The Use of Site Suitability Analysis to Model Changes in Beach Geomorphology Due to Coastal Structures

by

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To my family

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List of Abbreviations

DEM	Digital Elevation Model
DN	Digital Number
GOM	Gulf of Mexico
NIR	Near Infrared
NOAA	National Oceanographic and Atmospheric Association
SSC	Suspended-Sediment Concentration
SWAT	Soil and Water Assessment Tool
USGS	United States Geological Survey
VNIR	Very Near Infrared

Abstract

Understanding how human needs and innovations affect the environment plays a fundamental role in ensuring the longevity of our earth's natural features. While expansion and urbanization help to enlarge human influence, and allow for the growing human population, special care must be taken to maintain a mutually beneficial relationship with earth systems and physical phenomena. This relationship between growing population and environment can be seen as more and more people make their way to the coastlines of the world to support livelihood as well as recreation. However, living along the coast sometimes requires modifications to ensure the protection of those deciding to live there. This study examines the management of one such relationship between the everchanging coastline of Galveston Island and the Galveston Seawall set as the first line of defense against storm surges and rising tides. While seawalls are meant to protect coastal populations form extreme flooding events and hurricanes, the long-term result of a seawall is often the erosion of the natural beaches which those living along the coast have come to enjoy. Galveston Island represents a city whose seawall has stood for over a hundred years, built just after the Great Storm of 1901. This spatial study analyzes the coastal conservation and protection provided by the Galveston Seawall and Groins. Using sediment supply, beach area, landuse and coastal velocities, a site suitability analysis was generated showing locations prone to sediment deposition and creating a model for how these features interact with the gulf shoreline. From the results, it is recommended that local geography and earth systems be analyzed prior to the construction of coastal structures to avoid costly unforeseen coastal changes in the future.

Chapter 1 Introduction

Galveston Island represents a unique position in the study of human effect on the environment, and the costs associated with the protection of the city. The presence of the Galveston Seawall has increased the rate of erosion of the beach and the transport of much of this sediment down shore to the west. This process has been closing the channels at the west end of the island with the sediment which is being transported from the seawall beaches. Sections of Galveston’s beach have been sacrificed in order to maintain the protection afforded by the seawall, and large granite blocks have been used to prevent undercutting, but these interventions do not conserve the beach. However, being west of the mouth of the Mississippi River puts Galveston in a location where the silt and clay from the river accumulate on the shore, giving it a brown appearance and ultimately adding a new supply of sediment to Galveston’s sediment budget. Because the seawall cannot be removed to allow the sedimentation pattern to return, structures called groins have been created on the seaside of the seawall to trap suspended sediment being moved as a function of longshore drift.

Tracking the movement and volumes of sediment transported to Galveston is key to understanding what options are available for natural sediment supply. GIS and remote sensing data and techniques offer a way to analyze and process Landsat (multispectral satellite) data to analyze suspended sediment losses and accumulation along the Texas coastline. These data can then be digitized into vector format to calculate volumetric sediment sources. From there, the path along which the sediment flows can be determined. This information can be used to better understand the sediment budget available for this section of the Texas coastline.

1.1 The Study Area

Galveston Island's geography is also defined by a series of coastal structures meant to protect and preserve the coastline of the City of Galveston. The Galveston Seawall runs parallel to the coastline along the majority of the City of Galveston. Sections of the beach are sacrificed for the safety of the inhabitants, mostly on the western end of the seawall, away from major tourist destinations. Figure 1A shows the western end of the seawall, where large granite blocks are placed to prevent the undercutting of the seawall, no beach is preserved here. Along the majority of the seawall, structures called groins are present to naturally trap beach sand and sediment before it is washed away by the currents and tides. An example of one can be seen in Figure 1B, the structure is made of granite blocks that weather much more slowly than other rock types (McGowen, 1977).

The east end of Galveston creates the western edge of the channel that allows ships to pass in and out of Galveston Bay, and the Trinity Bay, as well as up into the Houston ship channel. To maintain this opening, one more coastal structure, known as a jetty, was constructed to hold open the mouth of this channel (Figure 1C). This channel naturally moves and closes due to the deposition of sediment on the east end of Galveston, but the jetties push the sediment out and around, maintaining the Channel opening. Galveston Island sits just off the Texas coastline around 40 miles south of the Houston area. It is comprised of the City of Galveston on the East half if the island, and Jamaica beach and wetlands on the west side. Geographically, Galveston is a barrier island with Galveston Bay to the north, channels from the Houston area to the east and west, and the Gulf of Mexico (GOM) to the south. Figure 1 show a Google Earth image of

Figure 1A: Seawall

Figure 1B: Groin

Figure 1C: Jetty

Figure 1: Photographs of the coastal structures defining Galveston's coastline taken by Michael Thibodaux

Galveston island and its relationship with the Texas coastline and proximity to the Houston area. Figure 2 also gives a preliminary look at the major geographic features that define the shape of the Galveston coast, mainly the channel between Galveston and Bolivar Peninsula which transports significant amounts of sediment out into the gulf.

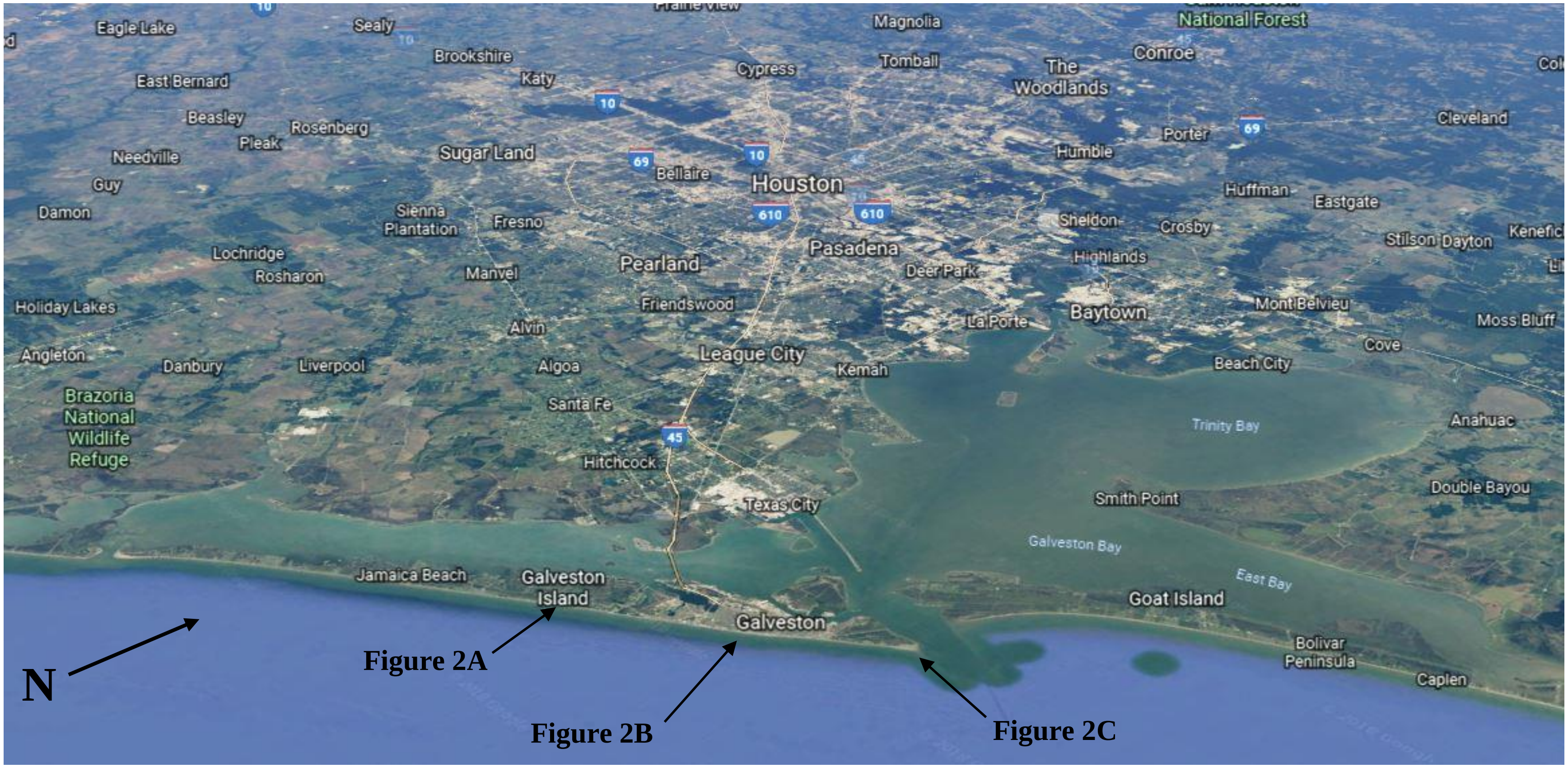


Figure 2: Google Earth view of Galveston Island and the Greater Houston Area. Locations are given for the pictures taken at the three different figure points showing the coastal structures. Google Earth (2018)

1.2 Motivation

After the great storm of 1901, Galveston Island was left mostly destroyed and completely vulnerable to future hurricanes and catastrophes. The Galveston Island authorities then decided to build a seawall to protect the inhabitants from natural disasters such as hurricanes. Though this greatly reduced the risk of hurricane damage to the city, it left the shoreline vulnerable to erosion between the cement wall and the longshore drift from the Mississippi River. The seawall created an erosional boundary that lead to longshore drift eroding away the beach, leaving the island in a position where it had to physically rebuild its beaches. Over time, structures known as groins, shown in Figure 2B, were used to reduce the erosion due to longshore drift by catching sediment being carried away from the output of the Mississippi River.

Using GIS applications, an analysis of the attributes that pertain to sediment erosion and longshore drift can greatly advance the way we approach coastal problems in the future. This quantifies information that is then used to spatially represent sediment loads and erosional rates along the Galveston seawall, and the western edge of the seawall looking at both areas with and without a seawall. This study also contributes temporal information on the long-term changes associated with the erosional and depositional locations on the Texas coastline. From this, and the statistics of erosion versus sedimentation, graphic models can be designed to visually represent sediment deposition capture from the Mississippi River and all the coast east of the seawall to the area directly in front of and west of the seawall.

The motivation for this study is twofold. First, to assess the effectiveness of the groins along the Galveston seawall to determine whether they are helping or hindering the natural sediment cycle. Second, this study seeks to integrate the disciplines of GIS, remote-sensing, and earth science, allowing the construction of a coastal database to house all the spatial data and track changes with new developments. For this purpose, the use of GIS software is not merely a tool, but the primary platform for analysis in this study. All of the information and data is derived from aerial photography, spatial attributes, multispectral data, and vector represented data.

This analysis looks to answer the question of how to balance the protection of natural features and human habitation at the same time for current features, and understand the changes that would occur with new features. Many attempts have been made to protect a coastal population at the expense of the environment around it. Exploring new ways to remotely track sediment flow and erosion eases the field work of scientists and support the temporal modeling of shoreline features under specific circumstances.

The results of this research offer insight on how GIS functions can be used to track and assess the changes in coastline geomorphology due to coastal structures and the major storm events they protect against. This research hopes to serve as a model for planning and managing the effects of coastal structures on the coastal environment. It also aims to create a model that allows for the analysis of the sediment budget through the comparison of accreting to eroding areas.

1.3 The Sediment Cycle and Coastal Structures

For the purposes of this investigation, a beach is the area of loose, unconsolidated sediment between the swash zone (area that is covered by water during high tide, and revealed during low tide) and the vegetation line. Beaches are the beginning of a longer cycle of consolidating small fragments of rock that wash down through streams and rivers from the mountains and lands of the shore that are deposited wherever the water takes them. The process begins with the weathering of mountains and outcrops, breaking the rock face into pieces. These pieces must then travel by falling, blown as dust, or washed away by rain into a nearby stream. The sediment can then be transported by stream, tributaries and rivers into larger bodies of water, like the Gulf of Mexico. Once out in the large body of water, currents bring the sediment back to land beginning deep on the coastal shelf and rising all the way up to the beach. Over millions of years of burial and heat, these sediments reform into sedimentary rock deep within the earth. Finally, as a result of a process known as subduction, dense oceanic plates "subduct" or move under continental plates, causing the land on the continental plate to lift and surface those sedimentary rocks through uplift, creating the mountains and outcrops and restarting the cycle (Boggs, 2012).

This means that coastlines are constantly changing and are one of the few natural features of the Earth that can change significantly in as few as 20 years. Urbanization has influenced this cycle in two major ways, by damming the rivers that transport the sediment, and by barricading the coastlines with seawalls to act as a buffer for storm surges from hurricanes. This causes a decrease in the amount of sediment available for the building of beaches, effectively moving the coastline back. When this movement encroaches on a solid barrier like a seawall, it begins to wash away any sand and sediment, eventually undercutting the seawall and leading to seawall collapses and failures.

The introduction of groins, long structures set perpendicular to the seawall made of hard rocks like granite, act as a way to capture the moving sediment to rebuild the beach to combat undercutting without having to totally rebuild the beach or completely block off the beach. Jetties are another coastal structure meant to stop the natural opening and closing of channels and merging of peninsulas to allow for sea travel from bays and rivers out into open water (Figure 3). These are much like groins and can help build beaches but can also block and redirect sediment out away from the beach, as can be seen on Galveston Island.

1.3.1 Longshore Drift

The most prevalent environmental mechanism acting on the Texas coastline is a phenomenon known as longshore drift. Longshore drift is the movement of sediment or other suspended materials down the coastline as a result of the angular current. The movement along the coast is created when the current direction occurs at an angle to the coastline. When the tidal ebb occurs, sediment from the beach is pulled back into the water, when the tidal flow occurs, that suspended sediment gathered from the ebb is deposited down the coastline, seen in Figure 3. This motion is what specifically causes barrier islands to move and channels to close, and is a natural part of the sediment cycle, as stated above.

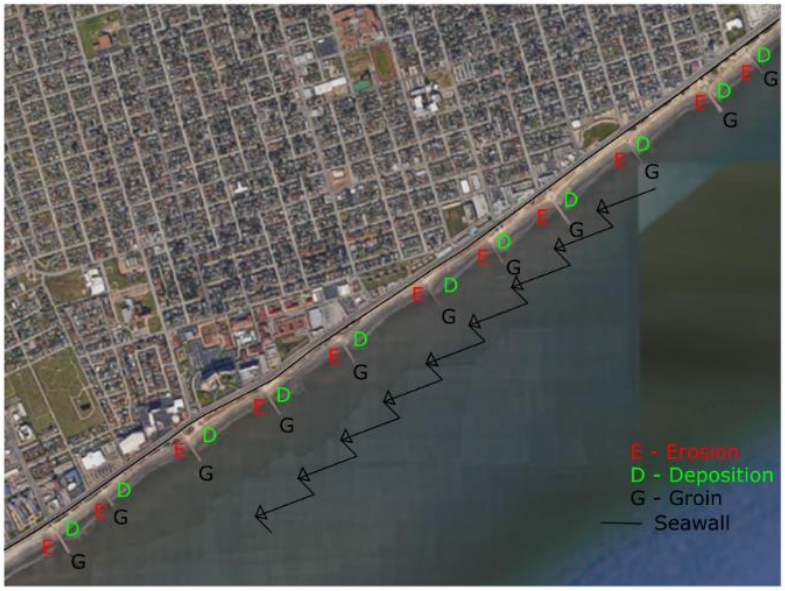


Figure 3: Google Earth image of part of the Galveston Seawall showing how longshore drift moves sediment along the coast to the south-west, and how the groins affect the sediment movement. Google Earth (2018)

What is unique about the longshore drift of Texas is that there are many tributaries and rivers influencing the longshore drift and adding other sources of suspended sediment to the coastal environment. These sources include the Houston Ship channel, the Trinity River, and the Mississippi River. Each of these sources expels large amounts of sediment and water into the natural current of the Gulf of Mexico, disrupting the natural eastward movement of the beaches, and transporting the silts and muds form the Texas heartlands into the Gulf. If is these influences that lead to the belief that supply of deposition is not the problem creating the heavy offset in erosional rates, but some factor of the coastal structures and Galveston's geographic location.

1.4 Nourishment projects

The importance of understanding how Galveston Island is affected by its geographic location and human interaction can be seen in the cities' need for beach nourishment projects. According to an article written by Mary Beth Bassett, the public relations and tourism coordinator for the City of Galveston, the island is currently undergoing a $19.5 million beach expansion project to combat the current effects of tidal and longshore erosion along the beaches. Projects like this one have been in place since 2015, and, to date, $44 million have been spent replenishing the Galveston beaches (Bassett 2017).

Though nourishment projects are a temporary solution to the erosional problem caused by the combination of tides and marine structures, the island would benefit from a long-term solution to ensure the health of the beaches, without endangering the coastal population. Beach nourishment projects are costly and time consuming, constraining much of the cities resources into finishing the project before the tourism season begins. In order to determine a solution, a more thorough understanding of the coastal geography and natural processes along with the needs of the population is required to find a middle ground for both protection and preservation. Creating connections between these key elements could lead to saving millions of dollars in beach nourishment funds, while finding a way to work co-dependently with the coastline.

1.5 Thesis Organization

The remainder of this thesis consists of four chapters. Previous studies in the field of coastal conservation and coastal management and vulnerability are discussed in chapter 2. The methodology for the gathering and processing of the required data is described in chapter 3. Results of the study as well as final analytical maps and data layers can be found in chapter 4. Finally, the resulting management model and recommendations from the study, as well as the conclusions, are found in chapter 5.

Chapter 2 Related Work

Increasing amounts of research are being calculated to the Texas coastline to model future effects of erosion on the growing number of people choosing to live close to the beaches. This includes using different geospatial and remote sensing techniques to assess the volumetric quantity of sand along the Texas coastline. The resulting studies give an indication of areas that are losing or gaining sediment due to the natural processes of the Gulf of Mexico. However, those studies consider the Texas coast as all uniform beach, providing little to no mention of the Galveston Sea wall, the Galveston Groin Fields, or the jetties that have re-routed the Brazos River. These man-made structures play a key part in the assessment of the erosional and depositional region along the Texas coastline, and affect many of the regulations and natural phenomenon related to beach conservation. This study uses the geomorphology of the Texas coastline along with the urban installments meant to combat the destruction of property to assess the impact these features have on beach erosion.

2.1 The Coastal System in GIS

GIS applications offer new and expansive research opportunities when evaluating coastal systems, especially for the implementation of human development and coastal geography. Mapping coastlines and the complex features that make up its system have been constantly progressing, looking for new technologies to expand upon human understanding and interpretation of the coastal zone. In the past, researchers began with the simple vector models of the coastline and showed the temporal change from year-to-year or before and after major events (Cowell and Zeng, 2003). This format of mapping coastline changes, while being a simple and effective for depicting the ability to use simple GIS applications, does not capture all the complexities associated with the coastal zone. This includes features such as tides, mean sea level change, and erosional changes. To fully understand these features and effectively map them and their uncertainties, raster datasets and DEM's are more appropriate to use and analyze as fields rather than objects (Cowell and Zeng, 2003).

When collecting data related to sediment budget and coastal geomorphology, satellite imagery and the ability to use spectral bands and reflectance signatures to map suspended sediment in the coastal waters and being transported by local streams and rivers. Lodhi and Rundquist (1998) performed an experiment to determine if different suspended-sediment concentrations (SSC) could be classified using a spectrpradiometer. Their findings were successful and opened a new realm of research into the transportation of sediment and pollutants through the natural eddies and currents of hydrologic systems. This finding allows for the classification and understanding of the movement of not only the sediment supply but also gave a visual representation of the flow directions to and around the coastline (Figure 4).

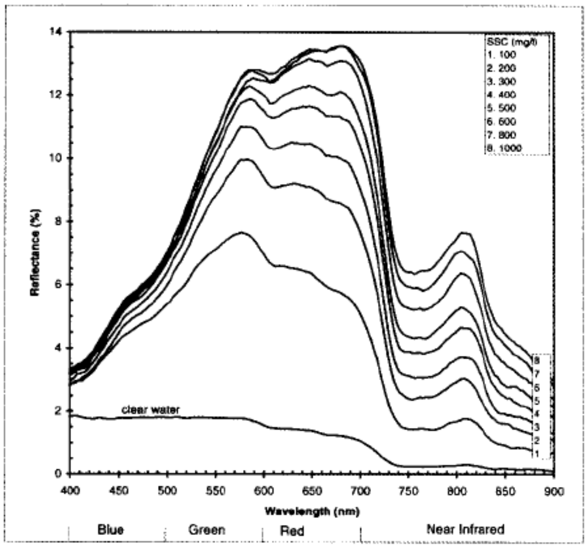


Figure 4: Spectral reflectance of water with varying levels of suspended sediment concentration (Lodhi and Rundquist, 1998)

Later in 2002, Schmugge and Kustas (2002) developed a more precise method of predicting suspended sediment in mg/L using remotely sensed data and very near infrared (VNIR) band data. The results of the study by Schmugge and Kastus can be seen in Figure 5, with a range of suspended sediment volumes and their respective reflectance values.

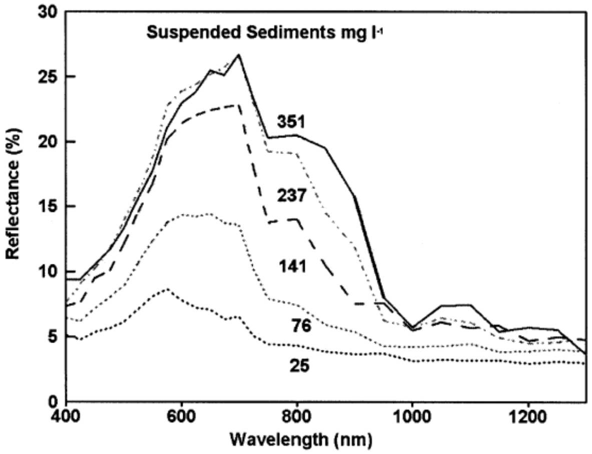


Figure 5: The relationship between reflectance and wavelength as affected by the concentration of suspended sediment (Schmugge and Kustas, 2002)

Tracking sediment transportation requires many initial data layers and an understanding of how these layers relate to the analysis of a normal sediment budget versus a human altered one. In a study of the sediment transportation into Galveston Bay and Matagorda Bay, both of which are included in the analysis of this project, Omani (2012) emphasized many of the datasets required for the analysis of sediment transportation to the coastal zone in a GIS. These include DEM's for the delineation of boundaries, land use for the interpretation of the source of the sediment, soil for the type of sediment, and weather stations for transportation methods (Omani 2012). This study reflects many of these same datasets pertaining more to the coastline, referring to these curtail layers as a building block to understand the many sources of sediment accessible to the Galveston Coastline.

2.2 GIS and Coastal Vulnerability

In many ways, building a GIS is the ultimate method in assessing coastal conservation due to its ability to take readily available datasets and analyze them multiple ways with many different temporal, spatial, and spectral scales. Studies in coastal vulnerability and geomorphology emphasize the use of GIS as the primary method in accurately depicting and processing spatial data to produce vulnerability indices. One such study performed by Boateng (2012) on the coast of Ghana, for example, sought to use a GIS analysis to recommend a fuller approach to the coastal erosion problem by understanding entire dynamic system of the beach opposed to localized hard-engineering solutions.

In Boateng's analysis Ghana's coastline, four case study areas were highlighted along the coast representing different geomorphological processes operating to increase erosional rates in order to better define contributing factors. Area one represents an area with a heavy fluvial sediment discharge from the Volta River and lagoons in an area that has a known erosional issue. Area two is the most developed section of the beach. Area three is a long section of engineered coastline. And area four represents a stretch of coast between a major city and the mouth of the River Ankobra. This observation of differing coastal geomorphic environments is highly significant to this study of modeling a GIS for coastal structures because of its diversity compacted in one study area (Boateng 2012).

Then, using the shoreline positions from 1895, 1996, and 2002, as well as Landsat images and ground points to check datum accuracy, this study interpreted significant gains and losses in beach areas. The beach land gain/loss analysis uses digital image processing and a collection of shapefiles and maps to create an overlay map to highlight areas of change over the 107 years of coastal activity. Changes in shoreline were graphed by splitting the shoreline into 1 km sections and measuring the distance between the differing shorelines, then using the root mean squared error equation to check for accuracy (Boateng 2012).

This process gives a quantitative value for the total gains and losses in each of the four study sections stated above, correlating different coastal environments with how much erosion or deposition is expected. The results show that study area 1 with the lagoons and the fluvial system has the worst erosion and the second highest deposition, case area four has the lowest erosional rates and the highest depositional levels. This study is a great example of not only the use of GIS in understanding coastal geomorphology and conservation but helps understand the potential coastal structures have in Galveston, which is a major city with a river and a channel upstream feeding the coastline. However, this thesis seeks to use coastal features as fields and not objects, since today the data is more dynamic and can be much more easily obtained for specific times and days.

Another study by Szlafsztein and Sterr (2007) gives a much more detailed exploration into the use of digital images, maps, and statistic data to create a vulnerability index of Para Brazil. Using a combination of socioeconomic and natural variables, the two researchers are able to score, classify and weight these variables to determine areas of Para's coast that are vulnerable to coastal natural disasters. This same idea of data sources and integration is what furls this study of the Galveston coastline, and how the formation of a strong GIS is the best was to consolidate the amount and variation in the data required.

In the creation of the vulnerability GIS of Para, Szlafsztein and Sterr (2007) emphasize a few key variables in the data collection and pre-processing that are integral to this study and to future studies looking to highlight natural phenomena through Landsat imagery and maps. Much, if not all of the data required for their process came from raw data, and had to be transformed, corrected, and updated to reflect the temporal and spatial scales needed for the analysis (Szlafsztein and Sterr 2007). This study lends itself to the idea that the data must be specifically created for the final overlaying and weighting, inconsistent data from a variety of years and areas will lead to unrelated results to the question being asked.

The final analysis of this study by Szlafsztein and Sterr (2007) uses a two-fold integration process of first combining the 2D socioeconomic information by a series of Boolean logic and mathematical operators, and the natural data through a series of overlays. Here the overlays represent a more “real world” interpretation of how each fundamental layer can be compiled using an overlay to show interactions and combinations of feature values (Szlafsztein and Sterr 2007). This overlay process creates an entirely new layer that cannot be created from a single processed image. This is the foundation for the method of how best to study the coastline of Galveston, where the weighted overlay will be the final analytical tool used for determining depositional likelihood.

2.3 Geomorphology of the Texas Coastline

Galveston Island sits on in a unique section of the Texas coastline that has sediment fed to its beaches from as far away as the Mississippi River. Researchers such as Miller and Cruise (1995), successfully used Landsat Thematic Mapper to model drainage of sediment, which plays a critical role in the natural erosion and deposition of the beach. Patterns of erosion and deposition are closely tracked so potential problems, such as washouts or the over-building of sediment, can be tracked. Paine, Caudle, and Andrews (2014), in their report on the Texas Gulf Coast shoreline movement, discuss how beach erosion in the Galveston area is exacerbated by the increased of subsidence, making the sea-level rise there more worrisome. This changing sea-level affects the entire coastline, yet areas like Galveston require closer inspection because of the number of people who live near, or along, the beach.

Studies on sea-level rise and beach erosion encounter another contribution to the geomorphology of beaches in the form of storm surges (Dellapenna, 2013). Coastal weather patterns can create a drastic change in sea level in the form of a storm surge, where waves begin moving sediment from much higher along the foreshore than they normally would (Leatherman 1984, 14). These surges proceed to remove the sediment higher along the beach face, causing changes to the beach-vegetation boundary. These changes occur naturally yet can be devastating to those people living along the coast. Major erosional events due to storm surges can destroy or destabilize homes, making these events especially helpful to track for those living in beach homes (Morton and Paine 1985, 9)

2.4 Urban Effects

Though erosion is a natural part of the sediment system for any coastal area, human involvement and protection creates a new factor meant to both preserve the properties of those living near the beach and maintain a healthy beach system for plant and animal growth. In Galveston, the beaches and island atmosphere bring in huge numbers of tourists, making tourism one of their major industries (Phillips and Jones 2006, 4). For this reason, it is important for the Galveston economy to keep beaches as healthy as possible, including keeping a healthy sediment supply. Preserving both the urban development and environmental systems has become difficult due to the construction of the Galveston seawall, built after the Great Storm of 1901. The U.S Army Corps of Engineers saw the seawall as an erosional threat to the beachfront and built a series of groins (linear structures perpendicular to the coast that trap sediment) to prevent total sediment loss from the shoreline (King 2007).

Because of this association of heavy erosion and seawalls, Galveston County has stopped building seawalls to protect those new homes that are being built along the beach. This means that these homes are open to storm surges that move and erode the beach, destroying homes in the processes. Homes along the coast are built with storms and rising tides in mind, which makes them less susceptible to storm surges. However, Texas laws on defining public and private property regarding beaches lead to a more pressing issue. Texas law state that if the vegetation line of a beach (where sand meets grass) moves and makes your property beyond the vegetation line (Morton and Paine, 1985), it is then legally owned by the state and must be removed at the expense of the owner (Bowling and Amsler 2015). It is for this reason that many residents are trying to build smaller, less intrusive seawalls to prevent erosion and the loss of their legally owned homes.

2.5 Effects of Longshore Drift

The study of erosion in Galveston is unique because of the presence of the built-up seawall. Many of the recent erosional studies analyze the natural effects of erosion and characterizing environmental features that may reduce or enhance erosional rates. These studies are useful as standards for erosion and help quantify the process for different geographic settings. All coastal areas are susceptible to beach erosion, and the analysis of the erosional rates and distribution are widely studied. A case study in South Africa outlines many of the concepts associated with analyzing shoreline erosion using Landsat data. This study assessed land coverage and vegetation health to assess the susceptibility of coastal regions to erosion. Other areas that are susceptible to erosion are those with low vegetation or with vegetation in poor health (Callaghan, Engelbrecht, and Kemp 2015, 68). This study gives incites on costal features that are used to assess erosion, and also the global scale at which beach erosion is affecting the interaction between the creeping urbanization of rural cities and the coastal environments where more and more people are headed.

In the eastern United States, a controversial beach management project has been ongoing in South Carolina to both protect the new homes built along the coast and a rare species of animal who called that land their home. Since 1970, Seabrook Island has been combating beach erosion with a combination of seawalls, inlet relocation projects, and soft engineering solutions such as beach nourishment projects. These have led to the movement of new sand to cover all but 2,500 feet of the 8,800 feet of seawall (Kana, Driscoll, Fox, and Nelson 2014,8), restoring much of the dune land landward of the beach. However, sand still erodes from key inlets around the island and has to be replenished. In this case, the replenishment comes from the transportation of sand from areas where it is accreting and moving it to areas experiencing erosion. This case may not completely solve the erosional problem or maintain a natural way to sustain current beach behaviors, but it does exhibit a way to accrete sand in quantities that help replenish the beach.

Closer to the study area concerned in this analysis, a study conducted by Robert Morton and Jeffery Paine analyzed the effect of the change in erosional patterns after a major hurricane (Hurricane Alicia). In this event, more than 2 million cubic yards of sediment was eroded, creating the fore beach sand bars present in the shallows of the Gulf of Mexico (Morton and Paine 1985, 9-10). The retreat of the beach sediment was analyzed using areal imagery and regions were defined by beach shortening and sand bar building. These sand bars are of interest to the study of erosion due to longshore drift because of the retreating path that is created by the wave motion. These bars represent a depositional area for sediment away from the shore, which may act as a good location for the construction of a sediment diverter. This study also demonstrates that hurricane sediment movement is a major threat to the Texas coast, and any structure constructed off the shore must be resilient against major storms.

Chapter 3 Methodology

This chapter walks through the data requirements, preprocessing, and final GIS analysis that defines the coastal geomorphology model explored in this thesis. The first section outlines how the analysis works, while the others define the necessary data and steps to create the final site map.

3.1 Research Design

The methodology for this GIS of the Galveston Island coastal systems stems from the cyclical interaction of the natural processes, infrastructure, and geographic features of the island (Figure 6). In one sentence, the natural processes and environmental cycles that shape Galveston's geography influence the need for infrastructural changes, such as coastal structures, which then change the flow of those natural processes. This cyclical nature helps to break down the data requirements by aspects of these three main categories.

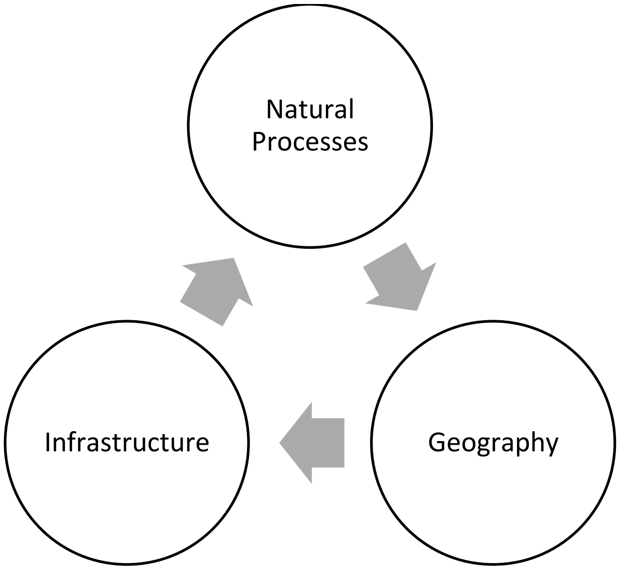


Figure 6: Cyclical relationship of data necessary for this study, optimizing the use and understanding of GIS for this analysis

Classification of suspended sediment, the bulk of the preprocessing, was created using multispectral Landsat data. Using Lodhi and Rundquist's (1989) spectral bands for the varying amounts of suspended sediment, density sliced Landsat data was quantified for the amount suspended sediment feeding the Galveston coastline. This was accomplished using the TerraSet software's IDRISI remote sensing analysis to create density slices of the coast of the Gulf of Mexico, Galveston Bay, East Bay and Trinity Bay.

The pattern and amount of sediment that is conserved by groins was modeled using a simple composite of the NIR Landsat band. This begins with converting digital number values (DN) to reflectance, then resampling the two years of changes data (2008 and 2018), and finally making the composite with the 2018 NIR as band 1, 2008 NIR as band 2, and the 2018 NIR as band 3. The result created a green and purple map showing how the beach has grown and specifies what reflectance values represent the beach. This was used to show beach growth and the relative depositional age of the beach with dryer beach being older and less likely to erode than wetter, younger beach.

The Galveston seawall and the corresponding groins are located on the eastern urban section of the island to protect the bulk of Downtown Galveston. Opposed to acquiring land use data for one specific date, each dataset has its own associated land use classification to represent changes to the coastal structures after both Hurricanes Ike and Harvey. This information also contributes to the analysis of beach erosional areas and the major erosional sections of the beach, correlating the location of the erosion to the coastal structures and the necessity for said protective structures.

The velocity at which sediment moves gives key information on whether the sediment has the ability to be deposited or not. Areas with higher velocity continues to move sediment further down the shore, whereas slow-moving currents have a higher likelihood of depositing its sediment. In the analysis of the effectiveness of the Galveston coastal structures, knowing whether or not the groins fall along a section of coast that is positioned to catch the slow-moving sediment helps define the effectiveness of the groin positions down the coastline, highlighting any gap or areas not being built. By using ArcMap's Inverse Distance Weighted (IDW) interpolation tool, point data from NOAA (2018) current velocity acquisition stations were interpolated into a continuous raster data for analysis with the other datasets.

3.2 Remote Sensing and Landsat Data

Remote sensing is an extremely valuable way of obtaining a variety of coastal data that can be processed and selected for specific temporal and spatial scales. This increases the effectiveness of many studies by creating what specific data is required, opposed to merely finding pre-existing data to analyze. This type of data gathering and integration is also seen in Schiebe, Harrington, and Ritches' (1991) Study of lake Chicot, Arkansas. This study uses an integration of remote sensing and GIS allows for the interpretation of temporally specific data, encompassing a decade's worth of catastrophic erosional events, as well as sediment building projects.

For this study, the primary satellite used for data collection is the Landsat 5 Thematic Mapper (TM) and Landsat 8. The Landsat satellite program is the world's longest running continuous remote sensing programs, using multispectral cameras to acquire moderate resolution reflectance values of the earth's surface. Landsat 5TM covers 7 wavelength bands from 2008 through 2011, covering the first half of the temporal scale for this study, and Landsat 8 cover 9 bands for 2014 through 2018, the second half. The study of suspended sediment and coastal movement pay close attention to the near infrared bands of each (Band 5 in Landsat 8 and Bands 4 and 5 in Landsat 5TM). This is mainly through its use in land change composites and the creation of land mask for sediment analysis of water features only.

3.3 Data Requirements and Sources

To make this process as repeatable as possible, open sourced data that can be processed and gathered by anyone was used for the entirety of the study. For this analysis, the data used was primarily raster data from Landsat images, showing the entire Galveston Island coastal zone required for most of the study. Because the coastal area was classified as a zone without clear boundaries, a more continuous style of data collection is necessary. Data processing began with 2008 and 2018 data on the days before, during, and after the two-major hurricanes, (Ike and Harvey respectively). Hurricanes show the largest increase in coastal erosion and deposition with their large storm surges, creating a great place to start when looking for changes in geomorphology of the coastline. This data was collected using USGS Earth Explorer (2018), a free public database containing both Landsat 8 and Landsat 5TM data. Table 1 shows the ways in which the same Landsat data was processed to create the different physical phenomena of the Texas coastline.

Landuse data is vital to understanding this study because it incorporates the human need for alteration of coastline such as the introduction of seawalls and groins. Areas that have little to no population do not require any kind of protection from storm surges, making them valuable control areas for sediment movement and capture on a natural shoreline. Galveston has a relatively high population that lives right along the coast, increasing their need for coastal protection. Landsat data was available at the same time every day, making for consistency of temporal resolution. So that each section of Landsat data acquired has a relatively close timeframe. This means that the tidal height should be about the same every day. Table 2 shows a timeline of what days the Landsat data is collected for and how these days relate to those of major events captured within the data. Increases in tidal height may mean that there is activity from a storm surge or a highly erosional event that is occurring. Comparing the time and date that the length of data was collected along with the title chart gives a relative sea level for that time and day both of which is found online through the National Oceanic and Atmospheric Administration, NOAA.

Table 1: Raw data and sources

Variables	Measurement	Data Format	Spatial Resolution	Temporal Scale	Data Source
Beach Area	Raster Classification	Landsat Data	30m	2008-2017	USGS Earth Explorer
Water Velocity	Interpolated Surface	NOAA Current data points	NA	2008-2018	NOAA
Sediment Supply	Raster Classification	Landsat Data	30m	2008-2018	USGS Earth Explorer
Land use	Raster classification	Landsat Data	30m	2008-2018	USGS Earth Explorer

Source: USGS Earth Explorer and NOAA

After assessing the need of shoreline structures to prevent beach erosion, the sediment supplies and velocities were factored in, to show if they would either interfere or help with sediment deposition. Understanding the sediment budget and the effect of longshore drift to the coastline may indicate some value of the effect of these man-made structures for erosion prevention. Many of these shoreline structures are meant to only combat immediate effects of longshore drift by eroding and depositing in the same small section. However, many of the major tributaries and rivers that exit the coastline to the east of Galveston expel large amounts of sediment that maybe useful in understanding the settlement supplies to the Galveston Beaches.

Table 2: Erosional Landsat data timeline with major coastal events

Timeline	Data Year	Date	Satellite	Resolution
Event	Hurricane Ike	Sep 1 – 15 2008	NA	NA
Data Used	2008 Data	Sep 04, 2008	Landsat 5	30m
Data Used	2011 Data	Oct 31, 2011	Landsat 5	30m
Data Used	2014 Data	Oct 07, 2014	Landsat 8	30m
Event	Galveston Beach Expansion Project	May 2015 – Nov 2015	NA	NA
Event	Hurricane Harvey	Aug 17 – Sep 17 2017	NA	NA
Data Used	2018 Data	Jan 01, 2018	Landsat 8	30m

3.4 Image Processing and Analysis

Procedures for the assessment of the Galveston Island marine structures reflect that of an integrated site suitability analyses and a change detection analysis. This began with the dataset that covers the necessary temporal and spatial resolution, the Landsat 5 and Landsat 8 multispectral data. The data processing was divided into those datasets that were compiled using remote sensing techniques and those that were interpolated form point data.

3.3.1 Sediment Supply

The sediment supply density slice analysis used Landsat 8 data to show the sediment patterns and suspended amounts for January 1, 2018. Gulf of Mexico current direction and flow rates stay relatively constant between the ten years in question (2008 – 2018), therefore using a single most recent image of sediment density added the most relevant data to today's climate than an average sediment supply. The density slice analysis used band 4 from Landsat 8 to specify what spectral range of DN values represent the different amounts of suspended sediment. First, the only area needing analysis is the water, in this case Galveston Bay and Trinity Bay. Therefore, a mask was created using the Landsat NIR Band in an overlay with Band 4, which refined the spectral analysis to just the water. Second, using the sediment classification reflectance values, shown in Table 3, from Lodhi and Rundquist, the raster image was reclassified to match the amount of suspended sediment.

Table 3: Reflectance values for the suspended sediment loads

Class	**Load (mg/L)**	**Reflectance**
1	Clear Water	.005-.02
2	100	.02-.025
3	200	.025-.03
4	300	.03-.035
5	400	.035.045
6	500	.045-.055
7	600	.055-.065
8	800	.065-.075
9	1000	.075-.095

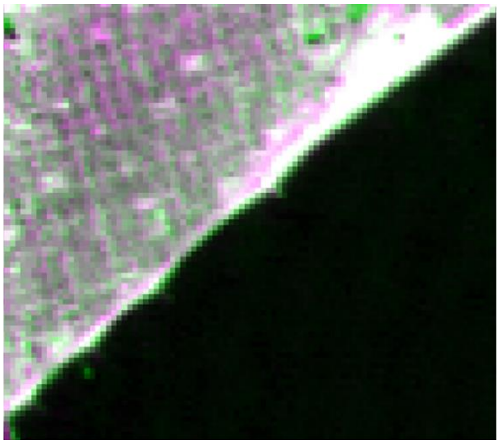
3.3.2 Landuse

For the purpose of this analysis, the landuse for the Galveston area needed to be very simple, defining areas that will inhibit the coastal geomorphology, and those areas that it will not. For this reason, an ISOCLUSTER unsupervised classification was used to break the study area into sand/beach, urban, rural, and water. Because groins only fall along the line of the seawall, the landuse information highlighted areas of beach that would otherwise be undercut and eroded, if not for the presence of groins.

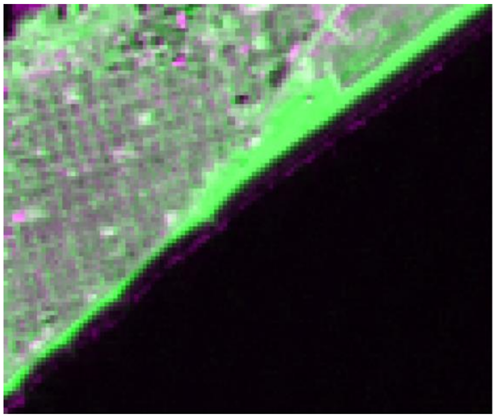
3.3.3 Beach Dynamics

Beach erosion, because it deals with the change of beach over the 10 years in question, first had to be resampled in order to be analyzed in a composite featuring Landsat 5 and Landsat 8 data. This ensured that the same reflectance values represent the same feature across all maps, and the composite cannot be created without this step. The composite was created using 2018 resampled Landsat 8, band 5 data as composite band 1, 2008 Landsat 5TM band 4 as composite band 2, and the same 2018 data as composite band 1 for composite band 3. Figure 7 shows the product of this composite showing areas that have changes from 2008 to 2018 in purple and areas that have not changed in green.

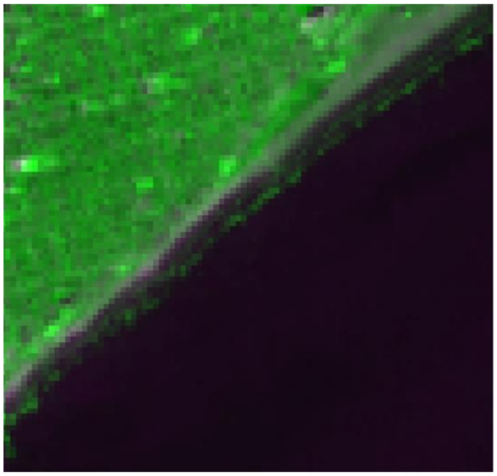
For the purposed of showing the change in coastline over the last 10 years, this analysis was completed every three years following 2008. This helped to give a sense of the changes that can occur in one decade. These images also portray the beach after Hurricane Ike in 2008, the Galveston Island nourishment project in 2015, and Hurricane Harvey in 2017. All these events shape and change the Galveston Coastline and a progressive or regressive way and need to be considered when looking at the long-term geomorphology of the coastline.



2008-2011



2011-2014



2014-2018

Figure 7: Beach change Landsat analysis where purple show growth and green shows no change

Finally, using the layer properties from the composer window in IDRISI, the spectral signature from the beach was obtained by moving the max min sliders until nothing was left but the building of the beach that was highlighted with purple from the 2008-2018 composite. For the Galveston beaches, the total spectral range was 30-65, which was then further classified by the spectrum of wet and dry sand, creating an erodibility index. Table 4 shows the relationship between the spectral signatures and the erodibility. The lower spectral values are the wetter, less erodible sections of beach, where as the higher values represent dunes and other dry structures that are the first to be leveled in the event of a storm surge.

Table 4: Beach Erodibility

Spectral Range	**Moisture**	**Erodibility**	**Age of Deposition**
30-37	Wet	Low	Youngest
37-44	Moderately wet	🟩	
44-51	Intermediate	🟨	
51-58	Dry	🟧	
58-65	Dune	High	Oldest

3.3.4 Velocity Modeling

Current velocity data began as point data with the speed and direction of the flow given in the attributes at each gauge station. This data was used in an IDW interpolation to create a continuous surface of velocity for the coastal region. IDW was used in this case because of the ability for boundaries to be set and the interaction between the currents and the coast to be preserved. This models some of the key interactions between the jetties and the sediment supply

Table 5: Current gage Information from NOAA used in the production of the velocity IDW

NAME	*Ebb Direction*	*Flood Direction*	*Depth in feet*	*LAT*	*LON*	*Current Motion*	*Date*	*Ebb Height (relative to MSL)*	*Flood Height (relative to MSL)*
Galveston Bay Ent.	*91*	*272*	*5*	*29.3487*	*-94.7142*	*Subordinate*	*9/29/2017 0:00*	*-59.1*	*60.9*
Bolivar Roads	*125*	*295*	*8*	*29.3433*	*-94.7813*	*Subordinate*	*9/29/2017 0:00*	*-66.8*	*73.8*
Galveston Channel, west end	*103*	*272*	*14*	*29.31*	*-94.82*	*Subordinate*	*9/29/2017 0:00*	*-72.9*	*73.8*
Galveston Causeway RR. bridge	*99*	*266*	*10*	*29.2975*	*-94.8858*	*Harmonic*	*9/29/2017 0:00*	*-53.4*	*20.6*
Houston Channel, W of Port Bolivar	*135*	*313*	*3*	*29.3647*	*-94.7967*	*Subordinate*	*9/29/2017 0:00*	*-60.7*	*81.2*
Houston Ship Channel	*154*	*341*	*7*	*29.5073*	*-94.8747*	*Subordinate*	*9/29/2017 0:00*	*-30.4*	*36.9*
Morgan's Point	*163*	*336*	*6*	*29.6798*	*-94.9817*	*Subordinate*	*9/29/2017 0:00*	*-30.4*	*22.1*
Matagorda Channel	*142*	*317*	*15*	*28.4217*	*-96.3233*	*Subordinate*	*9/29/2017 0:00*	*-87.2*	*126*
Aransas Pass	*118*	*300*	*15*	*27.8338*	*-97.0442*	*Subordinate*	*9/29/2017 0:00*	*-76.2*	*65.9*
Port Ingleside	*102*	*286*	*5*	*27.815*	*-97.23*	*Subordinate*	*9/29/2017 0:00*	*-25.4*	*42*
Texas Point	*145*	*335*	*10*	*29.65*	*93.8267*	*Subordinate*	*9/29/2017 0:00*	*-94.5*	*44.5*

and coincides with the sediment map showing where most of the sediment is coming from. Using the applicable gauge stations in Table 5 for the Galveston area from NOAA, a vector file of the point locations, along with annotations for the speed and direction of the currents at each station, was used to create the IDW. The specific current being mapped here is the ebb, or the outward moving current, which is what draws the sediment away from the beach.

3.3.5 Weighted Overlay and Suitability Optimization

Coastal properties such as velocity and sediment supply represent a range of acceptable values, where some are better than others but still all are impactful. Sediment supply is a good example of this, even though it is reasoned that with more available suspended sediment higher depositional rates are expected, any sediment supply to an area is better than none. This means that when quantifying the suitability of different sediment loads, saying that one amount would have no impact would not be true. On top of scaling suitability, weighting allows for the ranking of each layer as a whole, making the analysis able to reflect the unique processes and features of the study area. For this reason, a weighted overlay allows for the optimization of data features suitability on a scale, in this study, from 1-4. The four layers shown in Table 6 are weighted 35% each to velocity and sediment supply, 20% to landuse, and 10% to beach erodibility, and each data layer is optimized for deposition.

Table 6: Suitability values used to optimize the depositional suitability along the Galveston Seawall

Layer 1: Sediment Density			**Layer 2: Landbase**			**Layer 3: Erodibility**			**Layer 4: Velocity**		
Suitability		Weight	Suitability		Weight	Suitability		Weight	Suitability		Weight
700 - 1000	4	0.35	Beach and Sand	4	0.2	30-37	4	0.1	46.25 - 30	4	0.35
500 - 600	3		Vegetation	3		37-51	3		62.50 – 46.25	3	
300 - 400	2		Urban	2		51-58	2		8.75 – 62.50	2	
100 - 200	1		Water	1		58-65	1		95 – 78.75	1	

For this study, the optimal depositional environment consists of high sediment, low velocity in areas of low erodibility along the beach. The respective values for weighting are shown in Table 6, as well as the assigned suitability factor for each set of features under study. 4 represents the most suitable condition and 1 represents the least suitable environment.

Chapter 4 Results

Understanding the way coastal structures alter the sediment cycle along the beach provides valuable insight into the long-term effects that urbanization has on island cities. Constructing this GIS, by combining aspects from remote sensing and spatial analysis, created a model that can vary in temporal scale, from months, to years, to decades. When considering the overall effectiveness of coastal structures, many models show the change over a number of years, but this analysis will be looking primarily at the role coastal structures have on changing the suitability of the swash zone just off the coastline.

4.1 Mapping Results

Final results are broken into two stages, the processing and analysis for the data layers, and the final overlay for the main resulting map. Each data layer is optimized for the accumulation of sediment along the Galveston coastline, looking to show the features of highest accumulation has the highest suitability. The final result, therefore, is an optimized weighted model of sediment depositional likelihood around Galveston Island, particularly along the City of Galveston where the seawall is.

4.1.1 Data Layer Results

Each data layer analyzed is represented as a map above and defines qualities for the geomorphology of the Texas coastline. Figure 8, the sediment density map, shows the sediment density as well as the current direction and the interaction between the southern flowing water from Galveston Bay and the GOM. As of 2018, much of the sediment that is supplying the Galveston coastline comes from Galveston Bay, utilizing sediment from the Trinity River, and the Houston watershed and bayou systems.

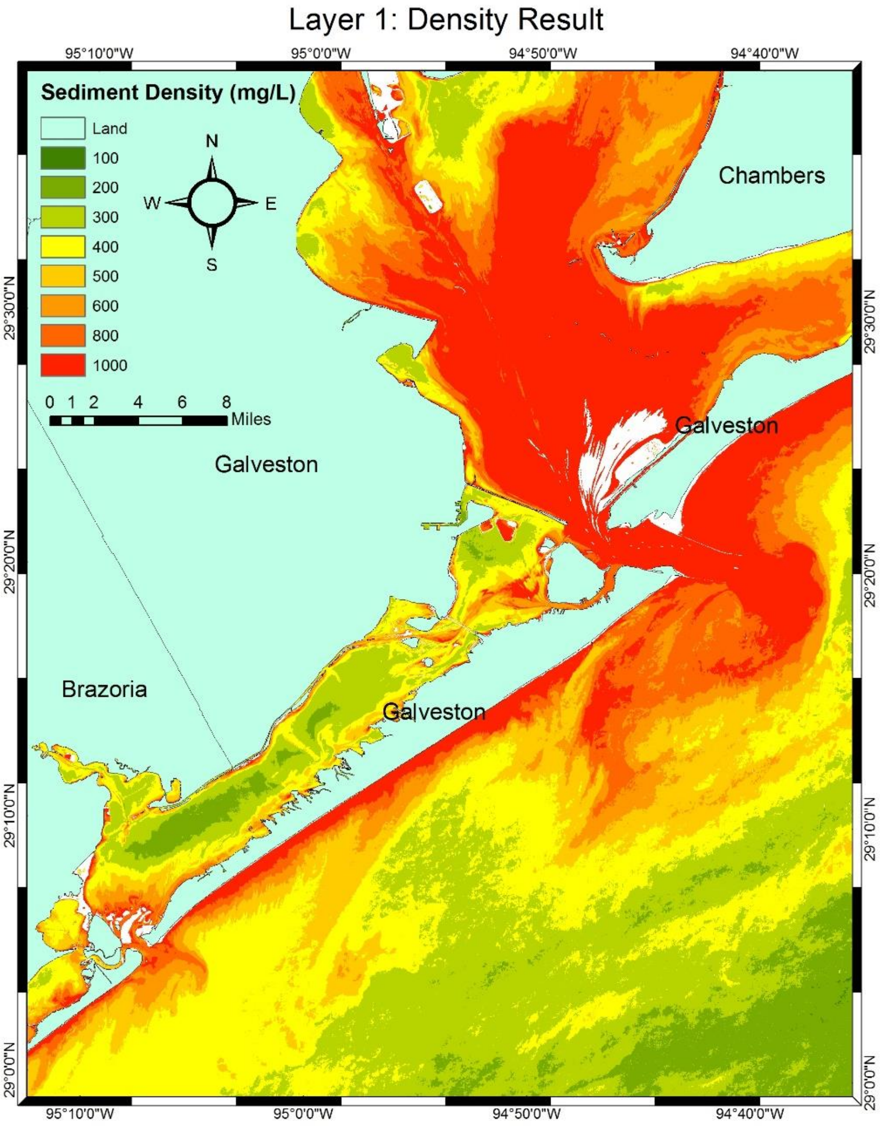


Figure 8: Sediment Density map showing the flow of sediment and sediment density values.

Incidentally, the beach rejuvenation project uses this same sediment, dredged from the Houston Ship Channel, as this is the closest sediment supply that also helps keep the ship channel deep and clean. It was initially hypothesized that the Mississippi River's wide distribution of sediment would add to the supply of Galveston Beaches. Though Figure 8 does show sediment to the east on the Bolivar Peninsula side, most of this sediment is being swept south with the current from the Galveston Channel and being deposited much farther West that the groins are positioned.

This westward deposition is due, in part, to the jetties that maintain the Galveston Channel. These structures redirect the sediment that would build the east side of Galveston Island and direct it out into deeper water. The effect of the jetties on the coastline can be seen in Figure 8 as well. The jetties cause bulges and deposition on either side of the channel and create strong currents along the length of the jetties. Due to the importance of the Houston Ship channel, these jetties are almost as significant as the Galveston Seawall for protection of the Houston/Galveston area infrastructure. However, it does contribute another attribute to the understanding of the changing geomorphology of Galveston Island.

The Galveston Island landuse map created from the ISOCLUST analysis in IRDISI portrays the relationship that the City of Galveston plays on the interaction between the beach and the natural retaining wall created by vegetation. As seen in Figure 9, the infrastructure has taken over the vegetation, and made the City of Galveston a much more vulnerable target for erosion. What this mean is the perspective of this layer in the weighting of a final product is that the coast in front of the city will not have as favorable of depositional index as areas with vegetation would.

As sediment was deposited and eroded, the pattern in which the beach is built was created in the differing reflectance values of sediment. Understanding how the sediment was deposited helps analyze those areas that continually build and those that do not.

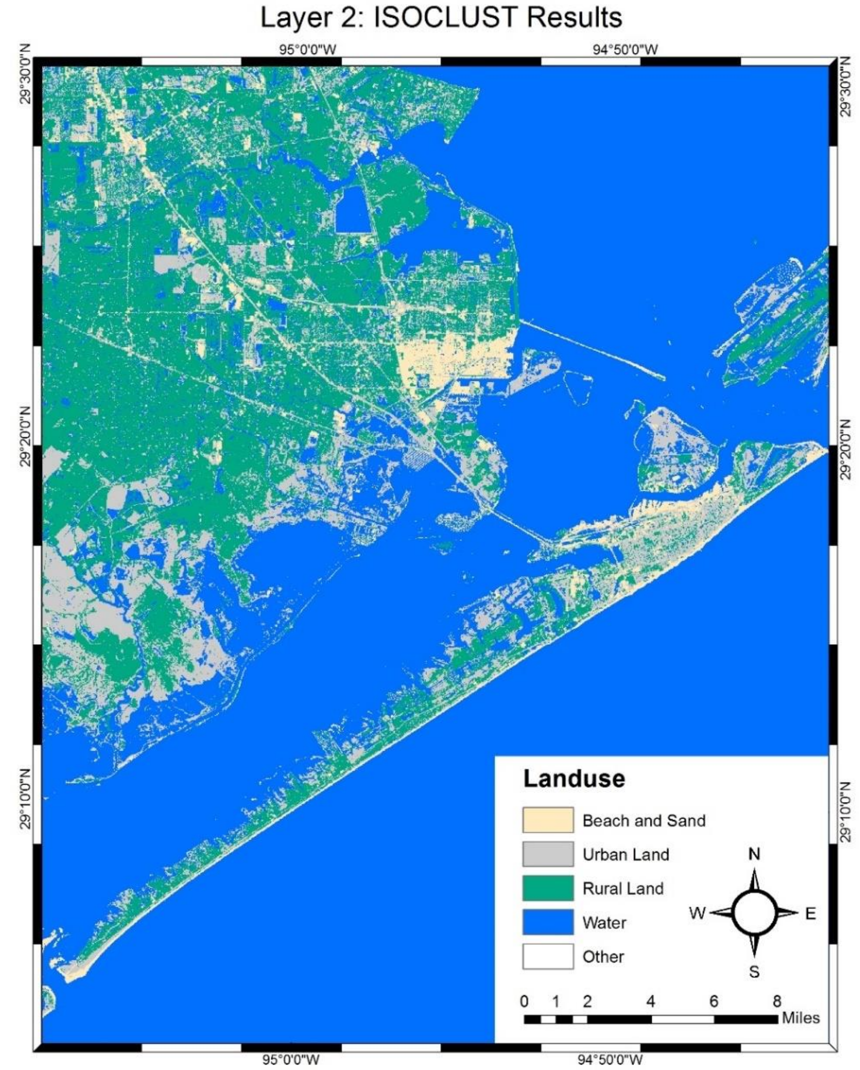


Figure 9: Landuse map of the Galveston area created using IDRISI ISOCLUST analysis

Figure 10 maps the reflectance patterns of the sand, showing how the beach built east of the groins develop into dunes (orange and red) and the west side of the groins are the first at risk of being eroded (green). This categorization of the beach helps in managing the risk of what sections would be in the most immediate danger from storm surges and long-term wave action.

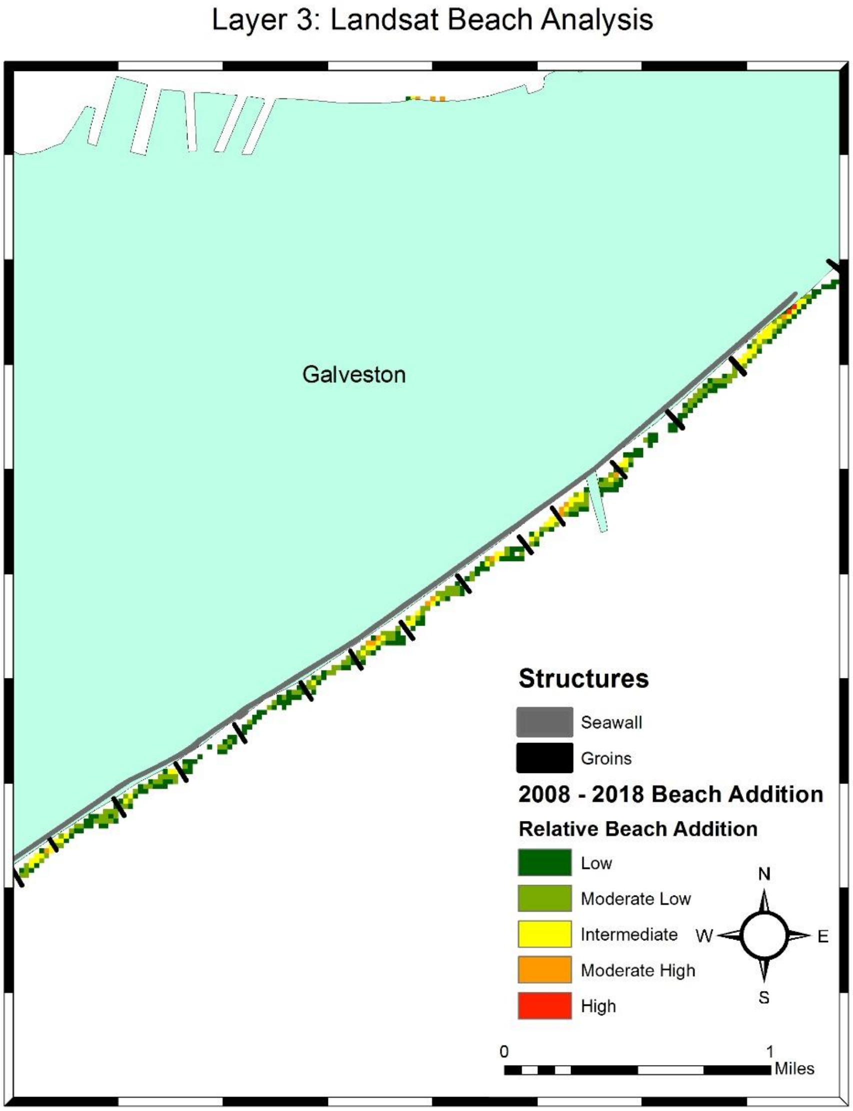


Figure 10: Beach erodibility analysis using 2008 and 2018 composite.

Figure 16, the current velocity model, is the most informative representation of the correlation between the channel and the GOM. The IDW interpolation of the Ebb points created a detailed understanding of how the islands and currents affect the velocity of water. Normally, sediment deposits in slow moving water, and smaller particle sizes move farther that larger particle sizes. This means that the small grain sized sand that makes up the Galveston beach was highly susceptible to move due to these high velocity currents. In this way, the rip currents created by the groins and jetties worked against the natural depositional pattern of beach building. It is for this reason that the velocity of the Gulf is of equal importance to the sediment movement because one is affected by the other.

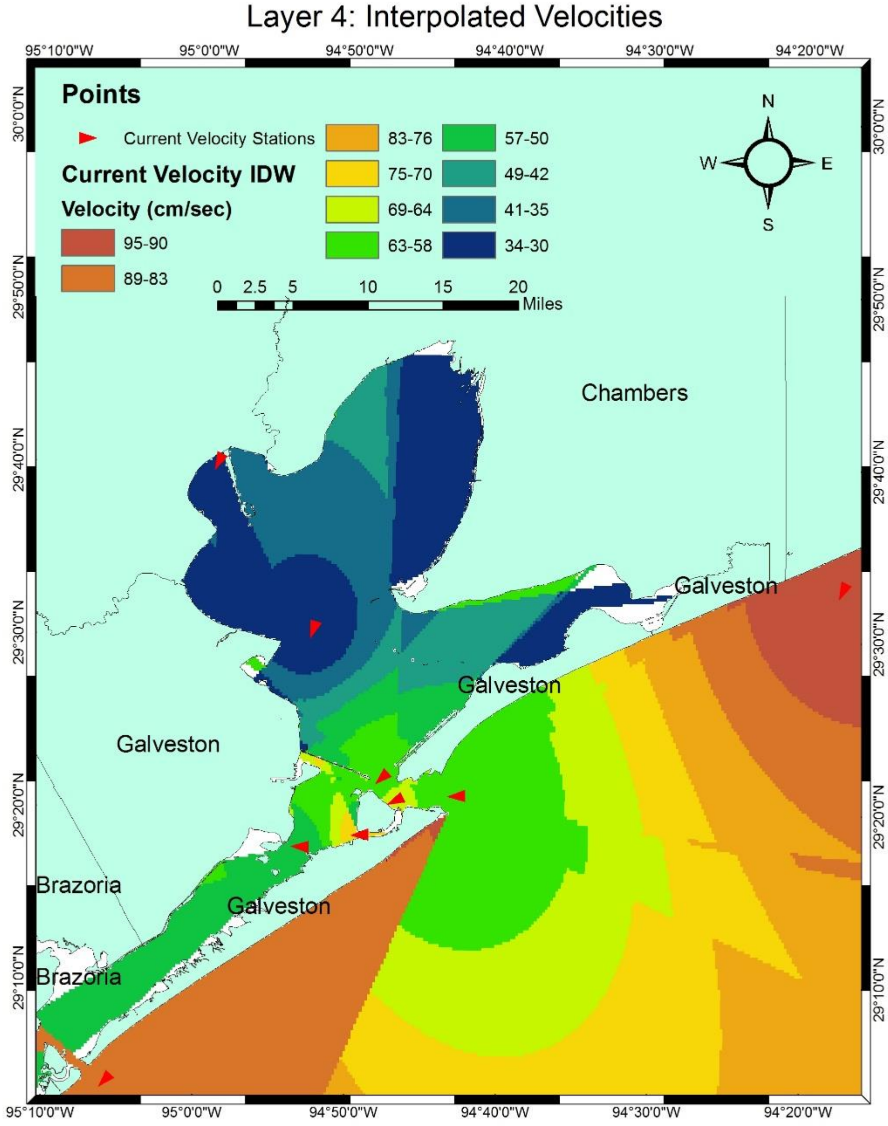


Figure 11: Velocity model created from IDW interpolation of current velocity points

4.1.2 Analytical Results

The site suitability results, using a weighted overlay in this experiment, show how coastal structures alter the beaches by changing the tidal environment to be more suited for deposition. The final resulting map (Figure 12) shows how the combination of groins alter the depositional environment, as is intended, but groin effectiveness is limited by the distance from the jetties maintaining the channel between Bolivar Peninsula and Galveston Island. These jetties effectively push sediment out away from the island into the lower velocity zones, where much of the sediment is dispersed.

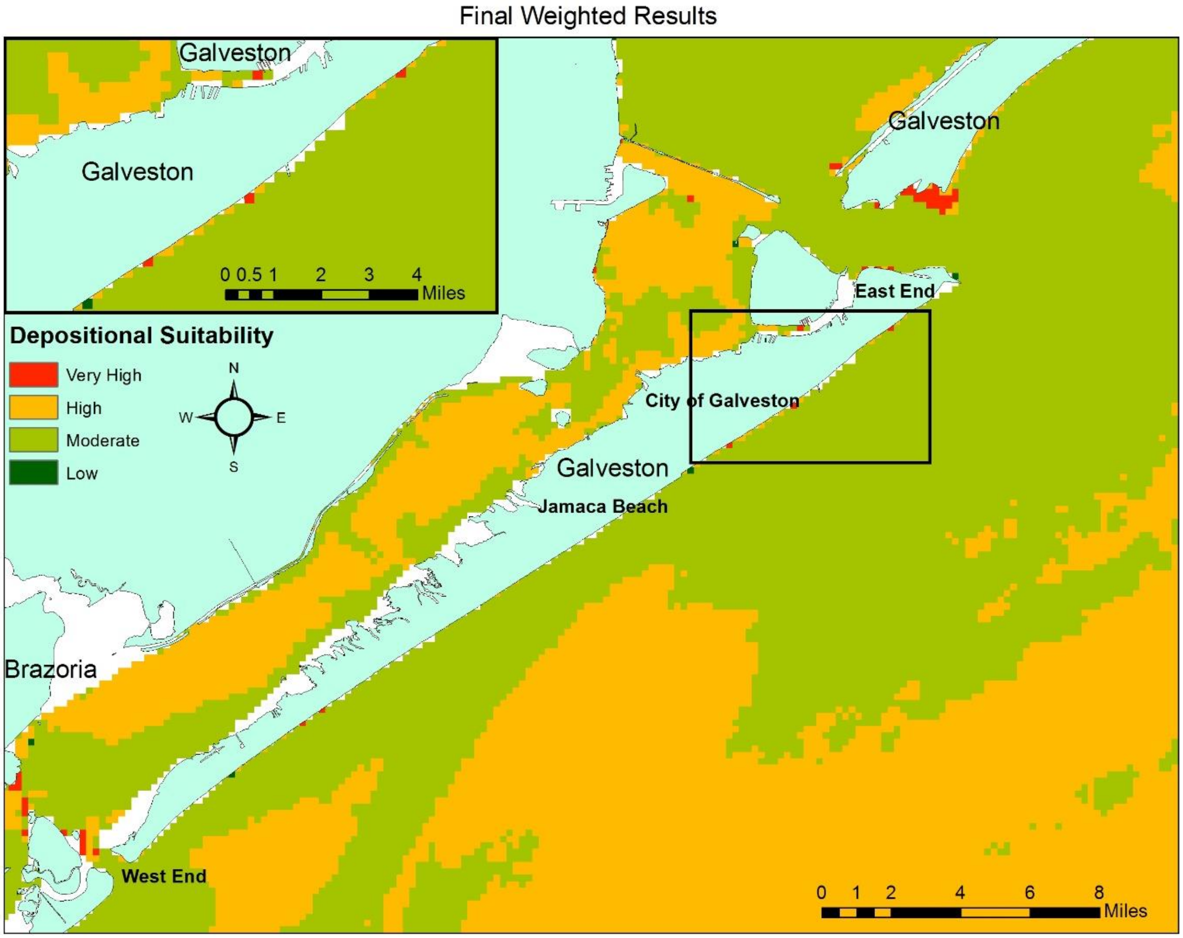


Figure 12: Final Weighted Overlay

This push by the jetties inadvertently created a gap in the deposition of sediment beginning at the eastern most part of the seawall and spanning around 2 miles of coastline to the east. This gap, incidentally, coincides with the area under construction of the current beach nourishment project. This depositional gap demonstrates the effect that coastal structures have on the natural coastal and oceanic processes that drive coastal deposition and erosion. Because Galveston has the unique geographic position as a major channel to the east and a raised, protected city to the west, their proximity puts deposition at a disadvantage.

4.2 Sediment Sources

The sediment density map and land use map show that most of the sediment supply for Galveston's coast comes from the Houston ship channel and bayou systems, the Trinity River and Galveston Bay. The sediment from the Mississippi is effectively blocked off by jetties, which then creates a rolling current pattern bringing sediment back along the west side of the jetties. This effect is great for adding sediment to Galveston's East Beach but creates a zone between the edge of the rolling sediment and where longshore drift normalizes farther to the west that does not receive proper amounts of sediment. This is a significant factor that has arisen as the coastal infrastructure has begun altering patterns of sediment distribution and current flows.

4.3 Management Model

Because of the diversity in geographic features that coastlines and urbanization can produce, a major point of this study is to model the natural phenomenon that impact coastal erosion and deposition, and how they interact with coastal structures. In general, this will begin by understanding the current direction of natural deposition. This is how the sediment analysis and velocity analysis are most appropriately used. Once the direction and sediment amounts are understood, the next step is to understand the major geographic features in the area. For example, is the coastline a barrier island, is it a cliff, is it a smooth transition into the majority of the state or country. These can help answer the question of what all features would need to be accounted for in the analysis, and highlight specific tendencies in the geomorphology, or pre-existing barriers or coastal structures causing erosion or deposition.

The differing geographies will also have unique relationships with the local infrastructure, such as proximity of towns to the coast, or the population count living on or near enough to the beach to be susceptible to tidal erosion, hurricanes, cyclones, or tsunamis. These relationships may also include channels for shipping, as in Galveston, where jetties may need to be, or may already be present to prevent channel movement or closing. Each of these factors equate to the understanding of each case and whether or not coastal structures are necessary and safe. Figure 13 shows the final work flow of how the data is compiled and separated. If by using the model, a section of beach is applicable for protection of a seawall or the construction of jetties, the analysis of the coast can begin immediately to monitor changes in geomorphology by the attribute of the physical phenomenon explored in this study. It is the hope of the author that this model serves to prolong a mutually beneficial relationship between the growing population of beach dwellers and the beaches.

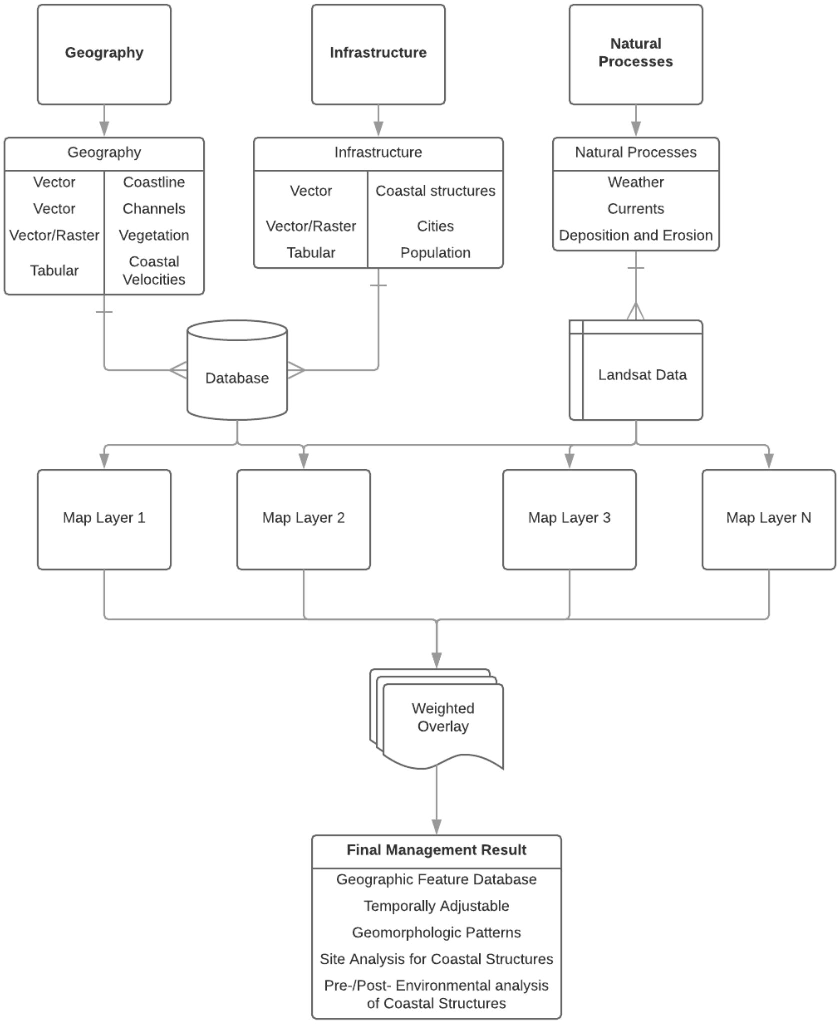


Figure 13: Standard model used for analysis of coastal regions in conjunction with coastal structures

4.4 Optimization

Optimizing the final analytical result is best accomplished by looking to the beach phenomena on Galveston. The final analysis shows a trend of deposition in the slower waters adjacent to the mouth of the Galveston Channel, which is expected from previous research. These areas are known to deposit large offshore sand bars, validating that a high depositional rate is expected in these areas. The final map also shows an area along the seawall to the west where depositional likelihood is at its lowest, adjacent to an area of high deposition. This is also a feature expected from the interaction of seawalls and groins, where each side of the groin has an area of high deposition and high erosion.

High depositional rates on the west end of Galveston Island help in validating the movement of the sediment from Galveston’s shores to the San Louis Pass. This area is not protected by jetties, and over the last ten years has experienced an increased amount of sediment deposition, closing the pass. This phenomenon is captured in Figure 12 by the high and very high area highlighted on the western tip of the island. The satellite imagery also shows that the beach is significantly thicker in this area, making it a spot of natural accumulation.

Chapter 5 Discussion

The future of urbanization and coastal conservation will rely on understanding the strengths and weaknesses of the coastal structures that protect, conserve, and replenish the coastline. This can lead to better project planning for new coastal towns, as well as improve the retention rate of sediment from building seawall/groin systems. This analysis of the coastal structure on Galveston island represents a small, unique geographic location, whose coast is shaped by all three major structures. All over the world, coastal towns with and without coastal structures need to be able to assess their geographic susceptibility to storm surges, and if a seawall does exist, be able to analyze structures that may restore the balance of coastal geomorphology.

5.1 Conclusion

Maintaining coastal symbiosis of the natural oceanic phenomena and human development is a first step in the urbanization of the world's coastlines. Though managing all the steps and processes that need to be considered when analyzing a new section of beach's potential for coastal structures, erosional and depositional models in from other sources and from areas with similar geomorphic and geographic attributes can help begin a new project. This analysis of the seawall, groins and jetties that keep the people of Galveston Island safe from the demolition that occurred in the Great Storm of 1901 can also help in deciding future coastal structure placements.

By understanding that physical phenomena that shape the coast, such as current velocity, sediment movement, beach erodibility and landuse, decisions can be more accurately determined and managed if construction is to be instituted. By analyzing these features using the weighted overlay, different attributes can have varied importance depending on the location and trends found there. For future coastal management projects to begin, even without coastal structures, areas of beach with high building potential can be monitored for the recording of natural channel closures or movements, as well as pinpointing areas that would be able to withstand the construction of seawalls and groins. Most relevant for existing structures is understanding the effect that adding more protective measure to the beach, such as jetties to halt channel closure, will affect the existing geomorphology. Ensuring that all coastal structures are analyzed and monitored today can prevent costly future beach replenishment projects, while protecting our cities beaches alike.

This study was optimized for the geography and existing structures of Galveston island. This means that not all study regions will use the same weighting percent's or suitability indexes. Future work could include looking at how different weighting schemes would change the depositional likelihood of the Galveston coastline, and if the same regions showed similar depositional characteristics.

This analysis creates the skeletal system for what can become a much larger GIS for coastal monitoring that can be analyzed with large or small temporal scale, as necessary. This would be however, a large undertaking with all the variations that coastal systems realize in a single area, and the variation of data available. For future research, other analytical layers could be added such as month to month tidal movement. This would represent the slow, steady process that moves beaches and closes channels. This process would best be recorded in a database form, which could then be mapped for change, and added as a physical phenomenon layer to the final analysis.

Integrating other databases, such as population, could create positive correlations between growing infrastructure and coastal protection. This would help develop a population or housing threshold for a particular section of coastline and help guide finite numbers of residents and locations for particular beaches. This data, along with the beach dynamics, sediment flow and velocity analysis would be a particularly great combination for a site suitability analysis of different barriers islands for future development.

5.2 Recommendations

From the development of this coastal GIS and the trends seen by the results of the weighted overlay analysis, certain changes may allow for the enhanced protection of Galveston's beaches. For the Houston/Galveston area specifically, the jetties protecting the mouth of the Galveston channel create high currents and push sand further out to the west, leaving a section of beach excluded from the high amounts of sediment from the bay. It may be that some other structure is needed seaward to bring back and slow down the sediment being expelled so far out into the gulf by the jetties. It may also be considered that the jetties be shortened in order to allow for the longshore drift to naturally push the sediment back sooner, which may fill in the depositional gaps. If neither of these solutions if feasible, then the current approach of nourishing the beaches may be the only option Galveston Island has.

For cities and coastal communities looking to implement coastal structures in to the protection of their area, understanding the current geomorphology before beginning the project can be helpful in preventing costly negative effects. Preliminary suitability analysis can help emphasize areas that would work well to capture sediment, as well as give a thorough understanding of the interaction between the proposed infrastructure and the area it will disrupt. More and more coastal communities can be protected by coastal structures if the preplanning is done correctly and long-term effects are drawn out and planned for. The model created in this study is one of many options on how to go about analyzing the relationship between human endeavors and the natural splendor of the coast. Construction of a GIS before the construction of coastal structures can better help infrastructural planners know up to date how effective coastal structures and highlight areas that may be experiencing heavy erosional rates or undercutting before they become a problem.

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