no detectable sand-rich deposit. It is not too surprising that T3-2 is slightly thicker than T3-1, as the sediment deposits are known to be uneven and patchy in spots; however, the trend of a decreasing sediment thickness with distance inland still prevails along T3 (see Figure 4.9). T3-4 and T3-5 had a sand-rich deposit of ~ 1 cm, whereas T3-6 had no detectable sand-rich deposit. T3 lies along Perkins Levee and this route into the marsh was utilized in order to establish the pit sites. Utilizing the Perkins Levee made it easier to progress farther landward during field work (see Figure 5.7). T3 is the longest transect, with T3-1 being 295 m inland, and T3-6 being 1,630 m inland.

Similar to T1 and T2, the elevation along T3 slowly drops off farther landward towards the GIWW (Table 4.3). T3 is noteworthy for being the only transect that has pit sites with no detectable sand-rich deposit (T3-3 and T3-6). Currently, earthen levees (Figures 5.8 and 5.9) that were built in 2014 run parallel to the Gulf Coast in the vicinity of T3 (Sean Reed, U.S. Fish and Wildlife Service, 10 June 2019, e-mail). T3-1 is located landward of the earthen levee and was chosen due to being less anthropogenically impacted than the tidally flooded area of land seaward of the levee that runs parallel to the Gulf Coast. The earthen levees running parallel to the coast were built in 2014; and no hurricane had a storm surge high enough between 2014-2018 to overtop the levee and deposit sediment (Williams 2018). Therefore, the sand-rich deposit along T3 had to have been deposited prior to 2014 (see Figure 5.10). Similar to the geomorphic situation at T2, it is quite likely that there was less sediment available for deposition or that Perkins Levee itself inhibited sediment transport inland. All of the pit site locations along T3 were located east of Perkins Levee (see Figure 4.4). If the primary storm surge and wave action were coming from a slightly southwest direction, Perkins Levee could have blocked much of a storm surge deposit. It is also very likely that sand was deposited on T3-3 and T3-6, but for some reason it was not detectable during field work in summer

2018. It is possible the deposit may have been washed away by a storm surge return flow, or washed away by rain, or perhaps mixed in with the surrounding terrain via bioturbation. Additionally, it is possible that a cluster of grass or perhaps a nearby feral pig wallow acted as a disturbance to the storm surge; which could have altered sediment deposition in the vicinity of T3-3 and T3-6. Moreover, the sand-rich deposit is uneven even in very short distances in the vicinity of several of the pit sites along this transect. Perhaps uneven deposition and subsequent erosion of some of the sediment before being held in place by vegetation causes the deposit to appear uneven.

An interesting feature of T3-1 is that there was a 10 cm thick mud deposit above the sand-rich deposit (see Figure 4.5). This deposit is very likely a flood deposit from the heavy rains caused by Hurricane Harvey in late August of 2017. Flood waters caused by heavy rains of Hurricane Harvey were flowing seaward across the region (personal communication, Sean Reed, U.S. Fish and Wildlife Service, August 15, 2018). It is very likely that flood waters from Hurricane Harvey were blocked due to the earthen levee running parallel to the Gulf Coast (and seaward of T3-1); this would have allowed fluvial sediment to build up in stagnate water, and settle on the marsh surface (see Figure 5.11).

T4 is the westernmost transect in the study area and contains six pit sites. This transect is 5.5 km east of the center of High Island and is also the shortest transect amongst all four transects, as T4-8 is 880 m inland from the Gulf Coast. Similar to T2 and T3, the marsh along T4 was accessed by utilizing a levee (which stretches 1,110 m inland from the coastline). The two most seaward pit sites contain a thick sand-rich deposit; whereas the deposit drops dramatically landward of T4-2. T4-1 has a sand-rich deposit of ~53 cm, whereas T4-2 has a sand-rich deposit of ~58 cm. It is not too surprising that T4-2 is slightly thicker than T4-1, as the sediment deposits are known to be uneven and patchy in spots; however, the trend of a decreasing sediment thickness with distance inland still prevails along T4 (see Figure 4.12). T4-3 is landward and perpendicular to the long axis of a man-made ditch and has a sand-rich deposit of ~15 cm. There is a thick layer of organics at the surface here. It is quite likely that the ditches along T4 impacted overwash sedimentation dynamics, by serving as barriers to the marsh around them, as they were present prior to the landfall of Hurricane Ike (see Figure 5.12). T4-4 to T4-6 show a decreasing trend of the sand-rich deposit with a thickness of ~5 cm at T4-6 (880 m inland).

The marsh environment along T4 was challenging; as pit site locations were established where the author and field assistant were able to safely traverse the marsh. T4-1 and T4-2 are seaward and landward (respectively) of a man-made earthen levee that runs parallel to the Gulf Coast. This levee is part of the same barrier system that runs perpendicular to T3 and was built sometime in the year 2014 (Figure 5.13). T4-1 and T4-2 were chosen based on distance inland from the coastline. Moreover, T4-1 and T4-2 were also deemed to be a safe distance away from the drainage ditches containing alligators (the ditches run parallel to the coastline and were built in 2014 with the earthen levees). The thick sand-rich deposit at both sites appeared to have a mud cap sandwiched between a thick coarse sand layer in the bottom half of the pit, and a finer sand layer above the mud cap. At T4-1, the uppermost layer of finer sand is ~10 cm thick, the mud cap is ~4 cm thick, and the bottom coarser sand layer is ~39 cm thick. T4-2 has a similar lithology with a mud cap ~4 cm thick. The coarser sand-rich deposit was likely laid down at an early stage of storm surge inundation, whereas the mud cap was presumably deposited from standing waters after the passage of Hurricane Ike (Williams 2009; Hodge and Williams 2016). It is possible the uppermost layer of finer sand (at T4-1 and T4-2) was deposited due to the ebb flow of a storm surge or from reworked sediment due to rains or erosion from the nearby man-made levee constructed in 2014. T4-3 is located landward of a ditch that likely hindered the passage of any thick sand-rich deposits. Contrary to T4-1 to T4-3, T4-4 to T4-6 were established on the east side of the access levee, as the marsh environment landward of T4-3 (on the west side of the access levee) was deemed unsuitable and unsafe for pit site establishment (see Figure 5.13). T4-4 to T4-6 are similar to the most landward pit sites on the other transects in that the sand-rich deposit thins out farther inland. It is also noteworthy that the sand observed at T4-5 and T4-6 were finer grained than the more seaward pit sites, and in fact were finer grained than the most landward pit sites along T1, T2, and T3. The fining of the sand grain size is typically caused by the storm surge losing energy farther inland, as slower moving water moves smaller sediment particle sizes. It is likely that the ditches in the vicinity, as well as scrubbier vegetation (along T4) trapped more of the coarser sand closer to the coastline. It is very likely that the sand-rich deposit extends landward of 880 m; as the deposit at T4-6 was ~5 cm.

The differences in the storm surge sediment deposit cannot be caused by distance from the landfall location of Hurricane Ike. The most likely reasons for differing deposit thicknesses are due to the presence or absence of anthropogenic disturbances, amount of sand available in a particular area (such as foredune heights), the bathymetry of the nearshore environment, and the topography of the shore and marsh environments. The marsh in the vicinity of T1 was not impacted by anthropogenic barriers to sedimentation when Hurricane Ike made landfall in September 2008. This allowed a natural flow of sediment on the marsh. Additionally, T1-1 to T1-3 are located on a thick sandy washover fan. Landward of T1-3, the sand-rich deposit thinned out all the way to T1-8 (the elevation on this transect also decreased landward). The landward most pit sites on T1 are often flooded due to their very low elevations and proximity to Clam Lake (Hodge and Williams 2016). T2, T3, and T4 were all accessed by following a man-made path into the marsh along each transect. These paths pre-date the creation of McFaddin NWR (Sean Reed, U.S. Fish and Wildlife Service, 10 June 2019, e-mail).

5.2 Discussion of Regression Results

The multiple regression results align very well with the empirical results obtained in the field. Equation 4.2.1 was run in order to model storm surge deposit thickness based on distance inland and pit site elevation; whereas Equation 4.2.2 was run in order to model storm surge deposit thickness based on distance inland, distance from landfall, and pit site elevation. Both regression analyses had significant results. This means that multiple regression can be utilized in order to model hurricane overwash deposit thickness, based on the combination of pit site distance inland, pit site elevation, and transect radial distance from landfall. The three simple linear regressions were run individually in order to see if storm surge deposit thickness could be predicted based on each individual independent variable. Equation 4.2.3 was performed in order to predict sediment thickness based on radial distance from landfall. The result was not significant. This means that the deposit thickness does not significantly differ amongst all four transects solely based on their radial distance from the Hurricane Ike landfall location. This is not surprising based on the observed results (Tables 4.1, 4.2, 4.3 and 4.4).

Additionally, the entire study region was in the right-front quadrant of Hurricane Ike, and the storm surge was > 3 m in the study area (Figure 5.2). It is quite likely that transect locations would need to be much farther east and southwest of Galveston Island in order to obtain significant deposit variations based solely on radial distance from landfall (Berg 2009; see Figure 5.2).

Equation 4.2.4 was first performed in order to predict sediment thickness based on distance inland from the coastline. The result was significant and correlates very well with observed sediment thicknesses in the field (Tables 4.1, 4.2, 4.3, and 4.4). A Linear Curve trendline (for Equation 4.2.4) was computed to compare the observed pit sites vs. predicted pit sites (see Figure 5.14). The trendline represents where the pit sites would be expected to be found, however, it is not the best fit for predicting sediment thickness by distance inland. Additionally, it is important to note that there cannot be a negative amount of observed sediment, as the lowest possible observed value is 0 cm (Figure 5.14). An observed amount of 0 cm of the Hurricane Ike sediment deposit would mean that either the deposit never reached or settled in a specific location, or that the deposit was not preserved there (perhaps being washed away by rain or reworked via bioturbation).

A Logarithmic Curve trendline from Equation 4.2.4 is shown in Figure 5.15. The trendline shows how the predicted deposit thickness follows a similar pattern as the observed deposit thickness; as pit site distance from the coastline increases, the sediment thickness decreases. The Logarithmic trendline represents where the pit sites would be expected to be found, however, it is not the most accurate curve fit for predicting pit site sediment thickness based on distance inland. Moreover, it is important to note that there cannot be a negative amount of observed sediment, as the lowest possible observed value is 0 cm (Figure 5.15). An observed amount of 0 cm of the Hurricane Ike sediment deposit would mean that either the deposit never reached or settled in a specific location, or that the deposit was not preserved there (perhaps being washed away by rain or reworked via bioturbation).

The Power Law Curve was the final curve run utilizing Equation 4.2.4. The Power Law Curve is the most robust for predicting sediment thickness based on distance inland (Figure 5.16). The R^2 value was 0.538, which is higher than both the Linear and Logarithmic Curves. The results obtained in the field show that moving only a small distance can mean a big difference in how much sediment is deposited; and that moving a large distance can mean a small difference in how much sediment is deposited (e.g. Table 4.1, Figure 4.3). The way sediment thickness decreases going inland is not exactly linear. Therefore, the Power Law Curve is a new and unique way to help predict sediment thickness based on pit site distance inland. The comparison of the Power Law Curve against the Linear and Logarithmic Curves is seen in Figure 5.17. The Power Law Curve is the strongest and is the best reflection of the observed values, having the highest R^2 (see Figure 5.17).

Equation 4.2.5 was performed in order to predict sediment thickness based on pit site elevation above sea level. The result was significant. As pit site elevations increase, there is generally an increase in deposit thickness. This is mostly true; however, some outliers do exist, especially on T3 (see Tables 4.1, 4.2, 4.3, and 4.4). It is important to note that along each transect there is a general trend of decreasing elevation farther landwards towards the GIWW. It is quite likely that much of the sediment accretion across all four transects are caused by hurricane storm surge sediment deposition, even preceding Hurricane Ike. Previous research on a transect 700 m east of T1 found that hurricane sediment deposits (from Hurricanes' Ike, Rita, Carla, and Audrey) comprised between 24 and 93 percent of the sediment in fourteen cores extracted from the marsh (Hodge and Williams 2016). It is also known that storm surge deposits thin out farther inland (Williams and Denlinger 2013; Hodge and Williams 2016). Thus, for the East Texas Gulf Coast, the third linear regression results correlate well with the natural topography of the region, with the highest elevations along barrier foredunes along the coastline, and slowly decreasing in elevation towards sea level at the GIWW. The settlement of High Island, Texas, is an exception to this since it has been pushed upwards due to the presence of a salt diapir in the Earth's crust.

5.3 Discussion of ANOVA Results

Equation 4.2.6 was run to determine what variability existed between the three different groups of pit sites by distance inland. The result was significant and statistically shows that distance inland is a robust predictor in expected amount of sediment deposited by a hurricane storm surge. Group 3, which was closest to the coastline, had much thicker deposits than Groups 1 (>1000 m inland) and 2 (between 500 m to 1000 m inland). It is not surprising that three groups were determined by the hierarchical cluster analysis, given the extent of some of the study transects (Tables 4.1, 4.2, 4.3, and 4.4). The results of Equation 4.2.6 expand upon the significance of the empirical observations from the field as well as the regression analyses regarding the relationship between deposit thickness and pit site distance inland.

Equation 4.2.7 was computed to compare sediment thickness (cm) by distance from landfall (km) along four different transects. The results were not significant (see Table 4.13). This result is not surprising given that the regression results show that radial distance from the landfall location of Hurricane Ike was not a significant predictor of deposit thickness (Table 4.7). These results also correlate well with what was observed in the field, as T1 and T4 both had thick deposit thicknesses on their most seaward pit sites despite being 27 km apart from each other (see Tables 4.1 and 4.4; Figure 3.1). T1 is 73 km northeast of the landfall location, whereas T4 is 46 km northeast of the landfall location. The entire study area that encompasses all four transects was in the right-front quadrant of Hurricane Ike and experienced a storm surge of >3 m (see Figures 5.1 and 5.2). For radial distance to become a significant predictor of pit site deposit thickness, transects would need to be established at locations farther from the landfall location (these locations experienced a lower storm surge), and they would be added to the four transects in this study to analyze the differences between the right-front quadrant and locations farther away.

Equation 4.2.8 was computed in order to determine if there was an interaction on distance inland and distance from landfall on sediment thickness. The result was not significant (see Table 4.14). This means that the interaction between distance inland and distance from landfall location does not significantly affect pit site deposit thickness. This is not surprising since the regression and one-way ANOVA analyses showed how radial distance from landfall is not a significant predictor of storm surge deposit thickness. For this two-way factorial ANOVA to likely be significant, this study would need to involve additional transects to be established in areas farther from the landfall location of

Hurricane Ike. These results demonstrate the utility of using one-way and two-way factorial ANOVA in analyzing hurricane sediment deposition in coastal marshes along the northern Gulf of Mexico coastline.

5.4 Chapter Five Figures

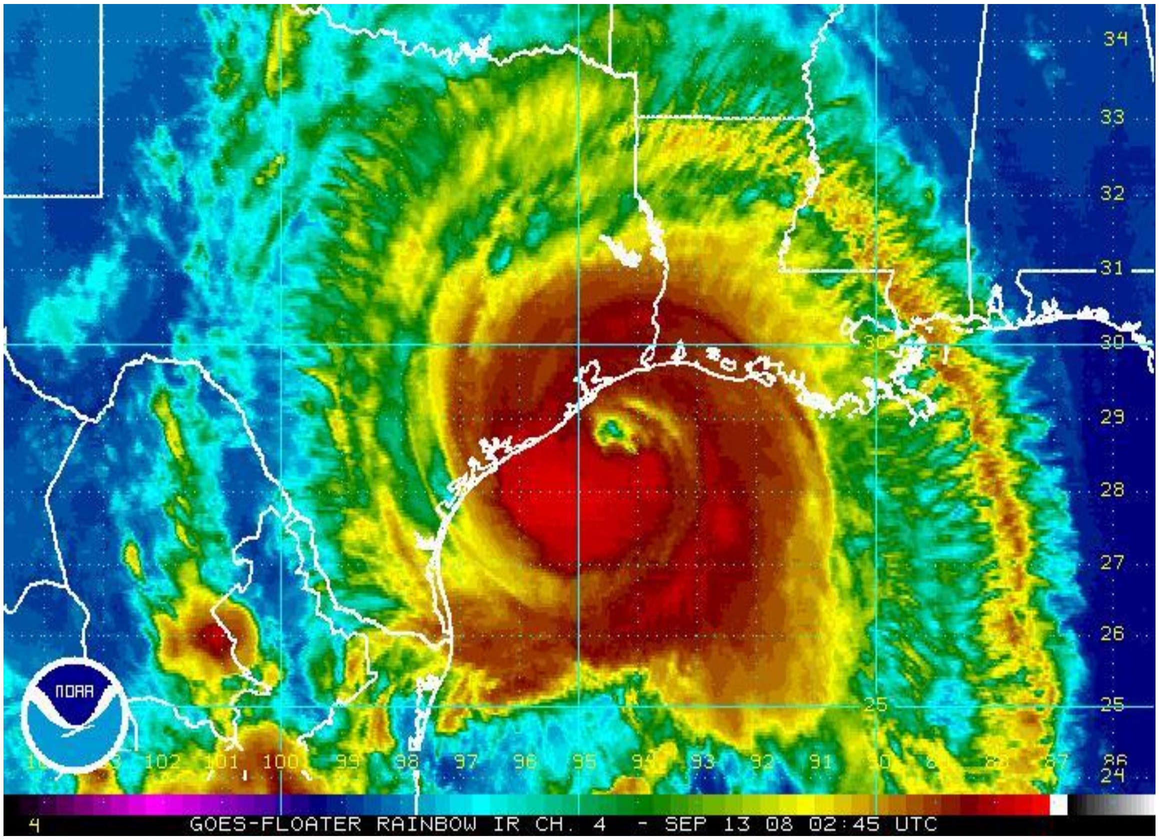

Figure 5.1. Enhanced infrared satellite image of Hurricane Ike shortly before landfall. The red colors indicate cooler temperatures corresponding to higher altitude cloud tops (NOAA 2008).

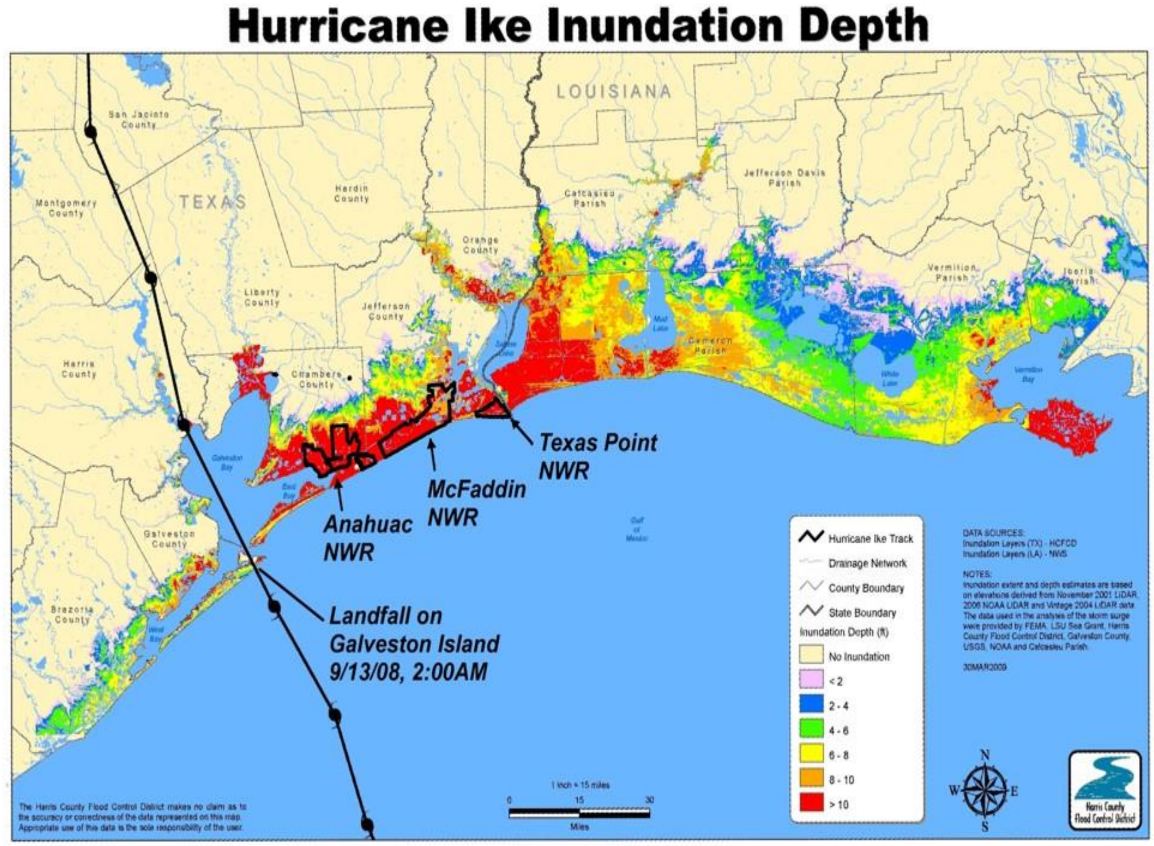

Figure 5.2. Hurricane Ike storm surge inundation depth. The areas in red, which includes most of McFaddin NWR, were inundated by > 3 m of seawater (Harris County Flood Control District 2009).

Figure 5.3. Washover fans on T1 four months after Hurricane Ike made landfall. This image shows the vicinity of T1 prior to the construction of nearby earthen levees (modified from Google Earth 2017).

Figure 5.4. T1 in January 2018 showing nearby earthen levee to the west (modified from Google Earth 2017).

Figure 5.5. T2 in January 2009 before earthen levees were built (modified from Google Earth 2017).

Figure 5.6. T2 with earthen levees as of January 2018 (modified from Google Earth 2017).

Figure 5.7. T3 was established by following Perkins Levee inland. Perkins Levee is visible in the center (background) of this image, as viewed from T3-6. Photo by author.

Figure 5.8. An earthen levee that runs parallel to the coastline along T3. This levee was built in 2014 by the U.S. Fish and Wildlife Service. Photo by author.

Figure 5.9. A view of T3-1. An earthen levee in the background is seaward of T3-1 and runs parallel to the coastline. Photo by Stephen Taylor.

Figure 5.10. T3 satellite image from January 2009. This image shows that the earthen levees parallel to Gulf Coast were non-existent when Hurricane Ike made landfall (modified from Google Earth 2017).

Figure 5.11. T3 satellite image from January 2018. This image shows recently added earthen levees seaward of T3-1 (modified from Google Earth 2017).

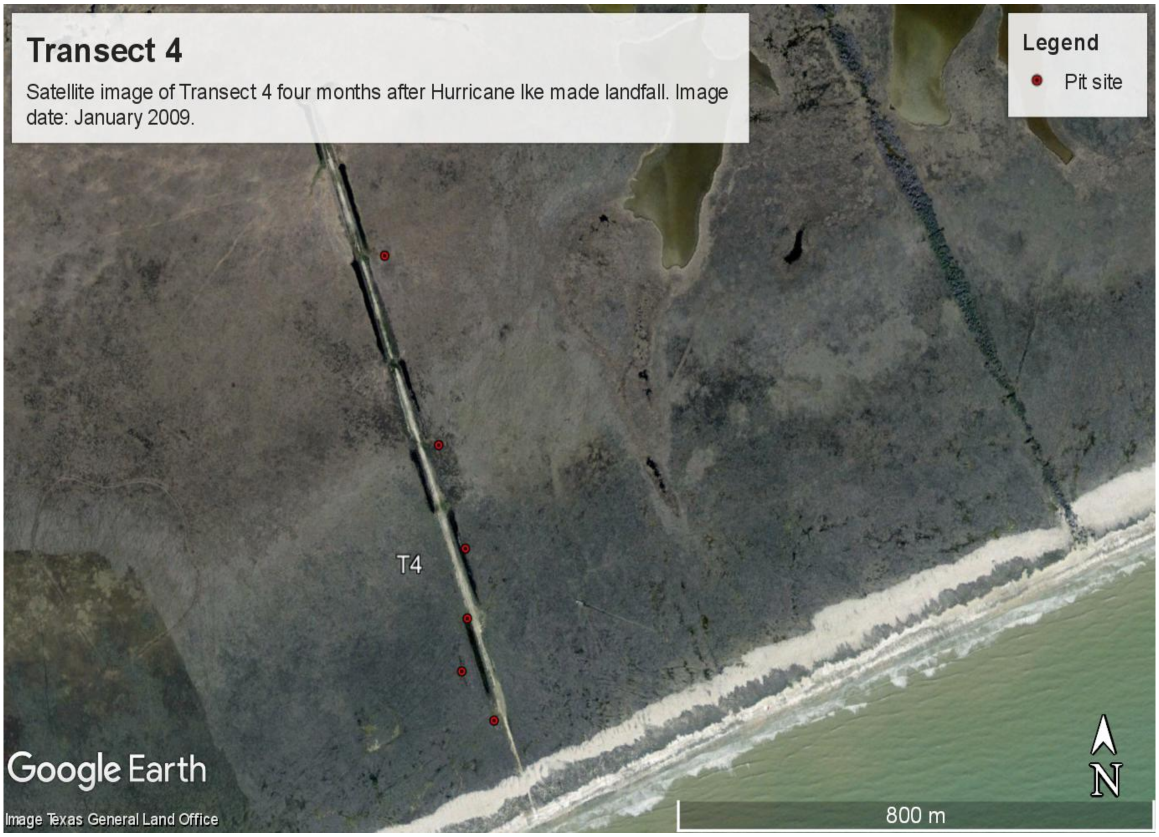

Figure 5.12. T4 before earthen levees were built. Prior to 2014, there were no earthen levees parallel to the Gulf Coast in the vicinity of T4 (modified from Google Earth 2017).

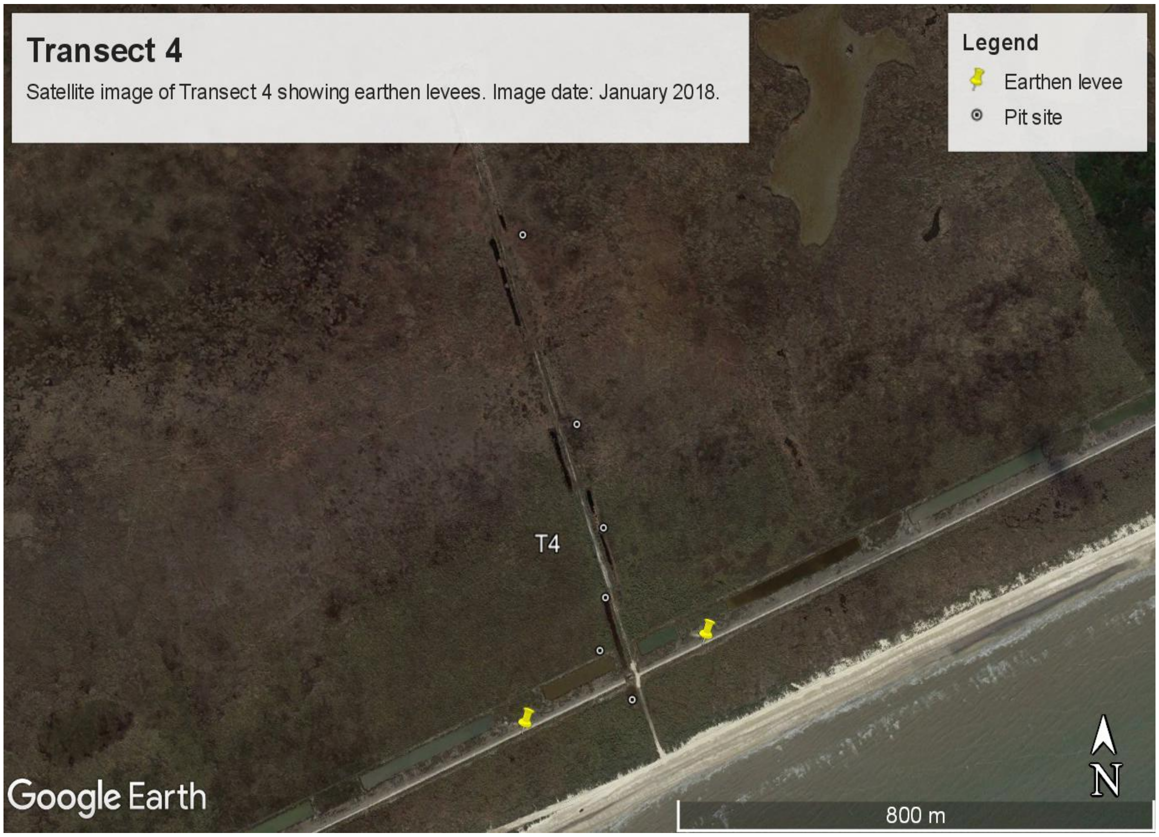

Figure 5.13. T4 showing the earthen levee built in 2014 (modified from Google Earth 2017).

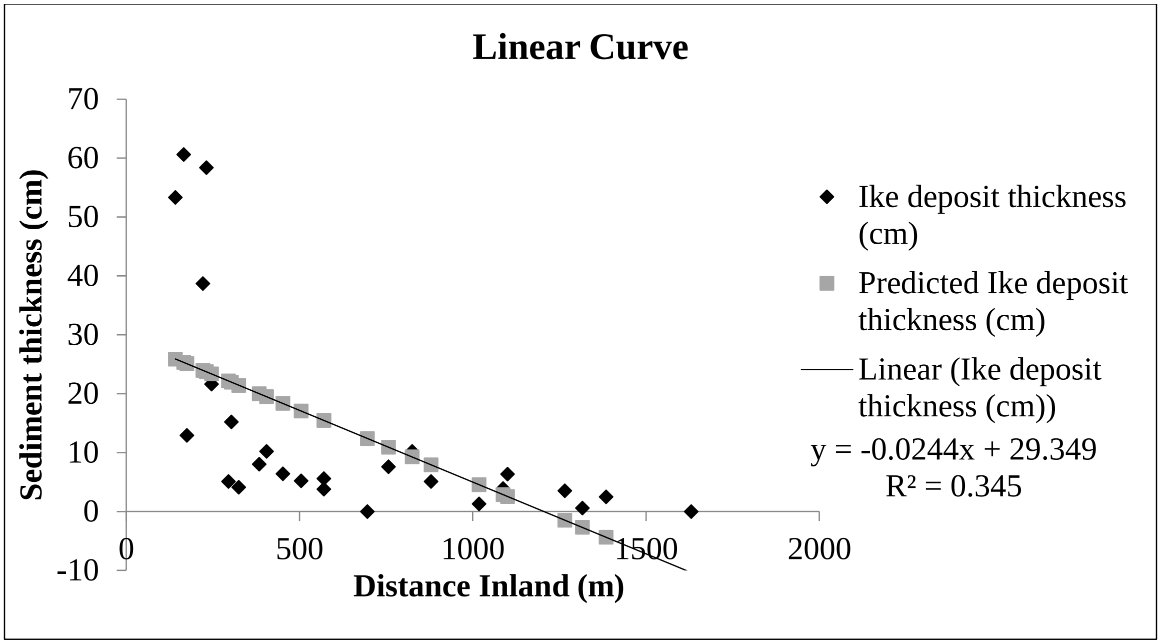

Figure 5.14. Equation 4.2.4 Linear Curve. The results are significant and show a decreasing sediment thickness trend with increasing distance inland. The Linear Curve trendline is a line of best fit for the predicted pit site locations.

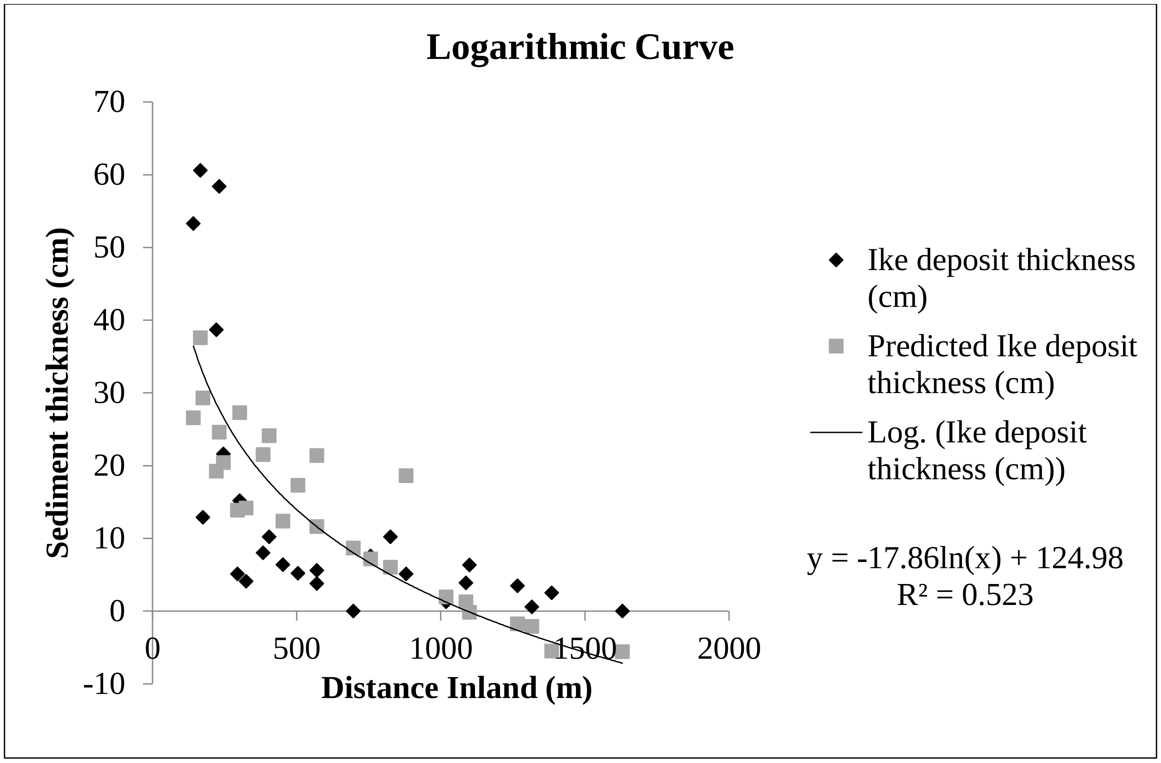

Figure 5.15. Equation 4.2.4 Logarithmic Curve. The results are significant and show a decreasing sediment thickness trend with increasing distance inland. The Logarithmic Curve trendline is a line of best fit for the predicted pit site locations.

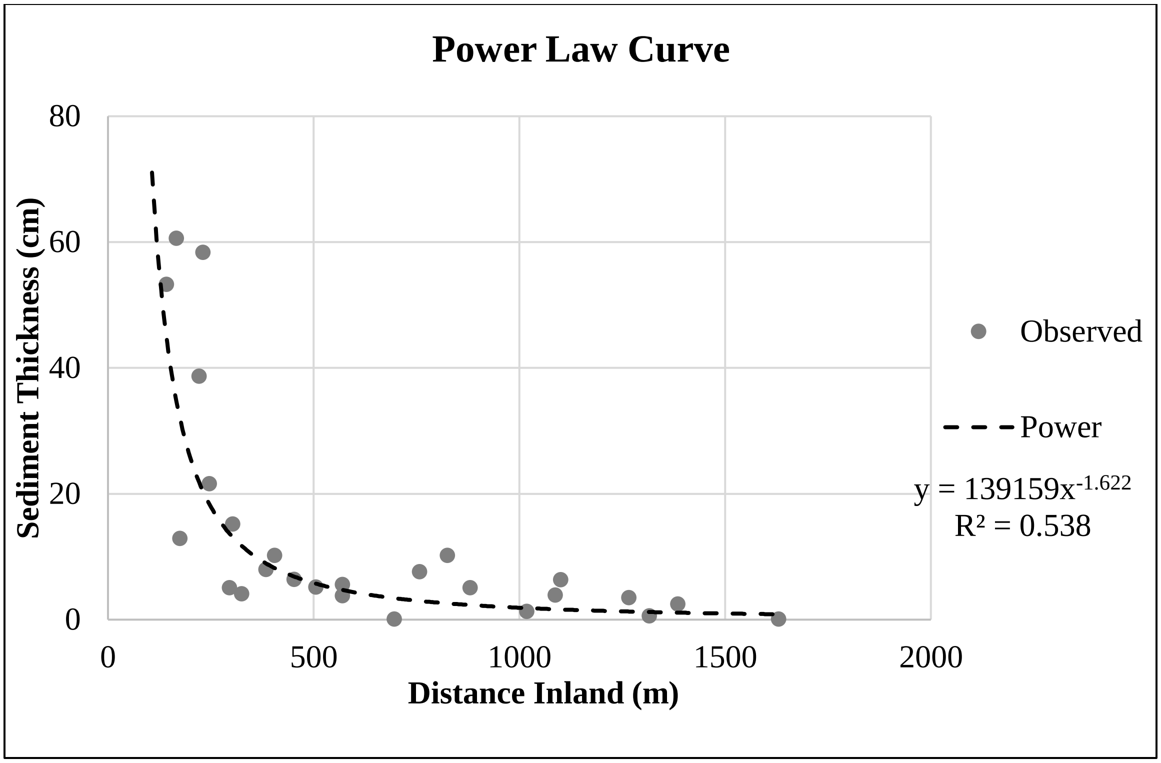

Figure 5.16. Equation 4.2.4 Power Law Curve. The Power Law Curve indicates where pit site locations would be expected. The Power Law Curve is unique in its robust ability to predict pit site deposit thickness based on distance inland.

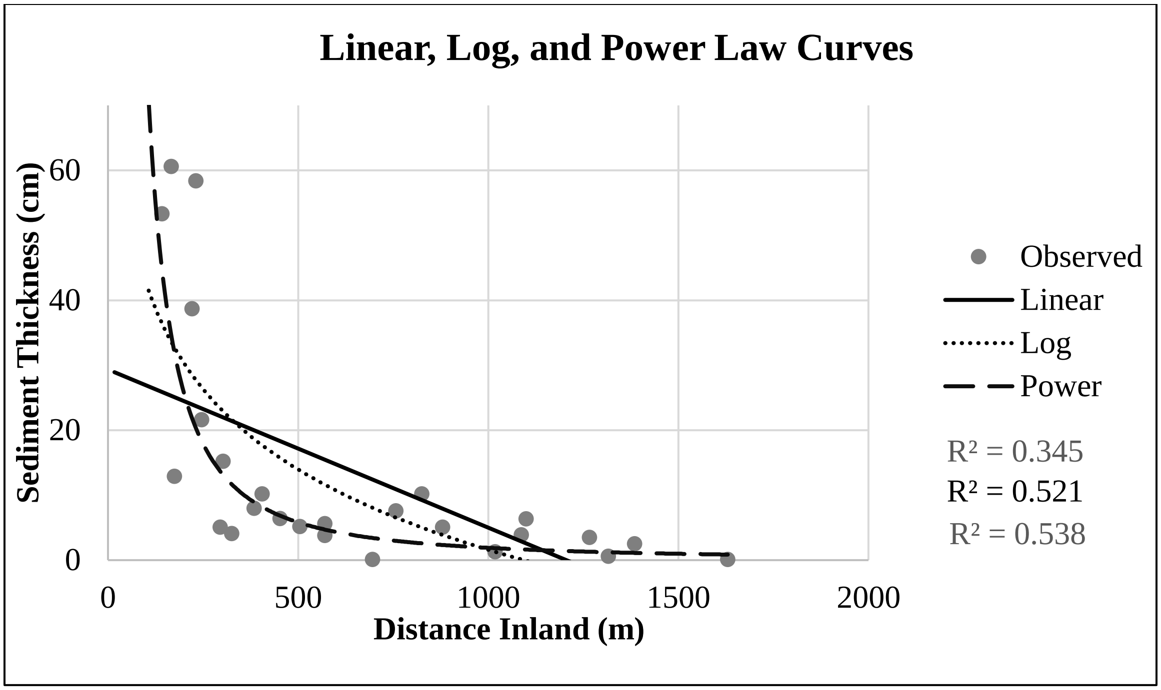

Figure 5.17. Linear, Logarithmic, and Power Law Curves. The Power Law Curve is the most robust at predicting sediment deposit thickness based on distance inland. The Linear Curve is the weakest, with an R^2 of 0.345; whereas the Power Law Curve is the strongest, with an R^2 of 0.538.

6. CONCLUSION

6.1 Summary

This study builds upon previous research on coastal marshes along the Gulf of Mexico coastline in East Texas. In the previous studies, hurricane storm surge sediment deposits were found from Hurricanes' Audrey, Carla, Rita and Ike (Crosby and Reese 2009; Williams 2010; Williams and Denlinger 2013; Hodge and Williams 2016). In this study, all four transects were located within the right-front quadrant of landfalling Hurricane Ike (see Figures 1.2, 1.3, 3.1, and 5.1). It is also known that the East Texas Gulf Coast has a plentiful supply of sand from the beaches and nearshore environment; largely transported by the alongshore currents from the Mississippi River (Bullard 1942). As expected, a sand-rich storm surge deposit derived from Hurricane Ike was found on all four transects in this study (see Tables 4.1, 4.2, 4.3, and 4.4). Due to the presence of thick coastal marsh grasses in the region, the storm surge deposits have largely been preserved, as opposed to being eroded away (see Figures 3.5 and 5.7; Williams 2010; Hodge and Williams 2016).

Changes in storm surge deposit thickness were expected and empirically confirmed along each transect of this study. Recent research has found that locations farther inland from the coastline have thinner storm deposits (Cahoon et al. 1995; Crosby and Reece 2009; Williams and Denlinger 2013; Hodge and Williams 2016). When a storm surge moves inland, it slows, loses strength, and eventually deposits what sediment it has onto the marsh surface. A general decrease in thickness of the Hurricane Ike deposit was observed along all four transects of this study, as pit sites located closer to the Gulf Coast are thicker than the pit sites farther inland (see Figures 4.3, 4.5, 4.9, and 4.12).

However, anomalous variations in the thickness of the Hurricane Ike sediment deposit did exist along each transect. Likely reasons for variations include: subtle changes in the pre-Ike topography, the presence of anthropogenic modifications (such as the pre-2008 levees that are perpendicular to the coastline), availability of sediment from beaches, foredunes, and the nearshore environment, and the reworking of sediment due to bioturbation (Butler 2002; Dixon, Peters, and Townsend 2015). In fact, red imported fire ants, blue crabs, hermit crabs, alligators, and feral pigs were all observed on the refuge during field work, and they play a role in conducting faunalpedoturbational activity on the marsh; this includes the sand-rich Hurricane Ike deposit (Figures 6.1 and 6.2).

Furthermore, some abnormal variations in sediment thicknesses likely exist due to how the deposit may have been reworked by rain and floodwaters before being held in place by the very resilient marsh grasses. Though not the focus of this study, a second sand bed was identified in some of the pit sites on T1 and T2. This second sand bed is very likely an overwash deposit driven by Hurricane Rita's storm surge. Previously, the Hurricane Rita sediment deposit was identified on McFaddin NWR and Texas Point NWR (Crosby and Reece 2009; Hodge and Williams 2016).

The results from the simple linear regression and multiple regression analyses showed that transect distance from the landfall location of Hurricane Ike was not a significant predictor of storm surge deposit thickness. This is because all four transects were within the right-front quadrant of Hurricane Ike when it made landfall and a high storm surge, >3 m, occurred across the study area. However, pit site distance inland was a significant predictor of storm surge deposit thickness. The sand-rich deposit generally decreased in thickness moving inland along each transect. To add to this, the Power Law

Curve has been identified as a new and unique method for predicting hurricane sediment deposition on coastal marshes along the northern Gulf of Mexico coastline. As seen in Figure 5.17, the Power Law Curve has the highest R^2 values and is the most significant predictor of storm surge deposit thickness based on distance inland. Additionally, pit site elevation was a significant predictor of the thickness of the sand-rich deposit. The pit sites closest to the Gulf Coast generally sit at higher elevations; whereas the marsh gradually loses elevation towards the GIWW (which is at sea level). This study demonstrates the utility of regression analysis for predicting hurricane storm surge sedimentation thickness on coastal marshes along the northern Gulf of Mexico coastline.

The results from the one-way ANOVA's and two-way factorial ANOVA revealed whether distance inland, distance from landfall location, and the interaction between distance inland and distance from landfall location have any significant effect on storm surge deposit thicknesses (respectively). Equation 4.2.6 had a significant result and shows that storm surge deposit thickness depends on how far inland each pit site is. In this analysis, there were three groupings of the pit sites based on distance inland from the coastline. Equation 4.2.7 was computed to compare sediment thickness by distance from landfall along four different transects. The sediment thickness did not significantly differ amongst the four transects based on transect distance from landfall.

Equation 4.2.8 shows that the interaction between distance inland and distance from landfall has no significant effect on sediment thickness. This study shows that ANOVA analysis is suitable for determining whether or not geographic variables such as distance from the coastline or distance from a hurricane landfall location have an impact on storm surge deposit thickness. The results of this study greatly expand knowledge on the spatial and volumetric extent of hurricane sediment deposits derived from Hurricane Ike on East Texas Gulf Coast marshes and show how regression and ANOVA analysis can be combined with a field work intensive study on coastal marsh sediment dynamics.

This study adds to a growing body of knowledge regarding hurricane derived sediment deposition on coastal marshes. In the face of sea-level rise and regional subsidence along the northern Gulf of Mexico coastline, it important for coastal managers to consider the implications of how hard structures reduce storm surge overwash. Proposals such as the "Ike Dike" near Galveston and Houston, and the possible building of hard structures around New York harbor need to consider the potential negative effects these structures could have on coastal ecosystems and natural sediment dynamics (Brown 2010; Grom and Warren 2018).

A major issue facing the East Texas Gulf Coast is continued population growth; especially in the Houston-The Woodlands-Sugar Land Metropolitan Statistical Area, which is one of the most populous metropolitan areas in the U.S. Not surprisingly, the counties comprising the Greater Houston Area have been identified as the most vulnerable region of the Texas coast when taking into account historic hurricane landfalls, population, and property values (Dixon and Fitzsimons 2001). This problem is compounded by factors that exacerbate flood conditions, such as the low-lying terrain that is frequently inundated by heavy rains, urbanized areas that are impervious to runoff (Earl and Vaughan 2015), sea-level rise and regional subsidence (Yuill, Lavoie, and Reed 2009) and global climate change that may be producing more frequent and extreme hurricanes in the region (e.g., Tropical Storm Allison, 2001; Hurricane Ike, 2008; Hurricane Harvey, 2017).

Furthermore, the economy of the region is heavily invested in petroleum extraction, petroleum refining, and shipping; as can be seen in the Houston Ship Channel and around High Island, Texas (Figure 6.3). There is no simple answer to the dilemma of how governments handle the issue of coastal inundation and shoreline retreat, as no two places have the same exact coastal geomorphology and socio-political situation. Some regions, such as the Netherlands, have been quite successful at managing their coastal zones with hard structures (Bijker 2002); whereas developing nations (e.g., The Bahamas, Bangladesh, and Indonesia) have a very high risk of losing low-lying land, which would very likely result in severe socio-economic consequences in those countries (Dasgupta et al. 2009). Due to the high frequency of hurricanes along the northern Gulf of Mexico coastline (Dixon and Fitzsimons 2001), many structures are built on stilts in order to escape from hurricane storm surge flooding (Figure 6.4). However, it is more likely that impacts from hurricanes would wane if policies are implemented that allow sediment to be deposited naturally, and if populations and infrastructure in this region are not established in flood prone areas (Rogers et al. 2015).

6.2 Future Research

This study has expanded knowledge about the Hurricane Ike sediment deposit on McFaddin NWR, however, much more can be learned. Several studies could be conducted that would be able to assess the deposit derived from Hurricane Rita's storm surge. In this study, a second sand layer was found at several pit sites along T1 and T2 and is very likely derived from Hurricane Rita's storm surge. It is not known how far west that the Hurricane Rita deposit could be identifiable, but it is possible to narrow down the western extent, especially if cores are extracted from the marsh. To the author's knowledge, the transect from the study by Hodge and Williams (2016) is the most westerly location where deposits from Hurricane Rita have been confidently identified.

The first specific follow up study along T1 could be to establish pit sites farther landward to find how far inland the Hurricane Ike deposit is identifiable. Another potential follow-up study could utilize cores along T1 in order to compare results with that from a study by Hodge and Williams (2016). This potential follow-up study would determine the extent of the sediment deposit from hurricanes' Rita, Carla, and Audrey and compare it to the results from Hodge and Williams (2016). Along T2, a few additional studies would aid in understanding sediment dynamics in that vicinity. Cores could be extracted to determine the extent of the deposit that likely exists from hurricanes' Rita and Carla. It would be interesting to see if a thin deposit exists from Hurricane Audrey as well; since Hurricane Audrey made landfall in southwestern Cameron Parish, Louisiana (which puts T2 in the left-front quadrant of the storm's track). Furthermore, T2 could be lengthened to determine how far inland the Hurricane Ike deposit is identifiable.

Several studies along T3 could be carried out as well. Perkins Levee (which was utilized to establish pit sites along the transect) appears to have divided the area in a hydrologic manner (see Figure 4.6). This study established pit sites on the east side of Perkins Levee; a future study could establish pit sites on the west side of Perkins Levee in order to determine what variations in sedimentation may exist in such a small geographic zone. Moreover, cores could be extracted from the same pit site locations as this study in order to determine if a sand-rich deposit from hurricanes' Rita, Audrey, and Carla exist. This potential study combined with results from a similar potential study along T2 would likely help narrow down where the westernmost boundary of identifiable sand from the Hurricane Rita deposit is located on the Texas Gulf Coast.

The area around T4 could also benefit from some additional studies. T4 is in close proximity to an earthen levee that is parallel to the coastline and is very near to some man-made ditches that stretch inland along the transect. If an area of marsh is safe to traverse with an ATV, then a transect could be established farther away from T4 in order to limit any possible anthropogenic impacts on storm surge deposition. The primary challenge around T4 is the very low-lying marshy terrain that is often flooded, as well as scrubby vegetation. Alligators and snakes are a hazard as well; as several alligators were seen while field work was conducted in August 2018. Another study would include increasing the length of T4, well beyond 880 m. A 5 cm thick sand-rich deposit from Hurricane Ike was identified at T4-6 (see Table 4.4), and it is very likely that this deposit is identifiable much farther inland. Another potential follow-up study in the vicinity of T4 would be to establish a transect farther west (west of High Island on the Bolivar Peninsula). The Anahuac NWR South Unit exists west of High Island, and this would allow field work to be legally conducted. A more westward transect would extend the radial distance between the westernmost and easternmost transects when determining if there is a relationship between radial distance from landfall and storm surge deposit thickness. It would also be possible to lengthen all four transects (T1-T4) up to the southern edge of the GIWW and even landward of the GIWW to investigate how far inland the Hurricane Ike sediment deposit extends. The marshes landward of the GIWW are within the confines of McFaddin NWR and this would allow field work to be legally conducted.

The Power Law Curve could be utilized as a follow up study on a transect about 700 m east of T1; which would build upon work by Hodge and Williams (2016). The Power Law Curve will also be applied to any future studies, such as new transects, or the extension of previous transects to investigate how far inland hurricane sediment deposits can be identified. A further study could establish transects farther east, in Cameron Parish, Louisiana, or beyond, to see where the Hurricane Ike sediment deposit starts to significantly thin out, due to a farther distance in the right-front quadrant away from the landfall location of Hurricane Ike. This potential study could be combined with regression and ANOVA analyses as well. The follow up studies that would utilize the Power Law Curve would determine how strong it is at predicting sediment deposit thicknesses throughout a variety of locations. The Logarithmic Curve would also be utilized, as the predictive power of both the Power Law Curve and Logarithmic Curves can be very similar (Figure 5.17). More studies utilizing the Power Law and Logarithmic Curves will provide greater insights regarding their efficacy of predicting sediment deposit thicknesses on coastal marshes.

Another avenue of research could involve the effects of faunalpedoturbational activity on hurricane sediment deposits, and how the marsh environment responds to this activity. For example, it’s quite possible that “muddy boots” field surveys could reveal the spatial extent of surficial sediments disturbed by feral pigs, *Sus scrofa* (see Figure 6.2). It is very likely that churned up sediment could be more easily eroded by storms, before the marsh grass re-establishes itself in a disturbed area. This avenue of research could be important in expanding the body of knoweldge regarding how an invasive species positively or negatively impacts the natural marsh environment.

Lastly, it is very likely that strong hurricanes will impact the East Texas Gulf Coast in the future. Future storm strikes would provide serendipitous opportunities to conduct more field work in the region, and if a storm is strong enough, it could bury the marsh grasses and the Hurricane Ike deposit which is still at or near the surface across most of the region. In fact, shortly after Hurricane Harvey made landfall (26 August 2017), field work was occurring on Matagorda Peninsula, Texas, which was in the right-front quadrant of landfalling Hurricane Harvey (personal communication, Bradley Rains, University of North Texas Graduate Student, April 3, 2019).

6.3 Concluding Statement

Research on hurricane sediment deposition has increased in recent decades and is likely to continue throughout the 21st century. Because of sea-level rise, regional subsidence, and anthropogenic impacts on coastal regions, it is more important than ever to document how hurricane sedimentation contributes to marsh aggradation. Though remote sensing, LiDAR, and geographic information systems have been very beneficial at revealing new insights and change detection in coastal wetlands, on-the-ground field work will still be absolutely essential to obtain the greatest possible understanding of these dynamic environments. Field work is extremely important to geomorphology in general, especially dynamic environments such as mountains and coastal regions (Butler 2013).

Miles Hayes is a pioneer in studying the geologic impacts of hurricane strikes on the Gulf of Mexico coastline and his research is very quantitative and field-work intensive (Hayes 2016). Thankfully, this tradition has carried on to the present (Hodge and Williams 2016; Walters and Kirwan 2016; Whitesides and Butler 2016). With the continually improving understanding of how hurricane sedimentation helps aggrade coastal wetlands, the knowledge gained from this study will better equip coastal management agencies in order to implement policies which encourage natural sediment accretion on coastal marshes along the northern Gulf of Mexico coastline.

6.4 Chapter Six Figures

Figure 6.1. A large, red imported fire ant mound, *Solenopsis invicta*, near T1-1. The Hurricane Ike sediment deposit is the material that makes up the mound. This mound was >30 cm tall and was accidentally disturbed by the author. See dark-colored dots (individual ants) on mound for scale. Photo by author.

Figure 6.2. Feral pigs, *Sus scrofa*, frequent McFaddin NWR and are very adept at conducting faunalpedoturbational activity in the region. The churned sand is the Hurricane Ike sediment deposit. Photo is in the vicinity of T1, looking towards the coastline. Photo by author.

Figure 6.3. Petroleum extraction is an important economic activity along the East Texas Gulf Coast. Photograph shows a pumpjack east of High Island, Texas. Photo by author.

Figure 6.4. A home on stilts near Sabine Pass, Texas. Almost every home in the vicinity is built on stilts due to the threat of hurricane storm surge flooding. Photo by author.

APPENDIX SECTION

FIELD WORK RESEARCH PERMIT

OMB Control # 1018-0102 | 1
Expiration Date: 06/30/2017

Research and Monitoring
Special Use Permit Application

Refuge Name: McFaddin & Texas Point National Wildlife Refuge

Address: P.O. Box 358 Sabine Pass, TX 77655

Attn: (Refuge Official) Douglas Head

E-Mail: douglas_head@fws.gov

Phone #: 409-971-2909

For Official Use Only

Approved Permit #: 21520-E-023

Station #: 21525

Permit Term: from 6-13-17 to 8-31-19

Douglas Head 6/13/17

Note: We do not require all information for each Research project. See instructions at the end of the notice and contact the refuge to determine applicability of a particular item. Attach additional sheets if the text spaces provided are inadequate.

1) Identify the type of Permit you are applying for: **New** (selected) **Renewal** **Modification** **Other**

Applicant Information

2) Principal investigator: Joshua Hodge

3) Is curriculum vitae or resume attached? **Yes** (selected) **No**

4a) Affiliation/Sponsoring Organization: Texas State University Geography Department

4b) Relationship to affiliation/sponsoring organization (professor, staff, student, etc.): PhD Student

5) Street Address: 900 Peques Street Apt 503

6) City/State/Zip: San Marcos, TX 78666

7) Phone #: 469-595-6578 8) Fax #: 512-245-8353 9) E-mail: jbh113@txstate.edu

10) List known assistants/subcontractors/subpermittees: (Only required if the assistants/subcontractors/subpermittees will be operating on the refuge without the permittee being present.)

Name	Address	Phone #

Project Information

11) Title of project: Geographic Patterns of Hurricane Storm Surge Sedimentation on Southeast Texas Gulf Coast Marshes: Implications for Coastal Marsh Aggradation

12a) Is full research proposal required? Yes No (selected)

12b) Is full research proposal attached? Yes No (selected)

Note: Depending on the research and monitoring project for which you are requesting a permit, we may ask you for the following project information (13 -25) if it is not included in your research proposal, or if you have not provided a full research proposal with this application. Please contact the specific refuge where the activity is being conducted to determine what information is required. Attach additional sheets to the application if the text spaces provided are inadequate.

FWS Form 3-1383-R
05/14

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