Identifying Erosional Trends of Upper Galveston Bay Salt Marshes from 2004-2018 High Resolution Imagery: A GIS and Remote Sensing Analysis

by

Jeremy Medina, B.S.

Texas State University

Advised by Dr. Nathan Currit

Committee Member Dr. Suzon Jammes

Contents

Abstract:

Remote sensing has been a part of contemporary wetland conservation practices for many years. Data generated by aerial and satellite imagery has proven invaluable to assessing the health of wetland environments. Utilizing imagery of a certain location over the course of many years can produce a time series which can be used to observe visual changes in the environment throughout the observed range of time. With Geographic Information Systems (GIS), it is possible to record these changes in the marsh as vector features for future use in presentations or modelling. In a place like Galveston Bay, Texas, coastal salt marshes and residential or urban centers coexisting near one another are commonplace, so tracking the health of the marsh based on anthropogenic actions, both conservational and detrimental, is key to preserving them. In turn, the marshes preserve the communities they reside by through hazard mitigation and economic opportunity. In this research, years of high-resolution remote sensing data were used as a guide for the digitization of two salt marsh sites along the coast of Upper Galveston Bay. Through a series of geoprocesses, the area of wetlands lost for each site was calculated and the rates of loss were compared over time, and the relationship of vegetation loss and regional subsidence was investigated. Anthropogenic processes were also noted as timestamps to check effects on the marsh, like constructed upstream drainage or physical damage from traversal through the marsh. By comparing the digitized marsh edge over the years to the most recent elevation captured with LiDAR, the effects that anthropogenic processes have had on the wetlands became more tangible. Through these observations, a stark difference is presented between the erosion of natural and constructed salt marsh. Understanding the relationships between these wetland environments and the communities they neighbor will be an important piece of knowledge as climate change continues to alter the globe's coasts.

Introduction:

Coastal erosion is an effect that alters coastlines all around the world. Sediments are routinely suspended and subsequently transported by water and wind. Prolonged erosion of this nature, along with insufficient deposition of geologic material, can dramatically change the geographic qualities of a coastal environment. The Gulf Coast of the United States has seen a loss of land and coastal environments from erosional processes for decades with the acceleration of sea level rise (SLR). These effects can have measurable impacts on coastal environments, both manmade and natural. Both exist on the coast of Galveston Bay, Texas, one of the most heavily populated regions in Texas due to the industries made available by the Gulf. Urban and industrial development have led to rising issues for coastal habitats in the Houston-Galveston area since the industrial revolution in the form of urban encroachment and subsidence. The salt marshes of Upper Galveston Bay are no exception. Many of them lie in close proximity to urban centers and are inextricably linked to the anthropogenic processes associated with them.

Galveston Bay is located between the East Texas mainland and Galveston Island, a sandy barrier island, as well as Bolivar Peninsula, situated to the northeast of Galveston Island on the Texas mainland. This estuarine system receives fresh water mainly from the San Jacinto river and salt water from the Gulf of Mexico through tidal inflow. The estuarine salinity and relatively shallow depth of this environment are ideal for coastal salt marshes. However, the vitality of these habitats is on the decline. Many of Galveston's wetlands have experienced vegetation and land loss due to becoming submerged through relative SLR (Thomas M. Ravens, Thomas, Roberts, & Santschi, 2009). Over the span of decades, projects have been performed to mitigate the erosion of wetland sediments or to create new foundations for marsh growth to varying degrees of success.

While wave action is typically the leading cause of erosion along much of the Gulf Coast, this is not the case for Galveston's estuarine environment due to the Bay's shallow average depth (Kolker, Allison, & Hameed, 2011). The reduced wave-induced erosion in Galveston wetlands allows for the opportunity to isolate the possible drivers of sedimentation. The main issue in Galveston Bay has been determined to be subsidence caused by urban sub sediment fluid extraction (Kolker et al., 2011). Extraction of this nature refers to the pumping of freshwater for municipal purposes in urban centers like Houston, League City, Baytown and other cities surrounding the Galveston and Trinity Bays. The other main fluids extracted are oil and gas by the petrochemical industries operating in the Houston-Galveston area. Removing these subsurface fluids causes the compaction of overlying geologic material, weighed down by urban development, to decrease in elevation as a result. The salt marshes of Galveston Bay, Texas are constantly undergoing subsidence. Documenting this effect for site-scale study areas can be difficult due to the broad nature of subsidence, but it is an inference for the region that was relied upon to inform the conclusions made regarding sediment transportation and deposition at each of the marshes.

These wetlands are environmentally and economically crucial to Galveston Bay and the towns and cities that lie on the coast. They provide drainage during heavy precipitation events, breeding grounds and food sources for estuarine wildlife, filtration of polluted runoff and buffer against storm surge in hurricane events. Additionally, soil of healthy emergent coastal wetlands with tall grasses is more biomass-laden and acts as a carbon sink. (Kulawardhana et al., 2015) However, Galveston salt marshes have been under threat for decades. The combined effects of urban development and SLR from climate change can have visible effects on the geomorphology of these salt marshes. Changes in erosion and deposition can, in turn, define the health of the urban population nearby. This research aimed to show how small-scale wetlands, which have significant benefits to the communities they are adjacent to, can be assessed using high resolution aerial imagery and GIS functions.

The goal of analyzing imagery of these two salt marshes was to gain insight on the sedimentary changes at each, based on the geologic events observed using identifiable imaged features. With the assumption that subsidence is constantly affecting the region by exacerbating sea level rise, digitization of the marsh shore over the course of more than a decade can show how the wetlands have responded to changes and damage over time. As subsidence persists, the greatest areas of loss should be in areas of natural wetland exposed to the bay, the least amount of loss in constructed marsh with higher elevations, and virtually no change in artificial or reinforced surfaces.

Mechanisms of Coastal Wetland Geology

Various models have been utilized in past studies of estuarine salt marshes and other coastal wetland environments. They rely on different functions of hydrodynamics and sedimentary geology to model sediment's probability of becoming suspended and transported elsewhere. These studies informed the observations made through the digitization process. The Simulating Waves Nearshore (SWAN) model, for example, was used in West Galveston Bay to measure variables of wind-generated waves, including frequency, diffraction, break depth and shoaling to determine the greatest cause of erosion on coastal wetland environments. With this model it was determined that West Galveston Bay was too shallow for wave action to be the primary driver of the erosion of the wetlands studied. Instead, it was deemed more likely that subsidence is the main cause of wetland deterioration by exacerbating the effects of SLR (Thomas M. Ravens et al., 2009).

Vegetation has also been modelled in coastal environments to judge the overall health of vegetative systems. The Vegetation Photosynthesis Model (VPM) is a mathematical model that has been used in conjunction with MODIS imagery and climate data of numerous study areas in North America, and shows that there is a distinct positive shift in photosynthesis, and therefore vegetation health, during the growing season (Zhang et al., 2016). USDA's NAIP imagery is always captured during the growing season, which not only provided the greatest photosynthetic activity, but was also a consistent sample selection of imagery. Both were measures to reduce variation and increase confidence in the data produced.

Spartina alterniflora (Smooth Cordgrass) and *Spartina* relatives, other grasses such as Widgeon Grass, Shoal Grass and submerged species like Turtle Grass are the dominant vegetation in Galveston salt marshes and are the primary actors of photosynthesis for these habitats (Kulawardhana et al., 2015). These grasses are commonplace in emergent salt marshes along the entirety of the Gulf Coast as well. Assumptions of how the marshes in Upper Galveston Bay behave can be drawn from observations in other similar environments like southern Louisiana, where measurements collected through the use of a piezocone penetrometer concluded that there was a spatial relation in the resistance to erosion of the soil and the presence of hydrophytes, specifically *Spartina alterniflora* (Jafari, Harris, Cadigan, & Chen, 2019).

As sea level rises and subsidence continues along the coast, coastal wetland environments are driven inland as their elevation decreases (Kulawardhana et al., 2015). This transition of landcover from dry upland sediments and the local flora to that of a salt marsh is a way for the marsh to counteract the shoreline marsh lost, but if the upland landcover in question is impervious due to urban development then there is no room for the wetland to retreat, resulting in the habitat's eventual drowning and erosion. As coastal wetlands creep upland so does the water that defines them. This leads to infiltration of salt water into upland soils and even cause damage to foundations and contaminate water sources in developed areas (Lynn Donelson Wright, 2019). Any additional effects that decrease elevation within the marsh could increase the rate of this inundation. To offset this, the most effective conservation efforts in salt marshes reinforce the marsh by raising the elevation and creating a steeper edge to provide greater resistance to degradation (Delaney, 2000).

Wearing and break down of coastal sediment results in lower median grain size and encourages erosion and transportation of sand grains further offshore (Lopez, Baeza-Brotons, Lopez, Tenza-Abril, & Aragones, 2019). This presents another obvious cause of erosion acceleration, as grains of sediment within a restricted bay system are more likely to stay within the system than being transported out to open sea. In a bay like Galveston Bay, erosion and sedimentation occurs in a relatively closed system (Black, Kurian, Mathew, & Baba, 2008). As grains of sand are cyclically eroded, transported and deposited in other locations in the bay, the grains become smaller and less angular. Starting mass and the state of degradation of the material sample has a direct relationship to the thickness of the activation layer of the sediment, or the layer of material that can be moved by longshore drift. This makes them easier to erode again, continuing the cycle at a higher rate. This effect is especially relevant to Galveston Bay in hurricane events. In certain sites in the Galveston Bay and San Luis area, major storms like Ike had been the cause of redistributing up to 50 m^3 of sediment to different areas of the bay (Hawkes & Horton, 2012). Hurricanes and tropical storms do not need to make frequent landfall to have a significant effect on erosional trends in a coastal environment. Oftentimes a powerful storm further off the coast can cause a rise in erosion by altering mean depth and wave height (Youn & Park, 2018). In estuarine systems like the Galveston and Trinity Bay system, wetland environments can receive sediment from upstream delivery and deposition from transport within the bay. Maintaining a supply of sediment is crucial for a salt marsh to receive new nutrients and retain elevation. In addition to the increased risk of erosion by sediment aging, the general trends seen in Galveston Bay indicate that sediment accretion is being reduced by anthropogenic processes in the estuary's inland freshwater sources, causing salt marsh deposition to be outpaced by enhanced sea level rise (Al Mukaimi, Dellapenna, & Williams, 2018).

The study and practice of wetland management by State agencies, non-profits and local governments have used NAIP imagery and GIS to identify, catalogue and track the vitality of wetland environments. Remote sensing or aerial imaging have been used to distinguish between potential jurisdictional wetlands and upland areas (Lyons, 1995). The relationship between GIS and wetland conservation has been evolving since its implementation. Now, the enhanced resolution of high-resolution imagery and the advancements in GIS software capabilities allow for multiple facets of observation of areas of interest.

Study Areas:

Salt marshes chosen for this study included Swan Marsh, located in Beach City, Texas, and Pine Gully, located in Seabrook, Texas. These sites were chosen for the similarities they share as well as the inherent differences derived by their location. Both are classified as estuarine salt marshes, containing primarily *S. alterniflora* as the emergent grass. Both sites are undergoing subsidence and are located near residential or industrial development. Like other coastal wetlands of this region sediment in and around each of these salt marshes is comprised largely of sand followed by silt (Al Mukaimi et al., 2018).

Pine Gully Park contains a salt marsh on the coast of Seabrook, TX, which was the subject of Galveston Bay Foundation's Marsh Mania event on May 17th, 2014. It lies south of the Pine Gully cemetery and the public area of the park. The surrounding locale is residential, with the nearby coastline reinforced with boulders to protect nearby properties. Recreational water access is not an issue for this marsh, and therefore would not be a major cause for erosion from trampling. Residents on the south bank have concrete access, and the northern residents have use of a large fishing pier and other means of access. In May-August of 2005, a silty sediment plug was deposited upstream of the marsh. This plug completely stopped freshwater flow from the upstream inlets under normal conditions, which raised concerns for possible flooding in Seabrook. (Ravens & Thomas, 2006) Between the unusual sediment delivery, apparent SLR augmented by subsidence, and ship-induced waves (Pine gully sits in close proximity to the Houston Ship Channel), erosion became an issue for the site for the next several years. During this time, it was locally debated whether this deposition was port related, with the nearby oil and gas activity upstream. According to the Harris-Galveston Subsidence District, the City of Seabrook, Pine Gully Park included, subsides as much as 1.0 cm per year.

Swan Marsh lies on the opposite side of the bay from Pine Gully, on the southwestern point of Beach City, TX, in Chambers County. The wetland lies just north of an oil field that has been operating since 1938. In the 1930's the marsh had an extensive construction of sandbars with marsh vegetation. Between 1906 and 2000 the zone where this marsh lies has subsided a recorded 1.2 m according to the Houston Galveston Subsidence District's 2008 report (Al Mukaimi et al., 2018). In that time, the previously extensive sedimentary network had been reduced to one major length of healthy marsh which largely encloses a tidal lagoon and connects to a larger contiguous marshland which spans roughly 0.65 km of length along the oil field and

0.35 km deep (From shore to approximated upland area). According to the Harris-Galveston Subsidence District, the area this marsh lies on subsides as much as 0.49 cm per year, approximately half the rate of Pine Gully. This is most likely due to the epicenter of subsidence in the Houston-Galveston Region being Houston itself. Being the more distal marsh from the city and on opposing sides from the other site in question.

Data:

This study relied upon the use of remote sensing imagery collected for the National Agriculture Imagery Program (NAIP) by the USDA to observe changes to the patterns of vegetation and landmass within Galveston Bay salt marshes over the course of 14 years. Imagery of this nature was accessed via web mapping service (WMS) through the Texas Natural Resources Information System (TNRIS) Datahub whenever possible. Certain years were not available as a WMS so they were downloaded as .tiff files for each relevant county. For the year 2008, NAIP imagery for Harris County is missing, so analyzing Pine Gully for this year was impossible. This is particularly unfortunate because Hurricane Ike landed in September of 2008 and observing the geomorphic changes pre- and post-Ike is best done with the closest timestamps possible.

Presence of *Spartina* family grasses were the primary indicator for marsh presence, and in turn, sediment retention. *S. alterniflora* and its relatives require an initially shallow environment to root and mature. While the actual delineation of wetlands using NAIP imagery is not generally advisable, there are distinctions from alternate landcover types in these regions that allow for observation of the geophysical changes within the marsh. Aerial imagery of wetland areas shows a lower value in the green band and a higher value in the blue band when compared to upland vegetation due to being inundated with water. Other distinctions are evident as well, which are visible due to the high spatial resolution of NAIP imagery. Trees, for example, cast shadows whereas those of salt marsh grasses are too small to be seen from aerial imagery. This study utilized this imagery to distinguish the shifts of land type between vegetation, bare land, and water at each of the study areas to determine when erosional shifts occur in response to natural disasters or anthropogenic events.

Additionally, a LiDAR-based Digital Elevation Model (DEM) was used to determine the elevational effects of visible anthropogenic events. 2018 LiDAR DEM data was originally collected by the TNRIS Stratmap program with a spatial resolution of 50 cm. This allowed for the assessment of elevation of small-scale study areas like Pine Gully and Swan Marsh, and comparison to NAIP imagery which was also taken on the same year. This imagery was used with the intention of providing additional dimensionality to the conditions of the study areas as of 2018.

Methods:

This project involved digitization of the marsh edges every year that NAIP imagery was available. Classifying between vegetation and lack of vegetation is more viable with NAIP imagery than with LANDSAT or MODIS at the scale required and does not require delineation of the marsh from upland environments. In addition to NAIP imagery, Google Earth Pro was used to observe when significant visible events occurred. Certain events that caused a visible change in the marsh were digitized in the Google Earth Pro software and exported as .kmz files. They were then converted to feature classes in ERSI's ArcGIS Pro, where they were overlaid with the NAIP services. All assets were projected on the WGS 84 geographic coordinate system. Because NAIP imagery is collected during the growing season of every even-numbered year via airplane, the temporal frequency of imagery observed for erosional changes was 2 years. LiDAR imagery of each site was used with the intention to measure the impact that past events within the marsh had on the elevation of the marsh. Using ArcGIS Pro, contour shapefiles were constructed for every 0.10 m. Each marsh required more than one .tiff, so the resulting contours were merged, then cleaned up by using a definition query to make only contours of substantial length visible.

Digitization of each marsh had to be done slightly differently due to the inherent geographic differences of the sites. Swan Marsh was digitized along the exposed portion of marsh to the bay, which features a broad outer arm of vegetation which changed drastically in the years of imagery observed. Each line that was created as a result was attributed according to the year. Then a one-way buffer was applied to each marsh edge line towards the upland direction, creating a polygon for each. All buffers were then clipped by the following year's buffer polygon, resulting in a shape that represented the change in marsh land type to water. These separate polygons were then merged into a single shapefile, and the areas of all polygons were calculated to provide a rate of lass for every two years.

Pine Gully is more channelized than Swan Marsh, with salt marsh on either side of the channel. To best observe this area, both banks of the channel were digitized, and these lines were attributed with the years of imagery they originated from. Following this, a channel line was created along the center of the channel until a bridge where the channel appears to become artificial. Then a sample point was created along the channel line every 15.24 m (50 ft). This was done to establish equally distanced transect lines for the measurements to follow. A total of 17 transect lines were drawn across the channel and channel width was measured for each year of digitized lines from the NAIP imagery.

Results:

Figure 1 displays Swan Marsh with the digitized retreat of the shore. In chronological order, the GBF Marsh Mania event took place at this site in 2002, resulting in the propagation of thousands of *S. alterniflora* plants by volunteers along the outside arm of the marsh. This continued to develop into healthy marsh through the years, but at the same time the lower portion of the marsh, proximal to the oil field, saw drastic deterioration. A non-vegetated portion developed and eroded northward as time went on, and the shape of the outer marsh flattened somewhat suddenly in 2010. Up to this point the shoreline had a distinct angular shape which was subsequently lost. This could indicate that some sort of threshold was reached in the sedimentary environment. It is possible that this corner of the marsh reached a depth that could not sustain marsh vegetation or retain the sediment required to maintain the wetland.

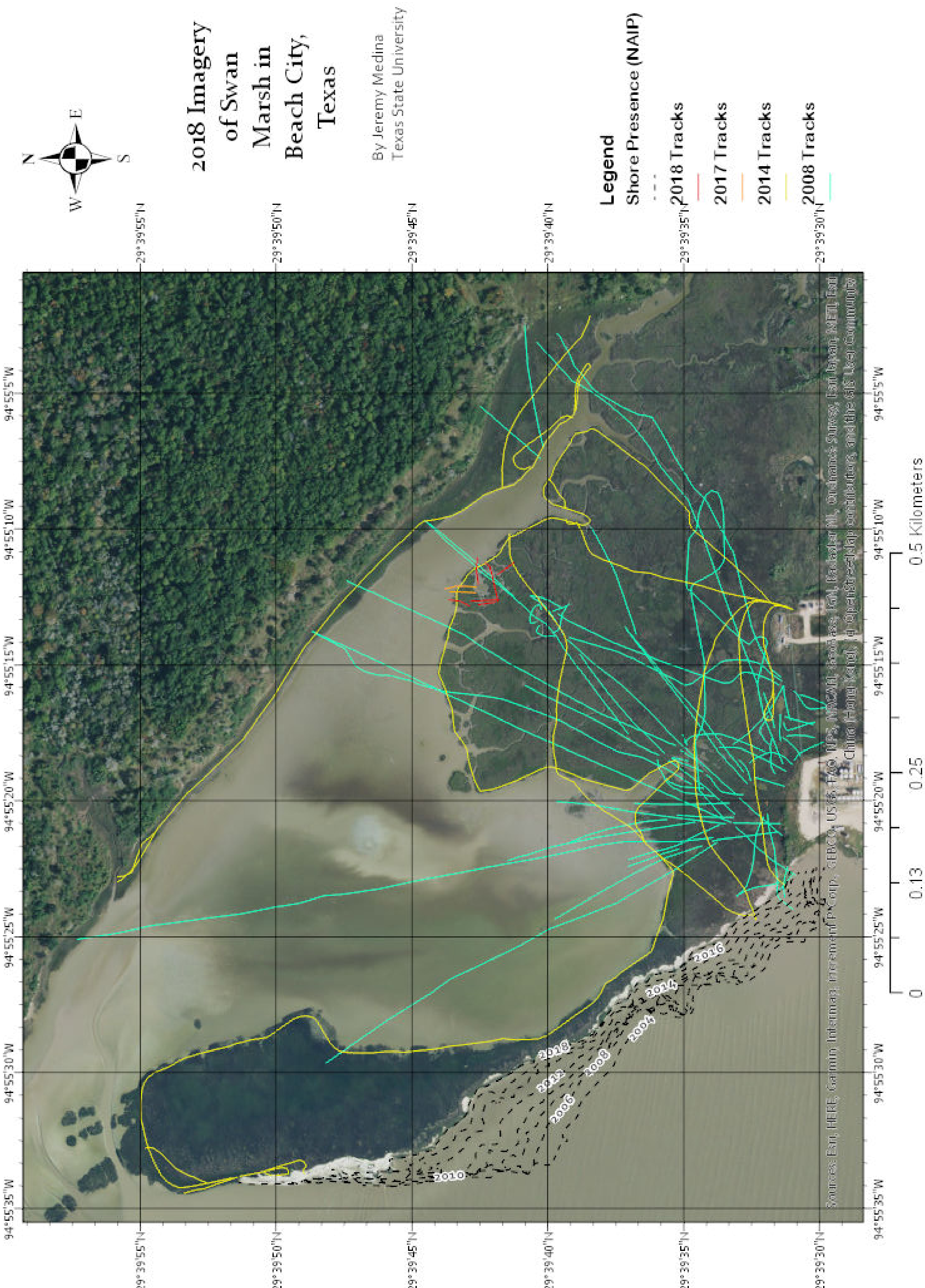

Figure 1: 2018 NAIP imagery of Swan Marsh with digitized shoreline position every year NAIP imagery was collected. Colored lines display the digitization of manmade tracks evident in Google Earth Pro imagery, with younger tracks in "warmer" colors.

As previously noted, Hurricane Ike made landfall on September 13th, 2008. Using the next available Google Earth imagery, it is possible to see gouges in the marsh where debris from the oil field were dragged through the wetland by storm surge. They appear to be cylindrical in shape, most likely tanks of some sort. By measuring with the built-in interface of Google Earth Pro, many of these tanks are recorded as large as 7 m and the 6.8 m storm surge of Ike carried these objects as after as 0.8 km through the marsh. Each of the objects left a visible drag gouge, but the next imagery showed a more striking picture, which was made during the cleanup phase. In order to retrieve these large objects, heavy machinery was operated through Swan Marsh, which was made evident by the numerous lines that appeared in pairs. These tracks webbed through the wetland and destroyed a significant portion of vegetation. The damage was particularly high where machinery seemed to have been driven in higher frequency during cleanup, near the oil field industrial site itself. More recently, in 2014, new tracks were created along with the implementation of some tubing-like material just off the shore from the marsh. The timing could suggest that these were measures to mitigate the impact of an oil spill which happened earlier that year. Main differences between these and the first set of tracks include the size and routes taken. The entity responsible for the 2014 tracks seem to have been more mindful of damage to the marsh. Their pathways lined the marsh along its perimeter rather than cutting through and they avoided crossing the same location multiple times in various directions and the vehicle used must have been much smaller by the apparent size of the tire tracks and the width between the parallel lines.

At the location of greatest loss, the salt marsh edge had retreated ~110 m between 2004 and 2018, as shown in **Figure 2**. Currently, some tracks closer to the water created in 2008 were in marshland that no longer exist due to erosion. However, it was also evident that the significant damage done to further upland vegetation, but still classified as salt marsh, had largely recovered by the 2010 NAIP image.

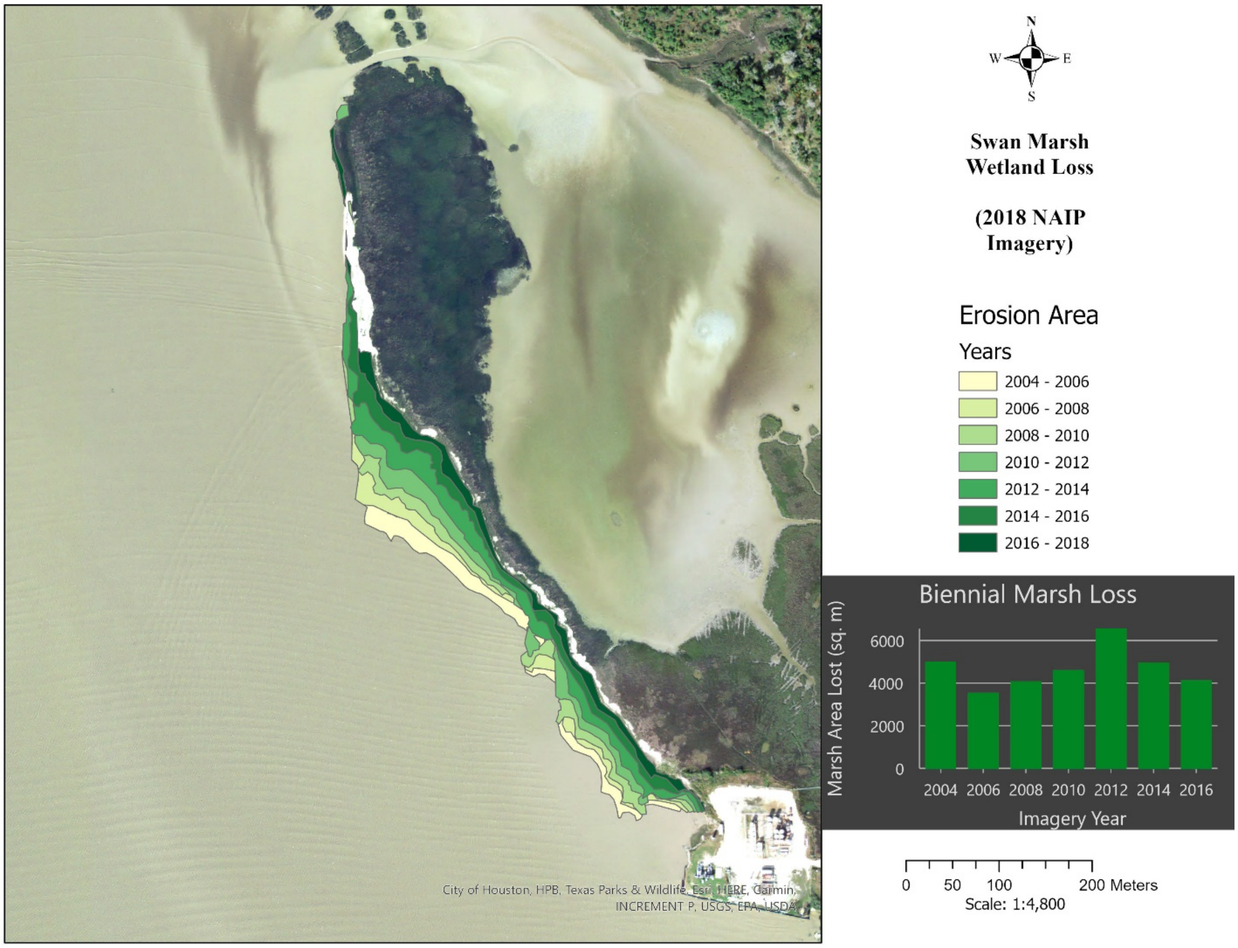

Figure 2: Focused extent of the outer arm of Swan Marsh. Area of Spartina wetlands loss was digitized and calculated, then displayed in a chart with the start year of imagery along the x-axis and m² of marshland lost along the y-axis.

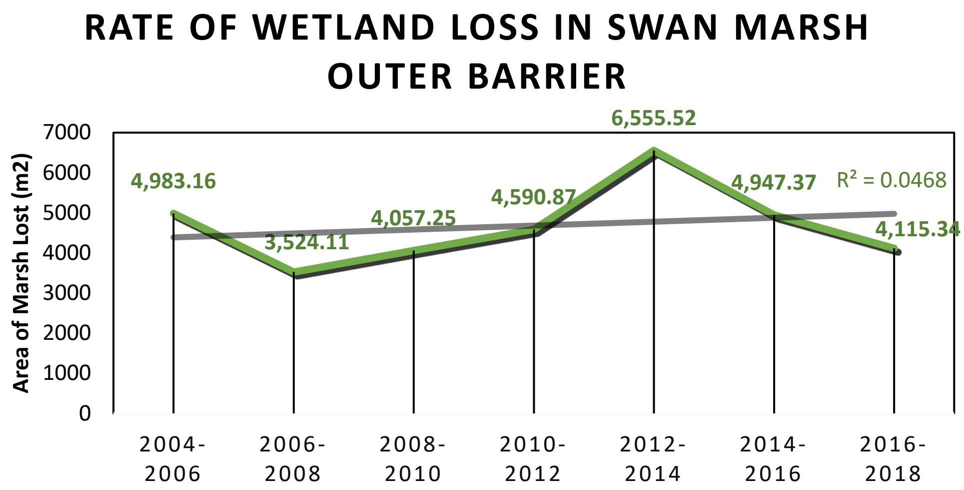

Figure 3: Amount of wetland lost in the outer arm of Swan Marsh every two years of NAIP Imagery.

Figure 3 was produced by calculating the area of wetland lost per year and exporting the resulting table. Each two-year period where NAIP imagery was collected are reflected to provide a basic representation of the story regarding the bayside barrier of the marsh. This area showed the most visible signs of wetland retreat, but how the deterioration progressed and when is what NAIP imagery can assist in answering. From the earliest collected imagery in 2004 to the most recent 2018 imagery, Swan Marsh has seen a loss of ~32,774 m^2, approximately 8.1 acres, of salt marsh in this segment of marshland alone. Between 2004 and 2006 the rate of loss starts relatively high, with ~4,983 m^2 of grasses lost. Then the degradation slows down between 2006 and 2008 where ~3,524 m^2 were lost, further thinning the bayside barrier. However, this period saw the lowest amount of marsh loss, as is evident by the area lost in the following two years, which included the Hurricane Ike event. A rise in erosion is expected during a hurricane event and redistribution of the sediment would take place throughout the bay system. Notably, though, the loss of *S. alterniflora* on the outer barrier is not as high here as it is in many subsequent periods. It is possible that the nutrients in redistributed sediment and influx of precipitation allowed the grasses to exhibit an increased resilience to the process of erosion. **Figure 4**, shown below, displays linked extents within Swan Marsh where the vehicle tracks were most dense (**Figure 1**). Based on the imagery, these tracks are devoid of vegetation, and are up to 0.5 m lower than the surrounding marsh. Notably, the smaller 2014 tracks are no longer visible in either images.

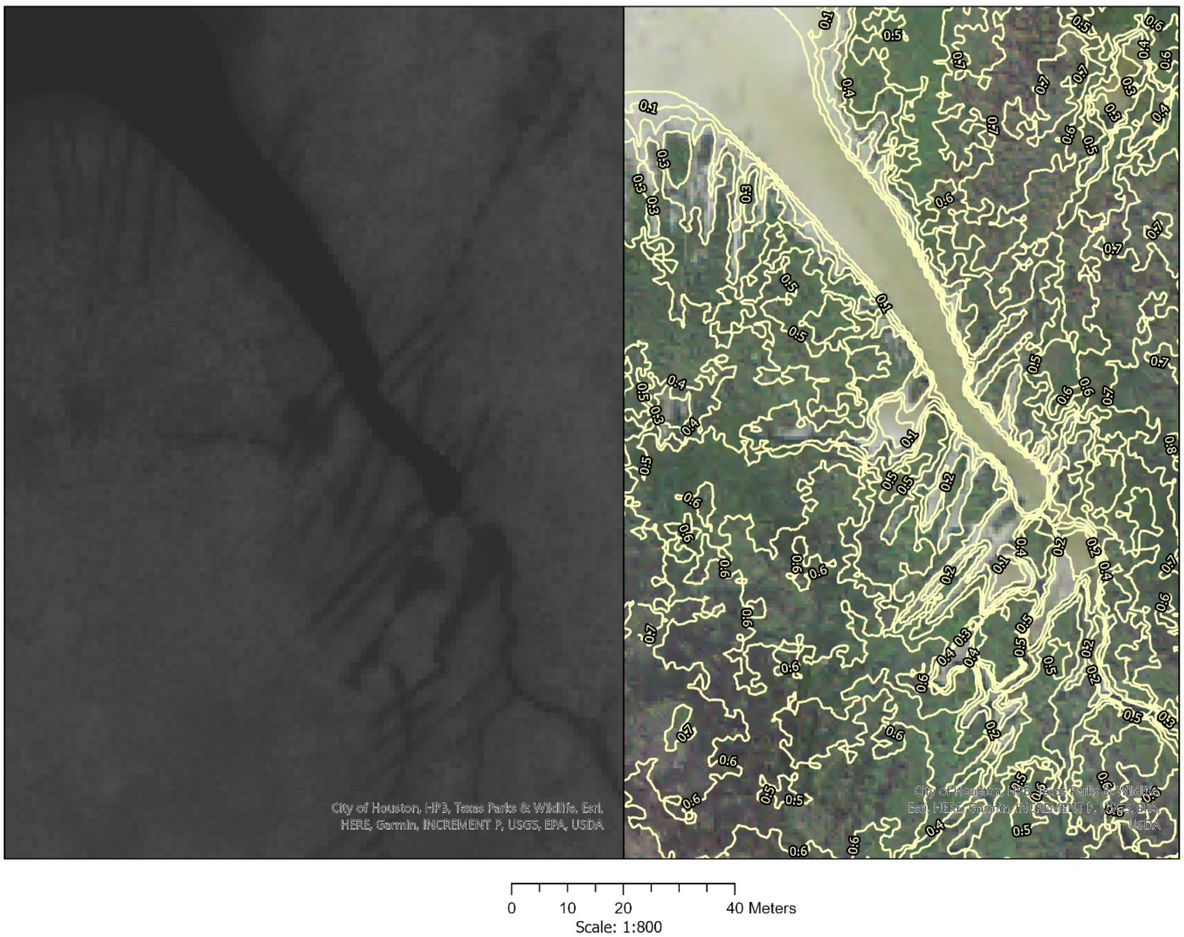

Figure 4: Linked extents of the Swan Marsh interior, displayed with 2018 LiDAR (Left) and 2018 NAIP imagery overlaid with 0.1 m contours built from the LiDAR (Right).

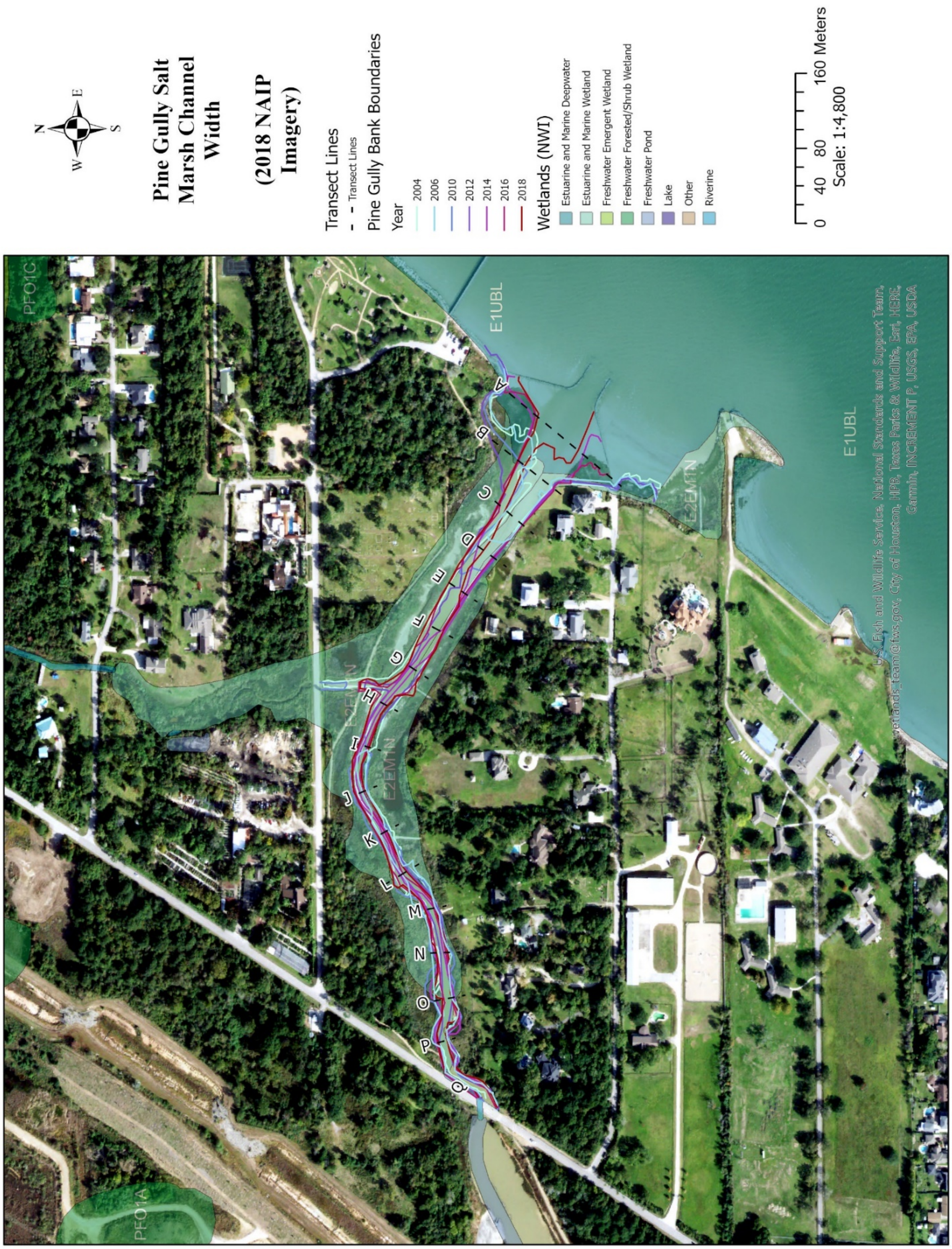

Figure 5: Map of Pine Gully with channel digitized according to each available year of NAIP Imagery. Shaded area represents recognized potential wetlands from the National Wetlands Inventory.

Table 1: Pine Gully channel width in meters along transects placed every 15.24 m (50 ft). R value calculated with channel mean over the course of years of subsidence.

Transect Label	2004	2006	2010	2012	2014	2016	2018		Transect Mean (m)
A	147.97	148.7	148.87	150.93	73.82	74.12	53.14		113.94
B	30.78	31.23	43.11	83.62	44.45	46.53	9.64		41.34
C	15.37	20.81	20.72	30.67	31.65	30.6	8.57		22.63
D	19.84	0	20.75	26.91	20.36	24.78	12.73		17.91
E	18.19	0	0	13.84	4.72	20.21	15.53		10.36
F	19.25	0	0	15.21	4.75	14.79	19.45		10.49
G	16.77	0	0	12.44	4.12	16.55	16.84		9.53
H	16.93	0	0	11.43	3.03	13.14	15.29		8.55
I	10.72	0	8.39	8.18	3.82	8.5	11.35		7.28
J	11.2	4.39	15.88	11.83	3.94	8.34	11.87		9.64
K	12.01	9.83	16.26	7.61	3.81	8.19	10.29		9.71
L	17.87	14.05	19.47	7.95	1.54	7.48	15.91		12.04
M	14.27	15.41	16.38	10.94	8.8	9.59	11.67		12.44
N	13.75	19.56	20.44	7.4	9.91	10.13	12.42		13.37
O	12.63	19.07	24.63	11.08	19	8.52	10.07		15.00
P	11.6	15.28	14.07	8.93	14.41	11.36	9.52		12.17
Q	5.3	6.42	5.06	5.81	8.7	9.8	7.45		6.93
Channel Mean (m)	23.20	17.93	22.00	24.99	15.34	18.98	14.81	r=	-0.53

Pine Gully has experienced a history of cyclic sedimentation and erosion, changing the hydrology of the waterway drastically over the range of years observed for this this project. This is illustrated in **Figure 5** with lines representing the banks of Pine Gully for every NAIP image available. Federal data in the form of the National Wetlands Inventory was utilized in this map to illustrate what the U.S Fish and Wildlife Service has identified as estuarine salt marsh in this site. As previously stated, water flow in the Gully was completely blocked by a sediment plug caused by ship-induced wave action forcing sediment suspended by longshore drift into the waterway where it would be deposited (T. M. Ravens & Thomas, 2006). This plug is present in the 2006 and 2010 imagery, and while the 2008 imagery was not available, it is reasonable to assume that the majority of sediment deposited here still remained during this time period. **Table 1** reflects this plug during these years with values of zero meters on the relevant transects. In the 2006 imagery, the plug is evident from Transect D through Transect I. This represents a length of dried-up gully stretched at least 91 m. Then in 2010 the plug has eroded back down to a length of at least 60 m (four transects, E through H). One of the most drastic shifts throughout the observed years is the decrease in channel with at the mouth of Pine Gully, recorded in Transect A. This can be attributed to the conservation efforts that took place in 2014.

The first year of NAIP imagery where the plug has been eroded to allow water to flow through the channel is 2012. Notably, this is the first year after the construction of a large drainage system just upstream of the roadway bridging the stream. Over the next 2-year period, the channel width constricted. The years following this period displayed a gradual shift of sedimentation towards the mouth of the channel. This change came after the implementation on a pair of jetties constructed to mitigate the ship-driven sedimentation that created the plug years prior. Over this period of time the marsh grasses propagated by the Marsh Mania event progressed well. Grasses elsewhere along the banks of Pine Gully, however, did not exhibit the same amount of growth.

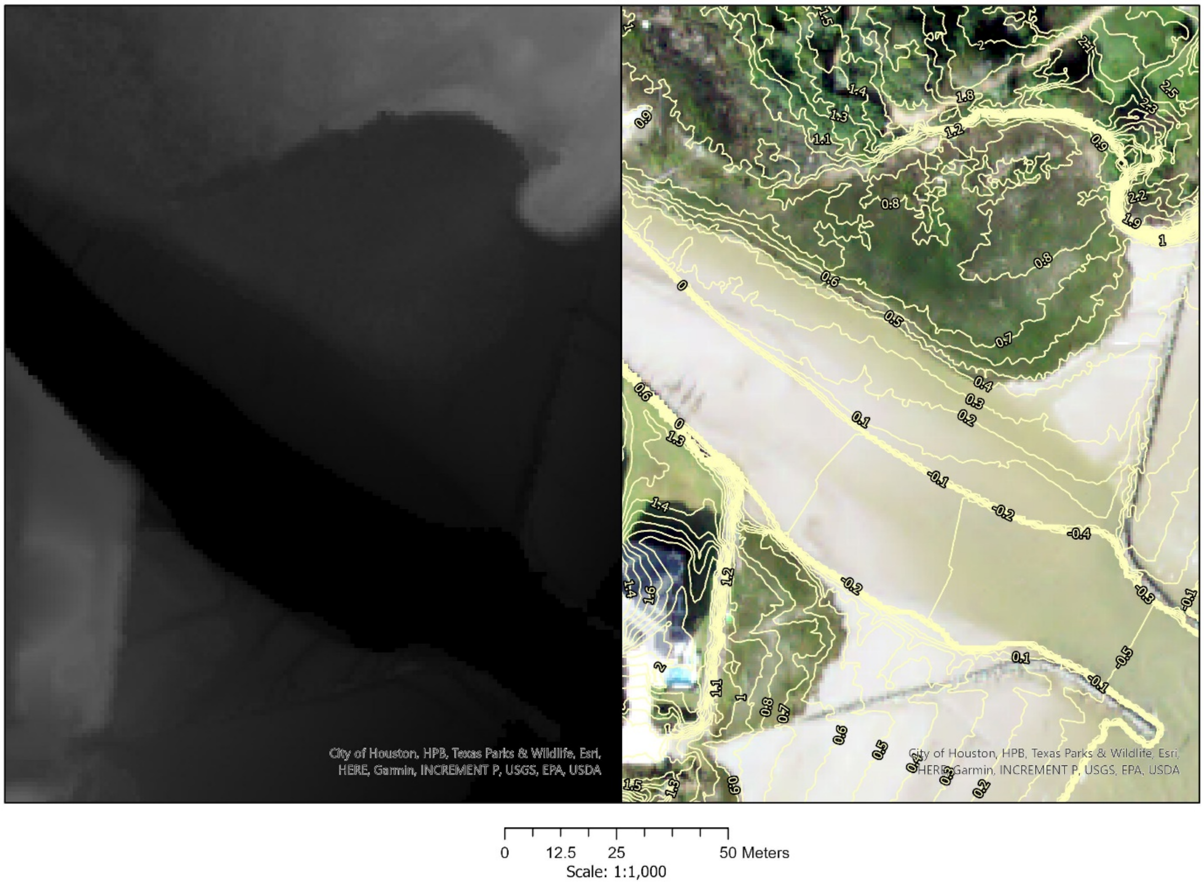

Figure 6: Linked extents of the mouth of Pine Gully, displayed in 2018 LiDAR imagery (Left) and 2018 NAIP imagery overlaid with 0.1 m contours built from the LiDAR (Right).

LiDAR imagery of the mouth of Pine Gully, shown in **Figure 6**, reveal the success of the Galveston Bay Foundation's Marsh Mania event, with the area of largest change being the growth of the planted *Spartina*. This patch of healthy vegetation lies as high as 80 cm above sea level, and the edge has a steep slope, consistent with a strong marsh shore. The contours created also reflect the accumulation of sediment as a low slope between the marsh and the jetties. Notably, though, the marsh vegetation edge along the channel has maintained a steep slope.

Discussion:

While subsidence has been recorded in both sites addressed by this study, Swan Marsh is displaying trends of being an erosional environment while Pine Gully is a depositional one. This is contrary to the trend that subsidence would be the primary driver of erosion in these marshes, seen elsewhere along the coast of Galveston Bay. Pine Gully subsides at approximately twice the rate as Swan Marsh, yet Swan Marsh is the one experiencing greater loss. This supports the findings by Al Mukaimi that increased accretion at this Pine Gully location offsets the effect of subsidence (Al Mukaimi et al., 2018). However, the differences arise when considering the stories of each of the salt marshes in question.

Because the primary use of the Pine Gully system is drainage from municipal areas in Seabrook, local construction shapes the hydrology and of the town which in turn affects the sedimentation and erosion along this salt marsh. In 2011 when the industrial drainage system was established, the NAIP imagery showed a drastic change in the depositions and erosional patterns of the Gully. The same is true with the establishment of the jetties at the mouth of the Gully, which similarly migrated sedimentation to the mouth and promoted the growth of the *S. alterniflora* planted by the GBF Marsh Mania event. Continued accretion of this type could lead to other problems, however. NAIP imagery as of 2018 reflects the water flowing out into Galveston Bay as sediment laden, displaying a brown plume of suspended material flowing along the bay's shoreline via longshore drift. If deposition at the mouth of Pine Gully continues, it is possible that another plug could form, similar to the one that developed in 2005. While smooth cordgrass usually provides shelter and spawning grounds for estuarine wildlife, it could not sustain this task if access from the Bay is restricted.

Swan Marsh tells a different story. The environment here is erosional and occurs mostly in the direction of the salt dome oil field located to the Southwest of the marsh. In the NAIP imagery for 2010 we see a major change in the geomorphology of the marsh. By this point, according to HGSD projections, the marsh had subsided by about 3 cm. This is not the only human-derived effect that is driving erosion at this location, though. Judging by the elevation reflected by the LiDAR DEM, it is evident that the vehicle tracks created over the course of 14 years have had an impact as well. While salt marshes are capable of natural recovery, this gouging of vegetation and sediment by vehicular action has left lasting damage to the marsh. The magnitude of visible damage in the 2018 imagery is not purely correlated by age of the tracks. In fact, the oldest tracks, created in 2008 display some of the most evident changes in elevation according to the 2018 LiDAR raster, while the next set of tracks are much less evident. This could be attributed to the size of machinery used that created the tracks. The purpose of the first use of machinery in the marsh was in response to hurricane Ike scattering large tanks and other debris through the wetland. The task of retrieving that equipment most likely required heavier machinery than what was used in 2014. In addition to this, the organizations in charge of operating within the marsh in all cases evident in the 2018 imagery display distinctly different patterns of transport through the marsh. During the Hurricane Ike cleanup in 2008, vehicle tracks appeared in straight lines fanning out from the CenterPoint Oil Field to the location of an object that was deposited by Ike. This pattern demanded increased traffic near the oil field, where all paths converge. In the Google Earth imagery, this resulted in a significant area of vegetation destroyed to the point where pairs of tracks were not recognizable, and thus could not be digitized on the map. The following occurrence of tracks (2014), which appeared with the presumed oil spill equipment, were created along the edges of the marsh. These tracks were smaller in size, suggesting the use of a light all-terrain vehicle, and the organization in control of this operation took care to reuse pathways, as shown in **Figure 1**. Most of the 2014 tracks are no longer evident in the marsh and do not display a great change in elevation according to LiDAR data. The tracks produced in 2017 onward appear localized in one specific area. In the Google imagery, some tracks through the bare sediment are visible, leading to a location where more *S. alterniflora* plants appear. It is highly likely that the use of vehicular transport at this time was to transport the plants to a staging ground where they were then distributed to the less accessible points of the marsh. Something like a trailer could have been used, which is more massive than an ATV or personal vehicle, yet lighter than heavy industrial machinery. The area where these tracks appear resulted in the erosion of marshland in a 34 m diameter basin, and a loss in elevation of 0.4 m. All of these operations suggest a direct correlation between vehicle dimensions and age of tracks with the erosion that follows. In all cases the appearance of these tracks have resulted in a decreased slope and an increase in surface area that is potentially open to the tide.

Conclusions:

By observing the changes these wetland environments experienced with high resolution aerial imagery, it is clear that they are highly responsive to the outside effects of the nearby development. NAIP imagery in conjunction with LiDAR is effective in tracking and displaying erosional changes in salt marsh environments. While the use of machinery and vehicular transport within a salt marsh are sometimes necessary to bolster the health of the wetland, care must be taken to ensure the process of operating within the marsh is not more harmful than the benefits produced by them in the long run. This is especially evident in Swan Marsh where machinery has been used multiple times over the 14 observed years. Depending on the magnitude of the work performed and the care taken to reduce the number of paths created through the wetland, long term erosional impacts have been caused by reducing the elevation and vegetation at the marshes edge where vehicles travelled. This is where the resistance to erosion of the marsh edge will be most compromised.

The future of Swan Marsh is in a precarious position. While most of the inner marsh and the constructed marsh on the northmost point of the outer barrier have seen little loss, the majority of the natural length of that outer barrier is degrading at a pace that the current manmade marsh has not been positioned to stop. Another concerning sign shown in the NAIP imagery is the aftermath of the cleanup following Hurricane Ike. As of the 2018 imagery, many of the vehicle tracks left 12 years prior are still devoid of vegetation, and significantly lower than the rest of the marsh. If erosion progresses to the point where the outer barrier is deteriorated completely, the inner marsh will become exposed and most susceptible to sea level rise, subsidence, and wave action. The unvegetated scars left by vehicle use are the points of lowest erosional resistance, and therefore would erode more rapidly if exposed. In areas where the tracks are highly concentrated, erosion exacerbating these weaknesses could result in rapid loss like the rates seen on the shoreline by the oil facility.

It is often difficult to identify predominant causes of excessive erosion or deposition occurring at any given location. There are innumerable factors that could play a role in changing the geologic environment of a salt marsh, and this is especially true for a marsh that neighbors urban development. Further imagery is required of Pine Gully to determine the state of the vitality in this wetland, although the narrowing of the mouth of the Gully from the planted *Spartina* through conservation efforts is a promising sign. At the time of this project's analysis, 2020 NAIP imagery had not been made available to the public. Such imagery could give a better idea as to the current sedimentary state of the environment.

In both cases of wetland sedimentation and erosion, this GIS approach can be used to better inform the communities that reside nearby on the success of revitalization projects or the effects that anthropogenic or natural events have had on the livelihood of the marsh. Digitization of features across multiple layers of imagery can be a lengthy manual process but it is a viable method for small scale areas like these to produce useful figures for conservation analyses. Data like this can be incorporated into GIS web applications, allowing dynamic customization of presentation tools for wetland conservationists. Coastal cities and large businesses alike should strive to respond to the visual cues being shown by these environments in a responsible manner. The benefits provided by salt marshes is well-documented, and cataloging the changes they experience can be of use in urban planning and conservation efforts.

References

Al Mukaimi, M. E., Dellapenna, T. M., & Williams, J. R. (2018). Enhanced land subsidence in Galveston Bay, Texas: interaction between sediment accumulation rates and relative sea level rise. *Estuarine, Coastal and Shelf Science, 207*, 183-193. doi:10.1016/j.ecss.2018.03.023

Black, K. P., Kurian, N. P., Mathew, J., & Baba, M. (2008). Open Coast Monsoonal Beach Dynamics. *Journal of Coastal Research, 241*, 1-12. doi:10.2112/04-0289.1

Delaney. (2000). Comparison of physical characteristics between creates and natural estuarine marshes in Galveston Bay, Texas. *Wetlands Ecology and Management*, 343-352.

Hawkes, A. D., & Horton, B. P. (2012). Sedimentary record of storm deposits from Hurricane Ike, Galveston and San Luis Islands, Texas. *Geomorphology, 171-172*, 180-189. doi:10.1016/j.geomorph.2012.05.017

Jafari, N. H., Harris, B. D., Cadigan, J. A., & Chen, Q. (2019). Piezocone penetrometer measurements in coastal Louisiana wetlands. *Ecological Engineering*, 338-347.

Kolker, A. S., Allison, M. A., & Hameed, S. (2011). An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. *Geophysical Research Letters, 38*(21), n/a-n/a. doi:10.1029/2011gl049458

Kulawardhana, R. W., Feagin, R. A., Popescu, S. C., Boutton, T. W., Yeager, K. M., & Bianchi, T. S. (2015). The role of elevation, relative sea-level history and vegetation transition in determining carbon distribution in Spartina alterniflora dominated salt marshes. *Estuarine, Coastal and Shelf Science, 154*, 48-57. doi:10.1016/j.ecss.2014.12.032

Lopez, M., Baeza-Brotons, F., Lopez, I., Tenza-Abril, A. J., & Aragones, L. (2019). Factors influencing the rate of beach sand wear: Activation layer thickness and sediment durability. *Sci Total Environ, 658*, 367-373. doi:10.1016/j.scitotenv.2018.12.211

Lynn Donelson Wright, C. R. N. (2019). *Tomorrow's Coasts: Complex and Impermanent* (C. W. Finkl Ed. Vol. 27). Cham, Switzerland: Springer.

Lyons, J. M., J. (1995). *Wetland and Environmental Applications of GIS* (1 ed. Vol. 1): CRC-Press.

Ravens, T. M., & Thomas, R. (2006). *Ship-wave induced sediment transport in tidal creeks.* Paper presented at the 6th International Conference on Environmental Problems in Coastal Regions including Oil and Chemical Spill Studies, COASTAL ENVIRONMENT 2006, CENV06, June 5, 2006 - June 7, 2006, Rhodes, Greece.

Ravens, T. M., Thomas, R. C., Roberts, K. A., & Santschi, P. H. (2009). Causes of Salt Marsh Erosion in Galveston Bay, Texas. *Journal of Coastal Research, 252*, 265-272. doi:10.2112/07-0942.1

Youn, D., & Park, Y. H. (2018). The Application of Mathematical Analysis to Examine the Beach Erosion along the Upper Texas Coast. *Journal of Coastal Research, 85*, 846-850. doi:10.2112/si85-170.1

Zhang, Y., Xiao, X., Jin, C., Dong, J., Zhou, S., Wagle, P., . . . Moore, B. (2016). Consistency between sun-induced chlorophyll fluorescence and gross primary production of vegetation in North America. *Remote Sensing of Environment, 183*, 154-169. doi:10.1016/j.rse.2016.05.015

Jeremy Medina

Department of Geography
601 University Dr.
Texas State University
San Marcos, TX 78666

15119 New Hastings Dr
Houston, TX 77095-2923
Tel: (512) 619-8229
Email: jqm4@txstate.edu

Education:

Current **MAGeo GIS Graduate Student**, Texas State University, Focus on GIS applications in coastal geology, Expected Graduation December 2021

B.S. in Ocean and Coastal Resources w/ Geology minor, Texas A&M University, Galveston, TX, December 2016

Research Experience:

Marine sediment core extraction in Galveston estuarine system & CHIRP sub-bottom profiling to identify coastal sedimentary structures.

Pb 210 analysis of marine sediment samples using Hotblock method to observe differences in sedimentation rates in Copano Bay at different intervals from river delta.

Numerical modelling of Eastern Canadian Shield rift system crust.

Certifications:

TAMU RAM General Safety Training, 2015

Software:

ESRI ArcMap & ArcGIS Pro, ArcGIS Enterprise and Online, Microsoft Office products (Excel, Word, Powerpoint), Google Earth Pro, Adobe Illustrator, Python, Linux, Generic Mapping Tools (GMT), Erdas

Work Experience:

2020-Present **GIS Technician – EHRA Inc. Engineering**

Provides GIS support to civil engineers in various projects through the creation and upkeep of GIS features, geodatabases, webmaps and web applications. Produces map exhibits for potential tracts for analysis by engineers.

2018-2020 **Graduate Assistant - Texas State University, Department of Geography**

Assisted in research by mapping geologic structures using various mapping tools for numerical modelling. Generated features and maps from ESRI Arcmap, GMT and other geographic software.

2017-2018 **Scheduler & Administrative Aide - Texas State Senate – Office of Sen. Larry Taylor**

Coordinated meetings, legislative obligations and travel arrangements for an elected public official. Functioned as bookkeeper for travel finances and maintained office supplies. Assisted in facilitating the Joint Interim Committee hearing to Study the Coastal Spine Project in October 2017.

2015-2016 **Research Assistant – Texas A&M University at Galveston, Department of Marine Science**

Worked alongside graduate students to collect, record and analyze coastal sediment samples in a variety of methods. Performed technical processes in geology labs on campus.

References:

Dr. Suzon Jammes, Senior Lecturer, Texas State University, Department of Geography, 601 University Dr., San Marcos , TX 78666, Tel: (512) 245-0377, Email: s_j143@txstate.edu

Dr. Timothy Dellapenna, Associate Professor, Texas A&M University at Galveston, Department of Marine Science, 200 Seawolf Parkway, Galveston, TX 77554, Tel: (409) 740-4952, Email: dellapet@tamug.edu