CONTRIBUTION OF HURRICANE IKE STORM SURGE SEDIMENTATION TO LONG-TERM AGGRADATION OF COASTAL MARSHES IN SOUTHEASTERN TEXAS AND SOUTHWESTERN LOUISIANA

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Coastal marshes and wetlands are vital natural resources that offer habitats for plants and animals, serve as ecological filtration for soil and water pollutants, and act as protection for coastlines. Fishing, both commercial and sport, has a large economic impact in the study area – the Gulf Coast between Galveston Bay, TX and Oak Grove, LA. The objective of this research was to determine the contribution of Hurricane Ike storm surge sedimentation to long-term marsh aggradation in Texas and Louisiana coastal marshes. The research hypothesized that Hurricane Ike’s storm surge deposit would be equal to decades and possibly even a century’s worth of the average annual non-storm sedimentation. A quantitative field study was performed. The storm surge deposit was examined in a series of 15 transects covering approximately 180 km east of Hurricane Ike’s landfall. Nine of the 15 transects were re-surveyed a year after the initial measurement to assess preservation of the deposit. The results demonstrate that Hurricane Ike contributed between 10 to 135 years’ worth of sediment to coastal marshes along the coasts of Texas and Louisiana, and the sediment deposits have been preserved for over two years.
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CHAPTER 1
INTRODUCTION

Coastal wetlands and marshes are important natural resources that offer many benefits. However, many coastal wetlands and marshes along the northern Gulf of Mexico are being lost as the area subsides and the sea level slowly rises (DeLuane & Pezeshki, 1994; Kennish 2001; Williams, 2003; Yuill, Lavoie & Reed, 2009). One way to combat the problem is through the natural aggradation of the marsh surface via sedimentation processes. While hurricane storm surges are primarily considered a force of destruction, research shows they are also a natural source of sediment for marsh surface accretion (Törnqvist et al., 2006; Turner, Baustian, Swenson & Spicer, 2006; Williams, 2008, 2010, 2011a, 2011b, 2012; Williams & Flanagan, 2009). However, there is uncertainty over the magnitude, distribution and significance of hurricane sediment inputs into coastal marshes, which could have important consequences for coastal management plans. Therefore, the objective of this thesis research was to determine the contribution of hurricane storm surge sedimentation to long-term marsh aggradation in Texas and Louisiana coastal marshes. The study examined hurricane storm surge deposits left by Hurricane Ike when it made landfall in September 2008. The results demonstrate that Hurricane Ike contributed between 10 to 135 years’ worth of sediment to coastal marshes along the coasts of Texas and Louisiana and the sediment deposits are preserved within marshes. These findings suggest that hurricanes are a potentially valuable source of mineral sediment for marsh and wetland aggradation.
1.1 Coastal Marsh and Wetland Functions

The tidal marshes of the Gulf of Mexico make up 53% of the total marshes in the United States (Mitch & Gosselink, 2000). They are most abundant in Louisiana, northeast Texas, and portions of Florida (Clewell, 1997, as cited in Reed, Hijuelos, & Fearnley, 2012). These marshes and wetlands offer many benefits—both ecologically and economically. They are highly productive ecosystems and serve as habitat and protection for many and varied species of plants and animals, including endangered species. Wetlands and marshes act as an ecological filtration system for soil and water pollution and as sites for groundwater recharge; they also produce and export organic carbon. Additionally, they serve as coastline protection against erosion, floods, and storms (Kennish, 2001; Reed et al., 2012; USGS, 1997a, 1997b, 1997c).

The economic value of coastal wetlands stems from multiple sources. The commercial and recreational fishing industries in these areas are economically important not only due to the sale of those products but also, for employment in fishing and related industries. According to the Louisiana Coastal Facts sheet provided through the Coastal Protection and Restoration Authority of Louisiana (2011), the value of the commercial catch was $272.9 million per 2008 figures, while 2009 recreational fishing contributed $1.7 billion to local economies and accounted for 20,000 jobs. Tourism related to recreational activities would also provide an economic benefit. In summary, the total economic and ecological value of coastal wetlands and marshes is significant.

1.2 Coastal Marsh and Wetland Loss

Regardless of their tremendous value, coastal wetlands and marshes are being lost at an
alarming rate. In the U.S., more than 50% of the original tidal salt marshes have been lost, the
greatest portion of which was estimated to be from land reclamation (Watzin & Gosselink, as
cited in Kennish, 2001). Eighty percent of that loss occurred in Louisiana (Kennish, 2001),
where the United States Geological Survey (1997c) estimated that the rate of coastal wetland
loss exceeds 65 km² per year. In Texas, the rate of Gulf shore lost annually is between one and
35 feet, over approximately 70% of the coastline (Morton & McKenna, 1999). Elements
contributing to wetland loss come from both natural and anthropogenic sources.
Unfortunately, one by-product of man-made interventions is inadvertent loss of marshes and
wetlands. For example, reservoirs on the Mississippi River, coupled with river diversions, both
trap sediment and channel it away from its natural course, respectively (Yuill et al., 2009).
Land-use change can also reduce riverine sediment inputs to marshes. As well, spoil banks
created from channel dredging alter the flow of water and sediments into wetland areas
(DeLaune & Pezeshki, 1994). And finally, sea walls and jetties designed to prevent erosion,
often exacerbate it in adjacent downdrift areas along the coast (Morton & McKenna, 1999).

Natural causes of coastal wetland and marsh loss include, flooding, salination, sea level
rise, and subsidence. Although the factors can occur independently, sea level rise and
subsidence may cause or increase the potential for flooding and salination (DeLaune &
Pezeshki, 1994; Kennish, 2001; Morton & McKenna, 1999; USGS, 1997a, 1997b, 1997c; Yuill et
al., 2009).

1.3 Coastal Subsidence and Sea Level Rise

Subsidence is the natural lowering of the land surface level that occurs in coastal
marshes and wetlands. Yuill et al. (2009) describes six distinct subsidence processes—tectonics, Holocene sediment compaction (“sediment compaction”), sediment loading, glacial isostatic adjustment, fluid withdrawal, and surface water drainage and management. Each may exist independently but typically occur in conjunction with others. For example, areas subject to fault shifting (tectonics) may also be subject to sediment compaction from the overlying weight of organic and mineral sediment concurrently. However, some processes are more prominent in certain areas and require more emphasis when fighting wetland and marsh losses in specific regions. For instance, river deltas consist of more organic sediments that are subject to greater sediment compaction; therefore, offsetting subsidence from sediment compaction is a prominent issue for coastal protection in deltaic regions. Due to the magnitude of the Mississippi River delta on the southern Louisiana coast, sediment compaction is a primary reason the region suffers from the greatest loss of wetlands and marshes in the U.S. (Kennish, 2001; Yuill et al., 2009). In Texas, coastal subsidence is generally a consequence of reduced mineral sediment supply from littoral surfaces, river deposits, and impoundment at jetties (Morton & McKenna, 1999). But, fluid withdrawal related to hydrocarbon production (gas and petroleum industries) and groundwater withdrawal is a probable factor in both Texas and Louisiana coastal regions as well (Yuill et al., 2009).

Flooding and salination can occur from natural storm events and as a byproduct of anthropogenic interventions but may also be a result of marsh surface level subsidence. As the land surface level declines, coastal marshes and wetlands are more susceptible to flooding and salt water inundation. Both negatively impact plant growth that, in turn, contributes to greater subsidence from the loss of sediment-anchoring vegetation. This situation establishes a cycle
that compounds the problems caused by each factor independently (DeLaune & Pezeshki, 1994).

Rising sea levels also play a major role in the loss of coastal wetlands and marshes (DeLaune & Pezeshki, 1994; Kennish, 2001; Morton & McKenna, 1999; USGS, 1997a, 1997b, 1997c; Yuill et al., 2009). Ocean volumes are increasing worldwide due to thermal expansion and melting polar ice caused by climate change. This increase is referred to as global or eustatic sea level rise (ESLR) which naturally results in greater coastal land inundation and the potential for wetland and marsh losses. For example, in 2001, in the Mississippi delta region, the estimated annual ESLR was 10 mm per year; in Texas, the rate was approximately 5 to 7 mm per year (Kennish, 2001). However, when considered in concert with subsidence—referred to as relative sea level rise (RSLR)—the potential for loss is multiplied. The RSLR on the southern Louisiana coast, exacerbated by deltaic sediment compaction and other subsidence processes, coupled with anthropogenic factors, exacerbate the loss of wetlands and marshes along its coast (Kennish, 2001; Yuill et al., 2009).

Closely related to the issue of RSLR, submergence is the net effect of all factors that increase the level of water relative to the land surface level. When the rate of accretion, or increases in sediments, is less than RSLR, land submergence occurs. Generally, the rate of accretion is not keeping pace with the rate of RSLR in many Gulf coastal areas. Furthermore, research completed by the USGS (1997b; [n.d.]) found that the amount of marsh surface accretion was lower than expected, indicating that the rate of submergence is underestimated.

Climate change has led to other factors likely to affect coastal marsh and wetland surface levels. Webster, Holland, Curry and Chang found that the sea surface temperature
(SST) in the tropics has increased by 0.5°C from 1970 to 2004. As SST increases, the potential for tropical cyclones (hurricanes, tropical storms and typhoons) is projected to increase as well. Additionally, Emmanuel (2005) found that tropical SST is highly correlated with hurricane power dissipation. This supports historical storm data which shows that Category 4 and 5 hurricanes nearly doubled in the same period. In general, research based on hurricane data analysis and modeling projects that stronger storms will not only occur more frequently, but will also have longer durations (Emanuel, 2005; Holland & Webster, 2007; Webster et al., 2005). These tropical cyclones will most likely be responsible for significant morphological changes in coastal marshes and wetlands—especially sediment transport.

1.4 Gulf of Mexico Coastal Management

Numerous plans have been created to manage and protect Gulf Coastal shores; the important role of sediment dynamics and budgets are typically incorporated into those plans. While individual states develop their own plans and programs surrounding all issues related to coastal management factors, some regional initiatives are also in progress. One of those, the Gulf Regional Sediment Management Master Plan (GRSMMP) was established by the Gulf of Mexico Alliance (GOMA) specifically to manage the use of sediments for habitat creation and restoration. The plan covers the entire Gulf Coast through Texas, Louisiana, Mississippi, Alabama, and Florida. It provides a guide for the use of all sediment resources with emphasis on management of dredged materials (Byrnes & Berlinghoff, 2012; Gulf of Mexico Foundation, 2009; Reed et al., 2012). It supports sharing information plus developing management
principals and enforceable policies across the region. It further highlights the importance of monitoring current and future effects on ecological factors such as fauna and habitat.

In Texas and Louisiana, coastal protection is handled through a variety of laws and rules generated as a result of needs highlighted in coastal management assessments. Texas coastal zone management policies are the province of the Texas Coastal Management Program (TCMP) administered by the Texas General Land Office (TGLO). They are broadly designed to maintain public access to Gulf beaches, protect sand dunes and utilize proper methods for stabilizing the coastline and protecting it from erosion. Local governments are required to develop additional plans that meet the minimum state requirements for preservation and restoration (Morton & McKenna, 1999).

Two key recent plans relevant to this research are the *Texas Coastal Management Program Section 309 Assessment and Strategies Report 2011-2015* (TCMP) (Hart Research Institute, 2010) and the *West Galveston Bay Regional Sediment Management Master Plan* (WGB-RSMP) (GOMA, 2009). The TCMP assesses (in five-year increments) performance of past strategies and plans future goals for preserving and restoring coastal areas. Those plans are funded through U.S. Department of Commerce, Section 309 grants and are designed to meet guidelines provided in the Coastal Zone Management Act of 1972. They cover all aspects of coastal management needs, including issues related to sediment dynamics, erosion, subsidence, rising sea levels, climate change, and storm surge impacts (Hart Research Institute, 2010). The WGB-RSMP was created as part of the development of the GRSMMP to promote understanding of sediment changes, identify needs for purposes of protection, restoration, and conservation, as well as proposing and supporting sediment management plans (GOMA, 2009).
Those plans and others are designed to counter higher severity threats in Texas such as coastal development, erosion, ESLR, and hydrology changes.

In Louisiana, the Department of Natural Resources, Office of Coastal Restoration and Management, is the primary agency for oversight of coastal management resources and planning. Its mission is to preserve, protect, restore and improve the coastal region of Louisiana. It is also responsible for implementing the Louisiana Coastal Management Program (LCMP) which also reports on the use of U.S. Department of Commerce Section 309 funding for projects for the enhancement of coastal resources. The report generated assessed progress on coastal resources in nine enhancement areas from 2006 through 2011, and suggested strategies for future enhancement projects (Office of Coastal Restoration and Management, 2010).

For both Texas and Louisiana coastal management planners, reducing the loss of valuable shoreline, beaches, wetlands and marshes is the greatest challenge. Whether the loss occurs through any combination of erosion, subsidence, submergence, sea level rise or from anthropogenic causes, one solution for the problem is to increase the land surface area through accretion (DeLaune & Pezeshki, 1994; USGS, 1997b, 1997c, [n.d.]) Sediment, both organic and inorganic (mineral sediment), is the natural agent of marsh surface accretion. The natural decomposition of vegetation detritus produces organic sediment. But, mineral sediment, such as clay, silt or sand, is a better material for land surface aggradation of marshes and wetlands due to greater density and resistance to compression (Turner, Swenson, Milan & Lee, 2007). Some sources of mineral sediment supply are the littoral system and riverine deposits. The littoral system encompasses the shallow, near-shore environment plus beaches and dunes.
Deposition from sediment held in suspension in rivers and streams occurs continually in deltaic environments and episodically during periods of overbank flooding.

The problem for many coastal areas, including Texas and Louisiana, is that the current supply of mineral sediment is inadequate to offset the rate of shoreline subsidence and submergence. For example, organic sediments decay resulting in greater subsidence due to compaction (Swenson, Milan & Lee, 2007; Turner et al., 2007; Yuill et al, 2009). The supply of mineral sediment is also reduced in many ways. Man-made interventions such as reservoirs, dams and levees constructed along the banks of rivers considerably lessen the amount of mineral sediment reaching marshes since much of it gets trapped upstream instead (Yuill et al., 2009). Furthermore, river diversions redirect both sediment and water that ultimately replenish wetlands and marshes. This has been documented in the Mississippi River deltaic region where the proportion of sediment inputs has declined markedly (Kennish, 2001; Yuill et al., 2009). Sand impoundment around seawalls and jetties is another example of how anthropogenic coastline modifications lead to sediment redirection resulting in unfavorable change in coastal environments (Morton & McKenna, 1999).

Hurricanes and other strong storms are other sources for potential wetland aggradation. These storms deposit large amounts of sediment in a relatively short amount of time (Törnqvist et al., 2006; Turner, Baustian, Swenson & Spicer, 2006; Williams, 2008, 2010, 2011a, 2011b, 2012; Williams & Flanagan, 2009). Turner et al. (2006) calculated that hurricanes with a rating of Category 3 or higher, have the potential to add significantly more sediments than from overbank flooding or the Caernarvon Diversion. Therefore, they represent another, important natural resource requiring incorporation into coastal management plans.
2.1 Storm Surge Sedimentation

Because of the vital functions attributed to wetlands and marshes, and their vulnerability to relative sea level changes, it has become increasingly important to predict elevation change through aggradation of sediments on the marsh surface (Williams, 2003). Many studies (Dingler & Reiss, 1995; Fitzgerald et al., 1994; Wang et al., 2006) highlight the more destructive side of a hurricane storm surge—the erosion that wipes out beaches and other recreational areas; that type of geomorphologic change is easier to observe and measure. However, studies by Törnqvist et al. (2006), Turner et al. (2006), Williams (2008, 2010, 2011a, 2011b, 2012), and Williams and Flanagan (2009), show that hurricanes are not just a force of destruction through erosion. Hurricane storm surges may also be an important natural source for mineral sediment in coastal marshes though the sedimentation that occurs over the long-term is more difficult to quantify.

A storm surge is the elevation of sea level beyond its normal range. 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. The area of greatest storm surge is located along the right-front quadrant of a landfalling hurricane in the Northern Hemisphere. The counter-clockwise circulation of the winds in the storm causes the greatest buildup of water along shorelines in this quadrant. The counter-clockwise circulation of winds in the left-front
quadrant of the landfalling hurricane will create a much lower storm surge due to the winds blowing from inland out to sea, pushing water away from the coast (Figure 2.1; Liu, 2004).

Figure 2.1. Storm surge height and storm wind direction. In the northern hemisphere, a hurricane making landfall generates a storm surge that is greater on its right-front quadrant than its left-front quadrant, due to the counter-clockwise circulation of winds (Liu, 2004).

Many factors determine whether or not a storm surge inundates nearshore terrestrial environments and the depth of storm surge flooding; these 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 et al., 2005). It is common for intense hurricanes to generate storm surges several meters in height that flood nearshore environments many kilometers inland (Figure 2.2).
Hurricane storm surges commonly transport sediment inland from bays, the nearshore seafloor, beaches, and dunes, to form storm surge deposits in nearshore terrestrial environments, including marshes and woodlands (Figure 2.3). 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; Figure 2.3).

Figure 2.2. Incoming storm surge on a shallow nearshore slope (NOAA, 2010).

Figure 2.3. Thickness and percent sand present in Hurricane Ike (2008) storm surge deposit on the McFaddin National Wildlife Refuge, Texas. The storm surge deposit fines and thins with increasing distance inland (modified from Williams, 2010).
Near the shoreline, storm surge deposits are typically thicker and sandier, and commonly form washover fans or terraces (Williams, 2011a; Figures 2.4 and 2.5).

Figure 2.4. Aerial photograph showing Hurricane Ike washover fans landward of a heavily eroded beach in southeastern Texas (modified from Williams, 2011a).

Figure 2.5. Aerial photograph showing a Hurricane Ike washover terrace in southwestern Louisiana (modified from Williams, 2011a).
Williams and Flanagan (2009) observed prominent foreset laminations in a Hurricane Rita (2005) sandy washover fan and concluded that this part of the storm surge deposit was probably deposited as traction load in a “subaqueous prograding washover fan.” 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 (Williams, 2008; Figure 2.6). Smaller sediment particles, such as clay and silt, weigh less and remain in the storm surge’s water column for longer, therefore traveling much farther inland than larger particles, such as sand and pebbles.

Figure 2.6. Storm surge deposit 945 meters inland at the McFaddin National Wildlife Refuge, Texas, consisting of about 3 cm of fine-sandy mud. Note abrupt contact with underlying buried organic-rich marsh surface and plant stems in upright growth position, suggesting they were encased by sediment deposited from suspension (Williams, 2010).

Hurricane storm surge sedimentation contributes to vertical accretion of coastal marshes (Mitsch & Gosselink, 1984; Nyman et al., 1995; Liu, 2004; Turner et al., 2006; Williams, 2010; Williams, 2011b; Williams & Flanagan, 2009). Nyman et al. (1995) found that accretion
resulting from Hurricane Andrew was equivalent to 4 – 11 times the normal annual marsh accretion rates. They also noted that no hurricane storm surge deposits were found to the left of landfall, which is consistent with reduced storm surge heights in the left-front quadrant of a landfalling hurricane (Figure 2.1). One of their conclusions was that hurricane sedimentation alone may be enough to negate coastal marsh subsidence.

Turner et al. (2006) estimated that Hurricanes Rita and Katrina deposited 131 million metric tons of sediment onto Louisiana coastal marshes. This is about 62% of the annual suspended sediment load of the Mississippi River (Turner et al., 2006). According to the study findings, the average category 3 storm is able to deposit 1.7 times the sediment potentially available through annual overbank flooding of the Mississippi River, 4.6 times more than the annual amount of inorganic sediment being moved through crevasses in an unconfined channel, and 72 times more than the Caernarvon Diversion of the Mississippi River (Turner et al., 2006). The Caernarvon Diversion is a portion of the Mississippi River that is diverted into the marshes in the area with the specific intent of delivering sediment to help aggrade the area. It is part of Louisiana’s coastal marsh restoration program (Turner et al., 2006). Turner et al. (2006) concluded that hurricane storm surge sedimentation may be the primary inorganic sediment source for many coastal marshes. Törnqvist et al. (2006) dispute some of these findings. They suggest Turner et al.’s (2006) annualized hurricane deposition rate is considerably overestimated and the riverine deposition rate is considerably underestimated. However, they concede that hurricane sediment deposition may still be significant enough to warrant consideration in coastal restoration planning (Törnqvist et al., 2006).
Williams and Flanagan (2009) conducted a field survey of Hurricane Rita (2005) storm surge deposits in November 2005 and again in April 2007. They found that the deposits are well preserved in coastal marsh and woodland environments. The storm surge deposit formed a wedge of sediments that fined and thinned inland. The deposit consisted of about 50 cm of sand within 10 m of the shore and became thin (ca. 1 cm), muddy and discontinuous by 420 m inland (Williams & Flanagan, 2009). Long-term sedimentation rates in the marsh soil under the storm surge deposit located in their study area in Louisiana were calculated to be between 0.24 and 0.71 cm per year using Cesium-137 dating. Based on these rates, they determined that a single hurricane storm surge deposit can be the equivalent of over a century of normal, long-term non-storm sedimentation. Based on this information, they concluded that hurricane sedimentation may significantly contribute to long-term sedimentation in coastal marshes on the Gulf Coast.

Williams (2010) documented Hurricane Ike storm surge sedimentation on the McFaddin Wildlife Refuge on the upper Texas coast in January 2009, four months after landfall. The storm surge deposit had two distinct parts, a sandy washover fan deposit, and a finer, thinner blanket of sediment from suspension, extending much farther inland (Williams, 2010). Hurricane Ike’s storm surge deposit aggraded the marsh surface by adding sand and mud in thicknesses of 51-64 cm near shore and thinning inland (Williams, 2010).

Using hurricanes Audrey (1957), Rita (2005), and Ike (2008), Williams (2011b) researched hurricane storm surge sedimentation in the coastal marshes of the Chenier Plain of southwestern Louisiana, near Johnson’s Bayou. The marshes in the study area were trenched and cored, allowing for the thickness of these storm surge deposits to be measured and the
textures of each deposit to be studied. Each deposit reflected the intensity of the hurricane that had deposited it and distance from landfall. For example, Hurricane Audrey made landfall as a category 4 storm that generated a 3 to 4 m storm surge (Landreneau & Shamburger, 2009; Williams, 2011b). Its storm surge deposit is fairly sandy, thick, and well-preserved and extends inland up to 887 m (Williams, 2011b). The calculated average annual sedimentation rates in the study area are 0.2 to 0.7 cm per year, with the greatest sedimentation rates generally being closer to shore and decreasing inland (Williams, 2011b). These storm surge deposit thicknesses in concert with the calculated sedimentation rates in the area indicate that hurricanes Rita and Audrey accounted for between 70% and 90% of the known coastal marsh aggradation in the study area since 1957. This suggests that hurricanes are a very important part of sedimentation in coastal marshes (Williams, 2011b).

One commonly used research methodology for hurricane storm surge sedimentation studies is pit excavation into the storm surge deposit followed by measurement of the deposit thicknesses. However, with advances in technology, Light Detection and Ranging (LIDAR) survey technology has become more viable. Zhang et al. (2005) used LIDAR to complete a topographical study of 40 km of the Florida coastline along the Atlantic Ocean before and after Hurricane Floyd. Two surveys were done pre- and post-storm with the objective of examining the storm surge impact on beach erosion and sediment deposition. The results found changes in sediment distribution in both longshore and onshore/offshore directions with accretion and erosion in various sectors. A modest net beach volume loss per unit length (-0.2 m$^3$/m$^2$) was noted overall. Potentially more significant, the technology allowed a faster and more cost effective way to cover a large study area.
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 addressing hurricanes as a contributing force to coastal marsh aggradation. There is a need for more information on the role of hurricane storm surge sedimentation in long-term marsh aggradation to help resolve these issues.

2.2 Study Area

The aim of this project was to determine the contribution of 2008’s Hurricane Ike storm surge sedimentation to long-term marsh aggradation in Texas and Louisiana coastal marshes. The research hypothesized that Hurricane Ike’s storm surge deposit would be equal to decades and possibly even a century’s worth of the average annual non-storm sedimentation.

Sampling took place along the Gulf Coast from Galveston Bay, Texas, to Oak Grove, Louisiana. In Texas, the area includes the Bolivar Peninsula, on the east side of Galveston Bay, and the McFaddin National Wildlife Refuge, near High Island—where only a small part of the area is developed. Much of the coastline of the study area is low-lying, wave-dominated, and has a low tidal range. The low-lying marshes, gently sloping sandy beaches, and low foredunes (where present) are prone to significant morphological impacts when hurricanes and tropical storms make landfall (Williams, 2010).

Hurricane Ike made landfall near Galveston, Texas, on September 13, 2008, as a strong category 2 hurricane with maximum sustained winds of 175 km per hour. The hurricane-force
winds impacted the Gulf coastline from Galveston eastward into Louisiana (Doran et al., 2009; Figure 2.7). Along the upper Texas Coast, Hurricane Ike’s storm surge averaged between 3 and 5 meters in height (Doran et al., 2009). A storm surge height of 5 meters was measured on the Bolivar Peninsula (Doran et al., 2009; Figures 8 and 9). The McFaddin National Wildlife Refuge saw a storm surge of at least 3 meters (Williams, 2010).

Foredunes and berms in these areas were low prior to the storm, on the order of one to two meters in height. The hurricane’s storm surge easily overtopped and partially eroded the dunes, flooding the coastal marshes behind them with sediment-laden water for tens of kilometers inland (Doran et al., 2009). The study area coincides with the right-front quadrant of the landfalling hurricane - in the zone of maximum storm surge inundation (Figure 2.7) plus the area of hurricane-force winds (Figure 2.8). The study area extends along approximately 180 kilometers of coastline, from Point Bolivar in Texas to Oak Grove in Louisiana (Figure 2.9).

Figure 2.7. Hurricane Ike Wind Field. Hurricane Ike made landfall at Galveston, Texas with hurricane force winds extending along the upper Texas coast and into Louisiana (NOAA).
Figure 2.8. Modeled storm surge heights along the Upper Texas Coast and western Louisiana (NOAA, 2008). Hurricane Ike’s greatest storm surge, 3 – 5 m high, is along the coast between the Bolivar Peninsula and Sabine Lake.

Figure 2.9. Hurricane Ike storm surge deposit located on the Bolivar Peninsula near Galveston (photograph taken by Dr. Harry Williams in January 2009). This location is approximately 25 km from landfall and 500 m inland. The sandy sediment is probably derived from a nearby beach.
Figure 2.10. Study area extending from Point Bolivar, Texas to Oak Grove, Louisiana. The transects show where spade pits were dug to measure deposit thicknesses and take samples (modified from Williams and Denlinger, 2013).
CHAPTER 3

METHODS

3.1 Preservation of Storm Surge Deposit

The storm surge deposit was examined in a series of 15 transects positioned from Point Bolivar, on the upper Texas coast, to Oak Grove, on the southwestern Louisiana coast, approximately 180 km east of Hurricane Ike’s landfall (Figure 2.10). Transects 1, 3, 4, 5, 8, 13 and 15 were surveyed in January 2009; transects 9, 11, 12, and 14 were surveyed in May 2009. Transects 6 and 10 were surveyed in May 2010 and transects 2 and 7 were surveyed in October 2010. Each transect was aligned with the storm surge direction to allow sampling of the deposit near the shoreline to progressively farther inland locations. This number of transects generated a large number of measurements and allowed sampling of the deposits across a range of proximal to distal locations (from near landfall to the eastern limit of hurricane-force winds). Spade pits were excavated along each transect to allow the thickness of storm surge sediments to be measured. The spade pits were continued inland until either the end of the deposit was found, or, an obstacle, such as a body of water, prohibited further pits from being excavated. The end of the deposit was defined as the point where the deposit becomes thin and discontinuous. Following the methodology of Williams and Flanagan (2009) the pits were initially placed 20-50 m apart near the shoreline, where deposit thickness decreased rapidly. Spacing was increased to about 100 m when deposit thickness became more uniform, farther inland. The thickness of the deposit on each side of each pit was averaged to obtain a representative thickness. The base of the storm surge deposit formed a sharp clear boundary with the underlying buried marsh surface and was easily recognized in the field (Figure 3.1).
This contact was readily identifiable in the field because of: (i) the contrast in lithology between the sandy low-organic-content storm surge deposit and the underlying muddy, organic-rich, rooted marsh sediments; (ii) the presence of plants, still rooted in the underlying marsh, enclosed by storm surge sediments; and (iii) the presence of organic litter on the buried marsh surface (Williams, 2012) (Figure 3.1). The location of each pit was recorded by GPS.

Figure 3.1. Clear contact between storm surge deposit (clean, white sand at the top) and underlying marsh (darker organic-rich muddy marsh sediments at the bottom of the pit) (photograph taken by Dr. Harry Williams, January 2009, Transect 1, pit site 2).

Preservation of the storm surge deposit was assessed by repeat survey of deposit thicknesses at transects 1, 3, 4, 5, 8, 9, 11, 13, and 14 in January 2010, approximately fifteen months after landfall. A repeat survey of Transect 15 was also conducted in May 2009. Trench locations along each transect were relocated by GPS and another trench was excavated
adjacent to the original trench. The thickness of the storm surge deposit was again recorded, based on averaging the thickness on each side of the trench. Transect 9’s repeat survey was mostly a failed attempt due to several of the pit sites being inaccessible to re-survey because of standing water, therefore, this repeat survey was not used to assess deposit preservation.

3.2 Contribution of Storm Surge Deposit to Long-Term Marsh Sedimentation

In January 2009, samples of marsh sediments underlying the storm surge deposit at selected trench locations were collected for Cesium-137 analysis. Samples were collected from the western (transect 4) and central (transect 8) parts of the study area (Figure 2.1). The eastern part of the study area is represented by samples taken from transect 13 as part of a study of Hurricane Rita (2005) storm surge deposits, conducted by Williams and Flanagan (2009). Trenches were positioned along each transect to cover a range of locations from nearshore to inland locations. Samples of uniform volume were collected at 2 cm intervals from the side of selected trenches down to 40-50 cm depth below the marsh surface. This sampling method had the advantage of causing no compaction of the sediment samples.

Cesium-137 dating is well established as a tool for estimating sedimentation rates in a variety of depositional environments (Ritchie and McHenry, 1990). Cesium-137 is part of the fallout from nuclear weapons testing that became widespread in the 1950s (Williams and Flanagan, 2009). The Nuclear Test Ban Treaty banned above-ground testing in 1964, so Cesium-137 fallout declines dramatically that year leaving a peak of Cesium-137 fallout in 1963. The approach commonly used is to identify the depth within a sediment column to the 1963 peak in Cesium-137 concentration, corresponding to the fallout maximum (in the southern U.S.)
Identifying the 1963 peak allows the thickness of sediment accumulated since 1963 to be determined. Dividing the thickness of sediment accumulated by the number of years since 1963 yields an average annual sedimentation rate.

Sometimes there is no clear 1963 peak, possibly due to a coarse sampling interval (2 or 3 cm), bioturbation, or a low sedimentation rate in the area (Williams and Flanagan, 2009). If there is no 1963 peak, then another Cesium-137 marker must be used in the dating process. The year 1950 is estimated as the first year there is sufficient Cesium-137 present within a sediment profile to be measurable; consequently, the depth at which Cesium-137 concentration falls to zero is assumed to correspond to the year 1950 (Heit and Miller, 1987; Williams and Flanagan, 2009; Milan, et al., 1995) (Figure 3.2).

Figure 3.2. Cesium-137 levels present in a sediment core, showing the peak in 1963 and the point at which the cesium content falls to zero, in 1950 (modified from Heit and Miller, 1987).

Cesium-137 concentrations were counted on a gamma ray spectrometer having a solid state Ge (Li) detector. Gamma rays corresponding to the branched decay of Cesium-137 to
Barium-137, which yields a gamma of 0.661 MeV, were measured for 24-48 hours per sample. Cesium-137 concentrations are reported as counts/gram-second of dried sediment. Average background radiation was calculated and subtracted from the counts.

The Cesium-137 analysis of samples collected for this study yielded no clear 1963 peak, so the depth to the 1950 marker horizon was used in the sedimentation rate calculations (Figure 4.1). The average annual sedimentation rate for transects 4 and 8, was calculated by taking the depth in centimeters to 1950, and dividing it by 58, the number of years between 1950 and 2008 (the year Hurricane Ike made landfall). The average annual sedimentation rate for transect 13, for a marsh underlying a Hurricane Rita (2005) storm surge deposit (Williams and Flanagan, 2009), was calculated by taking the depth in centimeters to 1950, and dividing it by 55, the number of years between 1950 and 2005. The average annual sedimentation rate was needed to establish a baseline of normal sedimentation for comparison with the amount of sediment that Hurricane Ike, or other hurricanes, could add to a coastal marsh in a short amount of time. A second calculation was performed to determine Hurricane Ike’s contribution to overall sedimentation (in years’ worth of sedimentation at normal rates). That measurement was obtained by taking the overlying thickness of the Hurricane Ike deposit at each pit location and dividing by the calculated average annual sedimentation rate at that site.
CHAPTER 4

RESULTS

4.1 Preservation of the Storm Surge Deposit

Along the nine transects included in this part of the study, the storm surge deposit forms a wedge of sediments that tapers inland (Figure 4.1). The maximum thickness of the deposit is about 85 cm, recorded at the first trench in Transect 15, which was located on a sandy washover terrace (Williams, 2010; Figure 2.5). Inland extent of the storm surge deposit varies from 306 m (Transect 14) to 2,365 m (Transect 1). The repeat surveys of transects showed small gains and losses in deposit thickness at trench sites, with relatively little net change. Five transects showed small gains in average thickness, varying from 0.1 cm at transect 3, to 3.3 cm at transect 11; four transects showed a small loss in average thickness varying from -0.1 cm at transect 13, to -1.5 cm at transect 5 (Table 4.1).

Possible mechanisms that caused these changes include redistribution of sediment by wind and rainwash, and the growth of plants, which presumably causes an increase in deposit thickness due to displacement of sediments by penetrating roots and rhizomes. Similar changes in sediment distribution, with little overall net change, were observed for a Hurricane Rita storm surge deposit in a Louisiana coastal marsh (Williams, 2009).
Figure 4.1. Changes in storm surge deposit thickness along profiles resurveyed between January 2009 and January 2010. Distance inland is measured from the seaward edge of vegetated foredunes (the first trench along transect 15 was 44 m seaward of the vegetation line). The storm surge deposit extended over 1,000 m inland at transect 15, but only the first four trenches could be resurveyed because of standing water.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Average Storm Surge Deposit Thickness 2009 (cm)</th>
<th>Average Storm Surge Deposit Thickness 2010 (cm)</th>
<th>Change in Average Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.4</td>
<td>31.5</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>24.6</td>
<td>24.9</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>7.3</td>
<td>8.3</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>22.3</td>
<td>20.8</td>
<td>-1.5</td>
</tr>
<tr>
<td>8</td>
<td>23.8</td>
<td>25.6</td>
<td>1.8</td>
</tr>
<tr>
<td>11</td>
<td>5.3</td>
<td>7.3</td>
<td>2.0</td>
</tr>
<tr>
<td>13</td>
<td>13.2</td>
<td>13.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>14</td>
<td>3.6</td>
<td>2.8</td>
<td>-0.8</td>
</tr>
<tr>
<td>15*</td>
<td>20.9</td>
<td>19.5</td>
<td>-1.4</td>
</tr>
</tbody>
</table>

*Transect 15 re-surveyed in May 2009.

In January 2009, the surface of the storm surge deposit was sparsely vegetated. Relatively thick, sandy, washover fans had formed along much of the shoreline and these were largely unvegetated, having completely buried most marsh vegetation. Farther inland, marsh vegetation was still in place, but had been partially buried by storm surge sediments and much of the vegetation had been killed, presumably by saltwater inundation.

By January 2010, vegetation was re-established in much of the study area; marsh plants that had survived inundation and partial burial showed signs of new growth and the surface of washover fans had been colonized by new plant communities. Given the stabilizing effect of the relatively dense vegetation cover, it is assumed that the storm surge sediment thicknesses recorded in 2010 will be preserved in the long-term. Similar vegetation re-establishment was noted on the six transects that were not resurveyed and it is assumed that these storm surge deposits will also be preserved. Although roots and rhizomes had penetrated the storm surge sediments, the resulting bioturbation appeared concentrated in the upper few centimeters of
the deposit and had not obscured the sharp contact between the storm surge deposit and underlying buried marsh surface.

4.2 Contribution of Storm Surge Deposit to Long-Term Marsh Sedimentation

Cesium-137 concentrations are plotted against sediment depth in Figure 4.2. At all fourteen trench sites tested, Cesium-137 is present in near-surface sediments and falls to zero at depth, showing that all the sites contain a record of recent sedimentation (At sites 4-1 and 8-3 the Cesium-137 concentration apparently falls to zero below the limit of sampling. These profiles were extrapolated to provide an estimate of the depth to zero concentration. Extrapolation shown by dashed line in following profiles).
Figure 4.2. Cesium-137 profiles. Profiles are identified by transect and trench number (e.g. T4-1 is transect 4, trench 1).

The profiles of Cesium-137 concentration do not conform to the “ideal” shape with a clear 1963 peak (Figure 4.2). Possible reasons for this include the relatively coarse sampling interval used (2 cm) and vertical mixing of sediments caused by bioturbation. It is also possible that reworked sediments containing Cesium-137 have been washed into these sites, increasing near-surface Cesium-137 concentrations or that erosion has occurred, truncating the profiles.
(although no evidence of erosion of the marsh surface was observed at the trench sites). Given the lack of an unambiguous 1963 peak in the profiles, dating was instead based on the assumption that the depth at which the Cesium-137 concentration falls to zero corresponds to the year 1950 (Milan, et al., 1995). This provides an estimate of maximum sedimentation rates because it is unlikely that bioturbation or other processes could raise all traces of Cesium-137 from lower to higher in the marsh profile, thus raising the apparent position of the 1950 marker horizon (Williams and Flanagan, 2009). Long-term sedimentation rates were calculated by dividing the depth to the 1950 marker horizon by 58 years (Table 4.2), with the exception of transect 13, for which 55 years was used in the calculation.

Table 4.2. Decadal-scale average marsh sedimentation rates derived from Cesium-137 analysis and contribution of Hurricane Ike to long-term sedimentation.

<table>
<thead>
<tr>
<th>Transect - Trench</th>
<th>Distance Inland (m)</th>
<th>Marsh Deposition: Pre-Hurricane Ike since 1950 (cm)</th>
<th>Average Marsh Sedimentation Rates (pre-Hurricane Ike) (cm/year)</th>
<th>Hurricane Ike Storm Surge Deposit Preserved Thickness (cm)</th>
<th>Number of Years Equivalent</th>
<th>Contribution of Hurricane Ike to Long-term Sedimentation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>aT 4-1 T 4-2</td>
<td>108</td>
<td>55</td>
<td>0.95</td>
<td>41</td>
<td>43</td>
<td>43</td>
</tr>
<tr>
<td>T 4-3 T 4-6</td>
<td>204</td>
<td>18</td>
<td>0.31</td>
<td>31</td>
<td>100</td>
<td>63</td>
</tr>
<tr>
<td>aT 8-3 T 8-5</td>
<td>286</td>
<td>12</td>
<td>0.21</td>
<td>28</td>
<td>135</td>
<td>70</td>
</tr>
<tr>
<td>T 8-7 T 8-7</td>
<td>613</td>
<td>15</td>
<td>0.26</td>
<td>16.5</td>
<td>64</td>
<td>52</td>
</tr>
<tr>
<td>aT 13-1 T 13-2</td>
<td>175</td>
<td>47</td>
<td>0.81</td>
<td>49</td>
<td>60</td>
<td>51</td>
</tr>
<tr>
<td>T 13-3 T 13-4</td>
<td>265</td>
<td>14</td>
<td>0.41</td>
<td>41</td>
<td>112</td>
<td>66</td>
</tr>
<tr>
<td>T 13-5 T 13-6</td>
<td>400</td>
<td>18</td>
<td>0.31</td>
<td>15</td>
<td>48</td>
<td>45</td>
</tr>
<tr>
<td>T 13-7</td>
<td>10</td>
<td>39</td>
<td>0.71</td>
<td>38</td>
<td>54</td>
<td>49</td>
</tr>
<tr>
<td>aT 13-1</td>
<td>70</td>
<td>14.5</td>
<td>0.26</td>
<td>9</td>
<td>34</td>
<td>38</td>
</tr>
<tr>
<td>T 13-3 T 13-4</td>
<td>130</td>
<td>19.5</td>
<td>0.35</td>
<td>8</td>
<td>23</td>
<td>29</td>
</tr>
<tr>
<td>T 13-5 T 13-6</td>
<td>200</td>
<td>13</td>
<td>0.24</td>
<td>12</td>
<td>34</td>
<td>48</td>
</tr>
<tr>
<td>T 13-7</td>
<td>260</td>
<td>27</td>
<td>0.49</td>
<td>15.7516</td>
<td>33</td>
<td>37</td>
</tr>
<tr>
<td>T 13-7</td>
<td>330</td>
<td>17</td>
<td>0.31</td>
<td>3</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>T 13-7</td>
<td>420</td>
<td>22.5</td>
<td>0.41</td>
<td>6</td>
<td>15</td>
<td>21</td>
</tr>
</tbody>
</table>

Previous research on the contributions of hurricanes to long-term coastal aggradation provided evidence for the significance of storm surge deposition to sedimentation in coastal marshes and woodlands (Liu, 2004; Mitsch & Gosselink, 1984; Nyman et al., 1995; Turner et al., 2006; Williams, 2010; Williams, 2011b; Williams, 2012; Williams & Flanagan, 2009). Findings from this study, on Hurricane Ike’s sedimentation, support that research. Although wind, rainwash and the growth of plants probably caused some redistribution of Hurricane Ike’s storm surge deposit and small gains or losses in deposit thickness, overall there was little net change in the deposit. The re-establishment of vegetation cover with accompanying sediment binding root systems also showed little net change. This suggests that the storm surge deposit is well-preserved in these low-energy marsh environments.

Furthermore, decadal-scale marsh sedimentation derived from Cesium-137 dating provided sedimentation rates ranging from 0.21 to 0.95 cm per year exclusive of Hurricane Ike’s sediment input. Based on these sedimentation rates, Hurricane Ike’s storm surge deposit is equivalent to between 10 and 135 years of non-storm marsh sedimentation and represents 15%-70% of the long-term aggradation since 1950 (Table 4.2). These results reflect variability due to a number of factors. First, the contributions to sedimentation decline because the deposit thickness decreases with distance inland and distance from landfall. Factors within the storm itself such as wind speed, wave height and storm surge height, also contributed. Finally, land features such as coastal barriers, topography, vegetation and sediment supply further affected the results (Williams, 2012).
The focus of this study was Hurricane Ike’s contribution to long-term marsh aggradation. However, it is probable that other storms and hurricanes occurring between 1950 and 2008 have contributed to sedimentation in the study area. For example, at transect 13 in southwestern Louisiana, a sediment bed deposited by Hurricane Rita in 2005 was clearly discernible when research was conducted by Williams in 2011. Williams (2011b) found further evidence that the sediment beds deposited by Hurricane Audrey (1957), Hurricane Rita (2005) and Hurricane Ike (2008) all contributed to marsh aggradation at a coastal marsh site in that area. Combining the deposits of multiple hurricanes greatly increases the significance of hurricane sediment inputs at this site. The maximum number of years of non-storm sedimentation represented by the combined inputs is 126 years, compared to only 54 years for Hurricane Ike alone. The percentage contribution of storm surge inputs to long-term sedimentation since 1950 rises to 70% for the combined inputs, compared to 49% for Hurricane Ike alone (Table 5.1). The combined sediment input from these hurricanes accounted for up to almost 90% of sedimentation in the marsh since 1957.


<table>
<thead>
<tr>
<th>Transect - Trench</th>
<th>Distance Inland (m)</th>
<th>Marsh Deposition: 1950 - 2005 (cm)</th>
<th>Average Marsh Sedimentation Rates (cm/year)</th>
<th>Thickness of Combined Storm Surge Deposits* (cm)</th>
<th>Number of Years Equivalent</th>
<th>Contribution of Hurricanes to Long-term Sedimentation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 13-1</td>
<td>10</td>
<td>39</td>
<td>0.71</td>
<td>62</td>
<td>87</td>
<td>61</td>
</tr>
<tr>
<td>T 13-2</td>
<td>70</td>
<td>14.5</td>
<td>0.26</td>
<td>33</td>
<td>126</td>
<td>70</td>
</tr>
<tr>
<td>T 13-3</td>
<td>130</td>
<td>19.5</td>
<td>0.35</td>
<td>25</td>
<td>71</td>
<td>56</td>
</tr>
<tr>
<td>T 13-4</td>
<td>200</td>
<td>13</td>
<td>0.24</td>
<td>28</td>
<td>118</td>
<td>68</td>
</tr>
<tr>
<td>T 13-5</td>
<td>260</td>
<td>27</td>
<td>0.49</td>
<td>37</td>
<td>76</td>
<td>58</td>
</tr>
<tr>
<td>T 13-6</td>
<td>330</td>
<td>17</td>
<td>0.31</td>
<td>10</td>
<td>32</td>
<td>37</td>
</tr>
<tr>
<td>T 13-7</td>
<td>420</td>
<td>22.5</td>
<td>0.41</td>
<td>15</td>
<td>37</td>
<td>40</td>
</tr>
</tbody>
</table>

Furthermore, Williams (2011b) noted that Hurricane Ike’s relatively thin, muddy storm-surge deposit at the site in southwestern Louisiana was obscured by bioturbation within 20 months after landfall. This suggests that storm surge sediment from smaller storms and hurricanes may be present at all the marsh sites included in this study, but may not be easily recognizable as visually distinct sediment beds. This may be the case in the Texas portion of the study area, where, unlike Louisiana, no recognizable, visually-distinct hurricane-derived sediment beds were noted in the subsurface of the marsh at trench sites sampled for Cesium-137 analysis.

The significance of hurricane-derived sediment inputs to long-term sedimentation in the study area partially depends on the frequency and magnitude of storm surge sedimentation. Although there is evidence of frequent and highly significant storm surge sediment inputs in Louisiana, in Texas it is unknown if older storm surge sediment beds, pre-dating Hurricane Ike, are present in the subsurface of marshes. In the HURDAT database maintained by the National Oceanic and Atmospheric Administration (NOAA, 2012), nine hurricanes, ranging from Category 1 to 4 (at landfall) made landfall within 120 km of Galveston between 1854 and 1983 (the 120 km radius encompasses the entire upper Texas coast). Six of those hurricanes were Category 3 or 4 at landfall. It seems highly likely that some of these intense hurricanes transported sediment into marshes on the upper Texas coast. If only two of these intense hurricanes had deposited sediment beds comparable to that of Hurricane Ike, the recurrence interval of hurricane-derived sediment input would be about 50 years, (three hurricanes in the period 1854-2008) and storm surge sedimentation at the sites studied would be close to, or greater than 50% of long-term sedimentation.
Other factors that affect sediment deposition include global climate change, ESLR, subsidence and submergence—all of which are either interrelated or exhibit a cause and effect type of relationship. Global climate change is believed to be a factor in the increase of both the SST and ESLR. As SST increases, the frequency, duration, and intensity of hurricanes is also expected to increase (Emanuel, 2005; Holland & Webster, 2007; Webster et al., 2005). As ESLR increases, insufficient land surface accretion coupled with subsidence will result in additional land surface submergence, or greater loss of coastal marshes and wetlands, if the cycle is not altered or stopped. Along the Texas and Louisiana coast, this problem is exacerbated by a low supply of mineral sediments and additional losses from man-made interventions. The results of this study show that hurricane storm surge deposition has the potential to offset some of those marsh and wetland losses resulting from the pattern described through the relationships above. With the projected increase in the frequency and intensity of storms, a large supply of storm surge deposits is possible. The “trick” is to provide property protection where needed without creating barriers that ultimately cause more harm than good—by reducing the potential volume of storm surge sedimentation. This is a challenge for scientists, governments and coastal management planners. Understanding the forces surrounding these powerful storms, plus the natural accretion and subsidence processes, is crucial and it underscores the importance of continuous research. An example was provided by Turner et al. (2006) that contrasted the natural deposition of sediments from hurricanes with the costly Caernarvon Diversion of the Mississippi River. He calculated that the addition of sediments to wetlands by an average Category 3 or greater hurricane is 72 times greater than that delivered by the diversion. Additionally, because this is a dynamic process, whereby conditions vary and change
over time, learning more about the causes of erosion in some areas and deposition in others is also necessary. Coastal management policies should be designed for local and regional variations and to improve the line of defense—based on natural conditions plus weather and storm patterns.

Aside from storm sedimentation, other sources of mineral sediment input into marshes in the study area may include fluvial inputs from bayous and aeolian inputs from exposed tidal flats and beaches. The magnitudes of these sources in the study area are unknown, but are likely limited. Most aeolian sediment throughout the study area is presumably trapped only a short distance inland by foredunes. Much of the study area in Texas is a peninsula surrounded by water, which restricts fluvial input. In southwestern Louisiana, fluvial input is restricted due to the relatively small size of the bayous. Regardless of the volume or extent of the input, theses are elements of accretion that are not factored out of the transect sediment measurements or ultimately, the research study findings. Therefore, it potentially adds a small amount of error into all figures and calculations. Additionally, it is another natural source of sediment supply which should be understood and considered by coastal management planners.

Changes in technology increase the potential for using other methods to study the effects of hurricanes and their resulting storm surges in coastal areas. The use of LIDAR survey technology allows for mapping of coastal areas before and after these storms. Used in concert with specialized computer programs, detailed information can quickly be obtained regarding changes in land topography. Though accuracy has increased, the use of the method is somewhat limited from potential errors due to issues surrounding aircraft trajectory, orientation, and laser ranging (Zhang et al., 2005). Furthermore, although the costs per survey
might decrease over time, the initial costs for purchasing highly technical equipment and programs, and to get training would likely be expensive. Additionally, as with all things technical, the updates for programs, related training, and equipment maintenance would ensure a minimum constant level of expense.

The advances in technology highlight the limitations inherent in the manual measurement process. Covering large study areas requires greater time, effort and cost per endeavor than can potentially be accomplished through the use of technology such as LIDAR (Zhang et al., 2005). Relevant changes in the storm surge deposit can be missed due to the comparative infrequency of transects. Additionally, for repeat surveys, transects are dug adjacent to the previous location so unknown minor variances are built-in automatically. Finally, the potential for human error through this type of field work is present. Locating the placement of previous and new transects, collecting samples manually, and taking measurements are a few of the areas where alterations can make a small difference in the results—especially when the units of measurement recorded and compared are very small, as in this research.

Lastly, research on hurricane and extra tropical storm surge deposits deal with dynamic environments and weather patterns. As previously noted, both storm and land characteristics shape the deposit. Therefore, results from research on conditions surrounding one hurricane, such as Hurricane Ike, do not automatically carry over to all hurricanes. To potentially facilitate usefulness in coastal management planning, continuous and ongoing research is necessary because of constant changes in the natural environment.
Hurricane Ike’s storm surge deposited sediment into coastal marshes along 180 km of the Southeastern Texas and Southwestern Louisiana coastlines. Repeat surveys of the deposit show some initial minor redistribution of sediments, most likely due to wind and rainwash. But by 25 months after landfall, vegetation cover was well-established and long-term preservation of the deposit seems likely. Comparison of the thickness of storm surge sedimentation to decadal-scale sedimentation rates in underlying marsh sediments at fourteen marsh sites, suggests the storm surge deposit is equivalent to between 10 and 135 years of non-storm marsh sedimentation, and represents 15%-70% of long-term aggradation since 1950.

In Louisiana there is evidence that other hurricanes pre-dating Hurricane Ike, also contributed to long-term marsh aggradation; however, older hurricane-derived sediment beds were not noted in Texas marshes included in this study. Given the frequency and magnitude of nearby landfalling hurricanes in the historical record, it is likely that storms and hurricanes older than Hurricane Ike have also contributed to long-term marsh sedimentation in the Texas portion of the study area.

The results of this study add support to a growing body of evidence that hurricane storm surges may be the predominant natural mechanism for the transport of sediment into coastal marshes along the northern Gulf of Mexico (Turner et al., 2006; Williams & Flanagan, 2009; Williams, 2011b; Williams & Denlinger, 2013). Specifically, the findings of this and other recent research show that hurricane-derived sediment inputs frequently account for more than half of long-term sedimentation. Hurricanes also represent the predominant source of long-term
marsh aggradation. Their potential contributions to sediment deposition and land surface aggradation should be recognized by coastal management planners faced with shore, wetland and marsh losses and the devastating consequences to the economy and environment. Coastal management plans should incorporate strategies that do not inhibit storm surge sedimentation; rather, they should protect the natural processes that will help maintain or increase marsh surface elevation.

There are several possible avenues for future research in this area. This study focused specifically on the contributions of Hurricane Ike to the long-term overall average annual sedimentation rate in the coastal marshes of the study area. The results show that it contributed significantly through sediment deposits; but, it is only one storm. In the core samples taken in the Texas portion of the study area, the storm sediment layer attributed to Hurricane Ike was the only distinct hurricane contribution though the presence of deposits from other storms is probable. To clarify the contribution of hurricanes in general, future research could investigate older hurricane deposits in Texas to estimate a possible recurrence interval and facilitate more accurate calculations of the rate of sedimentation in the area’s coastal marshes.

While the results of this study confirm that hurricane sediment deposits are one potential source for marsh and wetland aggradation, aeolian and fluvial sources of mineral sediment deposition were also present in the coastal marshes in the study area as well. However, those sources are limited by the geographical features of the area and therefore, have little potential effect on aggradation. Additional research quantifying the impact of these
sources of sediment deposits would enhance our general knowledge of forces at work to aggrade the marsh surface.

Lastly, the volume of information surrounding the potential benefits of hurricane sediment deposition is limited. Greater understanding could be achieved by conducting additional research in the original study area after the next Category 3 or greater hurricane makes landfall in the near vicinity. By resurveying the same transects used in this field work, the preservation of Hurricane Ike deposits could be reassessed and compared with the erosion wrought by the new storm. A “net storm effect” calculation might be performed to further refine the significance of hurricane sediment deposition to overall sedimentation rates, and ultimately, help preserve coastal wetlands and marshes. Furthermore, with the data now available surrounding all aspects of hurricane events, additional analyses surrounding the effects of climate change, SST, and other meteorological factors could potentially enhance scientists’ ability to better predict hurricane incidence, strength, and frequency. This in turn, could benefit coastal management planning processes by generating more accurate projections for potential natural sediment inputs and outputs. Any information that enhances understanding of sediment dynamics might also help offset the additional costs and negative by-products of man-made interventions, the unnatural alternative.

In summary, Hurricane Ike deposited large amounts of sediment into Texas and Louisiana coastal marshes which were preserved over the course of this study. The results of this field research add to the existing body of knowledge which concludes that hurricanes are a significant source of mineral sediment deposition in coastal marshes. Because of the insufficient supply of mineral sediments, in the study area, plus the tremendous need to
protect, preserve, and restore a valuable natural resource, coastal management plans should be designed to allow for storm surge deposits. This becomes more important relevant to factors and processes related to climate change and the expectation of increased hurricane incidence frequency, intensity and duration. Additional research is needed in all of these areas.
REFERENCES


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