RISING ABOVE: IMPACTS OF COASTAL POLICIES WITH RESPECT TO SEA LEVEL RISE IN GALVESTON BAY, TEXAS

A Thesis

by

RACHEL R. EDWARDS

BA, University of North Carolina- Chapel Hill, 2014

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER of SCIENCE

in

COASTAL AND MARINE SYSTEM SCIENCE

Texas A&M University-Corpus Christi
Corpus Christi, Texas

December 2016

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This thesis meets the standards for scope and quality of
Texas A&M University-Corpus Christi and is hereby approved.

James Gibeaut, Ph.D.
Chair

Richard McLaughlin, J.S.D
Committee Member

David Yoskowitz, Ph.D.
Committee Member

December 2016

ABSTRACT

RISING ABOVE: IMPACTS OF COASTAL POLICIES WITH RESPECT TO SEA LEVEL RISE IN GALVESTON BAY, TEXAS

The Galveston Bay region in Texas is at particular risk of sea level rise (SLR) induced hazards because of its unique geography and geology, including relatively high subsidence rates due to mineral and groundwater extractions. SLR is an exceptionally difficult public policy problem because shorelines have a dynamic nature while typically laws are static. This study examines the effects that four different development strategies could have on landscape structure. Using the Sea Level Affecting Marshes Model (SLAMM), the possible effects of SLR under four development strategy scenarios and three SLR scenarios are examined in four regional subsites that each represents a different natural and built environment. The scenarios are (1) “Armoring Removed” which serves as a control and employs no shoreline protection, (2) Current Armored Shoreline which models the current situation regarding development and armoring, (3) Green Infrastructure which shows what may happen if living shorelines were used instead of armoring, and (4) All Armored (AA) which describes the armoring of the entire site. SLAMM predicted that Developed and Undeveloped Uplands were greatest under the AA scenario and that Marshes and Flats were greatest under the LS scenario. The predictions that armoring would protect uplands and LS would result in more marshes is expected given knowledge of how these strategies work. Action should be taken immediately to develop policies that foster resiliency and avoid the worst outcomes for both human and natural wetland communities in Galveston Bay. This work is part of a larger study on living with sea level rise along the Texas coast.

DEDICATION

To all those who came before and paved the road for me to get here as well as to those who will come after.

I dedicate this thesis work to my family. My dad, Tom, is a source of constant encouragement. I could not count how many “carpe diem” and “the world is your oyster” texts and snail mails I received from him. My mother, Susan, likewise spent hours on the phone with me offering priceless wisdom and perspective on matters both academic, professional, and personal. My sister, Isabel, was a source of constant inspiration; she is extraordinarily talented, and that made me work harder in hopes of not being left behind! I hope that my efforts will, in one way or the other, make this world better for her and her generation.

I also dedicate this work to my friends who I cherish.

As Isaac Newton said, if I have seen further it is only by standing upon the shoulders of giants.

ACKNOWLEDGEMENTS

I owe many thanks to my committee members: Dr. James Gibeaut, Dr. Richard McLaughlin, and Dr. David Yoskowitz. They are leaders in their fields, and their work has been influential on protecting coastal communities and the environment. I have gained much knowledge and confidence in the time that I have been fortunate to study under them, and they are an inspiring reminder that I, too, have the potential to make a positive impact.

Working in Dr. Gibeaut's Coastal and Marine Geospatial Lab has been an incredible opportunity. The people, particularly Mukesh Subedee, Luz Lumb, Marissa Dotson, and Dr. Anthony Reisinger, have all been invaluable resources, and I am grateful for their help and ideas.

Thank you to the National Oceanic and Atmospheric Administration's Environmental Cooperative Science Center and the Houston Endowment for funding my studies and professional development activities over the last two and a half years, including travel to conferences and for allowing me to work on R/V *Falkor*. I also owe a tremendous thank you to the Schmidt Ocean Institute for allowing me to participate on the six-week research cruise; it was truly a once-in-a-lifetime opportunity.

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“Earth belongs to each generation during its course, fully and in its own right, [but] no generation can contract debts greater than may be paid during the course of its own existence.”

Thomas Jefferson

September 6, 1789

CHAPTER I: INTRODUCTION TO SEA LEVEL RISE AND COASTAL POLICY

IMPORTANCE

Legend says that Canute the Great was an immensely powerful Viking king. His couriers praised and flattered him by saying that he was the greatest man on Earth and that he was so powerful that nobody or nothing would dare disobey him. Canute was a sensible man and tired of such claims. He ordered his throne to be put on the dry beach in front of a rising tide, and he commanded the sea to not lap at his feet. His couriers were proven wrong, of course, since the water rose despite his ban. Like the long-ago couriers found out, the sea does not stop for anyone or anything, and it is proving to be one of the largest problems in modern times. It affects the government's management of resources, coastal property owners, and the public because of its "myriad" of impacts including temporary and permanent inundation, flood and storm damage, wetland loss and habitat change, erosion, saltwater intrusion, rising water tables/impeded drainage and lowered coastal property values (Nicholls and Lowe, 2004; Ravens, 2009).

Galveston Bay, TX is the most biologically productive estuary in Texas ("Galveston Bay Estuary Program", 2013). It is a very important region both from an ecologic and anthropogenic perspective. It has the second largest fisheries production of any estuary in the United States and is a hub for birdwatchers. Galveston Bay is also home to one of the largest petrochemical complexes in the world as well as Houston, three international ports, and the Houston Ship Channel (HSC). Most of the area around Galveston Bay is less than two meters above sea level with nearly fifty percent of it at less than one meter above (NOAA, n.d.). Galveston's Pier 21 tidal gauge measured a relative SLR rate of 6.4mm/year, most of which is due to subsidence (Zervas, 2009). The region is extremely vulnerable to SLR because of its natural properties including low elevation, low relief, and small tidal range. These all mean that small changes in sea level have a relatively large effect.

SLR's damage potential rises as assets and population increase in coastal zones because of the increased exposure to coastal hazards. Galveston Bay has high concentrations of assets and population. Galveston Bay is home to one of the United States' primary oil and gas hubs. Other potential socioeconomic impacts of a higher sea level include the following: loss of property and coastal habitats; increased flood risk and loss of life; damage to infrastructure; loss of tourism, recreation and transportation functions; loss of cultural resources and values; and impacts on agriculture and aquaculture (Nicholls and Lowe, 2004). Furthermore, SLR in Galveston Bay is projected to impact infrastructure including roads, railroads, airports, houses, private businesses and public buildings (Subedee et. al, 2016). For these reasons, SLR in Galveston Bay has the potential to hurt the economies of both Texas and the United States.

Under natural conditions, SLR triggers wetland migration to higher elevations. Anthropogenic processes can inhibit that natural progression, however, in a process known as coastal squeeze (Torio and Chmura, 2013). Coastal squeeze reduces ecosystem services and can have negative costs that are oftentimes not accounted for in cost-benefit analyses (Sutton-Grier et. al, 2015). Because human development has such a large effect on ecologic communities, response strategies or public policies in regards to SLR can have implications far into the future. Additional study is necessary to gain a broader understanding of SLR impacts including the long-term effects of community response strategies that may be enacted.

This chapter explores laws and policies that can be used to prepare the Galveston Bay region for SLR. In Chapter 2, a discussion of how these potential policies were implemented within a SLR impacts modeling software will be discussed. This evaluation describes the potential future legal ramifications of SLR as well as an evaluation of ecosystem services gained or lost due to wetland changes. A greater recognition of the complexity and far-reaching effects of resiliency strategies will be a first step in providing the necessary research to communities so that they can construct policies that target their individual priorities. This work is part of a larger multidisciplinary project on living with SLR on the Texas coast which involves the Coastal and Marine Geospatial Sciences, Coastal and Marine Policy and Law, and Socio-Economic Groups.

PAST VULNERABILITY

Hurricane Ike was the third costliest storm in United States history with estimated financial losses of $21.3 billion and 121 human deaths (Mitigation Assessment Team Report, 2009). Ike made landfall over Galveston in September 2008. It was a category two hurricane with maximum sustained winds of almost 110 miles per hour. Storm surge raised water levels in parts of Galveston Bay by over 10m ("Hurricane Ike Inundation Depth", 2009). There was approximately $2.74 billion of damages to houses just from flooding (Hurricane Ike Impact Report, 2008). It affected every industry in the area including health care, agriculture, fishing and tourism as well as the ecology of the surrounding wetlands and water environments; sediments deposited on oyster beds killed the reefs and impacted the surrounding fishing grounds. Ranches received heavy damage to fencing and equipment, and salt deposited from flood waters impacted the productivity of croplands and fields for several years following the hurricane.

In addition to damages to the people and environment, all of the United States was impacted by damages to oil and gas refineries ("Hurricane Effects on Oil and Natural Gas Production Depend on Storm Trajectory, Strength", 2013). The U.S. Department of Energy closed fourteen oil refineries in the region because of Ike which caused cascading effects such as increased gas prices and gas shortages across the United States (Mitigation Assessment Team Report, 2009). Texas identified a need of $2.4 billion to repair erosion damages, dredge waterways and repair infrastructure to "navigable waterways, ports and coastlines" (Hurricane Ike Impact Report, 2008). The Port of Galveston had damages from saltwater and sediment deposits. The impacts of Ike indicate the present vulnerability to the region to big storms. A FEMA report warns that land subsidence, erosion and SLR may cause increased vulnerability and that worse damage may be incurred from similar storms in the future (Koumoudis, 2009). The region is not just vulnerable to large storms, however; cumulative costs of storm surge damage from smaller, more frequent storms as sea level rises could be just as great as a single big storm (Warner and Tissot, 2012).

SLR itself is not a direct threat to human life, but rather it is the storm surge on top of SLR that has the potential to cause widespread damage. As damaging as Hurricane Ike was, the same storm could be much more damaging if it occurs from a SLR-induced higher water platform (Mousavi et. al, 2009). By raising the level from which waves "attack" the shore, SLR enables a greater rate of erosion. Combined with storms and hurricanes that are forecasted to be stronger due to climate change, storm surge will cause even more erosion since it will be able to reach higher on the land/sea interface (Leatherman et. al, 2000). It also allows flooding at places that were previously less vulnerable; for instance, the sea wall along New York's Manhattan Island is now twenty times more likely to be overtopped than it was 170 years ago, and hundreds of thousands of people who previously were not located in potential flooding areas are now located in potentially hazardous areas (Talke et. al, 2014; Thompson, 2014). This provides evidence that continued research into the issue is necessary, particularly in regards to policies that address protection against the growing hazards of SLR.

MOTIVATION AND SCOPE

SLR is an "enormously complex public policy problem" because beaches have a dynamic nature while laws are static (Caldwell and Segall, 2007). A single shoreline will advance and retreat at various times in geologic history, and at a single time certain beaches will be eroding while others will be accreting. These constant changes are oftentimes caused by changes in sea level. The rate of SLR has increased due to global climate change and anthropogenic activities in the last two hundred years and is a driver of shoreline retreat in many locations (Jevreveva et. al, 2014). Furthermore, human migration patterns are putting additional stresses on coastal environments ("Coastal Development: Is overbuilding putting coastal regions at risk?", 2014).

Large scale anthropogenic releases of greenhouse gases began with the Industrial Revolution (Rockstrom et al., 2009). The scientific consensus is that SLR is directly tied to a warming atmosphere due to anthropogenic activities (IPCC, 2014). If, as it happened throughout history until modern times, there was no infrastructure installed in coastal areas, wetland habitats would simply migrate inland. However, the installation of immobile structures along the dynamic land/sea interface creates a net loss of coastal habitats and environments in a process called coastal squeeze (Torio and Chmura, 2013). Coastal squeeze occurs when wetland environments lose their areal extent due to being caught between rising seas and structures; this restriction has limited marshes' ability to vertically accrete or migrate inland and has led to a greater risk of inundation and erosion. (Fig. 1). An estimated 10 percent of Galveston Bay's shorelines are already armored and thus are subject to coastal squeeze (Gonzalez, 2011).

FIGURE 1: BUILT STRUCTURES LIMIT THE MIGRATION OF MARSHES (MINOGUE, 2013).

Development-induced coastal squeeze has caused the areal extent of Galveston Bay's wetlands to decrease. The marsh losses can cause a negative feedback loop whereby habitat conversion results in an alteration of ecosystem services. At the global scale, wetland habitats including marshes and mangroves are carbon sinks, and their destruction releases significant amounts of carbon into the atmosphere which in turn exacerbates SLR (Chmura, 2011). This process can leave humans further vulnerable to storms and erosion. Thus, the protection of marshes and other wetland habitats is one of the easiest and simplest solutions to initiate adaptation to SLR and mitigate climate change impacts (Duarte et al., 2013).

This negative feedback loop largely occurs because people settle coastal areas without enough consideration of environmental issues (McGranahan et al., 2007). It is estimated that at least 25 percent of houses within 500 feet of the US coast will be lost to SLR by 2060 (Nichols and Bruch, 2008). Furthermore, greenhouse gas emissions can remain in the atmosphere for extended periods of time (Neumayer, 2000). This means that, even in the hypothetical scenario that greenhouse gasses were to stop being released immediately, the planet still has a commitment to change. The anthropogenic additions to atmospheric gasses will continue trapping solar thermal energy leading to additional SLR. It is estimated that, given a 2m rise in sea level, 2.4% of the global population could be displaced by 2100 due to the inundation of infrastructure in urban landscapes (Nicholls et al., 2011).

Coastal development affects Texas in general and Galveston Bay in particular. Twenty-five percent of Texas's population lives in its eighteen coastal counties, and 75 percent of that 25 percent lives on the west side of Galveston Bay; conversely, the east side of Galveston Bay is quite rural (Merrell et al., 2010). Texas had a 154 percent increase in coastline counties' population density from 1960-2008, and it is predicted that there will be an 80 percent increase in population from 2005 to 2040 (Wilson and Fischetti, 2010; Lester and Gonzalez, 2011). Eighteen million people are expected to live in the Galveston Bay watershed by 2040 (Lester et al., 2013). Galveston Bay's natural characteristics make the region vulnerable to SLR, and migration patterns towards the coast only exacerbate the issues.

It is obvious that the region is susceptible to SLR, but what are the options for learning to live with it? This chapter discusses current laws in Texas that address SLR and issues that must be considered when writing policies. It also gives an overview of policy options including an in-depth exploration of four particular responses: (1) leaving currently armored shorelines as they are, (2) building living shorelines, (3) armoring shorelines, and (4) organized retreat. A brief discussion of several other response options is also included. It is not feasible to wait to gain a complete understanding of the system before determining how to adapt, and it is too late to protect developed areas that are already armored (Nichols and Bruch, 2008). This is because it is difficult to uninstall existing armoring; doing so requires the development of a new land/sea equilibrium further inland and thus causes much erosion. As such, the focus of this chapter will be on emphasizing options for undeveloped areas. Policies have a greater chance of making a positive impact in undeveloped areas both by improving human safety and by protecting natural ecosystems.

STUDY AREA

Galveston Bay is a shallow estuary with protective barrier islands and has been named an estuary of national significance by the Environmental Protection Agency National Estuary Program (Schroeder and Wiseman, 1999). Galveston Bay has 600 square miles of Open Water and 232 miles of shoreline, and its watershed extends 27,000 square miles up to the Dallas-Ft. Worth complex ("Galveston Bay Estuary Program", 2013). An estimated 75 percent of North America's bird species pass through the bay including endangered species such as the piping plover (Arkema et al., 2013; GulfBase, 2016). The Central Flyway, a path for an estimated 400 species of migratory birds, cuts through the region as does the Great Coastal Birding Trail which offers 500 miles of sites for birdwatchers ("Bird Migration: Birds of the Central Flyway").

Galveston Bay is also an extremely significant metropolis to both Texas and the United States due to its industry, trade, and petrochemical importance. Houston, located northwest of the bay, is the fifth largest city in the United States. The Port of Houston is the largest port in the country in regards to foreign tonnage and second in overall tonnage, and the Gulf Intracoastal Waterway runs through the bay. The region is home to the United States' largest concentration of oil refineries; approximately 26 percent of the United States' gasoline, 42 percent of base chemical production, and 60 percent of jet fuel production is produced in the region ("The Port of Houston Authority", n.d.). Infrastructure is worth an estimated $100 billion, and the ports generate hundreds of thousands of jobs annually. Galveston Bay also has the third largest concentration of privately owned marinas in the country ("Galveston Bay Estuary Program", 2013).

The entire bay system is made up of four sub-bays: Trinity, Christmas, East and West Bays. The East and West Bays are lagoons created around 7.7 ka and 7.5 ka respectively, and Trinity Bay is an incised valley that was created around 5.3 ka (Rodriguez et al., 2004). The Texas City Dike and a series of large natural oyster reefs inhibit hydrodynamic mixing between the sub-bays; dredge deposits also affect localized currents. The Texas City Dike additionally interrupts longshore transport and has altered the salinity regime in West Bay, causing decreased sediment supply and higher salinities.

West Bay’s natural inlet, San Luis Pass, also results in greater tides and greater salinities relative to East Bay (Lester and Gonzalez, 2011).

Galveston Bay has been impacted significantly by development, pollution and wastewater, channelization, dredging, and other alterations (Handley et al., 2007). For example, the average depth of the bay is just over 2 m, but the Houston Ship Channel, which is 200m wide and 50 miles long, is dredged to 15 m (Fig. 2). About 75 percent of the freshwater flow comes from the Trinity River located at the northeast quadrant of the bay, and freshwater discharge is the primary driver for salinity distribution (Orlando, 1993). Thus, Galveston Bay has a strong salinity gradient (Fig. 3) that is close to 0 psu at the north end of the bay where the Trinity and San Jacinto Rivers discharge to 35 psu where the bay connects to the Gulf (Lester and Gonzalez, 2011). Psu stands for Practical Salinity Unit and describes how saline a parcel of water is. Additionally, there is a precipitation gradient caused by more precipitation on the west side of the bay than the east.

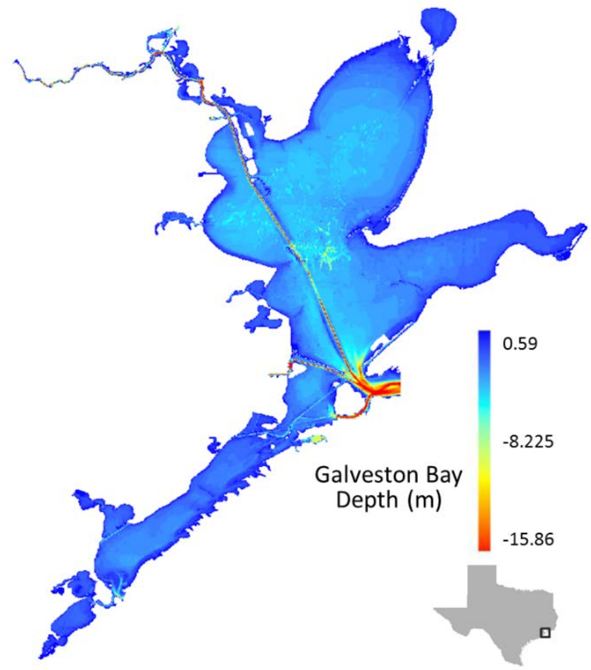

FIGURE 2: GALVESTON BAY DEPTH MAP

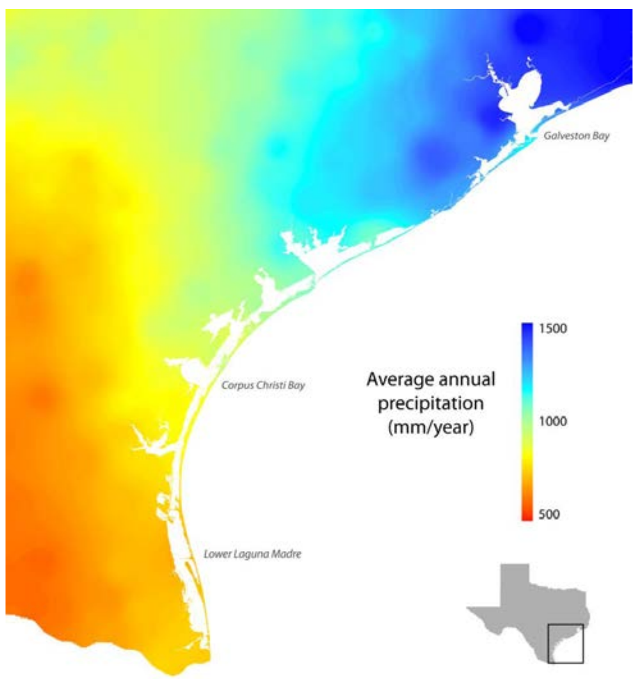

FIGURE 3: AVERAGE ANNUAL PRECIPITATION RATES ON THE TEXAS COAST FROM 2000-2013 (DOTSON, 2016).

Galveston Bay's average wave heights are 0.6 m in water 3 m deep and 1.2 m in water that is 15 m deep (Morton and McGowen, 1980). The system is microtidal. Astronomical tides average 0.3 m, and they are mostly diurnal (Schroeder and Wiseman, 1999). Wind tides can be an additional 1 m, and storm surge can be up to 7 m (Lester and Gonzalez, 2011). The chance of flooding for a given year is expected to increase with SLR (Warner and Tissot, 2012). Gulf and bay shorelines in the region exhibit highly variable shoreline change rates from -4.5 ft to +4.5 ft per year (Fig. 4). Measurements indicate that sediments are accreting on Galveston's coast at a rate of about 0.20 cm/year (Ravens, 2009; Dolan and Wallace, 2012). Coastal change in the Galveston Bay region has been affected through the use of dams, the diversion of rivers causing delta erosion and formation, and by affecting flooding events all of which change the natural flow and sediment transport. The damming of the Mississippi and Trinity Rivers decreased sediment accretion rates up to 75 percent (Ravens, 2009). Partially for these reasons, 78 percent of the Gulf shoreline saw retreat of its net shoreline in the period between 1850 to 1982 (Morton and Paine, 1986). If there was enough sediment in the system so that shorelines could maintain their positions and marshes and tidal flats could vertically accrete, then the effects of SLR would be lessened, but this is not the case in Galveston Bay.

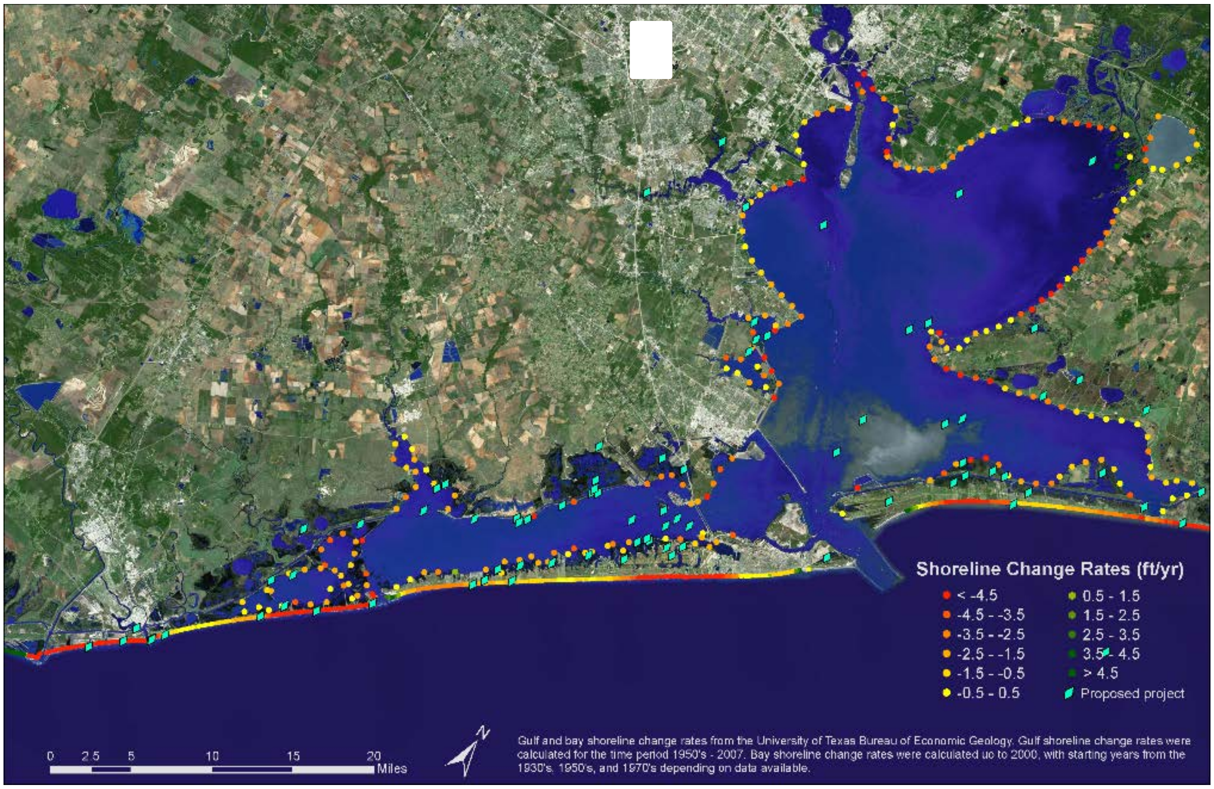

FIGURE 4: GALVESTON BAY'S AVERAGE ANNUAL GULF AND BAY SHORELINE CHANGE RATES FROM THE 1950S TO 2007 FROM THE UNIVERSITY OF TEXAS BUREAU OF ECONOMIC GEOLOGY.

Subsidence is a characteristic that increases Galveston Bay's vulnerability to SLR. Subsidence is when the land surface lowers relative to a fixed datum to natural processes or anthropogenic causes. The area around Galveston Bay is subsiding to a small degree because of natural sediment compaction and tectonics (Paine, 1993). The predominant cause of subsidence in the region, however, is groundwater and oil and gas extractions which initiated geologic fault movements (White and Morton, 1997). The extractions result in a lack of volume and internal pressure which causes the land to gradually, consistently, and permanently sink, which then threatens both built and natural environments. Over a thirty-year period, nearly 5,000 square miles of land subsided at least 15 cm with some areas subsiding more than 3 m; additionally, more than 31 square miles of land was permanently inundated (“Subsidence and Groundwater Regulation FAQs,” n.d.).

The neighborhood of Brownwood was one area that succumbed to subsidence (Ingebritsen and Galloway, 2014). Located in Baytown, TX, which is north of Galveston Bay along the Houston Ship Channel, the neighborhood originally was only inundated by hurricanes and large storms. Over time as the land subsided by more than 3 m, even mild storms, wind, and high tides could cause the inundation of houses (Fig. 5). The neighborhood was abandoned in 1983, many houses were bought out by FEMA, and the neighborhood was turned into wetland habitats by the Baytown Nature Center. No houses exist today in the once-affluent neighborhood because of subsidence and SLR (Ingebritsen and Galloway, 2014). Groundwater extraction peaked in 1970, and in response the Houston-Galveston Subsidence District was created in 1975 to minimize subsidence in the region through the regulation of groundwater withdrawal (Coplin and Galloway, 1999). They have been largely successful as evidenced by the fact that subsidence rates are lessening.

FIGURE 5: THE BROWNWOOD NEIGHBORHOOD HAD SUBSIDENCE-CAUSED UNCONTROLLED FLOODING ("BNC INFORMATION", 2016).

These historical lessons provide evidence that coastal systems respond rapidly to change. Although the geomorphology of coastal areas has changed throughout geologic time, these changes have all been exacerbated by anthropogenic processes; humans are now the dominant control on coastal change in a virtually instantaneous time period (Vitousek et. al, 1997). An ongoing increase in SLR rate will continue to severely impact low gradient coasts, especially since the reaction time of policy makers tends to be slow.

General Overview: Coastal Squeeze and Ecosystem Services

Coastal ecosystems are among the most productive, valuable, and vulnerable habitats in the world due to the ecosystem services they provide (Costanza et al., 1997). Ecosystem services are the processes and conditions generated by ecosystems that are critical to sustaining human life (Salzman et al., 2001). These include flood and drought attenuation, water purification, detoxification of pollution, removal of excess nutrients, carbon sequestration, storm protection, the provision of nursery grounds for nearly all fish species at some stage of their life cycle, the protection of biodiversity, the catching of excess sediments resulting in accretion, and economic benefits including farming, fishing and recreational activities. Recent research has begun looking at quantifying the financial value of ecosystem services which is proving to be great; the collective value of all ecosystem services in 2011 was estimated to be $125 trillion (Costanza et al., 2014). Should ecosystems disintegrate, the cost of artificially purifying water just in the United States could be billions of dollars (Salzman et al., 2001). Additionally, the loss of 1 ha of wetlands is estimated to cause an average of $33,000 more damage per major storm (Living Shorelines, 2015). Overall, Galveston Bay's ecosystem services are estimated to be over $5 billion per year (SSPEED, 2014).

Coastal settlements, which represent a disproportionate amount of the United States' population, are more at risk of hazards related to sea level rise (National Coastal Population Report: Population Trends from 1970 to 2020, 2013). The increased vulnerability partially caused by climate change-induced eroding shorelines and stronger storms leave humans and infrastructure along the coast at a greater risk for SLR-related hazards. Marshes can protect communities against sea level rise and can mitigate the associated impacts (Sutton-Grier et. al, 2015). The friction from marsh vegetation dissipates wave energy which reduces the inundation risk for inland areas (Currin, 2010). This protective capability has the potential to be leveraged by coastal communities. Marshes, which act as a buffer between the open water and the shoreline, can protect coastal development from increased risks which can lead to higher property values, increased infrastructure investment, lower insurance rates, and a stronger local economy (Geselbracht et al., 2015). Marshes have many other socioeconomic non-monetary values. They are a carbon sink since they sequester large amounts of biomass. This can reduce the accumulation of greenhouse gasses in the atmosphere and potentially lower the future impacts of climate change. Marshes are also a nursery habitat for many organisms including fish and birds which impacts the local economy. An acre of salt marsh can add up to $1.89/acre to the value of the Gulf Coast blue crab fishery alone, and in England the value of an acre of salt marsh for waterfowl habitat is estimated to be greater than $600 (Barbier et al., 2011). Both fishing and birdwatching are huge contributors for the local economy in and around Galveston Bay (Whittington et. al, 1994).

Marshes are dynamic systems that have non-linear, variable responses to SLR. They are also one of the fastest-disappearing wetland types (Bridgham et. al, 2006). The areal extent of salt marshes has decreased by about 50% globally while some areas such as the western United States have seen decreases greater than 90% as a result of SLR, decreased sediment supply, and coastal squeeze (Barbier et al., 2011; Lester and Gonzalez, 2011). Flood waters which carry sediment can cause marshes to accrete vertically at higher rates and thus prevent them from being inundated and drowned. Certain species increase their productivity in response to flooding durations; conversely, floods can also cause marsh collapse. This can occur either when flood waters carry too much sediment and bury the vegetation or when salinity and/or pollutant changes impact the vegetation. The death of vegetation releases the previously contained carbon back into the system which can trigger a negative feedback loop (Chmura, 2011). The ability of marshes to "engineer their environment" reinforces "their remarkable capacity for supplying ecosystems services" (Duarte et al., 2013).

Ecosystem services are important to consider when determining the benefits and drawbacks of potential policy responses to SLR since the loss of wetlands through coastal squeeze causes a net loss of ecosystem services. One study found that there would be a loss of nearly $88 million/year in fresh marsh ecosystem services and nearly $14 million/year in salt marsh ecosystem services from present to 2100 given a 0.69 m rise in sea level (Yoskowitz et al., 2012). The six ecosystem services under study were disturbance regulation, recreation, food, aesthetics, nutrient cycling, and soil retention. For these reasons, preserving and conserving wetlands is among the "cheapest, safest, and easiest" solutions to reduce the effects of and promote adaptation to climate change (Duarte et al., 2013).

BACKGROUND ON EXISTING LAWS

This work is part of a larger study on living with SLR on the Texas coast. Earlier work completed through the project examined government documents including comprehensive plans of coastal counties and municipalities in Florida to see which ones mentioned SLR. Florida was chosen as an initial step in this study because it is the Gulf state most prepared for SLR. Accordingly, it was expected that the government would address relevant and necessary changes in the coastal zone in preparation of the changing landscape. While some municipal governments have done so, this was complicated by the unofficial policy that Florida Department of Environmental Protection adopted in 2011 which bans employees from using the terms "sea level rise" or "climate change" (Korten, 2015).

The same work was also completed in Texas. Texas and Florida can thus be compared in an effort to see the strengths and weaknesses of each; this analysis can hopefully then be used to inform policy makers and thereby potentially structure future governmental plans in regards to preparing against SLR hazards. Initial results of the analysis of Texas governmental documents indicate that while the state has begun preliminary work, overall the state is unprepared for SLR. The researchers found that 26 of 195 local governments in Florida mentioned SLR as of 2015 (Ruppert and Stewart, 2015). This is in contrast to Texas; of the eighteen counties and approximately 50 municipalities investigated, only six counties and five municipalities mentioned SLR.

The Texas Coastal Erosion Planning and Response Act of 1999 (Tex. Nat. Res. Code § 33.607) aims to prepare the state for SLR. It is a statewide program designed to fund projects that battle erosion in critical Gulf- and bay-facing areas along the coast. It emphasizes the use of dune restoration and beach renourishment coupled with monitoring and studies to prevent the shoreline from retreating landward ("Coastal Erosion Planning and Response Act", 2016). It has also budgeted for removing structures that are located on the public beach because of erosion. Beyond this, Texas' Gulf- and bay-facing beaches are subject to different laws and regulations. An overview of them follows.

GULF-FACING BEACHES

Texas has some of the most progressive laws of any state in the United States when it comes to protecting Gulf of Mexico-facing beaches. These laws include the Texas Open Beaches Act of 1959 (TOBA) and the Dune Protection Act (DPA). TOBA (Tex. Nat. Res. Code § 61.011) ensures that the public has unrestricted access to Gulf-facing beaches through a public easement while DPA (31 Tex. Admin. Code § 15.3) protects dunes by preventing construction upon them. TOBA was enacted in 1959 and was incorporated into the Texas Constitution by public referendum in 2009 following concern over the possibility of losing public access to Texas Gulf beaches. It attempts to balance public and private interests. The liberal interpretation of the courts in regards to TOBA has led to the development of a "rolling easement doctrine" which allow the public to use the beach seaward of the vegetated dune line as it moves due to natural forces (McLaughlin, 2011). Texas courts have also applied custom-based laws to justify rolling easements because, in order for them to be useful and "reflect the reality of the public's actual use of the beach, [the easements] must migrate as did the customary use from which it arose" (Caldwell and Segall, 2007).

Rolling easements ensure sandy beaches are able to migrate inland as the water level rises (Fig. 7). Courts have held that the purpose of TOBA was to provide the public with unrestricted access to public beaches and that not allowing the public's use to shift with the changing contours of the beach would, in some cases, cause the public's use to entirely disappear. Rolling easements restrict development seaward of the easement's landward boundary and give the framework for the removal of structures that are located seaward of the landward boundary (Titus, 2011). They also prevent the installation of any artificial armoring, and existing houses or other structures are subject to removal when erosion or other processes move the vegetation line landward of the structures (Titus, 2011). This not only guarantees the public's right to Texas' Gulf-facing beaches, but it also protects the sandy beach from being eroded due to artificial armoring.

DPA requires each county with a Gulf-facing beach to establish a line along beach dunes, no further landward than 1,000 feet (approximately 305m) from the mean high water line along the Gulf (Tex. Nat. Res. Code § 63.012). Seaward of this "dune protection line," a permit must be obtained in order to partake in any activities that disturb the dunes. This effectively prevents development from intruding on the beach, thus protecting the beach and dune system. Local legislation in Texas can additionally enact setback rules that prevent development, the most stringent of which is Nueces County. The County disallows most construction from the seaward edge of the dune at the line of vegetation landward to 350 feet (McLaughlin, 2011). These progressive laws do an excellent job of protecting Gulf-facing beaches and maintaining the ecosystem services they provide, and they serve to buffer the effects of SLR.

Severance v. Patterson

Severance v. Patterson (2012) is a recent case that weakened TOBA and thus the protection of Texas' Gulf-facing beaches. Ms. Carol Severance, a resident of California, bought three properties in Galveston with the intention of renting them as vacation homes. When she purchased the houses, she was required to sign a notice titled Disclosure Notice Concerning Legal and Economic Risks of Purchasing Coastal Real Property Near a Beach that stated that the houses were located in vulnerable locations- two were completely and one was partially seaward of the vegetation line, and one had been on a Texas General Land Office list for homes seaward of the vegetation land since 1999 (Fig. 6) - and thus they were subject to removal. In 2005, Hurricane Rita eroded the beach considerably, and in 2006 a notice sent to Ms. Severance reiterated that the houses were subject to removal. Ms. Severance filed suit against Texas Land Commissioner Jerry Patterson after partnering with Pacific Legal, a conservative property rights non-profit.

FIGURE 6: A SEVERANCE HOUSE AFTER HURRICANE RITA (ROGER WILLIAMS UNIVERSITY, N.D.).

After moving through the court system multiple times, the Texas Supreme Court found in a highly controversial decision that structures are only subject to removal under TOBA when imperceptible erosion causes the loss. The court claims a distinction between avulsion which are “sudden occurrences” and erosion which occurs “imperceptibly” (Howe, 2010). They held that, in this case, despite evidence of years of imperceptible erosion, the overnight erosion caused by Hurricane Rita was avulsive, and thus TOBA did not apply.

The distinctions between avulsion and erosion, while important in a legal context, have limited value in applied science. This finding demonstrates an unclear understanding of geology and natural processes; the ocean and thus shoreline are dynamic and constantly changing. The distinction between erosion and avulsion is ambiguous and effectively requires the re-establishments of easements after each hurricane season. Additionally, it guarantees that the State will be involved in expensive court cases with individual landowners for years to come. Lastly and most importantly, it “defeats the purpose of [T]OBA: to maintain public beach access” (Wiener, 2009).

The Severance case had immediate consequences beginning with the cancellation of a $40 million beach renourishment project in West Galveston (Roper, 2013). Because public funds are not permitted to be used to benefit private homeowners and there was confusion regarding whether a public easement existed on the beach in question- as believed prior to Severance- or whether Severance did away with the public easement, the project which would have reduced the vulnerability of coastal homes had to be cancelled.

In 2013, House Bill (HB) 3459 was enacted which gives the Texas General Land (GLO) commissioner the ability to determine whether avulsion or erosion occurred in certain cases. It offers a three-year moratorium to allow the area to settle naturally; during that time, the public easement is 200 feet from mean low tide (MLT). After that period of time, the commissioner may be advised by the Bureau of Economic Geology of the University of Texas to determine whether the change was avulsive or if it was "within the normal rate of erosion" (Patterson, 2014). If determined to be erosive, the public easement will roll to the vegetation line. As long as the commissioner listens to the science, this bill is a step towards protecting Texas' beaches and public access to them. A commissioner who errs on the side of private property rights, however, could be dangerous to both as the Severance case so clearly demonstrated.

TOBA protects Gulf-facing sandy beaches from coastal squeeze by requiring the removal of any structures that are seaward of the vegetation line. Erosion and accretion are natural processes, but erosion is becoming dominant partially due to SLR. TOBA protects the public's right of access which Texans have historically treasured; this is evidenced by the fact that it was voted into the state Constitution, but the Severance decision dealt it a significant blow. By not removing structures, under some circumstances, that are seaward of the vegetation line, Gulf-facing beaches are more vulnerable to SLR-induced coastal squeeze.

BAY-FACING BEACHES

Although Texas' Gulf-facing beaches are protected by some of the most progressive laws in the United States, its 3,300 miles of bay-facing shorelines have much less protection; private property may only be subject only to the owner's will. Texas law provides the GLO only with jurisdiction on public lands that are below the mean high tide line (MHTL). If a rising sea is triggering erosion, the land owner must only get the land surveyed (Residential Application Packet, 2013). Armoring may then be installed as long as it is just above the MHTL and thus not on public lands, regardless of whether coastal squeeze will cause the loss of wetland habitats and their ecosystem services which benefit everyone. The only protection bay-facing wetlands and beaches have in Texas are standard, federal laws such as the Clean Water Act Section 404 which protects coastal wetlands or any incorporated city ordinances.

Because unincorporated communities are under state law and since no state laws exist to protect wetland habitats, unincorporated communities do not have the legal authority to protect coastal habitats (52 Tex. Jur. 3d Municipal Corporations § 139; 8B Tex. Jur. Pl & Pr. Forms § 176:2 (2d ed.)). Thus, there are very few protections for undeveloped bay-facing properties that are unincorporated. The current state legislature has placed an emphasis on protecting private property owners, and therefore it can be expected that no protections for wetlands, above the MHTL, will be enacted at the state level. Incorporated cities should enact their own protections for bay-facing wetland habitats; hopefully protection under the law could then spread from community to community. This severe lack of regulation for bay-facing properties stands in stark contrast to the progressive protection given to Gulf-facing beaches by TOBA and DPA.

TAKINGS

The Bill of Rights was included in the Constitution out of fear that the federal government was too powerful. Stating that "private property [shall] not be taken for public use, without just compensation," the Fifth Amendment aims to prevent the federal, state or local government from infringing upon an individual's private property without due compensation. Any government action, including policies designed to protect property owners and civilians living in the coastal zone, which "deprives a landowner of all economically viable use of the property" can be considered a taking (Nichols and Bruch, 2008).

Legal protections for wetland habitats by nature almost always prevent the landowner from using his or her property in some way (Titus, 1998). For instance, the prohibition of armoring ensures that erosion will erode the private property. Should this type of regulation be considered a taking since the government is preventing the landowner from protecting what is legally his or hers? It depends upon how individual laws are written and what type of impact they may have on the owner's use of the property. Policies today must be cognizant of this, and laws and regulations need to be written in such a way that minimizes the probability that the state will be involved in costly court fees and payouts in regards to takings issues.

A consideration in takings cases is investment-backed expectations (Pelose and Caldwell, 2011). Coastal residents' expectations can be tempered through real estate listings notices and disclosure requirements that inform and warn the potential buyer of the effects of SLR. These notices can influence investor-backed expectations and thus minimize takings claims (Nichols and Bruch, 2008). Under Texas state law, Natural Resource Code Section 61.025 requires that all individuals buying land "in close proximity" to the Gulf sign a Disclosure Notice Concerning Legal and Economic Risks of Purchasing Coastal Real Property Near a Beach. It informs the buyer of "potential risks of economic loss" that inland properties do not have. It also informs the buyer that he or she may be financially responsible for removing the structure if it becomes located on the public beach due to erosion or storm events (Texas Nat. Res. Code § 61.025). Adopting similar notices in bay-facing areas would be very politically controversial and unrealistic.

To help avoid takings claims, regulations must, in accord with the Nollan v. California Coastal Commission (1987) case, have an essential nexus where the "purpose of the exaction condition… matches what would be the justification for an outright prohibition of the proposed development" (Wolf, 2013). It also, in accord with the Dolan v. City of Tigard (1994) case, must have a rough proportionality to the parcel as a whole whereby "the nature and extent of the real property interest being exacted" is "roughly proportional to the impact that the proposed development would have on the coastal environment" (Nichols and Bruch, 2008; Wolf, 2013). Both tests are designed so that a few people- the private property landowners- are not forced, in the words of Amendment 5, "to bear public burdens which, in all fairness and justice, should be borne by the public as a whole." Requiring an easement in exchange for a permit to build or renovate generally does not count as a takings, in accordance with the Nollan and Dolan cases.

The Fifth Amendment is designed to protect the private property owner from the government, not forces of nature. Thus, policies can minimize the risk of takings by emphasizing that its protections are in response to forces of nature and are not for its own benefit. Policies should explicitly state what is and is not allowed as well as the "background principles' attributes" of the new regulation (Wolf, 2013).

POLICY ISSUES FOR DYNAMIC SYSTEMS

There are many considerations that go into determining which policy or series of policies should be enacted to protect against SLR. Short- and long-term benefits, ecological and economic impacts, and legal issues including takings are some of the most important factors. Furthermore, the natural world is a dynamic system; static, rigid laws will not be effective in the long-term. This emphasizes the need for adaptive laws that "provide room for changing conditions and lessons learned" (Nichols and Bruch, 2008).

It is important to look at projected economic and ecologic costs when determining which SLR policies are most beneficial and effective at a given time in a given place. Policies are all restricted by the "values, perceptions, processes and power structures" that exist within a society, and adaptable societies are aware of "diverse values, appreciation, and understanding of specific and variable vulnerabilities to impacts" (Adger et al., 2008). Communities must also be aware that all SLR adaptations will lead to some loss either in developable land or in wetland habitats and their ecosystem services or in lost business opportunities if the community retreats. Furthermore, what works in one environment may not be suitable in another one. Factors that must be considered include whether the policy is designed to work in the short- or long-term, the high levels of uncertainty as to what sea level will actually do, what its effects will actually be, and what the community's cultural expectations are (Alexander et al., 2012).

Policies must be science-based. Those that "ignore the dynamics of coastal states and systems" can disrupt both natural and human systems with potentially "catastrophic" results (Higgins, 2008). This is the epitome of disaster since the entire purpose of policies is to protect the people who live in the coastal area, and, if the policies disrupt the system and endanger the people living nearby, it clearly failed. Unfortunately, if this were to occur, it would likely be too late for the sensitive ecosystem to recover. This emphasizes the need for well-thought-out, scientifically-based policies whose impacts have been thoroughly studied.

A dichotomy exists between the scientific community which overwhelmingly agrees that climate change is occurring and the general public which questions whether or not it is occurring (Marlon et. al, 2013). If no strategies to protect against SLR were enacted, the worst case is billions of dollars' worth of damage and the potential for casualties particularly from hurricanes. SLR makes coastal population more vulnerable to hurricanes since storm waves "attack" the shoreline from higher levels compared to lower sea levels. According to work done by Subedee et al. (2016), approximately 80,000 more people will be at risk of being displaced if Hurricane Ike was to occur in 2100 with 0.74 m of SLR compared to the number who actually were displaced when Ike hit in 2008. Additionally, 48 fire stations, hospitals, police stations, and schools are at risk given 0.74 m of SLR by 2100. Funds to combat huge natural disasters come directly from taxpayer-funded governmental organizations such as the Federal Emergency Management Agency (FEMA) which provides billions of dollars in aid. For instance, nearly $20 billion was paid just to Louisiana in the years before 2015 ("Louisiana Recovery Update: Katrina and Rita by the Numbers, 2015").

Conversely, if policies are enacted and the sea actually does not rise into the future, the worst case scenario will be that money was unnecessarily spent and businesses lost out on revenue from not building in coastal areas. The worst case scenario of proactive policies- that they were unnecessary- is much less than the worst case scenario of doing nothing, which is potentially increased structural damage and an increase in the number of human deaths.

OPTIONS

The Texas coast in general and Galveston Bay in particular are at a high to very high risk of adverse SLR impacts. As of 2014, 1.6 million people lived in the Galveston Bay region's hurricane evacuation zones and another million is predicted to move into the area by 2035 (SSPEED, 2014). With current roads and other limitations, it would take at minimum thirty-six hours to move the residents out of the hurricane evacuation zones, a process often wrought with chaos and other issues (Fig. 7). Many residents choose not to leave and thus are endangered, and those who do evacuate leave billions of dollars' worth of infrastructure behind. Hurricanes striking the coast when sea level is higher than it is today will place even more people at risk, thus emphasizing the need to plan for higher sea levels and the direct and indirect hazards it causes (van Aalst, 2006).

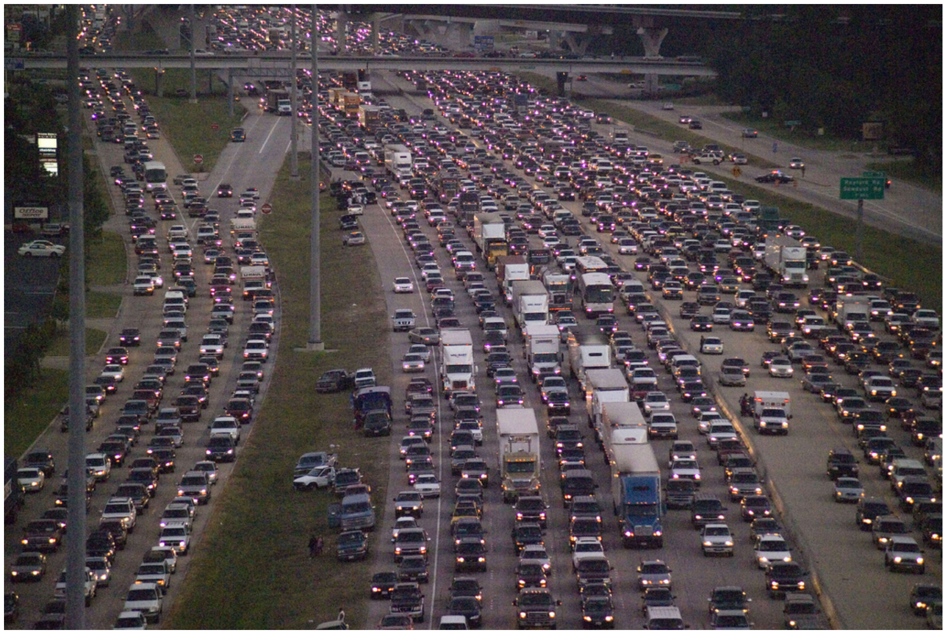

FIGURE 7: THERE WERE PROBLEMS WITH THE EVACUATION FROM HURRICANE RITA (HURRICANES: SCIENCE AND SOCIETY, 2005).

The Army Corps of Engineers' Regulation No. 1100-2-8162 "Incorporating Sea-Level Change in Civil Works Programs" works to integrate "the direct and indirect physical effects of projected sea-level change across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining Corps projects and systems of projects" (U.S. Army Corps of Engineers, 2011). However, the United States does not currently have, nor is there a dialogue about, a national program to protect its urban areas from SLR; it is up to individual states, cities, and communities to determine how to best combat it. Additionally, politicians do not prioritize SLR planning because "in political terms," SLR does not need to be "dealt with this week" (Janin and Mandia, 2012). While the facts that the sea is rising is widely accepted in the scientific community, there is a disproportionate level of discourse from nonexperts. The scientific knowledge of SLR and its effects has outpaced legislation and regulations. Consequently, this controversy makes it difficult for any SLR projects to gain traction and the financial support that is necessary for defensive projects, policies, or laws to be successfully executed or implemented. An exception to this is after a disaster such as Hurricane Sandy when funds are made available to research and prepare so that the city is not as vulnerable to a future, similar storm. Despite the tangle of financial, political and bureaucratic red tape, it is nevertheless necessary to begin developing and implementing plans to combat SLR immediately.

Policies designed to combat SLR have strong socio-political aspects; they must attempt to balance economic development and resource protection (Johnson, 2000). When determining what policy or policies to enact, a government must carefully define what, in the mind of its constituents, is a "superior" policy (McGuire, 2013, p. 75). For instance, a policy that is predicted to have a large economic benefit at a small financial cost may have such large ecological costs that the policy may actually be "inferior" (McGuire, 2013, p. 75). This emphasizes the need for the community to determine what it values, what it aims to protect through policies, and how far into the future it is willing to plan. Different policy options will be most suitable for different community values. In general, community members are not only concerned with the "economics and science" of policies but also their "fairness, transparency and morality" (Alexander et al., 2011). Additionally, communities must consider that in some locations the negative costs incurred by not armoring is less than the benefits derived by that action. One study in Tybee Island, GA, for example, compared the "estimated recreational benefits" to the costs incurred for armored beaches and those that were 20 m wider with no visible armorings (Landry et al., 2003). They found that the wider, unarmored beaches had "very huge" benefits compared to the estimated costs that are required to achieve the higher quality (Landry et al., 2003).

Four policy response options to SLR will be considered and modelled in this paper: "Current Armored Shoreline," All Armored, Living Shorelines and Armorings Removed. Additionally, several others will be briefly outlined. Living shorelines and armoring removed are considered sustainable options because they preserve ecosystem services and protect coastal residents. Current Armored Shoreline and All Armored, conversely, are unsustainable since they will not work once sea level reaches a certain level and either impacts structures directly or overtops the armoring.

CURRENT ARMORED SHORELINE

"Current Armored Shoreline" (CAS) is the term used to describe would happen if no further steps were taken to stabilize shorelines. CAS does not physically move people away from the coast into areas that are less vulnerable to flooding or storm surges through an organized retreat, nor is the area fortified against existing hazards with armorings. Many coastal communities in the United States have not enacted plans to adapt to SLR, thus they are on the CAS track. Under this lack of a policy, construction of houses or businesses is not significantly restricted along the coastline, more laws meant to protect wetland habitats are not enacted, and people are allowed to fortify private lands against SLR. Additionally, wetland habitats and the services they provide may be destroyed through coastal squeeze caused by development too close to the shoreline. This is an expensive choice as "substantial investments are already at risk and vulnerable" (California Department of Water Resources Integrated Regional Water Management, 2010).

SHORELINE ARMORING

The Dutch are the world's leaders in science-based SLR defenses (Goemans, 1986). The country's lowest point is more than 6.5m below sea level, and approximately two-thirds of the country is vulnerable to flooding (Janin and Mandia, 2012). The Dutch are planning for a SLR maximum of 4m by 2200; this kind of dialogue about the worst-case is vital and is also missing in the United States. For example, southern Louisiana is one of the most vulnerable regions in the United States to SLR and flooding, but its defense system was designed for a Category 3 hurricane and a 4.3m storm surge (Grunwald and Glasser, 2005).

The probability of a similar or more severe storm at some point in the future is inevitable; the strength of a 100-year storm or flood will increase over time as a result of global climate change (Gornitz, 1990). When the surge from such a strong storm hits defenses that were not designed to withstand such forces, devastation can result; for example, the breaking of levees during Hurricane Katrina caused much of the flooding of New Orleans. Although that break was caused by a weak structure, it also can occur due to a storm larger than it was designed to withhold (Grunwald and Glasser, 2005). The Dutch plan for a once every 10,000-year flood while New Orleans plans for a once every 100-year flood and New York City plans for a once every 500-year flood (Janin and Mandia, 2012). These ratios mean that any given year has a 1 in 100, 500, or 10,000 chance of being hit by a storm of a certain strength. The areas around Galveston Bay are not planning for a worst-case scenario either despite the fact that the planning, design, and installation of protective features should occur in the shortest amount of time possible. During the many years it will take to complete construction of any project, the city is without adequate protection and will be vulnerable.

Shoreline armoring is when structures are used to prevent the shoreline from moving. This approach is used by large cities such as New York City and Miami as well as other areas with "highly valued and immovable assets" whose infrastructure is so great that a retreat is not feasible (Alexander et al., 2011). While it can effectively prevent erosion at a particular section of shoreline, it generally exacerbates erosion down the beach and can cause the net loss of often-critical wetland habitats and the ecosystem services that they provide. Down-beach erosion is caused through the disruption of the longshore currents' erosional and depositional process that occurs naturally on all beaches. In addition, wave refraction erodes sediments around the sides of the armoring causing the typical crescent moon shape and can erode properties downdrift (Fig. 8).

FIGURE 8: WAVE REFRACTION CAN CAUSE MORE EROSION (VIRGINIA INSTITUTE OF MARINE SCIENCE, N.D.).

Armoring restricts access to sandy beaches and can completely cut off beach access from the general public (Griggs, 2005). It can also destroy the beach altogether through both coastal squeeze and through vertical erosion (Toft et. al, 2013). Vertical erosion (Fig. 9) occurs because waves reflect off the seawall and scour below the structure, thus deepening the water depth (Griggs, 2010). This steepens the slope underwater and causes subsequent waves to strike the seawall harder, thereby accelerating the need to have it reinforced. This is why seawalls and other armorings need to be regularly maintained (Griggs, 2005). If they are not reinforced, the structure can collapse and cause the loss of a significant amount of land (Fig. 10, Restore America's Estuaries, 2015). Even if they are structurally sound, a rising sea may still overtop static armoring structures that were designed when water was at a lower level. Issues such as these have led to a tightening of restrictions for armoring projects in states including Texas, Rhode Island and North Carolina.

FIGURE 9: SCOURING AROUND RIPRAP IN CORPUS CHRISTI, TX.

FIGURE 10: THE COLLAPSE OF ARMORING STRUCTURES CAUSES A LOSS OF THE LAND BEHIND IT. THE HOUSE, LOCATED IN HAWAII, IS NOW IN A HAZARDOUS LOCATION, AND THE TREE WAS PULLED UP FROM ITS ROOTS (NAMATA ET AL., 2016).

Shoreline armoring has large upfront capital costs. It is estimated that protecting some vulnerable areas in California through the construction of seawalls and levees would cost at minimum $14 billion to install and $1.4 billion per year in maintenance (California Department of Water Resources Integrated Regional Water Management, 2010). Due to the high coasts, it is necessary to balance the land saved with the monies spent and ecological damage inflicted. It is also necessary for the community that is considering the installation of armoring to consider the length of time that they want to keep the water at bay since "it is a matter of time until shoreline armoring fails… Armoring the coast simply delays the inevitable" (Pagano, 2012). Lastly, armoring has large negative costs which are rarely incorporated in cost-benefit analyses due to the loss of ecosystem services that occurs from coastal squeeze and the loss of wetland environments.

Shoreline armoring is a known and trusted method of dealing with SLR, and the permitting system is typically well established (Shipman et. al, 2010). Additionally, federal agencies are concerned about takings claims if they deny armoring permits (Titus, 1998). For these reasons, it is difficult to phase out of shoreline armoring as the primary method of defense and into more progressive methods.

LIVING SHORELINES

Artificial land/water interfaces almost always "disrupt highly diverse and productive plant and animal communities" and cause a loss of wetland habitats and their ecosystem services (Caldwell and Segall, 2007). Living shorelines, the name given to erosion and flooding control projects that utilize natural materials and vegetation, are an alternative to shoreline armoring on bay-side beaches which encourages the preservation or growth of coastal habitats and allows their migration when sea level rises (Fig. 11). It an ecologically friendly option which protects coastlines with few negative effects (Currin et. al, 2010).

FIGURE 11: THE DIFFERENCE IN ARMORING PROJECTS AND LIVING SHORELINES (MCSHANE, 2012).

Living shorelines include the planting of seagrasses, the use of natural materials, and artificial structures as needed to dissipate wave energy, prevent erosion, and enhance the ecological connectivity of the land/water interface. It is typically visually appealing, improves water quality, and restores or enhances habitats for wetland organisms including birds, fish, and other aquatic species (Currin et. al, 2010). It maintains or causes the growth of wetland habitats for a given area which can increase biodiversity and ecosystem services (Currin et. al, 2008). While armoring projects aim to prevent erosion through the reflection of wave energy, living shorelines absorb it since vegetation naturally attenuates wave energy through friction (Moller, 2006). Bagged oyster shells can also be placed in areas where oyster spat can attach and eventually create a reef, and sand and other natural materials can be used to protect the newly created wetland habitats. These oyster bags, reefs, and other materials are also valuable for attenuating wave energy (Meyer et. al, 1997). Living shorelines create more resilient shorelines than armoring does, and it does not cause down drift erosion like armoring projects often do. They are also self-maintaining once established (Gittman et. al, 2014).

There are several legal issues involved with living shorelines. While the ecologic and protective benefits of living shorelines are widely known, there are concerns on how they impact publically-owned submerged lands (Watkinson and Moon, 2006). Any materials placed to attenuate wave energy are almost always located below the MHTL and thus on publically-owned lands. Additionally, living shorelines can cause accretion which potentially reduces the area of the publically-owned submerged lands. In all states, if accretion occurs and is not due to the intentional actions of the land owner, then it becomes part of their property as was found in Brainard v. State 12 S.W.3d 6 (Texas 1999). If accretion occurs due to the landowner installing a living shoreline, however, would the property be retained by the State because of the intentional actions or would its ownership transfer to the owner anyways? The answer to that question is currently unknown, and thus it is one of the unresolved legal issues associated with living shoreline projects.

The various levels of agencies should work together to come up with a permitting system that is consistent and predictable as the process is oftentimes confusing at present; most living shoreline projects, but not all, must apply for a Clean Water Act Section 404 permit issued by the U.S. Army Corps of Engineers. As the loss of some submerged lands is typically preferable to the negative effects caused by shoreline armoring, the various levels of government should not only simplify the permitting process but also offer incentives for property owners to install living shorelines instead of armoring against SLR. At the same time, permitting officials must be conscientious that landowners are not using living shorelines to increase their private property at the expense of publically-owned submerged lands, as mentioned above.

ORGANIZED RETREAT

Because sea level is predicted to rise well into the future, the best long-term solution for certain areas may be organized retreat (Siders, 2013). It is an unpopular option that has potentially large benefits (Brennan, 2008). Since most armoring projects- short of massive levee and dike projects such as those that defend Rotterdam Harbor and New Orleans- protect against a maximum of several meters of SLR, the presence of armorings may only delay the inevitable hurricane or flooding damage. Furthermore, any storm that is greater than what the protections were designed to withstand will overtop the defenses and can cause widespread damage (Wang, 1994). In comparison to this is organized retreat which is the migration of settlements away from the shoreline, thus giving the rising water a place to go (Siders, 2013). There are multiple ways for communities to initiate a retreat.

Erosion setbacks enable the government to slowly initiate a retreat from rising water levels and eroding coasts. It can be applied in different ways, but a common option is limiting development in hazard-prone areas. This can be done by limiting growth in those locations by issuing a fewer number of building and renovation permits or by requiring the permit-granting institution to consider a future rate of SLR before issuance. Construction of mobile structures which can be picked up and moved in a migration away from the sea, such as the Yup'ik Eskimos did, is another option (Ford et al., 2007). It is also possible to physically move historic or otherwise important structures inland as demonstrated by North Carolina when the Cape Hatteras lighthouse was moved over 800m to protect it from erosion (National Park Service, n.d.). While this option allows for wetland habitat and beach migration, it comes with what are often prohibitively high costs (Deyle, n.d.). Another option is for the government, either at the state or federal level, to purchase private property in hazardous areas and demolish any buildings located on it (Siders, 2013). The government can also limit public support including utilities, road maintenance and fire and police services, although the ethics of this are questionable and there may be takings claims.

An organized retreat can be very expensive due to high opportunity costs, lost potential revenue, and the abandonment of structures (Kousky, 2014; Turbott, 2006). However, it preserves ecosystem services by allowing the wetland habitats to migrate inland, prevents a catastrophe when artificial structures are overtaken by the sea, and can be economically beneficial in the long run when the loss of whole cities is compared to the losses associated with slowly retreating at present (Titus, 1990; Turner *et. al*, 2007). It also may be the most feasible option for communities located in hazard-prone areas that cannot afford to invest in protection. Fairbourne, Wales is an example of such. It is located on a flood plain, and in 2014 it was determined that it would be decommissioned over the next forty years ("What is Fairbourne Moving Forward?", 2016).

Officials must be careful with the wording of the law and how it is implemented. This is to avoid triggering an onslaught of takings claims and also to protect those living in the coastal area since the potential for social inequality and compensation claims in an organized retreat strategy is large (Alexander et al., 2011). For instance, housing prices in Fairbourne "plummeted" after plans were implemented to decommission the village (Spillett, 2016). Additionally, organized retreat strategies can come at a great cost to individual property owners who are impacted as their property values could drop virtually overnight; while the policy must consider how to compensate those individuals, the overall strategy has the potential to offer great benefits to the community.

As high as the costs to initiate a retreat are, it still may be less than the cost to renourish the beach as found in a Nags Head, NC study. That study found that buying all the buildings expected to be lost to erosion in fifty years would cost $400 million (Pilkey and Young, 2009). That was found to be four times less than the upfront costs of a fourteen-mile beach renourishment project that would have to be renourished every three years over the same time span at a total cost of $1.6 billion (Pilkey and Young, 2009). Additionally, the removal of the structures resulting in wider beaches, unobstructed wetland habitats, and ease of access to the beach would result in higher values of houses for those not lost to erosion, moved, or demolished (Landry et al., 2003).

OTHER OPTIONS

There are multitudes of ways to combat SLR, and the ideal solution depends upon the individual location and the needs of its stakeholders. The education of stakeholders on the benefits and drawbacks of each of these options is paramount. Following is a brief discussion of other options that may be suitable for use in and around Galveston Bay.

RAISING STRUCTURES

The base elevation of structures can be raised with sediments such as dredged sand or by putting the structure on pylons. Galveston did both of these as a protection strategy after the Great Hurricane of 1900, and today the city of Miami Beach is incorporating a higher elevation in roads that they build as an adaptation to SLR (Allen, 2016). This allows for the continued use of the structure and protects from flooding that is as great as the structure is high. Structures are built with a thirty to sixty-year life. They must be designed with the consideration that the likelihood of what is currently a one hundred-year flood will be greater each year with Earth's changing climate and SLR. Raising structures helps protect against flooding, but it still prevents wetland migration because of coastal squeeze.

BEACH RENOURISHMENT

Beach renourishment is another way to mitigate erosion damage. It allows beach migration and maintains the services provided by the beach, but at a lesser extent than natural systems because sand is added to the littoral system (Peterson and Bishop, 2005). Beach renourishment really only protects any buildings in the immediate vicinity from erosion; while some sources claim that building up the beach protects it from being eroded away completely, the most sustainable long-term solution may be to move the buildings and allow the beach to migrate and naturally sustain itself. The cost to distribute dredged sand along a new or existing beach can be very great, there is an ecological impact of dredging the sand, and sand can be eroded quickly (Speybroeck et. al, 2006; Finkl, 1996). Renourished beaches can also damage any coral or oyster reefs offshore that are buried as the new sand erodes and buries the reefs. For instance, *Montastrea annularis* colonies up to 10 ft across were killed due to sedimentation stress in Broward County, FL (Goreau and Clark, 2001). Beach renourishment does allow for continued use of the beach until it is eroded again, which typically occurs every two to six years.

PRIVATIZATION OF INSURANCE

The National Flood Insurance Program (NFIP) is a federal program that creates a “moral hazard” by enabling people to live in dangerous areas that private insurance will not cover because they “burden society” (Nichols and Bruch, 2008). Federally-subsidized insurance was designed to develop areas that were not being settled in the free market due to inherent hazards; the federal government wanted to collect taxes on houses and businesses constructed and developed in the area (Burby, 2001). It incentivizes construction in areas that can be hazardous and can increase the confidence of the land owner who buys vulnerable property. However, when a hurricane or flood does harm the properties, the “magnitude of insurance losses” causes very large insurance payouts. This is a cycle of “foolish investment backed by foolish expectations” (Pagano, 2013).

NFIP shifts the risk of hazardous property ownership from the property owner to the taxpayer who funds NFIP. In 2003, NFIP was declared to be “actuarially unsound” by the General Accounting Office (Nichols and Bruch, 2008). While there are concerns about private property owners not being allowed to develop their own properties, there should also be concern about those owners who build in hazardous areas and then expect taxpayers- including those who live in noncoastal, nonhazardous areas- to provide subsidized flood insurance.

An option that is often overlooked but has great promise is the privatization of insurance. NFIP oftentimes offers insurance at a fraction of the cost that the free market does; by limiting NFIP through reduced coverage, people will be less willing to build businesses and homes in hazardous areas. The number of repetitive loss properties that are covered should also be lowered. There are many properties that insurance has repeatedly paid to renovate or rebuild after storms or floods, even when the cost of multiple repairs is more than the structure is actually worth (King, 2005). An extreme example is a house in Batchelor, Louisiana that has flooded over forty times and received nearly $500,000 in insurance payments over a period of 40 years (Bagley, 2016). Severe Repetitive Loss Properties are defined as those that are have either had four or more separate claims of at least $5,000 or two more claims where the value of the payments is in excess of the value of the property; homeowners whose houses meet that criteria are eligible for funds from FEMA for projects designed to reduce future flood losses while those who do not opt into the program are subject to a flood insurance premium increase ("Guidance for Severe Repetitive Loss Properties", 2011). The difference in cost between the repairs and the subsidized insurance is not equal. This dichotomy between the actual risk and the perceived risk is a major part of how NFIP got $23 billion in debt (National Flood Insurance Program 2016 Reinsurance Initiative, 2016).

The removal of federally-subsidized insurance triggers “negative capitalization” or laissez-faire. Negative capitalization occurs when increased costs and insurance rates make coastal development less attractive, and laissez-faire is a business term that describes letting the market adjust under little to no regulation. The Coastal Barrier Resources Act of 1982 is an example of federal law that designated certain coastal areas as ineligible for federal assistance in providing infrastructure and flood insurance through the NFIP (U.S. Fish and Wildlife Service, 2014). In theory, the removal of federally-subsidized insurance would cause such high damage costs after hurricanes and large storms that living in hazardous coastal areas would be financially unfeasible, and people would move away. As fewer people choose to live in those areas, the areas could, in ideal situations, revert back to a more natural state since it is less subject to coastal squeeze and population pressures. A drawback of this is the gentrification of the coast whereby the only individuals who can afford the risk of owning homes in coastal areas are those who are wealthy, such as has occurred in Bolivar Peninsula, TX.

There are considerable difficulties with weaning off of subsidized insurance as evidenced by the 2012 Biggert-Waters Flood Insurance Reform Act (BW-12) and how it was gutted through the Homeowner Flood Insurance Affordability Act of 2014 (HFIAA). BW-12 was enacted immediately after the nation witnessed the losses associated with Hurricane Sandy. It extended the National Flood Insurance Program (NFIP) for five years and required significant reform to make the program actuarially sound and to “ensure that flood insurance rates more accurately reflect current conditions (Federal Emergency Management Agency, n.d.). NFIP provided subsidized insurance for properties that did not qualify for flood insurance from private companies. The insurance offered by NFIP was unsustainable as the rates offered oftentimes did not “reflect the true risk of flooding” and thus there was not enough money in reserves to pay out future damages (Questions about the Biggert-Waters Flood Insurance Reform Act of 2012, n.d.). As of 2012, NFIP was nearly $30 billion in debt, and BW-12 was passed by Congress and signed into law by President Obama with the intentions of making the program more financially sound (Wetlands Watch, 2013).

BW-12 removed the subsidy that allowed certain policies to have rates lower than the true risk of flooding was, and most of the remaining policies were subject to a 5 percent rate increase. These increases were so that all policies paid the “full risk rate,” a rate that “reflects the risk assumed by NFIP… [plus] administrative expenses” (Questions about the Biggert-Waters Flood Insurance Reform Act of 2012, n.d.). Because NFIP rates had not increased for many years, the updated rates skyrocketed and led to public outrage. Many properties were grandfathered into the NFIP and thus the rates had not changed for several decades; new rates could be ten times what they were previously, up to $30,000 per year in some cases (Berginnis, 2013). The shocking increases led to many congressmen and women to withdraw support for the bill.

The passage of HFIAA in 2014 gutted BW-12 and effectively returned coastal insurance to the previous, unsustainable NFIP. It reversed the large rate increases caused by BW-12 and allowed certain policies to be grandfathered in. Concern now exists about how federally-subsidized flood insurance will be managed. The passage of a law that would ensure actuarially sound insurance protection for those living in hazardous coastal areas resulted in widespread outrage, but likewise it is nearly incomprehensible that NFIP, an actuarially unsound program that will be bankrupt without reforms, should be continued. NFIP desperately needs reform to ensure the continued protection of those living in hazardous coastal areas or else new, scientifically-based laws designed with the same goal must be designed and implemented. Another option is to offer a buyout to the owners of hazardous properties to remove the residents from the area; regardless of what happens to NFIP, properties should not be rebuilt after being repeatedly harmed by natural disasters.

HOUSTON-GALVESTON AREA PROTECTION SYSTEM

Hurricane Ike which hit in 2008 was a Category 2 hurricane with a 6m surge storm (Fig. 13). Ike hit Galveston Bay and the surrounding region and, with $30 billion worth of damages and dozens of deaths, was the deadliest and one of the costliest storms that has ever hit the United States (Blake and Gibney, 2011). Its damage would have been worse if not for the seawall that was erected after the Galveston Hurricane of 1900.

As often happens after great natural disasters, Ike created the political will to install more protection for Galveston and the surrounding area since it is so valuable: The Galveston area is home to the Texas City, Galveston and Houston ports which generate billions of dollars of revenue and hundreds of thousands of jobs annually as well as massive commercial fisheries, petrochemical processing plants and petroleum refineries.

The Houston-Galveston Area Protection System (H-GAPS) is a "comprehensive storm surge mitigation strategy" designed by Rice University's Severe Storm Prediction, Education and Evacuation from Disasters Center (SSPEED) (Bedient et al., 2015). They have brainstormed several different ideas to protect Galveston Bay from a large storm, the damages of which could be $100 billion and the loss of 50,000 jobs from a direct hit

(Bedient et al., 2015). They have designed the projects, modeled different protection options, and are working with various agencies to spread awareness and to gain traction for the ideas. H-GAPS would be proposed regardless of SLR, but additionally it would protect against storm surges which are predicted to get bigger with SLR. Even if it is built successfully, the region will still have to deal with direct impacts of SLR such as eroding shores, worse drainage after rains and drowning marshes.

H-GAPS includes structural projects such as the Centennial Gate, a project that would protect the most financially important areas north of the Houston Ship Channel and the western edge of Galveston Bay, and coordination with the scientists at Texas A&M- Galveston that are designing the Ike Dike which would span from San Luis Pass to the eastern end of Bolivar Peninsula. They also explore green projects including the Lone Star Coastal National Recreation Area (LSCNRA) and the Lone Star Coastal Exchange (LSCE) which hope to use private markets to protect wetland habitats. While part of the appeal of LSCNRA and LSCE are that they have little governmental oversight or regulations, both are predicted to have difficulties in establishing themselves in large part due to those reasons. In addition to structural armoring projects and protecting habitats through LSCNRA and LSCE, H-GAPS plans to reestablish oyster reefs for the benefits they provide including wave and erosion attenuation. Lastly, H-GAPS will evaluate each project to determine potential economic, environmental, and social impacts (Bedient et al., 2015).

Ike Dike

A project known as the Ike Dike is a huge and ambitious proposal; it was not designed by SSPEED, but H-GAPS scientists are coordinating with those at Texas A&M-

Galveston who developed the idea. It aims to protect Galveston Bay by providing a "coastal spine" to keep Gulf storm surge waters out through the installation of gates at the passes between barrier islands (Merrell et al., 2010). The proposed design would typically allow beach access, navigation and normal water circulation but, when closed or activated, would protect against a storm surge of approximately 5m. The project has three components:

1. The seawall erected after the Galveston Hurricane of 1900. The seawall has blocked storm surges from the Gulf but, due to its design, it does not protect against storm surges in the Bay. The two other components of the project aim to do that.

2. Land extensions which would be a revetment that extended the existing seawall and prevent flood waters from simply flowing around and then behind the seawall. They would be designed to look like dunes.

3. Flood gates that block the San Luis and Bolivar Roads passes which prevent Gulf waters from entering the Bay. It is possible that gates on the Intracoastal Waterway would be needed as well.

Modeling of the proposed Ike Dike has shown that storm surge levels in the Bay can be reduced up to nearly 2 m compared to the present setting (Merrell et al., 2010). This would protect the "industrial base with nationally strategic importance," those who live and work in the Galveston Bay system and the Bay's natural resources (Merrell et al., 2010). The construction of Ike Dike is a multibillion dollar project which would require federal investment. Still, the project would cost less than a large hurricane recovery effort and would minimize the need or likelihood of another botched evacuation like that of Hurricane Rita which caused 90 deaths.

A consideration of the Ike Dike is how it affects investment-backed expectations by those in the area buying and investing in coastal property and infrastructure. It could encourage development in hazard-prone areas that arguably should be left undeveloped. Certain residents in the affected areas have also expressed concerns that the gates will be an eyesore, will cause the loss of wetland habitats, and will create other environmental problems. Furthermore, it will not address the direct impacts of SLR causing loss of habitat and nuisance flooding.

Centennial Gate

While the Ike Dike is a huge and ambitious project designed to protect all of Galveston Bay, the Centennial Gate is designed to protect the entrance to the Houston Ship Channel (HSC) with levees and gates until a larger project can be completed (Fig. 12). It is to be located where the San Jacinto River empties into Galveston Bay, an area approximately 180m wide and nearly 14m deep (SSPEED, 2014). It would only protect the most financially important parts of Galveston Bay for both the Texas and the United States economies, including ports and refineries from the storm surge from a hurricane.

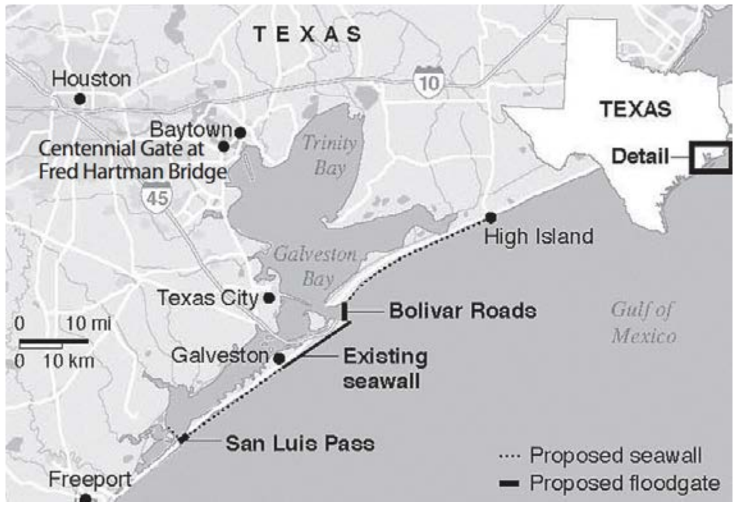

FIGURE 12: THE PROPOSED LOCATIONS OF THE CENTENNIAL GATE AND IKE DIKE (MERRELL ET AL., 2011).

There are currently two design proposals (Fig. 13). One option is to have two curved, rotating structures similar to the Netherlands' The Maeslant. The Maeslant is a massive structure which protects Rotterdam Harbor with two 22m high and 210m long gates which swing shut automatically when its computer senses water levels of a certain height. The other option is to have a linear structure which slides across HSC. While the Centennial Gate may raise the risk of storm surge flooding to other parts of Galveston Bay, it will reduce risks to the most economically important ports of Galveston Bay and thus protect Texas' economy. Models have indicated that the Centennial Gate would have reduced Hurricane Ike's storm surge by over 1m and could reduce the surge from a stronger hurricane by twice that.

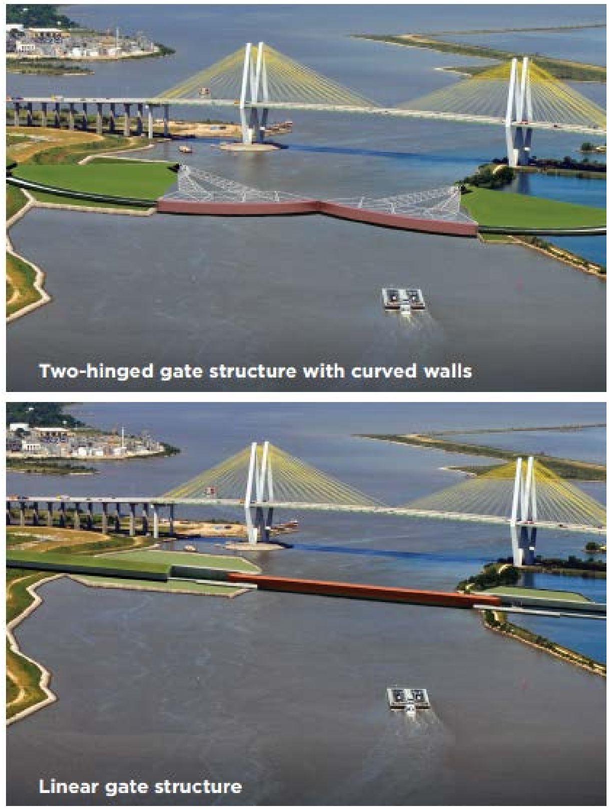

FIGURE 13: DEPICTIONS OF THE TWO POSSIBLE CENTENNIAL GATE DESIGNS (SSPEED, N.D.).

Because the Centennial Gate is a smaller project, it can be funded locally. It is expected to cost less than $2 billion and has the potential prevent hurricane damages that can reach $100 billion (SSPEED, 2011; SSPEED, 2014). Concerns about the Centennial Gate are that the areas it does not protect will have increased flooding risks, and also that hazardous areas will be developed because of the feeling of security that the Centennial Gate may provide.

Lone Star Coastal National Recreation Area

The Environmental Protection Agency (EPA) has stated that their “single greatest failing” and greatest challenge moving into the future is the “inadequate protection” of ecosystems and their services (Salzman et al., 2001). The Lone Star Coastal National

Recreation Area (LSCNRA) aims to combat this issue. If established, it would be a conglomeration of property (Fig. 14) owned by a variety of governmental, non-governmental, and private property owners and managed by the National Park Service (SSPEED, 2014). It is designed to be a financially self-sustaining nature center that draws tourists and naturalists. LSCNRA is predicted to be visited by two million people per year, generate at least $200 million and create thousands of new jobs within ten years (SSPEED, 2014).

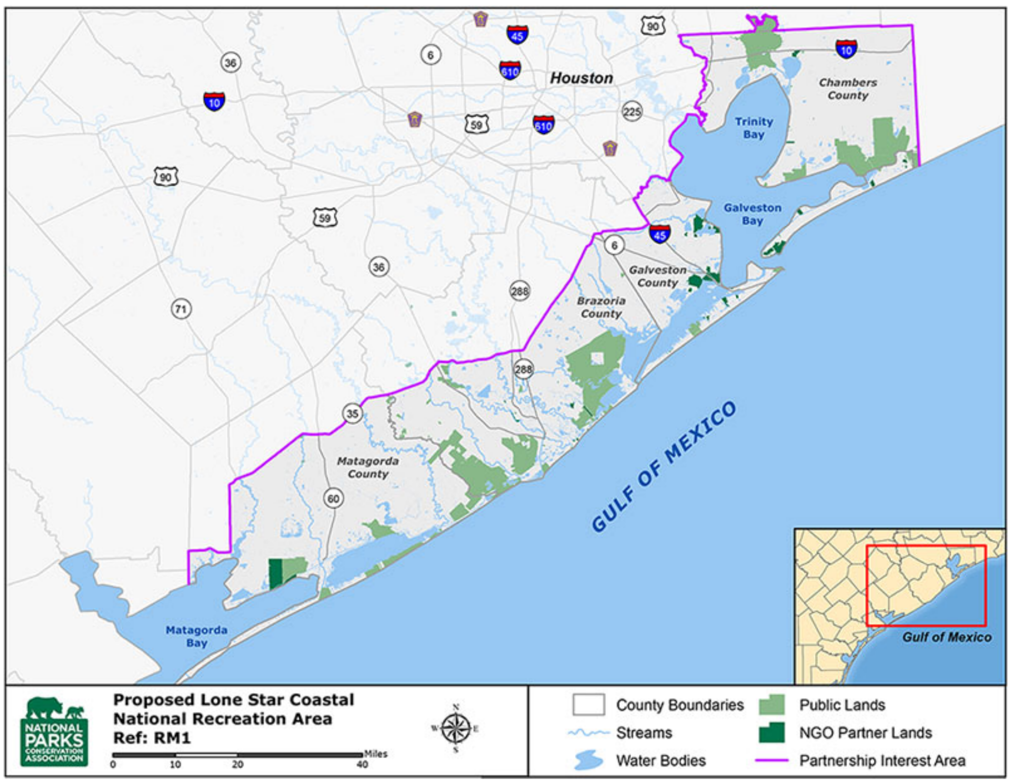

FIGURE 14: PROPOSED AREA FOR THE LSCNRA (EXPLORE LONE STAR COASTAL, 2014).

LSCNRA would protect the area's natural resources while offering recreational activities to visitors such as bird watching. It would also support Galveston Bay's commercial activities by creating and preserving habitats for commercially-important fish and shellfish species. This project has several key points in regards to preparing for SLR.

Firstly, wetlands would also be preserved and potentially even allowed to expand in areal extent. This would preserve ecosystem services and all the benefits associated with them. Secondly, by allowing water to flow freely and unrestricted into LSCNRA lands, developed areas would be safer from SLR-related hazards such as storm surge.

Lone Star Coastal Exchange

The Lone Star Coastal Exchange (LSCE) is a market-based ecosystem services online platform which would moderate financial exchanges over the inherent values of natural systems. It aims to be a financially feasible solution to protecting wetland habitats and their ecosystem services by creating a market that connects private owners of lands that are most at risk of hurricanes- those at a maximum of 6m above sea level- with buyers of ecologic services that are located on those lands. Proposed ecologic services to be turned into markets include floodwater attenuation, carbon sequestration, and conservation and/or creation of habitats for coastal wetlands, migratory waterfowl, coastal prairies, forest lands, endangered species, impervious surfaces, and carbon storage. Developing a carbon storage market in LSCE would be advantageous because it is expected to be a future global market (Salzman et al., 2001). Regulations, involuntary participation, and restrictions will not be involved, so LSCE must be economically feasible in order to start and continue, and the cooperation of the various levels of government and non-governmental organizations (NGOs) is a requirement.

CONSIDERATIONS

There are many factors that must be considered when determining if green, grey, or hybrid- the combination of manmade and natural elements- infrastructure is appropriate for a given shoreline, and because no two shorelines have the same set of parameters this process must be done for each unique situation. There is a need for region-specific ecosystem services valuation and to quantify the negative costs of grey infrastructure (Committee on Environment, Natural Resources, and Sustainability & National Science and Technology Council, 2015). The negative costs of each option must be identified. For grey infrastructure, this can include downdrift erosion and the loss of the ecosystems and their services that existed prior to the armoring installation. These two metrics allow for a more accurate picture to be painted of what exactly is at risk and what the benefits are of the various shoreline protection strategies.

It is also important to determine what time scale is under consideration in a given situation. For instance, living shorelines may not protect against erosion as well as armoring in the short term, but armoring may cause issues that living shorelines mitigate in the longer term. Another consideration is the type of hazards common in a given area and what natural vegetation or habitats are best suited to combat it. For instance, seagrasses are excellent for attenuating wave energy to mitigate erosion on a coastline, but they may not be solely appropriate to protect against strong storms since the stalks can break off when the wind and wave energy is too strong.

Another consideration is that different priorities will result in different response strategies. Less developed areas may be able to emphasize environmental benefits while more developed areas, particularly those with infrastructure that is necessary to regional or national economic activities- may need to utilize harder infrastructure strategies for protection purposes. Resilience and vulnerability must be managed alongside and balanced with economic growth, environmental quality, historical preservation, and other factors (Committee on Environment, Natural Resources, and Sustainability & National

Science and Technology Council, 2015). It is thus necessary in each situation to gather necessary and relevant data and to explicitly determine priorities and desired outcomes in order to determine the best course of action when installing green or hybrid infrastructure.

CONCLUSION

It is much easier socio-politically to be reactive instead of proactive, and within proactive plans it is easier to focus on the immediate future rather than what may happen in the long-term. Unfortunately, waiting until the effects of SLR are more obvious will set Texas behind the power curve; the largest benefits of early action may not be seen for several generations (Nicholls and Lowe, 2004). An analogy is compound interest which allows for a lesser amount of money that is invested earlier to generate a larger end sum than a greater amount of money that is invested later. Similarly, actions must occur immediately in order to best protect coastal areas, despite the uncertainty regarding how far and at what rate sea level will actually rise. As the story of Canute the Great and the fate of the Brownwood neighborhood indicate, the sea is rising and coastal communities' fate lie in the preparations made today.

SLR will impact the world's coasts, but today's actions will directly affect how severe those impacts are. Actions such as the installation of seawalls or the strengthening of dikes and levees have historically occurred after disasters such as Galveston's Great Hurricane of 1900 or Hurricane Katrina; taking action before disasters such as these would not only be less expensive but it would also save thousands of human lives. Proactive action has the greatest benefit when it is executed sooner; society can either invest in protective and adaptive measures immediately, or it can wait until natural disasters such as hurricanes and floods require a much greater investment in the future.

This chapter explores current laws and legal issues relating to SLR in Texas, and it also offers a discussion of the benefits and drawbacks of each of the policies that could be implemented. It is important to emphasize that policies should focus upon the systems which sustain human activities rather than the human activities themselves, and the policies should be proactive instead of reactive (Higgins, 2008). Short-term actions must be coupled with long-term efforts at all government levels (Biesbroek et al., 2008).

Much work remains to be done on this subject. Most obviously, there is too much uncertainty as to how far sea level will actually rise, particularly in regard to the rate of ice sheet melt and under different emission and adaptation scenarios in various environments. More study and knowledge is needed on this front as well as on the long-term effects of policy options. The dispersal of this knowledge through public outreach efforts and education is of supreme importance in getting the general public to realize the dangers associated with SLR. Secondly, with the exception of The Netherlands, no state or country has planned beyond 2100. Since most effects of SLR will occur in the long-term with the potential of 12m of SLR, studies should begin analyzing impacts over the next one thousand years (Nicholls and Lowe, 2004). Furthermore, different values will lead to the implementation of different strategies to combat SLR, so individual communities need to determine where their priorities in the coastal zone lie. Lastly, in order to identify potentially hazardous and/or threatened areas, it is necessary to predict areas of future population growth and those that are vulnerable to SLR and work to protect them from development (Caldwell and Segall, 2007).

Individual coastal communities have been or will be faced with responding to SLR in the near future, and community values and priorities will determine which response strategies are most appropriate for their given jurisdiction. The future outcome of wetlands is intrinsically linked to socio-economic conditions, policy decisions, and perceptions about their value; their future areal extent- whether they decrease, stay constant, or even increase- are directly affected by today's "complex economic and sociological decisions" (Kirwin and Megonigal, 2013). The effects of these relevant decisions may even have a bigger extent on the marshes than the rates and magnitude of SLR itself.

CHAPTER II: MODELING SEA LEVEL RISE RESPONSE STRATEGIES IN GALVESTON BAY

PROBLEM STATEMENT

Galveston Bay has one of the highest vulnerabilities to large storms and SLR in the country due to its high population pressures, costly infrastructure, and its natural properties (Arkema et al, 2013). The currently predominant protection paradigm emphasizes shoreline hardening as the primary mode to combat SLR. This is evidenced by the fact that 14,000 miles of the United States' coast has been armored, and one-third of the coast could be hardened by 2100 if recent trends continue (Kwok, 2015). In recent years, however, there has been recognition of the benefits that natural shorelines offer. This has resulted in a push towards utilizing living shorelines, a green infrastructure approach. There are many benefits of protecting the connectivity of land and sea in such a way. A better understanding of the potential effects that result from these protective measures will increase the knowledge of coastal communities in the Galveston Bay area.

SLR policies have different ecological and economic impacts. Although these effects are known, they have not been quantified for the Galveston Bay area. This chapter uses the computer model Sea Level Affecting Marshes Model (SLAMM) to simulate SLR into the future in order to quantify the effects of different SLR policies on various sites within Galveston Bay. This will be useful in determining the costs and benefits of various SLR policies on different built and ecological environments for other communities around Galveston Bay. Exploring these questions will be another step towards understanding how the fate of wetlands is intrinsically linked to coastal communities and, conversely, how coastal communities' resilience is tied into the preservation of wetlands. This knowledge may thus enable communities to make the best decision according to their unique environmental parameters and values. Furthermore, by tailoring SLAMM to individual climate regimes, this work can be scaled up in application to the entire Texas coast.

As an initial step towards considering the long-term effects of SLR-mitigation strategies, this chapter focuses on a desktop analysis that quantifies the areal extent of SLR-triggered biophysical change. Using SLAMM, the impacts of four different response strategies were modeled to the year 2100 at each of three different SLR scenarios for each of the four sites; as such, a total of twelve SLAMM runs were run at each of the four sites (Fig. 15). Emphasis is placed on modeling wetland responses to SLR with particular emphasis on marshes and developable dry land.

	Armor Removed	Current Armoring Scenario	All Armored	Living Shoreline
1.8 m	High/AR	High/CAS	High/AA	High/LS
0.74 m	Medium/AR	Medium/CAS	Medium/AA	Medium/LS
0.2m	Low/AR	Low/CAS	Low/AA	Low/LS

FIGURE 15: EACH OF THE FOUR SITES ARE MODELED TWELVE TIMES USING THREE SLR SCENARIOS AND FOUR RESPONSE STRATEGIES.

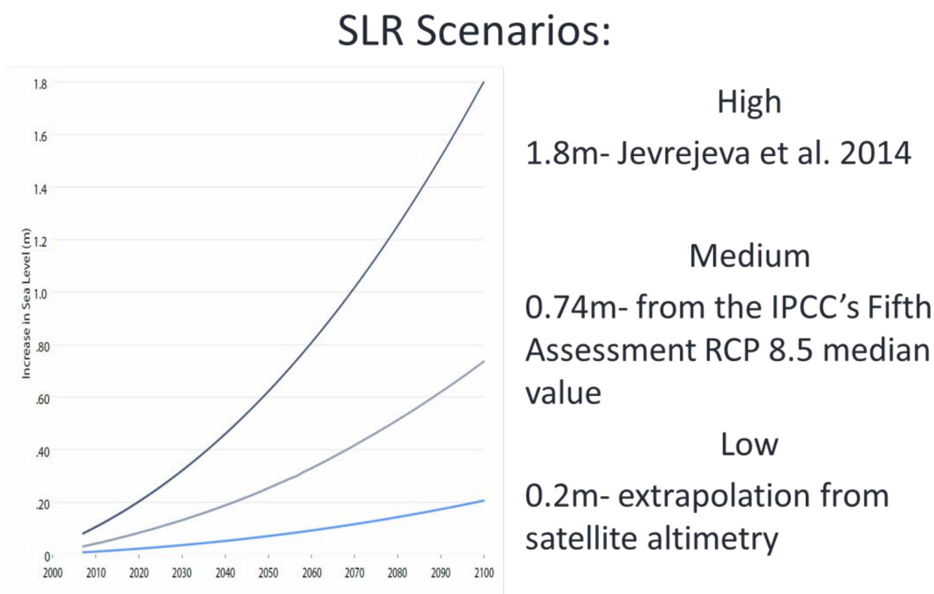

FIGURE 16: THE THREE SLR SCENARIOS MODELED.

The response strategies incorporated are: 1) Armor Removed whereby it is assumed that the shoreline is completely natural with no artificial structures, 2) Current Armored Shoreline which represents the locations of armoring in 2007, 3) All Armored which represents the continuous hardening of all shorelines, and 4) Living Shorelines which involves a generalized living shoreline for the length of the site's shoreline. "Armoring" is used as a catch-all term to describe all artificial structures used to fortify the shoreline, including seawalls and dikes. The three SLR scenarios were selected for the following reasons: 1) 0.206 m by 2100 which is an extrapolation of satellite altimetry data collected over the northwest Gulf of Mexico to 2100, 2) 0.74 m by 2100 which is the median value of the IPCC RCP8.5 mid-level scenario, and 3) 1.8 m by 2100 from Jevrejeva et al. (2014). The shapes of the curve used to get to 0.206 m and 1.8 m of SLR by 2100 is based upon the RCP8.5 scenario (Fig. 16). A land subsidence rate grid by Subedee et al. (2016), which was customized based on the historic rates for the region, is incorporated into the model to reveal relative sea level rise rates when combined with the global SLR scenarios. The four sites were chosen because they represent different natural and built environments, and thus the analysis can demonstrate the effects of public policies in different locations and settings around Galveston Bay.

SITES

FIGURE 17: THE LOCATIONS OF THE STUDY SITES.

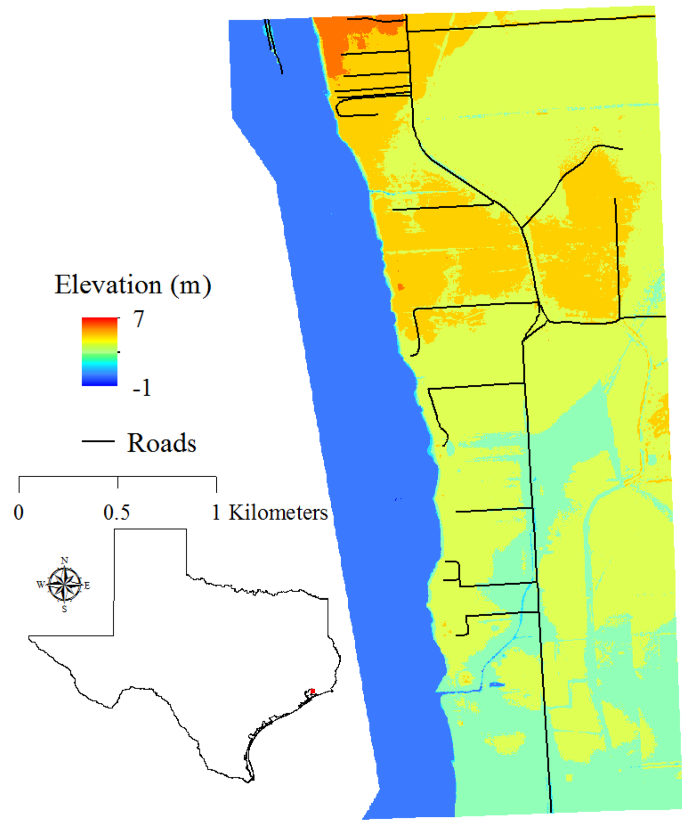

FIGURE 18: ANAHUAC

Anahuac (Fig. 18) borders Trinity Bay, which is in the northern part of the Galveston Bay system. It is a small, lightly developed town located in Chambers County with a population of approximately 2,000 people as of the 2010 census. Lake Anahuac is located to the north of the town. Its infrastructure is mostly houses, and S. Main St. runs north to south through the study site with several roads joining it from the east, northeast and west. Its shoreline has been armored in places to protect peoples' private property. Its natural shoreline consists of marshes, beaches, and some bluffs to the south. Subsidence rates range from -0.3 cm per year at the northeastern corner of the subsite to -0.32 cm per year at the western edge of the subsite.

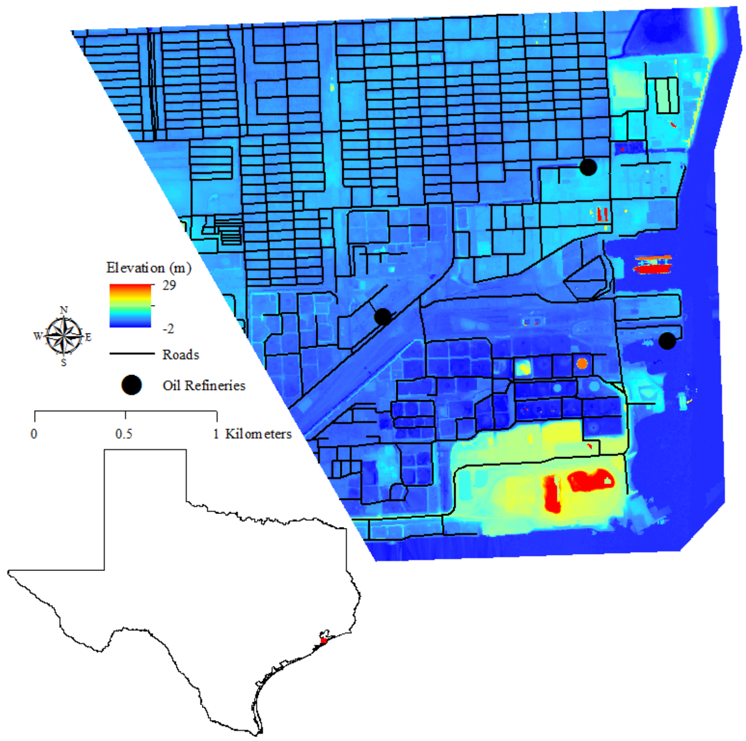

FIGURE 19: TEXAS CITY

Texas City, located in Chambers and Galveston Counties, is a very industrial city that borders Galveston Bay (Fig. 19). It has a port and is a petroleum refining and petrochemical manufacturing center that is vital to the energy consumption of both the Gulf region and the United States at large. It has an estimated $100 billion of oil and gas infrastructure, and the Port of Texas City is the third largest port in Texas and the eighth largest in the United States. The Texas City Dike extends almost to Galveston Island and is designed to protect Texas City from storm surges. Texas City also has a seventeen-mile long levee system designed to prevent flooding. The city is about 3m above sea level, and 65% of its area is water and marshlands. The shorelines within the study site are almost completely armored. Subsidence rates range between -0.30 and -0.33 mm per year.

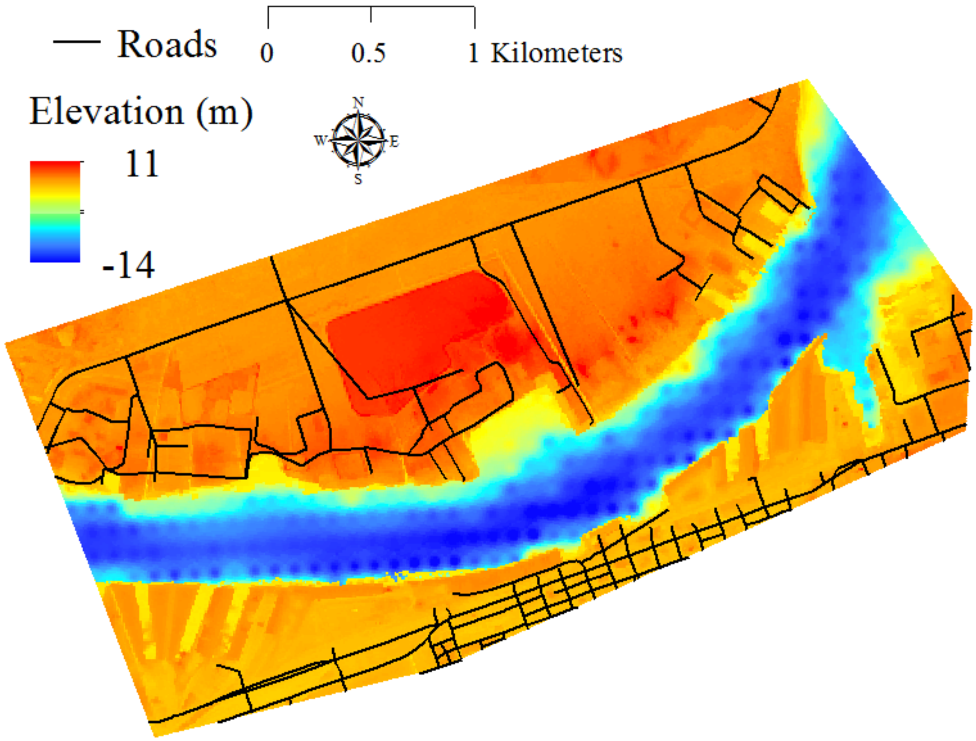

FIGURE 20: GALVESTON

Galveston Island (Fig. 20) is a barrier island that separates the Gulf of Mexico from Galveston Bay. It is about 28 miles long and up to 3 miles in width. Prior to the development of the island, sand dunes were up to 4.5 m in height; they were destroyed, largely through human effects, which made the island more vulnerable to large storms such as hurricanes. For example, the Galveston Hurricane of 1900 killed between 6,000 and 12,000 people and still ranks as the deadliest natural disaster in the United States. That hurricane also eroded the shoreline by 100m in some places and demolished hundreds of structures (*Galveston's Bulwark Against the Sea: History of the Galveston Seawall*, 1981). When rebuilding after the hurricane, the city installed a massive seawall that is 10 miles long and about 5m in height above MSL. The town of Galveston is now highly developed and is a tourist destination. Except for the area around the jetties located on the Bolivar Peninsula, Galveston has a long-term Gulf shoreline erosion average of 1.5 m per year. The Bolivar Roads jetties, in contrast, have accreted at rates up to 88.2 ft per year (Morton, 1974). The Bolivar jetties' accretion rate is at the expense of beaches downdrift, such as Surfside Beach, which are sediment starved. The Galveston site run in SLAMM includes part of both the barrier island and Pelican Island (Fig. 22). The shoreline in this area is mostly armored, and subsidence rates vary between -0.43 and -0.59 mm per year.

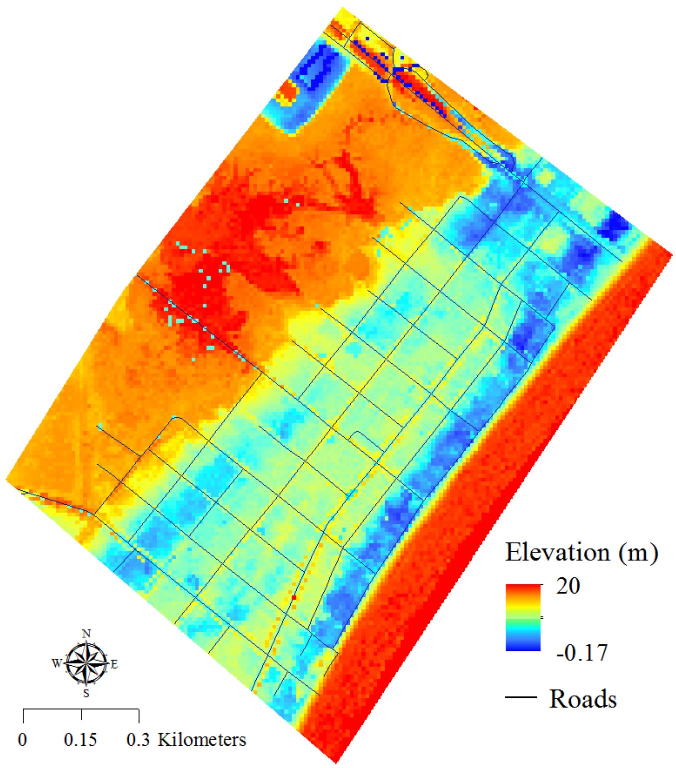

FIGURE 21: SURFSIDE

Surfside Beach is a small, low-lying town in southern Brazoria County located on the Gulf of Mexico (Fig. 21). It has a permanent population of less than 1,000 people. Surfside's Gulf shoreline average annual retreat rate is between 2.5 and 3.3 m per year. The region's erosion is caused to a slight degree by natural processes such as SLR and to a much larger degree by severely decreased sediment sources caused by anthropogenic changes to the Brazos River and the dredging of Freeport Harbor Ship Channel (Tresaugue, 2009). Surfside's subsidence rates are between -0.30 and -0.32 mm per year. Surfside borders the Gulf to the southeast which cannot be armored under Texas' legal regime. Because of coastal squeeze and erosion, Surfside beaches have very small dune systems which makes the area further vulnerable to SLR. The best long-term solution is arguably to retreat from the shoreline. However, Surfside's residents prefer beach renourishment instead of retreat.

SLAMM METHODOLOGY

For this study, the Sea Level Affecting Marshes Model (SLAMM) was used to calculate the areal extent of biophysical changes accompanied with different policies and SLR scenarios at the four sites around Galveston Bay. SLAMM is a rule-based model that is used to project changes on coastal wetlands in response to SLR and other "dominant processes" (Park, 2008; U.S. Fish and Wildlife Service, 2011). SLAMM has been used in many projects similar to this, but it was customized in several unique ways as part of earlier work completed with this larger SLR project (Subedee et al., 2016). The data inputs were created as part of earlier work done on the project and include the following:

1) A Bare Earth DEM in meters above NAVD88, created from LIDAR data.
2) A National Wetlands Inventory (NWI) wetland type layer which links GIS wetland categories to SLAMM's categories. It was rasterized in order to be usable within SLAMM.
3) Slope in degrees, calculated from the DEM.

4) Subsidence which specifies vertical land movement for the study site, calculated from data compiled around Galveston Bay.
5) Percent impervious cover, which indicates how developed or undeveloped an area is; at 25 percent impervious cover or higher, an area is considered to be developed.
6) VDATUM which converts NAVD88 to mean tide level (MTL) as required by SLAMM.

All the inputs were at 1m resolution; data that were originally at lower resolutions were converted using ArcMap's "resample" tool. Site and model parameters including sedimentation, accretion and erosion rates as well as scenario and execution options were specified to each site as part of the work done previously on the project by Subedee et al. (2016). SLAMM is generally used at lower resolutions than 1m, so other changes had to be made such as turning off the Soil Saturation module, which is unstable at high resolutions. The shoreline was defined to be the boundary between Open Water met non-Open Water habitats within SLAMM's Initial Condition outputs. To model policy scenarios for this study, this input terrain model was altered in the following ways.

ARMORING REMOVED

The Armoring Removed (AR) scenario acts as a control and utilizes no armorings, which is an umbrella term used to describe seawalls, dikes, groins, and other artificial structures; living shorelines; or other protective actions. A convoluting factor in the AR scenario is that of an "artificial armoring." Sites that had armorings as of 2007 cause issues within the DEM where the seaward side of the armoring has much lower elevations than the landward side of the armoring. So, although SLAMM was told for the AR scenario that there were no armorings, there was an artifact within the DEM that SLAMM interpreted as bluffs, so the rate of erosion was less than that which would occur in reality when an armoring was removed. This artifact was not removed because the processes that go into creating a new land/sea equilibrium when armorings are removed are extremely complex and would require specialized knowledge of the study area and an engineer; it was determined that that process would have been too intensive for the amount of knowledge that would have been derived.

ALL ARMORED

The input terrain model was altered to add armoring along the entire shoreline for the AA scenario. This was done by extracting the border between the Open Water and non-Open Water habitats, and using that boundary as SLAMM's armoring input file.

CURRENT ARMORED SHORELINE

Current Armored Shoreline (CAS) shows the protection paradigm as of 2007, which is when the data for this study was collected. The locations of armored shorelines for each site was extracted from an Environmental Sensitivity Index (ESI) file which was based on imagery collected in 2007. However, the imagery used to create the ESI does not align with the other layers used for the study, particularly the NWI and DEM. So, the ESI hardened shoreline locations were compared to the shoreline created for the AA scenario, and the locations of AA scenario armorings that corresponded to the ESI's armored shoreline locations were extracted to create the CAS armored shoreline. Because these armorings were not continuous, water could seep around them and inundate inland.

Living Shorelines

"Living shoreline" (LS) is a term that is coming into vogue to describe a wide array of shoreline protection strategies. They can range from using purely natural products like marsh grass plantings to hybrid infrastructure which incorporates both artificial structures and natural elements (Fig. 21). The design of living shorelines is site-specific and varies according to parameters including substrate type, grain size, wind energy, tidal flux, and average wave heights. As such, for these projects it is important to include engineers and other professionals in the planning. The nature of this project, however, required a generalization of this detailed and site-specific process. It is important to emphasize that the designs used for LS within this study is meant to inform a general understanding of what benefits can be expected from living shorelines. It is not meant to be a template to guide actual LS projects.

FIGURE 22: THE TERM "LIVING SHORELINE" CAN REFER TO A NUMBER OF DIFFERENT PROJECTS ON THE SPECTRUM OF GREEN TO HYBRID INFRASTRUCTURE (OYSTER RESTORATION WORKGROUP, N.D.).

For this project, marshes were protected using a sill. A commonly used rule of thumb is that the height of the sill should be equal to the mean tide level. This is tall enough to minimize erosion by decreasing wave energy while also being short enough to be overtopped regularly. Overtopping is important because it prevents stagnant water from growing copious amounts of algae. Furthermore, any suspended sediments carried within the wave will be dropped when it overtops the sill. Because the sill can be overtopped and accumulate sediments while simultaneously minimizing erosion, the accretion rate behind sills is generally higher than that found within natural marshes; marshes protected by living shorelines have been documented to have accretion rates that are up to two times greater than the accretion rates found in natural marshes (Currin et al., 2008). As such, the marsh accretion rate within SLAMM was doubled for the living shoreline scenarios.

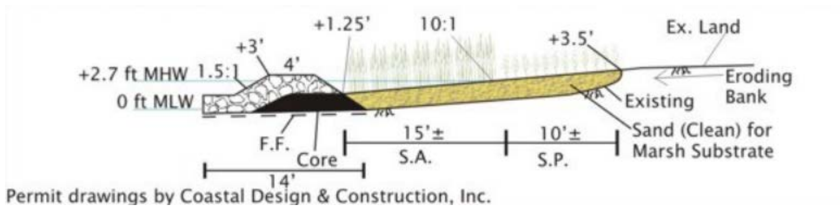

FIGURE 23: A DESIGN TEMPLATE FOR A LIVING SHORELINE IN VIRGINIA (HARDAWAY ET AL., 2014).

Fig. 23 is a template used for a project displayed on the Virginia Institute of Marine Science website. It was used within this project as a design model for living shorelines. Accordingly, for the Anahuac site, a 3m wide sill was placed 9m (approximately 25 ft) seaward of the shoreline. Because this project was completed at 1m resolution, 3m was the narrowest width that was possible to retain the trapezoidal shape, which is more stable than some other designs, as the template shows. The height of the first and third “steps” was equal to half of the mean tide line (MTL) and the height of the middle “step” is equal to MTL (Fig. 24). While the area behind the sill can be filled in with additional sediment to raise its elevation and kick start the benefits of LS projects, it is expensive and oftentimes not included on real world projects. It was not included in this project either.

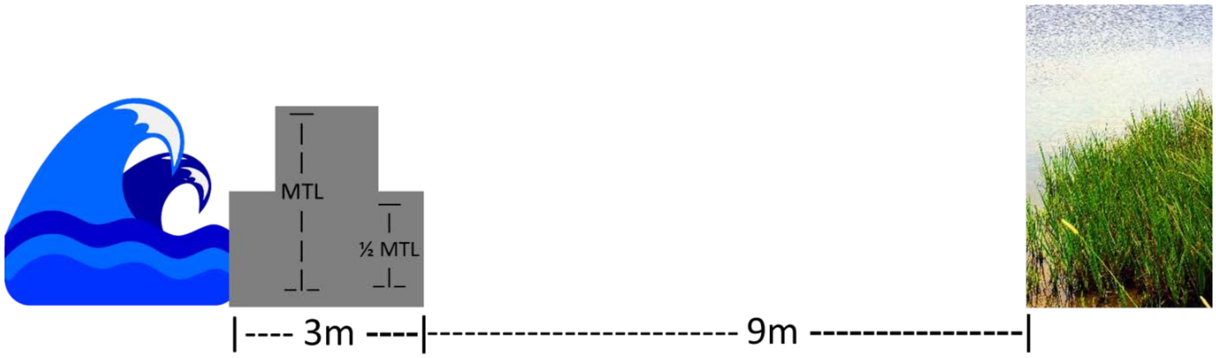

FIGURE 24: THE DESIGN TEMPLATE FOR SILLS USED IN THIS STUDY.

RESULTS

The output maps for each policy/SLR run are quite similar because the geographic changes are small relative to the study area size, and thus changes are very difficult to visually determine. As such, to explain differences between the scenarios, each was compared directly to the CAS scenario. As a reminder, CAS functions as a control and predicts what would happen with no anthropogenic changes to the shoreline. The following graphs have an x-axis which shows habitat type and a y-axis which shows aerial change expressed in square meters. Positive numbers indicate that the aerial extent for that habitat type is greater under than the first policy option while negative numbers indicate that the aerial extent is greater under the second scenario. For instance, the first Anahuac site under the low SLR scenario is CAS_2100 – Initial Condition, and Open Water has a value of 12,664 while Developed Upland has a value of -3,434. This means that the CAS_2100 output has 12,664 more m^2 of Open Water than the Initial Condition, but Initial Condition has 3,434 more m^2 of Developed Upland compared to CAS_2100.

SLAMM outputs include up to 22 habitat types which is difficult to analyze (Table 1). So, outputs were converted into a simpler six-category land classification.

Some sites had no Beaches and Dunes habitat or else the beaches and dune extent did not change from one scenario to the next; in those situations, Beaches and Dunes were omitted from the write-ups below. The Inundated Developed Land category class was created in Raster Calculator using the following expression:

Con((Raster(r"InitialCondition") == 1) & (Raster(r"2100_output ") > 1),83,Raster(r"2100_output")). This expression says that if a pixel is classified as Developed Uplands in the Initial Condition raster and anything other than Developed Uplands in the 2100 output, then classify it as Inundated Developed Land in the newly reclassified 2100 output raster.

TABLE 1: ORIGINAL AND RECLASSIFIED SLAMM CATEGORIES

Original SLAMM Category	Reclassified Category
Developed Dry Land	Developed Upland
Undeveloped Dry Land	Undeveloped Upland
Nontidal Swamp	Marshes and Flats
Tidal Swamp	Marshes and Flats
Cypress Swamp	Marshes and Flats
Inland Fresh Marsh	Marshes and Flats
Tidal Fresh Marsh	Marshes and Flats
Transitional Marsh/Scrub Shrub	Marshes and Flats
Regularly Flooded Marsh	Marshes and Flats
Mangrove	Marshes and Flats
Tidal Flat	Marshes and Flats
Irregularly Flooded Marsh	Marshes and Flats
Ocean Flat	Marshes and Flats
Estuarine Beach	Beaches and Dunes
Inland Shore	Beaches and Dunes
Rocky Intertidal	Beaches and Dunes
Ocean Beach	Beaches and Dunes
Inland Open Water	Open Water
Riverine Tidal Open Water	Open Water
Estuarine Open Water	Open Water
Tidal Creek	Open Water

Open Ocean	Open Water

LOW SLR- 0.206 M

The low SLR scenario comes from satellite data that was collected over the northwestern Gulf of Mexico between the years 1993 to 2014 which was extrapolated to 2100 (Nerem et. al, 2010). From an anthropocentric perspective, the low SLR scenario is by far the best-case scenario of the three SLR scenarios. Its shows fewer landscape changes than the medium and high SLR scenarios compared to present day. Human activities along the coast would be disrupted less than it is predicted for the other two SLR scenarios, and the shoreline erodes much less in this scenario. Ecosystem services would be changed slightly compared to the present, but not as massively as the medium and high SLR scenario.

Anahuac

Anahuac is not as susceptible to SLR as the other sites. There were SLR-induced changes at all the policy scenarios, but the changes were minimal at the low SLR scenario.

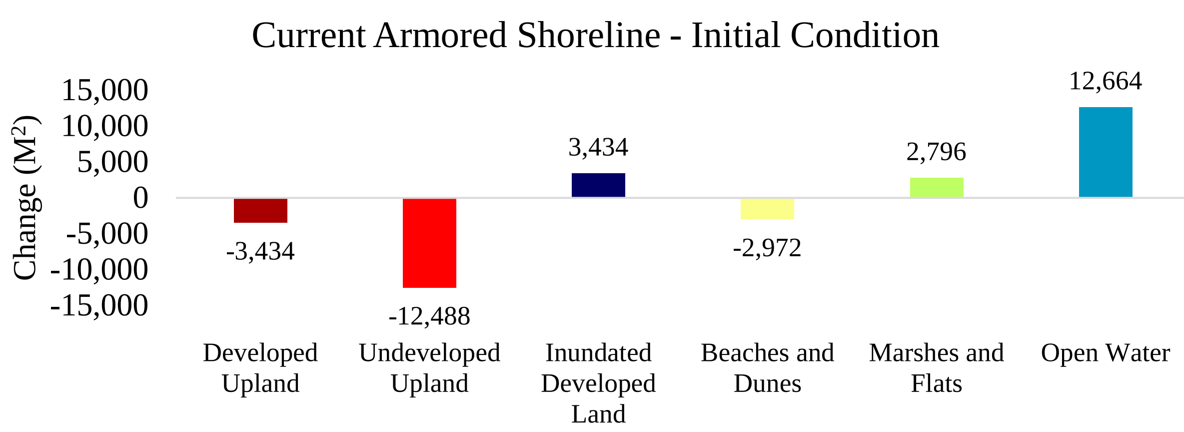

FIGURE 25: ANAHUAC'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO COMPARED TO INITIAL CONDITION.

This chart compares SLAMM's Initial Condition extent to that of the 2100 output of the Current Armored Shoreline policy scenario (Fig. 24). CAS has less Undeveloped Upland and Beaches and Dunes compared to the Initial Condition. Developed Uplands were inundated by Open Water. Considering their protection paradigm as of 2007, the Anahuac community can expect the following landscape changes by 2100: (1) higher water levels will cause erosion of Beaches and Dunes and hence shoreline retreat; and (2) some uplands will drown while others will convert to Marshes and Flats.

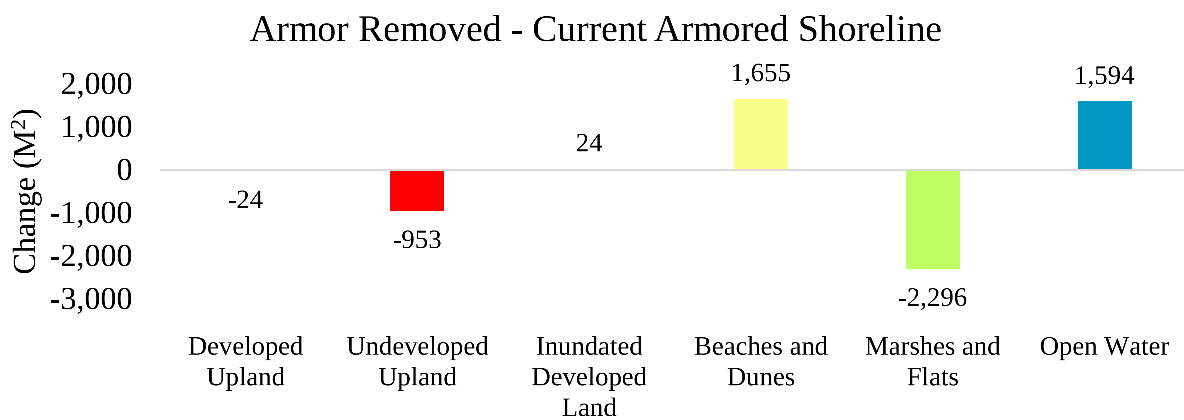

FIGURE 26: ANAHUAC'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

With no armoring present, RSL causes the shoreline to retreat, which causes the loss of some Marshes and Flats, while farther inland, Marshes and Flats are created through the conversion of Undeveloped Uplands (Fig. 25). The migration rate of Marshes and Flats is lower than the rate at which they drown, thus AR has less Marshes and Flats than CAS. This is because the armoring in the CAS scenario protects the Marshes and Flats from edge erosion. AR does not protect the uplands from SLR. AR protected 24 fewer m^2 of Developed Uplands from inundation than CAS.

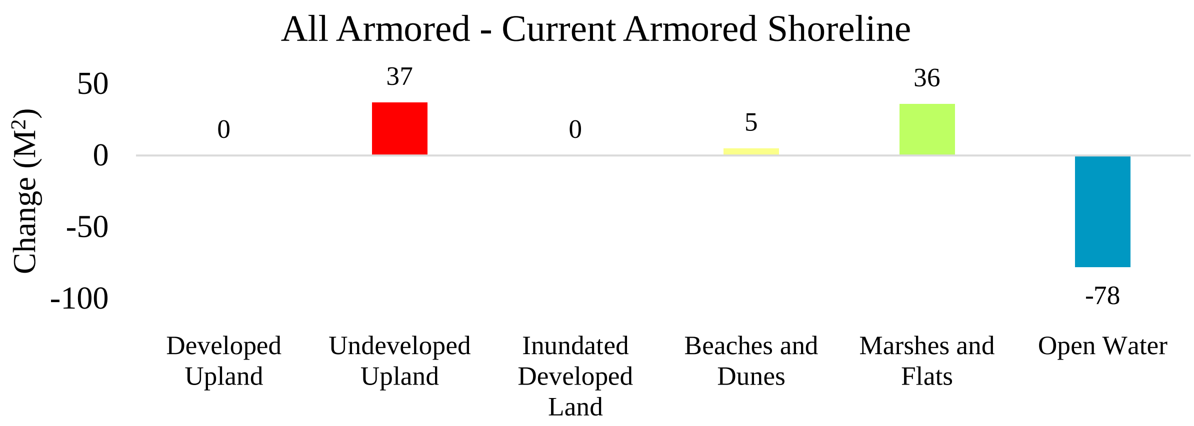

FIGURE 27: ANAHUAC'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The comparison of the AA and CAS 2100 outputs are fairly surprising; given knowledge of how coastal squeeze works, it was not expected that there would be a greater extent of Marshes and Flats in the AA scenario than the CAS scenario. The shoreline was specified for this study as the interface between non-Open Water and Open Water habitats. As such, when the shoreline was armored, its location was seaward of the Initial Condition Marshes and Flats. The AA armoring, however, was continuous while the CAS armoring was broken. Thus, as sea level rose in the CAS scenario, water inundated inland and caused the conversion of Marshes and Flats to Open Water. While the Marshes and Flats did migrate inland, it was at a slower rate than the conversion to Open Water, thus there was a net loss of Marshes and Flats in the CAS scenario whereas the AA scenario protected more Marshes and Flats. The CAS 2100 output also had less uplands because of the inland migration of Marshes and Flats. Accordingly, it is logical that there would be less Open Water in the AA scenario; the water inundated around the armoring in the CAS scenario whereas the water did not inundate inland in the AA scenario.

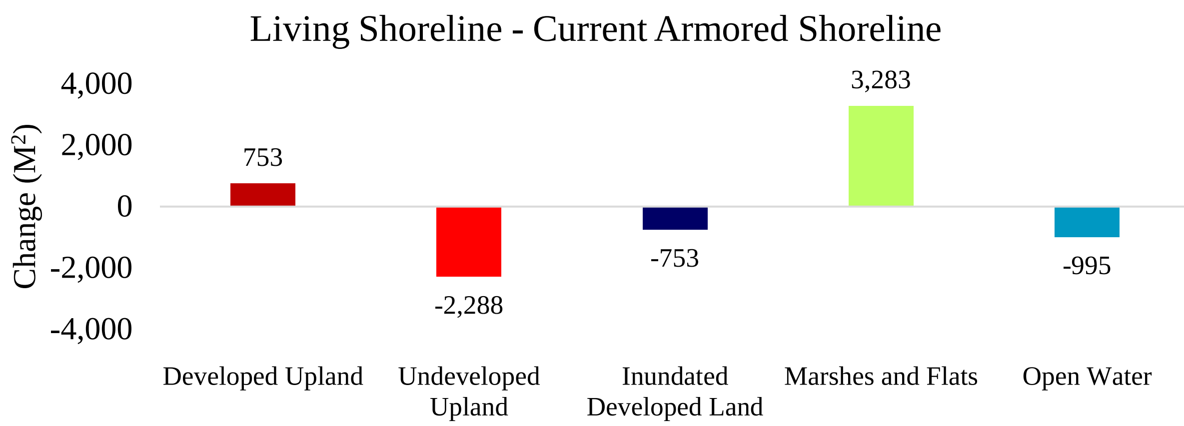

FIGURE 28: ANAHUAC'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The LS scenario had more Marshes and Flats in the 2100 output than the CAS scenario. Living shorelines did a better job at protecting Developed Upland than CAS. In the LS scenario, Marshes and Flats migrated into the Undeveloped Uplands whereas some of those same areas remained Undeveloped Uplands in the CAS scenario; Marsh and Flat migration inland is why LS had a smaller extent of Undeveloped Uplands.

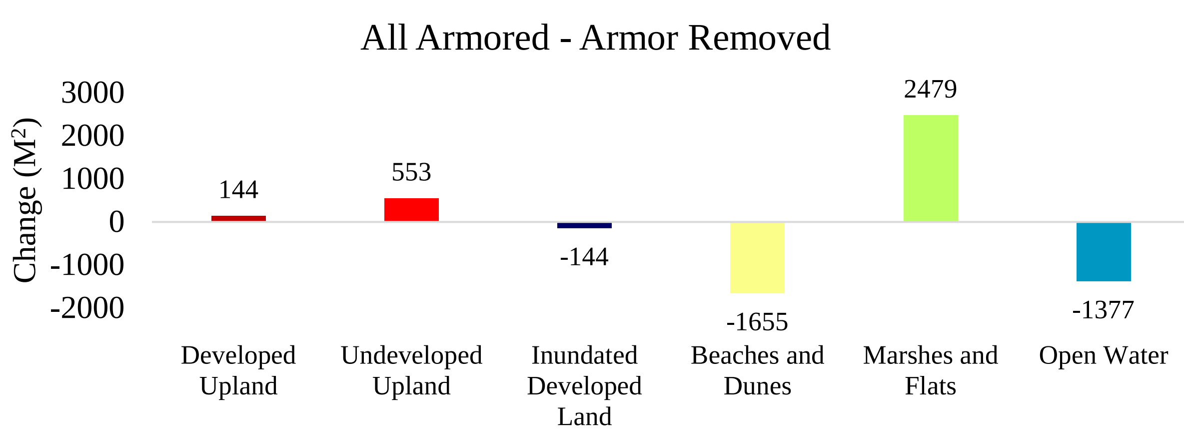

FIGURE 29: ANAHUAC'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMOR REMOVED 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The comparison between the AA and AR scenarios confirms what was stated earlier: the decision to define the shoreline as the boundary of Open Water and non-water habitats in SLAMM's Initial Condition output and in turn using that boundary as the location of dikes results in findings that are not as expected. If the above results were what would happen from armoring, there would be no debate over shoreline management strategies! These outputs indicate that AA is, by far, the superior policy option because it protects Developed and Undeveloped Uplands and Marshes and Flats from inundation and conversion from Open Water.

Texas City

Because Texas City's shoreline is so developed, the 0.206 m rise in sea level for this scenario has the potential to cause big economic impacts. Even though it does not occur at as large of a magnitude as it does in other scenarios, the conversion of uplands to other habitat types will likely have a negative economic impact upon the city.

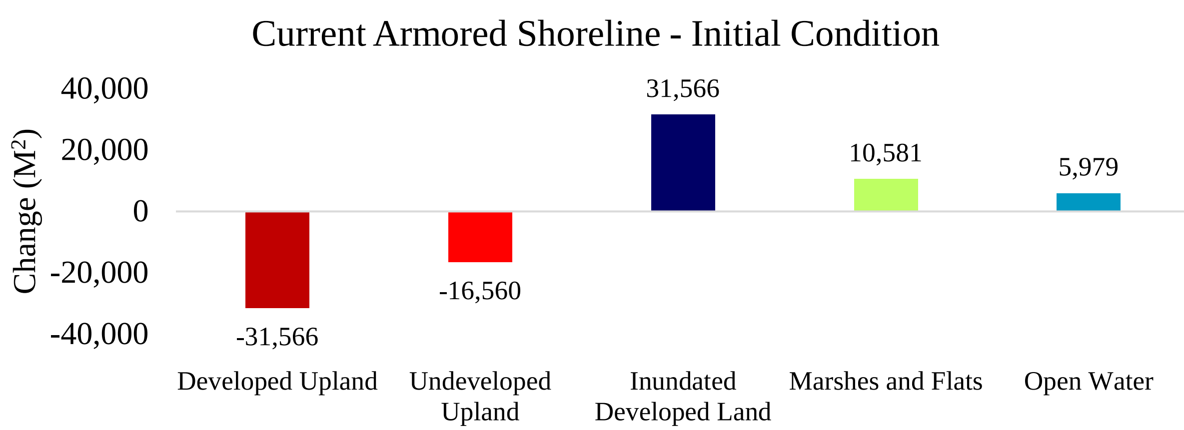

FIGURE 30: TEXAS CITY'S CURRENT ARMORED SHORELINE 2100 OUTPUT COMPARED TO ITS INITIAL CONDITION OUTPUT UNDER THE LOW SLR SCENARIO.

Developed Uplands were drowned from the Initial Condition to 2100 under the CAS scenario. The shoreline was eroded, which resulted in CAS having more Open Water, and Marshes and Flats moved into what was initially Undeveloped Uplands.

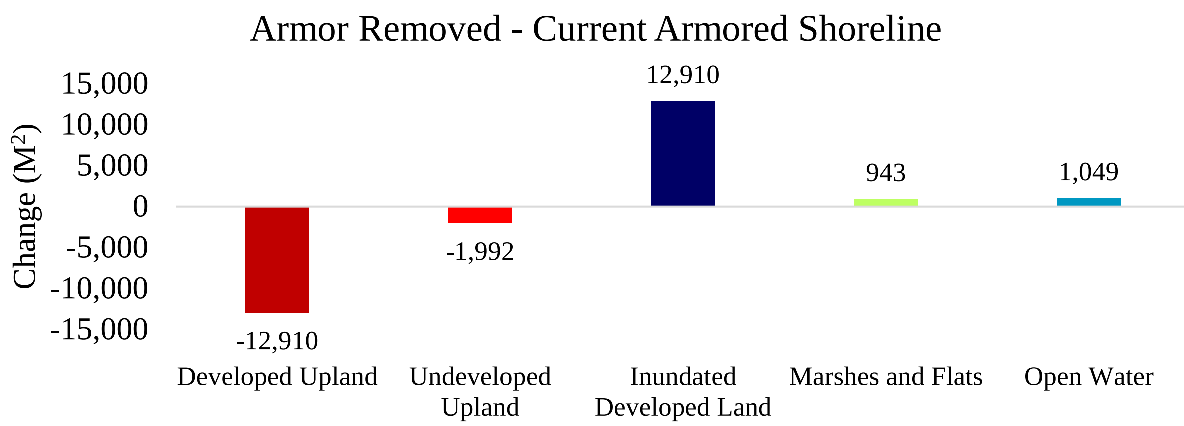

FIGURE 31: TEXAS CITY'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

Without armorings, Open Water will inundate farther inland and trigger the conversion of Undeveloped Uplands to Marshes and Flats such as would be expected. The AR scenario protected 12,910 less m^2 of Developed Uplands from inundation than CAS did.

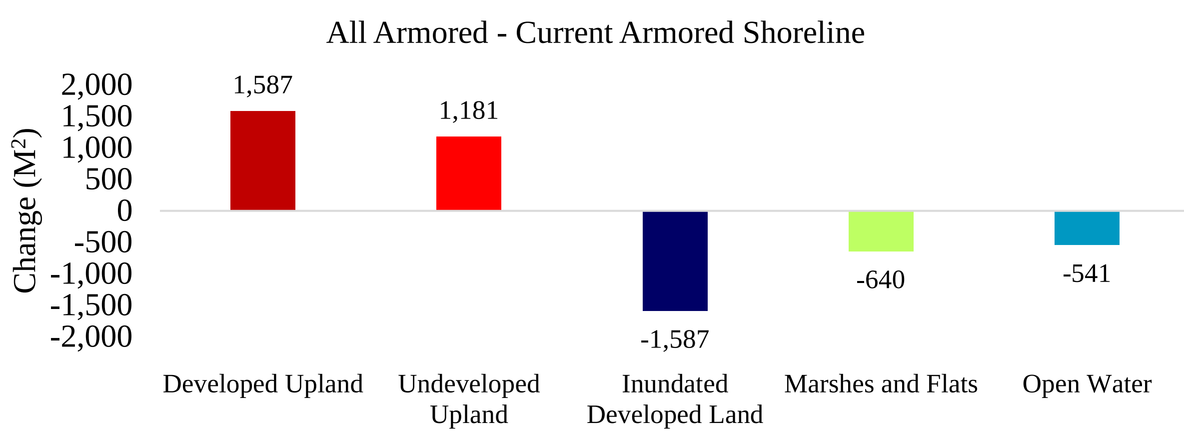

FIGURE 32: TEXAS CITY'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

Most of Texas City, as of 2007, was armored. As such, for this site, the AA and CAS armorings are very similar. AA will have less Marshes and Flats than CAS. AA had less Open Water and thus less shoreline erosion than CAS, and AA also protected more

Developed Uplands than CAS. The breaks in the CAS armoring will allow water to convert more Undeveloped Uplands to Marshes and Flats compared to the AA scenario. AA protected the Undeveloped Uplands from conversion to Inundated Developed Land.

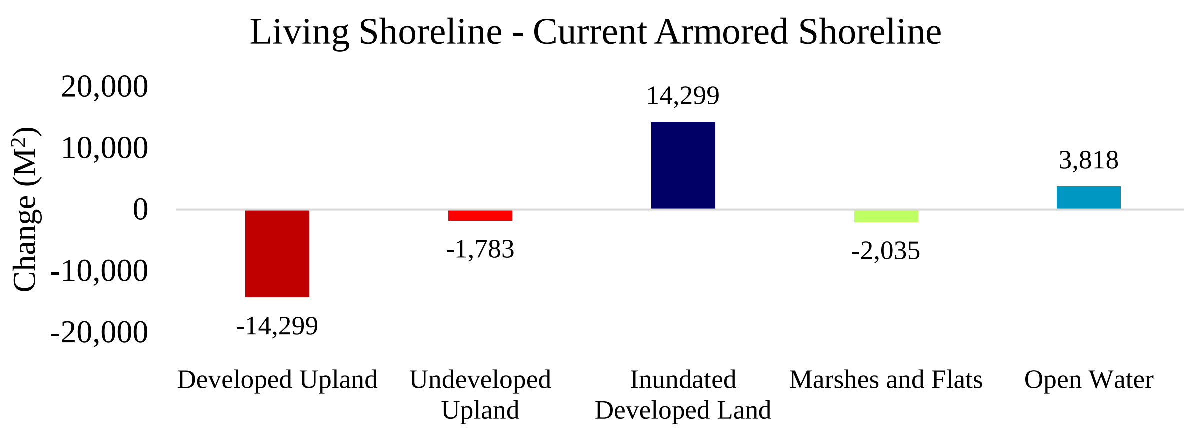

FIGURE 33: TEXAS CITY'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The LS scenario allowed more erosion and thus more Open Water than the CAS scenario. The doubled accretion rates for marshes in the LS scenario triggered the conversion of more uplands to marshes. There were more Developed Uplands and Undeveloped Uplands in CAS, and LS had more Marshes and Flats.

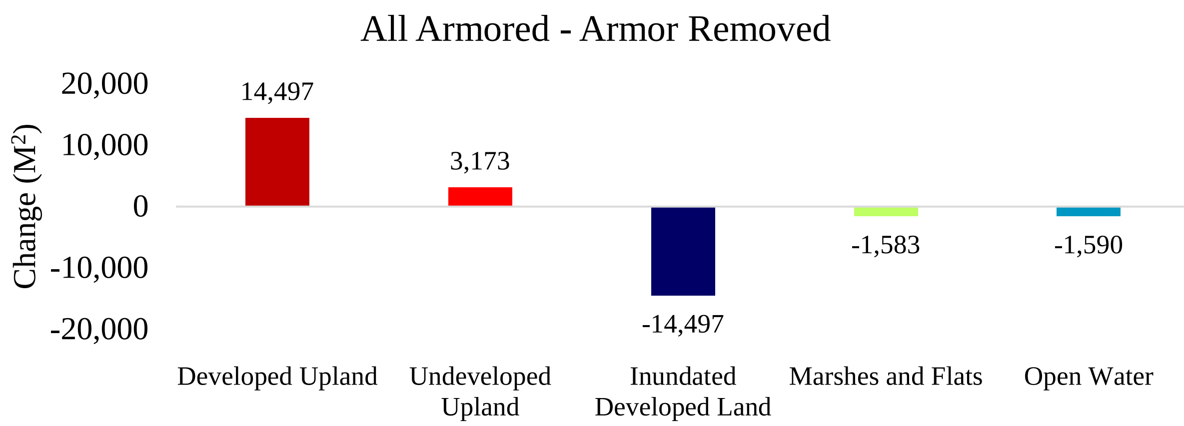

FIGURE 34: TEXAS CITY'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMOR REMOVED 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The AR scenario had more Marshes and Flats than the AA scenario did. This is due to increased inland inundation by water in the AR scenario which caused slight erosion of the shoreline and conversion of uplands to marshes; AA armorings protected the uplands from the rising sea but interfered with the migration of Marshes and Flats.

Galveston

Galveston had many armorings as of 2007. When armorings are dismantled in real life, the land which was previously behind the armoring erodes to reach a new equilibrium with the water. SLAMM does not consider that process which results in the outputs displaying more uplands than would be expected in real life. Rather, SLAMM considers the armoring artifacts within the DEM to be bluffed shorelines. The development of a new module within SLAMM to represent the removal of armorings would be a great next step for the model.

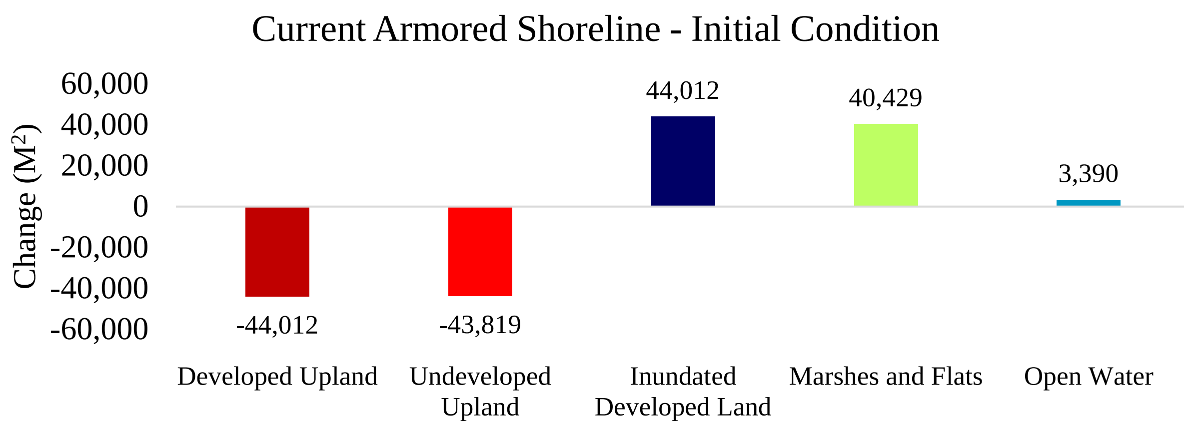

FIGURE 35: GALVESTON'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO COMPARED TO ITS INITIAL CONDITION.

SLR does not cause much shoreline erosion in Galveston; there is slightly more Open Water in CAS than the Initial Condition. There are also more Marshes and Flats in the CAS outputs in areas that were originally uplands in the Initial Condition. Several of the docks, which are classified as both developed and Undeveloped Uplands, located on the south portion of Pelican Island were affected by SLR in the CAS output. Portions of the docks are eroded while remaining areas converted to regularly flooded marsh. Of course, a usable dock cannot be marshy, so it can be assumed that they will be unusable unless they are maintained with adaptation to SLR in mind.

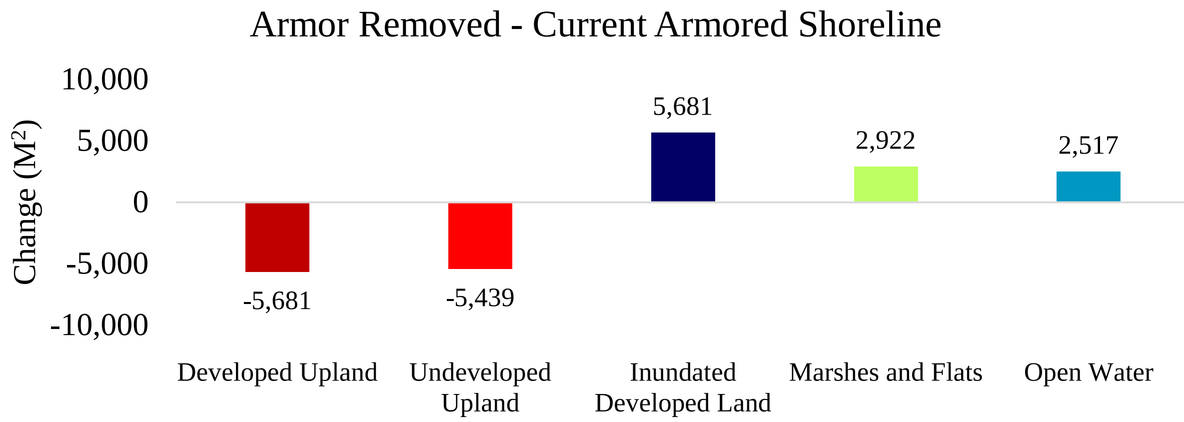

FIGURE 36: GALVESTON'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The shoreline eroded inland under the AR scenario, resulting in more Open Water. This also allowed upland conversion to Marshes and Flats compared to the CAS scenario. CAS armorings protected the uplands from erosion and conversion to Marshes and Flats. This scenario reflects a more accurate representation of coastal squeeze where marshes are lost due to the presence of armorings.

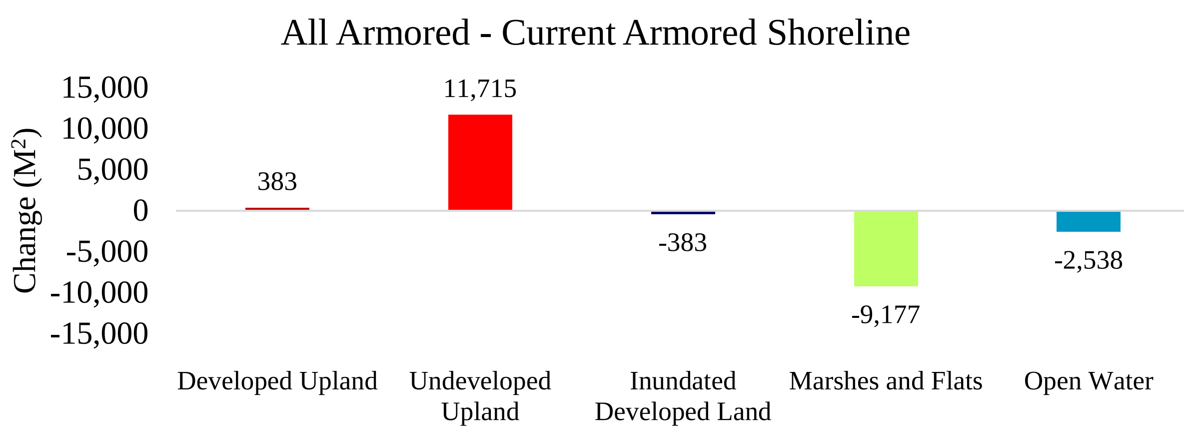

FIGURE 37: GALVESTON'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

Because Galveston's shoreline was quite developed and armored as of 2007, the difference between the AA and CAS 2100 outputs is not major. There are more Marshes and Flats in CAS and more Undeveloped Uplands in AA.

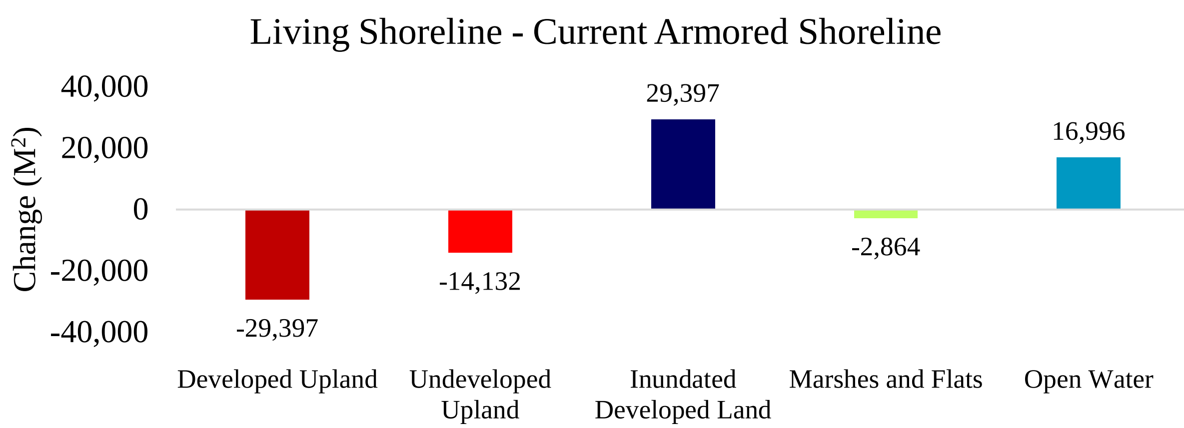

FIGURE 38: GALVESTON'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The shoreline eroded more in the LS scenario than the CAS scenario, resulting in more Open Water. There was also more conversion of uplands to Marshes and Flats, particularly transitional and regularly flooded marsh, in the LS output. While this may not be desirable from the community's standpoint due to the loss of uplands, a living shoreline in this situation would increase ecosystem services for the site.

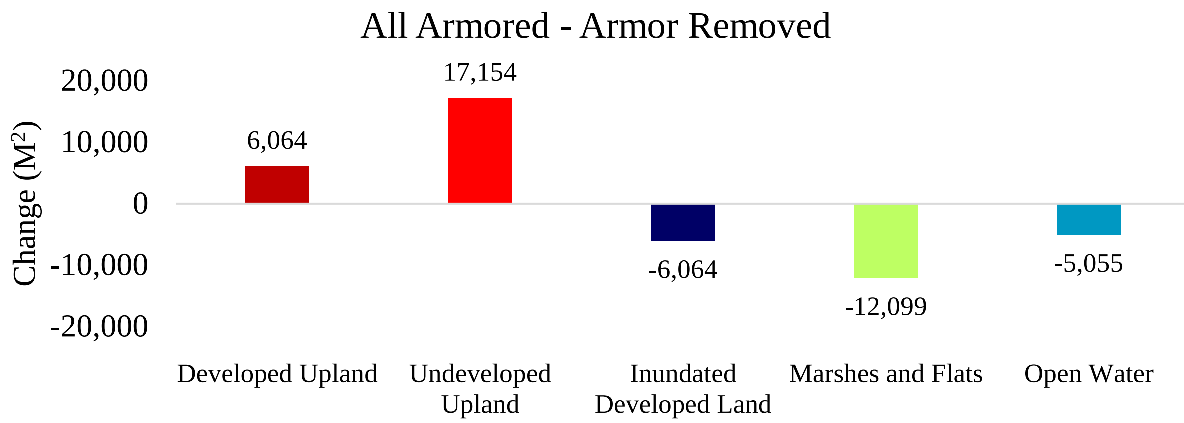

FIGURE 39: GALVESTON'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMOR REMOVED 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The AR scenario results in more Marshes and Flats compared to the AA outputs. The armoring in the AA scenario protects uplands from erosion and conversion to Marshes and Flats. This comparison accurately reflects the landscape changes that one would expect to see given knowledge of coastal squeeze.

Surfside Beach

Surfside Beach is located on a barrier island and has erosional issues due to natural properties and anthropogenic changes to the system. It is very susceptible to SLR, and the 0.206 m scenario triggered large changes in the landscape relative to the other sites.

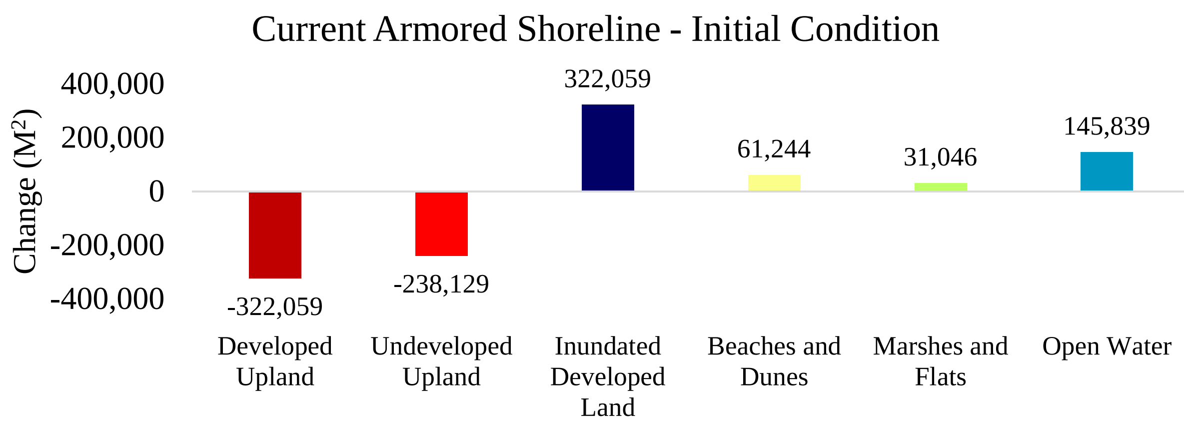

FIGURE 40: SURFSIDE BEACH'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO COMPARED TO ITS INITIAL CONDITION OUTPUT.

Surfside Beach had large impacts just from 0.206 m SLR. Many of its Developed and Undeveloped Uplands were lost from the Initial Condition to 2100 under the CAS scenario. The shoreline was eroded and caused more Open Water under the CAS scenario, and the SLR also caused the creation of more Beaches and Dunes and more Marshes and Flats. The increased extents of the Beaches and Dunes and Marshes and Flats in the CAS outputs reflect that Surfside did not have many armorings as of 2007, and thus the habitats were able to migrate inland away from the rising sea.

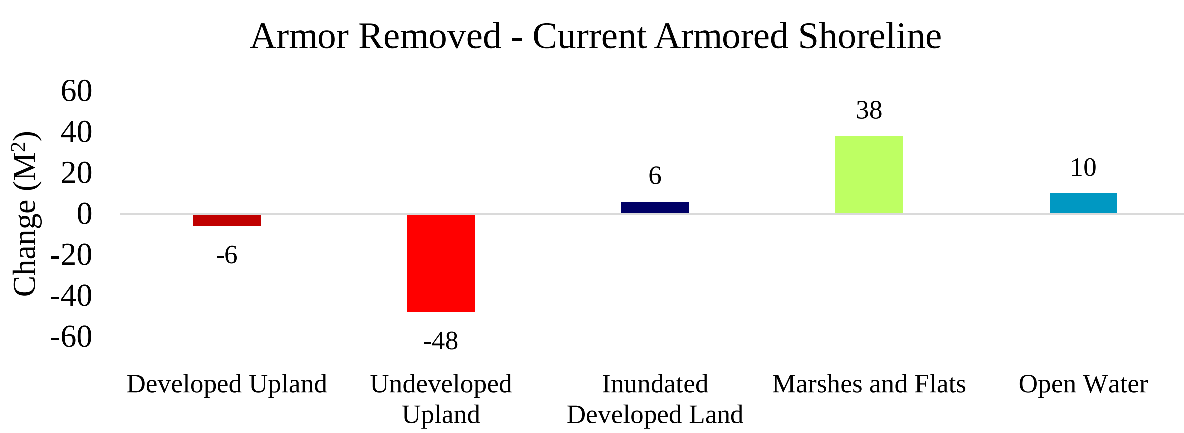

FIGURE 41:SURFSIDE BEACH'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The few existing armorings that exist in Surfside does not realistically protect against SLR. CAS protects more of the Undeveloped Uplands from conversion to Marshes and Flats.

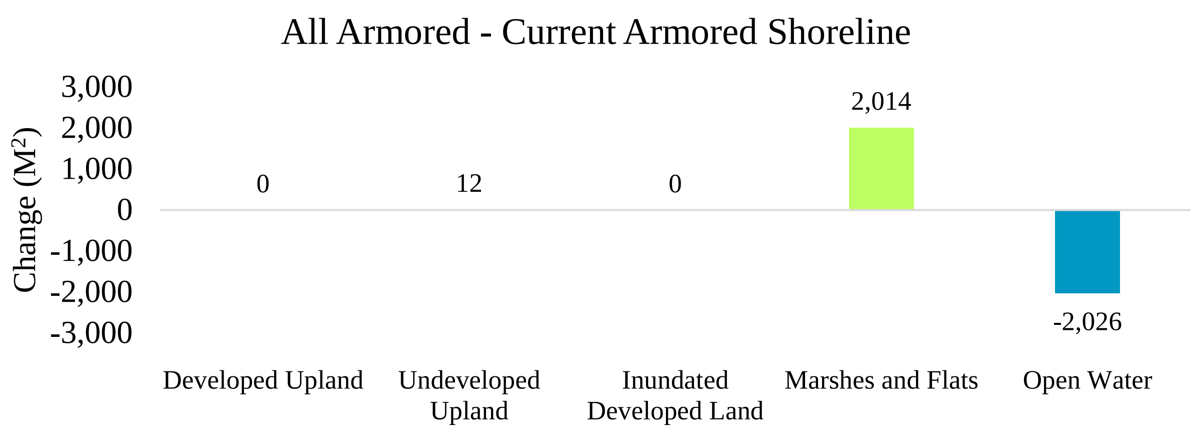

FIGURE 42: SURFSIDE BEACH'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

Because Surfside is facing the Gulf to the southeast and the northwest portion of the study site is marshy, there are limited amounts of armoring that the community can do. As such, armorings for the AA scenario were designated at the boundary between the deepest marshes and estuarine Open Water as well as the location of a small marina. AA had more Marshes and Flats, slightly more Undeveloped Uplands, and less Open Water. There was no difference in Developed Uplands.

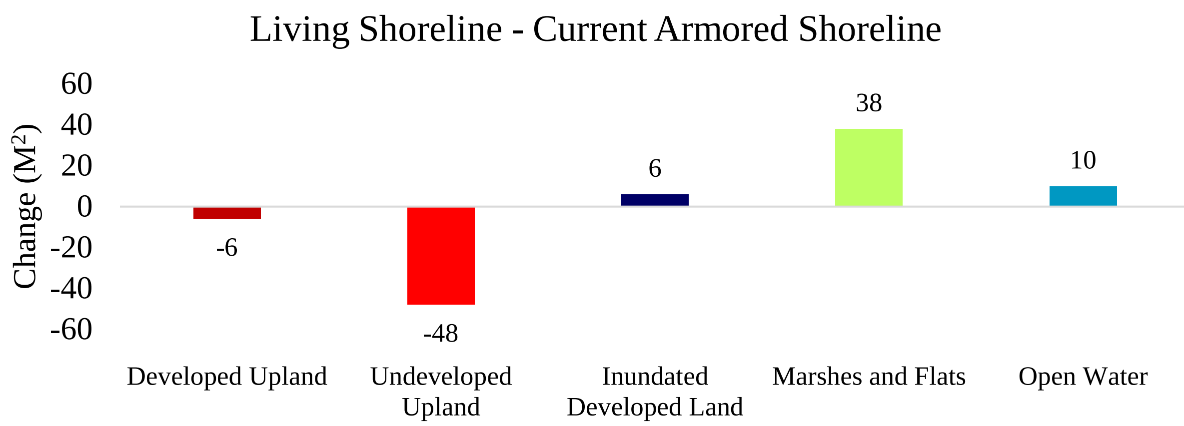

FIGURE 43: SURFSIDE BEACH'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

To model a living shoreline in Surfside, a single sill with its height equal to the tidal range was placed across the opening where the tidal flats connect to the Gulf Intracoastal Waterway. The armoring in the northeast section of the site where the marina was located was also included in the LS scenario. Surprisingly, LS protected Surfside from Open Water more than CAS did. LS protected more Beaches and Dunes and Marshes and Flats. CAS protected more uplands and had more Open Water than LS.

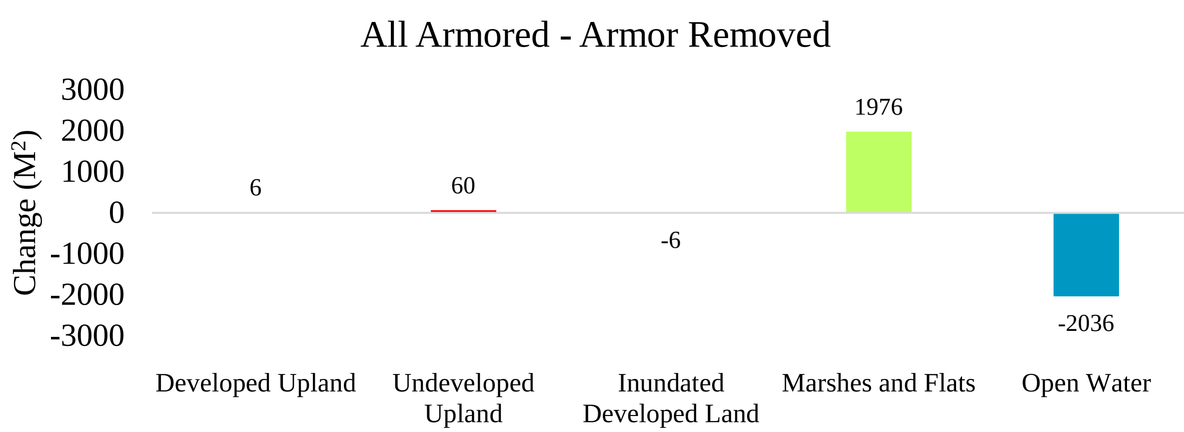

FIGURE 44: SURFSIDE BEACH'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMOR REMOVED 2100 OUTPUT UNDER THE LOW SLR SCENARIO.

The difference between AA and AR is slight because the Surfside site had so few armorings. There was more Open Water under the AR scenario. AA protected more Marshes and Flats and minimal amounts of uplands.

MEDIUM SLR- 0.74 M

0.74 m of SLR by 2100 will be disruptive to human life and industries along the coast. Should the sea rise by this much, human adaptation will be required, and vulnerabilities to storms and storm surges will be greatly heightened. It will not, however, be as devastating as 1.8 m SLR which is represented in the high SLR scenario.

Anahuac

Because Anahuac is only lightly developed, 0.74 m of SLR is not projected to have as big of an impact upon human life as it is in other sites. The shoreline is projected to erode inland, and there is conversion of uplands to marsh habitats.

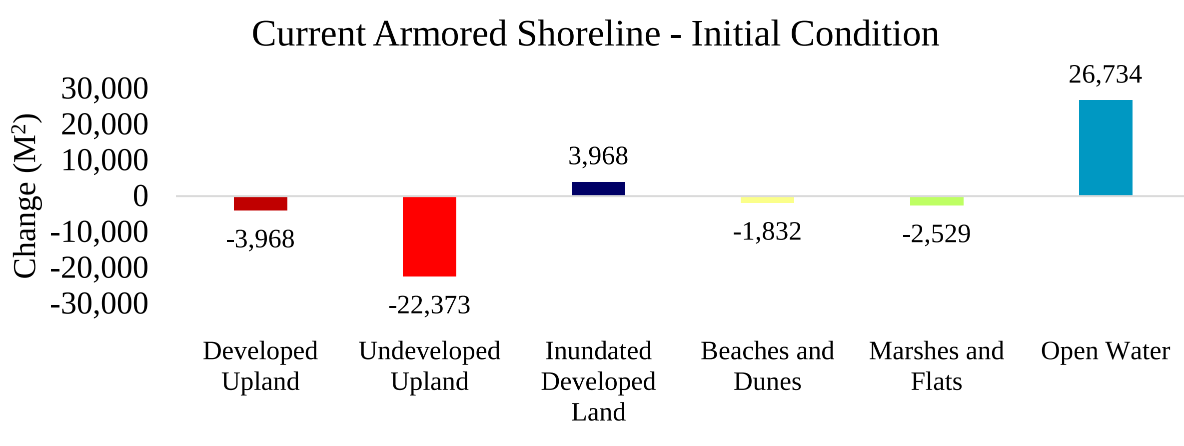

FIGURE 45: ANAHUAC'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO COMPARED TO ITS INITIAL CONDITION.

The areal extent of Anahuac's small beach grew from the Initial Condition to the 2100 output of the CAS scenario. Conversely, Undeveloped Uplands had a much greater areal extent in the Initial Condition; there was a decrease in Undeveloped Uplands' extent from Initial Condition to CAS 2100. These changes all reflect shoreline erosion and conversion to other habitat types triggered by SLR.

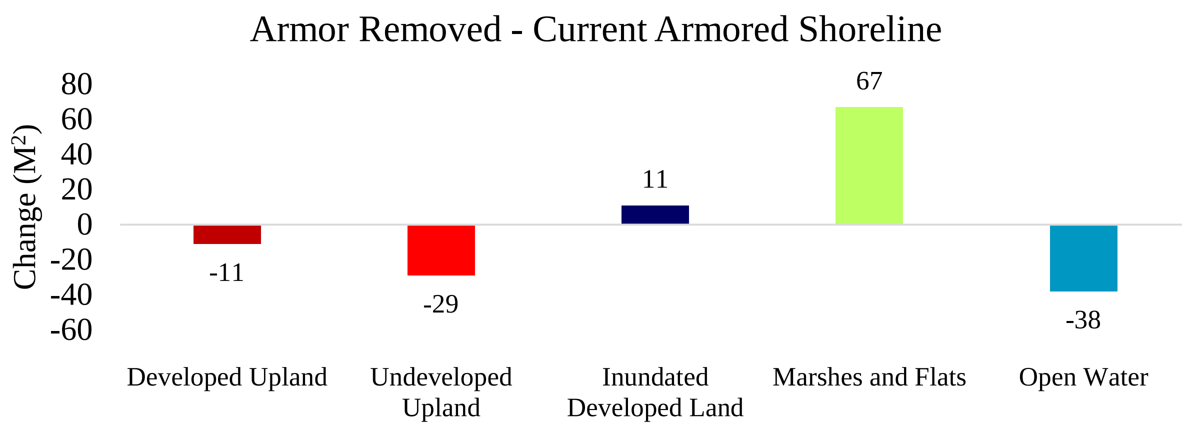

FIGURE 46: ANAHUAC'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

The differences in the AR and CAS scenarios is slight. CAS had more Marshes and Flats, and less than more of both Developed and Undeveloped Uplands. AR had more Open Water. Although the changes between the two scenarios is not large, the changes are what one would expect to see given coastal squeeze and a natural environment.

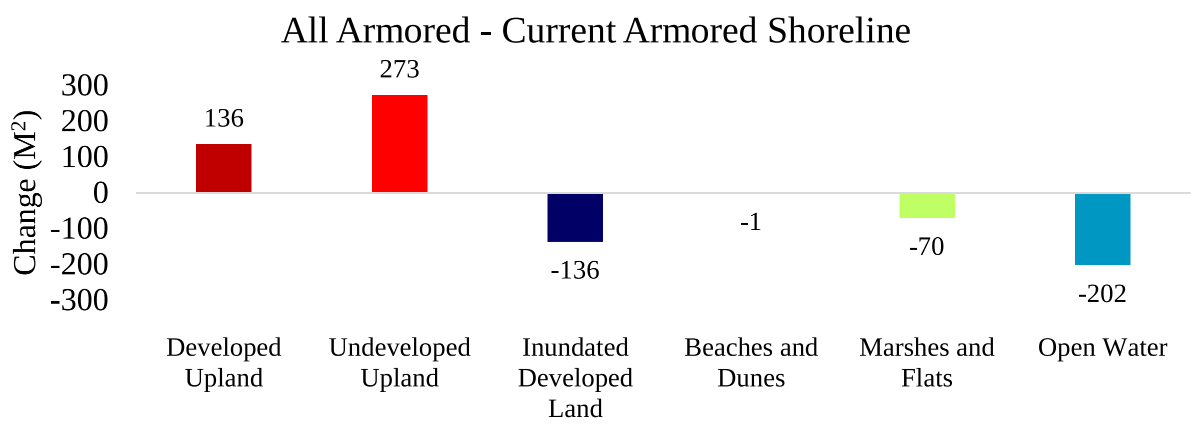

FIGURE 47: ANAHUAC'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

AA protected more uplands and Marshes and Flats whereas the breaks in the CAS armorings allowed more water to inundate inland and erode the shoreline.

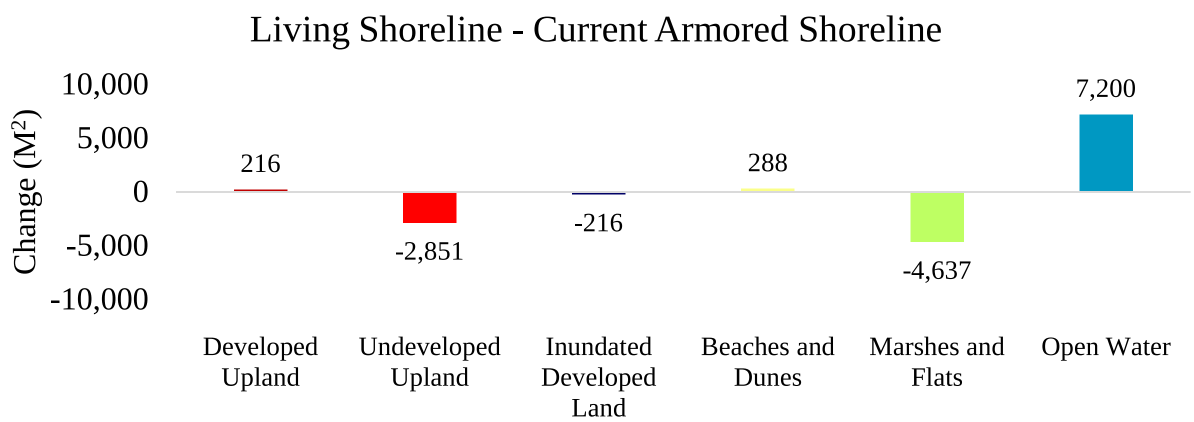

FIGURE 48: ANAHUAC'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

The purpose of using sills to create a living shoreline is to minimize erosion by decreasing wave energy and to allow increased marsh growth landward of the sill. The outputs from the LS scenario, however, does not reflect that. In this comparison, LS protects more Developed Uplands and Beaches and Dunes. Anahuac has several channels that drain water from the uplands into Galveston Bay. The LS scenario prevented those Developed Upland areas from converting into Marshes or Flats whereas they did convert in the CAS scenario. That is why LS has more Developed Uplands and less Marshes and Flats than CAS.

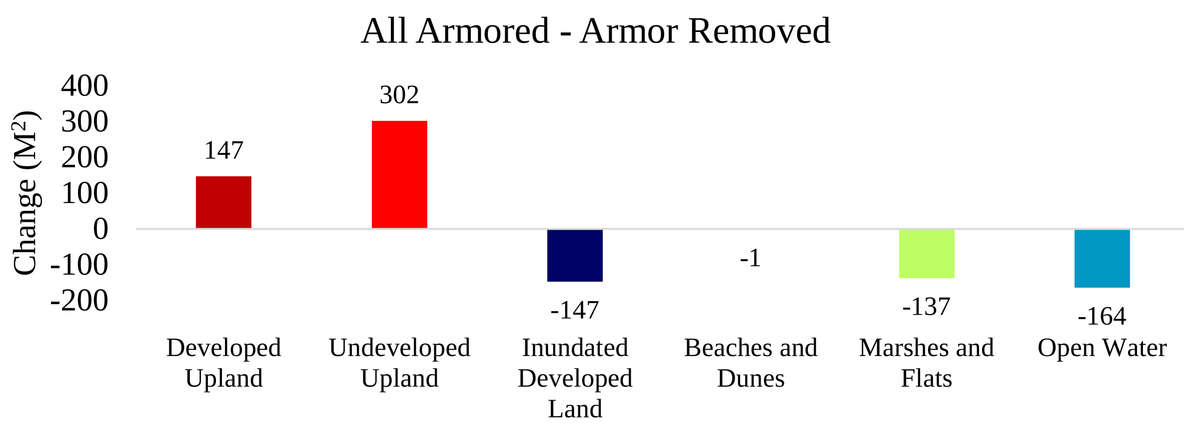

FIGURE 49: ANAHUAC'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMOR REMOVED 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

The differences between AA and AR outputs are also slight. There was -1 m^2 more Beaches and Dunes in the AR scenario. The other habitat types were fairly similar. This indicates that, for settings such as Anahuac, it is the magnitude of SLR that matters in the future, not what type of intervention humans pursue; if SLR is closer than 0.206 m than 0.74 m, human intervention is predicted to make a difference on the future landscape. However, if SLR is towards 0.74 m or higher, human life will be negatively impacted regardless of the type of protection strategy enacted.

Texas City

Under the medium SLR, Texas City has major landscape changes regardless of the policy response scenario. Marshes and Flats migrate much farther inland which could interrupt the many petrochemical activities in this region. The shoreline erodes for all policy scenarios, and docks which existed in 2007 are projected to be negatively impacted.

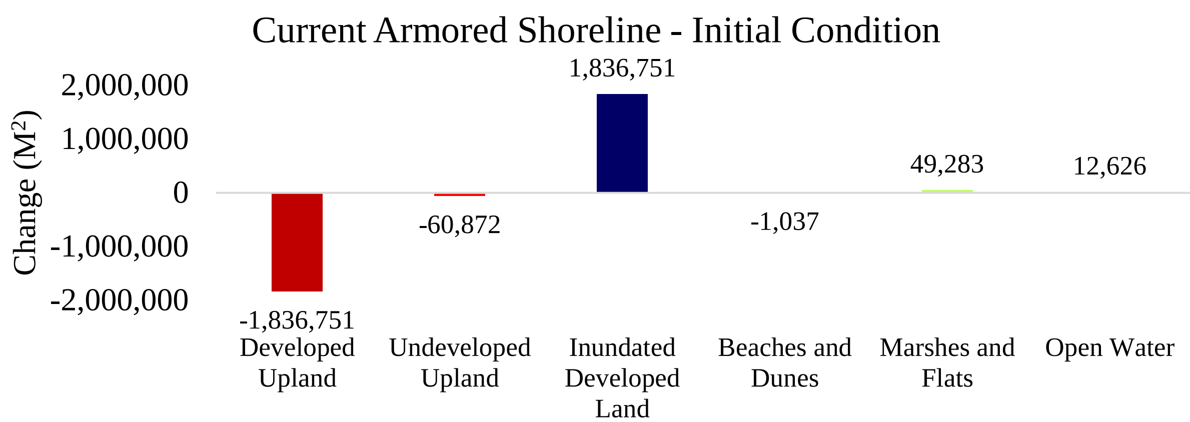

FIGURE 50: TEXAS CITY'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO COMPARED TO ITS INITIAL CONDITION.

Between the Initial Condition and the CAS output for the 0.74 m SLR scenario, quite a lot of changes occur. Water inundates farther inland and triggers the conversion of mostly Developed Uplands to Marshes and Flats; there are more Marshes and Flats in the CAS output than there was in the Initial Condition output (Fig. 34). The Initial Condition also had more Beaches and Dunes, Undeveloped Uplands, and Developed Uplands than the CAS output.

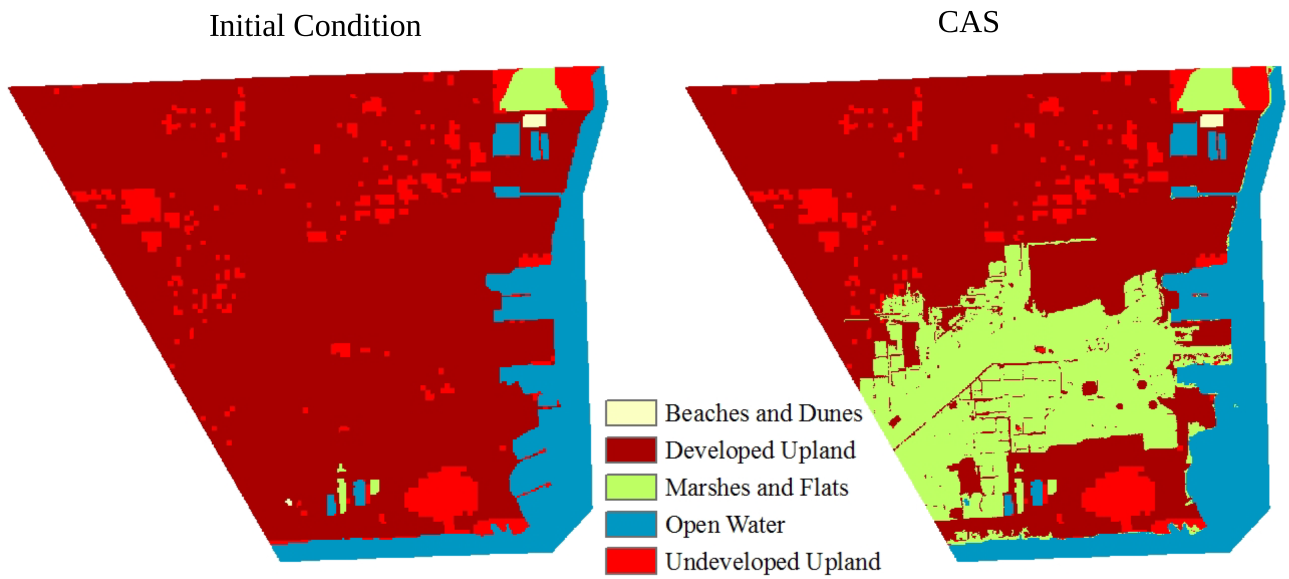

FIGURE 51: THE DIFFERENCE IN MARSH AND FLATS EXTENTS BETWEEN THE INITIAL CONDITION AND CAS 2100 OUTPUT FOR TEXAS CITY.

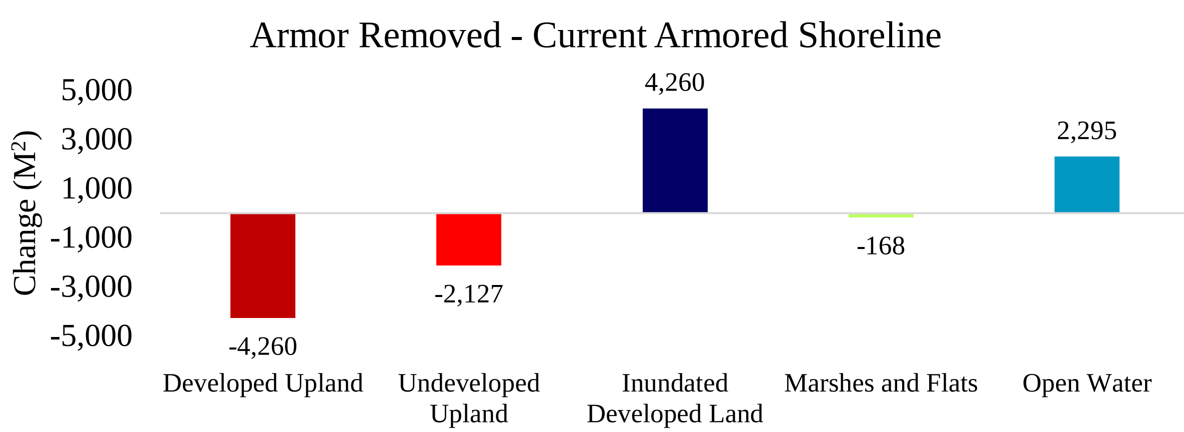

FIGURE 52: TEXAS CITY'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

CAS protected slightly more uplands from erosion and conversion than AR. The extent of Marshes and Flats is greater under CAS than AR; this was not expected and was due to the DEM and location of armorings in CAS. Although SLAMM assumed that no armorings were present under the AR scenario, the DEM reflects elevation changes due to armorings that existed when the DEM's LiDAR data was collected; the elevation of uplands landward of the armoring is higher than the elevation of the water seaward of the armoring. This likely was interpreted as a bluff within SLAMM and prevented Marshes and Flats from migrating landward in the AR scenario.

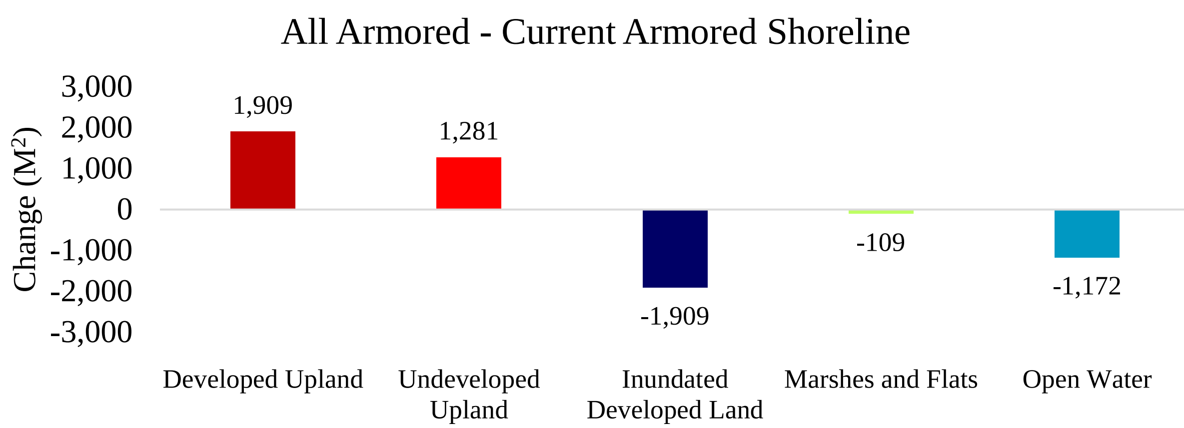

FIGURE 53: TEXAS CITY'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

The difference in habitat extents between AA and CAS outputs is fairly similar. Most of Texas City was armored as of 2007, hence there are not many differences between the armoring inputs for AA and CAS. The few gaps that there are in the CAS armorings, however, does allow water to inundate inwards and convert more uplands to Marshes and Flats.

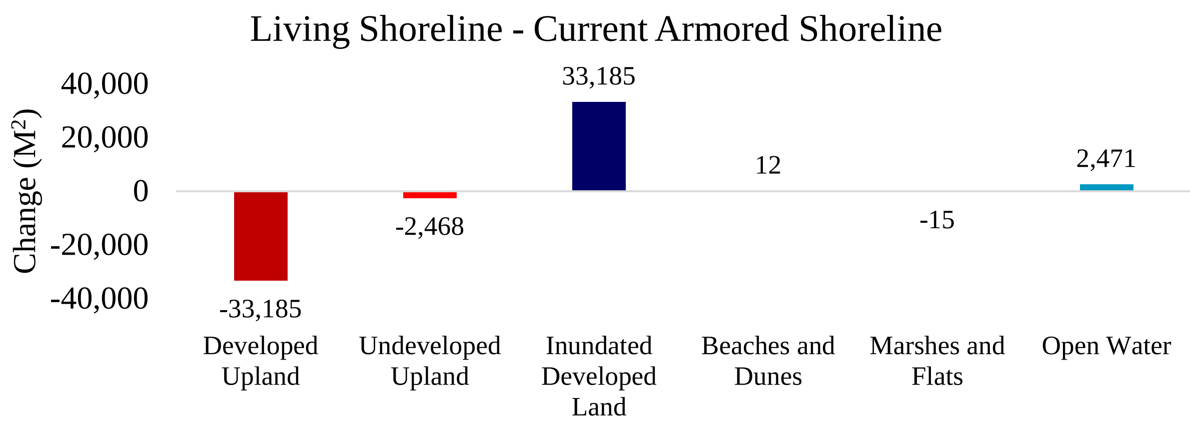

FIGURE 54: TEXAS CITY'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

Open Water inundated farther inland through erosion under the LS scenario; LS did not protect Texas City's uplands at this SLR scenario. There were more uplands under the CAS scenario whereas LS had more Marshes and Flats. Living shorelines may not be a good option for Texas City because of its infrastructure that is important to the region and the nation.

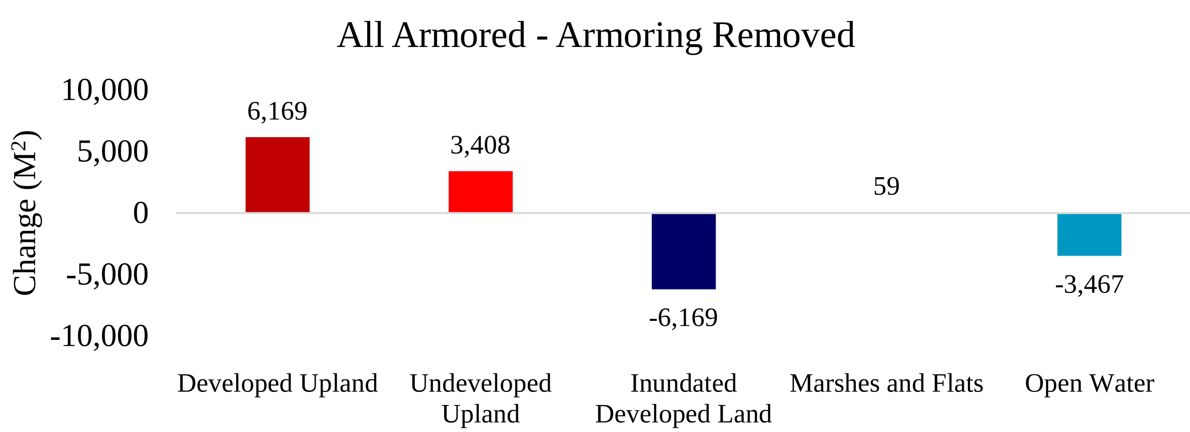

FIGURE 55: TEXAS CITY'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMORING REMOVED 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

AA protected nearly 10,000 m^2 more uplands than AR did. This number is probably a bit low because the AR scenario had elevation differences within the input

DEM from armorings that were already in place as of 2007 and, as previously discussed, SLAMM does not show as much erosion from removed armorings as would happen in real life. Also in real life, one would expect to see more Marshes and Flats under the AR scenario instead of the more Marshes and Flats that is seen in the AA scenario output. This is due to the location of armoring seaward of all marshes which protects them from inundation from Open Water.

Galveston

Galveston is projected to have many negative effects from a 0.74 m rise in sea level. Marshes migrated far inland, particularly on the south side of the study area, and the shoreline continued to erode inland. Pelican Island had some conversion to Marshes and Flats and some erosion as well, but it appeared to remain closer to its original landscape than the barrier island part of the site.

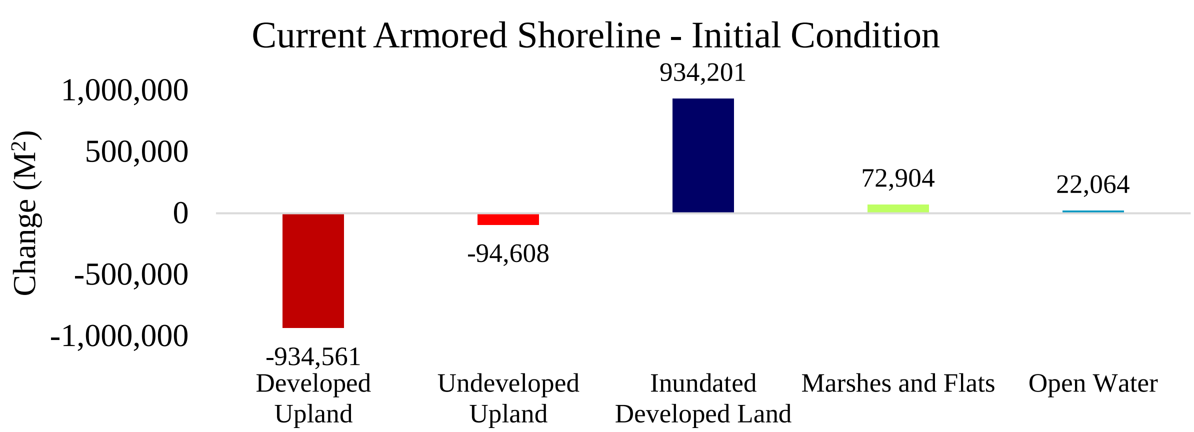

FIGURE 56: GALVESTON'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO COMPARED TO ITS INITIAL CONDITION.

The Initial Condition had more Developed and Undeveloped Uplands than the 2100 CAS output. CAS, however, had more Marshes and Flats. There was a slight change in Open Water between the two outputs which indicates that there was not much shoreline erosion occurring. Rather, the biggest change is the migration of transitional marsh which converted much of the uplands on the southern part of the study site.

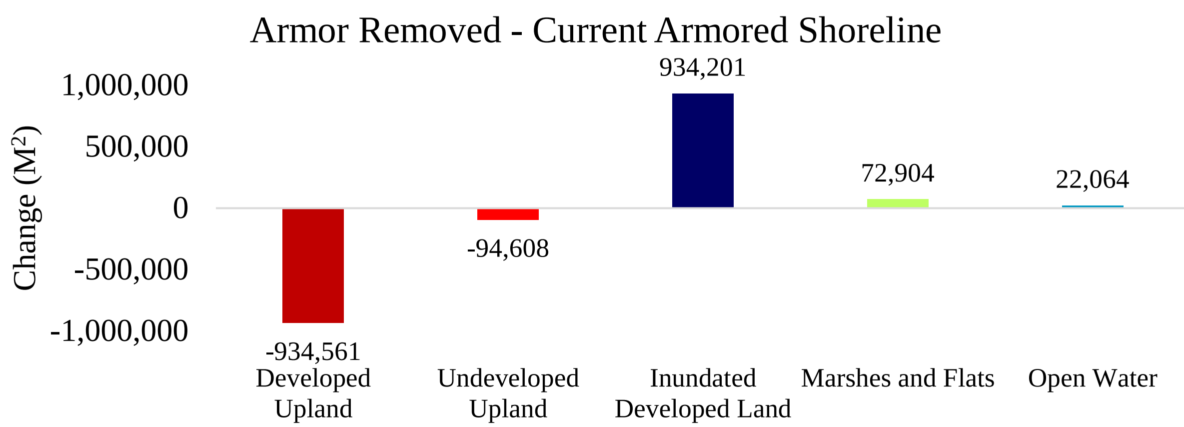

FIGURE 57: GALVESTON'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

These results also reflect what would be expected to happen. When no armorings are present, water erodes the shoreline and inundates inland, thus causing a decrease in the extent of Marshes and Flats and uplands.

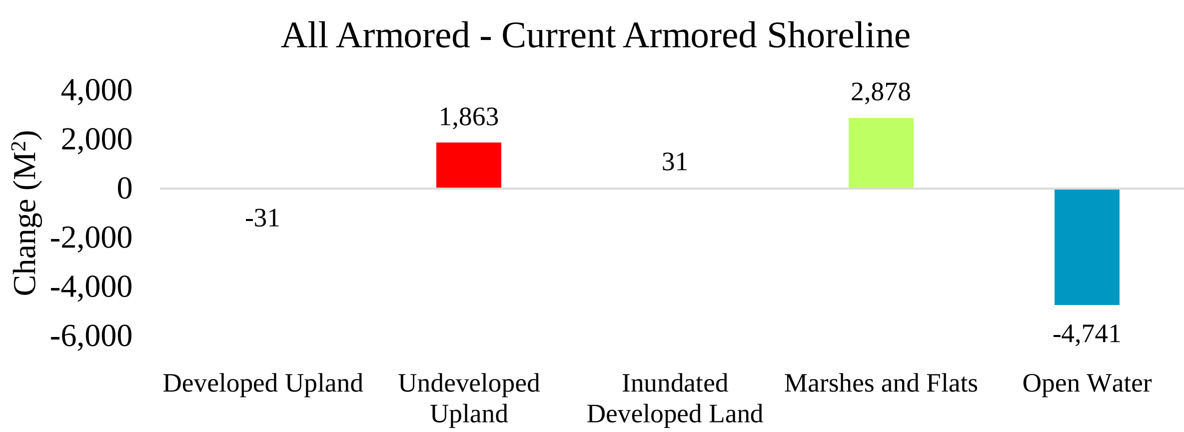

FIGURE 58: GALVESTON'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

This reflects what one would expect given knowledge of how SLAMM assumes that the armorings protect uplands and Marshes and Flats. The breaks in the CAS armorings allowed additional Open Water to inundate inland whereas the continuous armorings in CAS protected the uplands and Marshes and Flats.

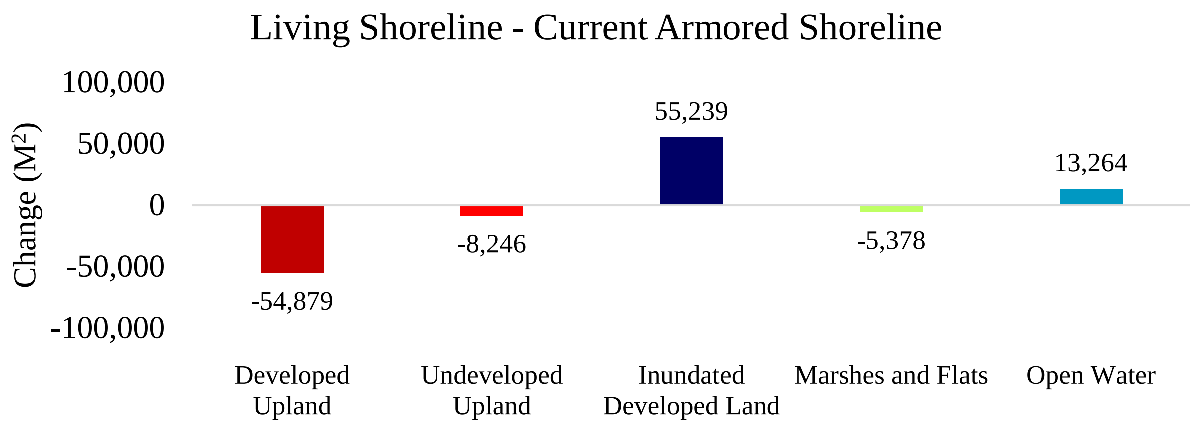

FIGURE 59: GALVESTON'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

This output reflects an accurate picture of what one can expect from living shorelines. The LS sill enabled more marsh development, which were able to migrate inland because there were no limiting structures. CAS protected more uplands, but because of the increased marshes in the LS scenario it will have more ecosystem services.

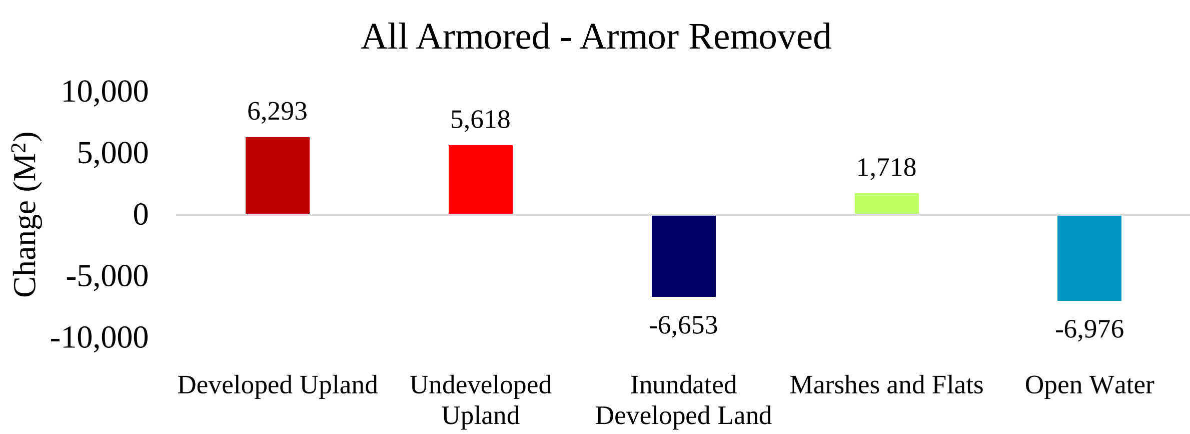

FIGURE 60: GALVESTON'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMOR REMOVED 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

Given knowledge of how previous SLAMM armoring scenarios worked, these findings are unsurprising. The armorings, which are seaward of all non-water habitats, protect the Marshes and Flats from inundation and subsequent conversion to Open Water. The armorings also protected uplands from inundation, conversion to other habitat types, and erosion.

Surfside Beach

Surfside is very vulnerable to SLR, and it is extremely affected by the 0.74 m change. Much of its uplands are converted to Marshes and Flats, and the shoreline is eroded and converted to Open Water.

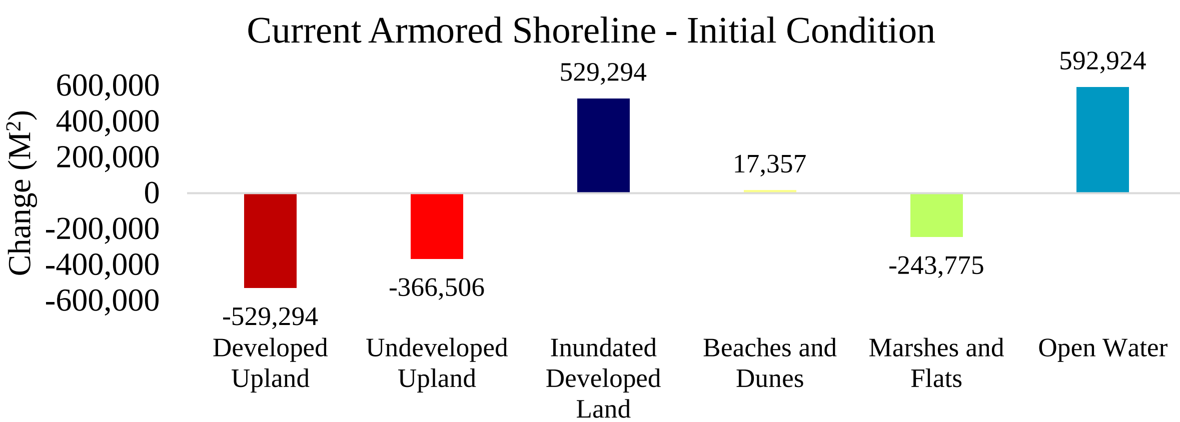

FIGURE 61: SURFSIDE BEACH'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO COMPARED TO ITS INITIAL CONDITION.

The difference between the Initial Condition and CAS outputs for the medium SLR scenario is large. The barrier island broke up as parts of it converted to Open Water; there was more Open Water and Beaches and Dunes in CAS. From the Initial Condition to CAS, Developed and Undeveloped Uplands were lost.

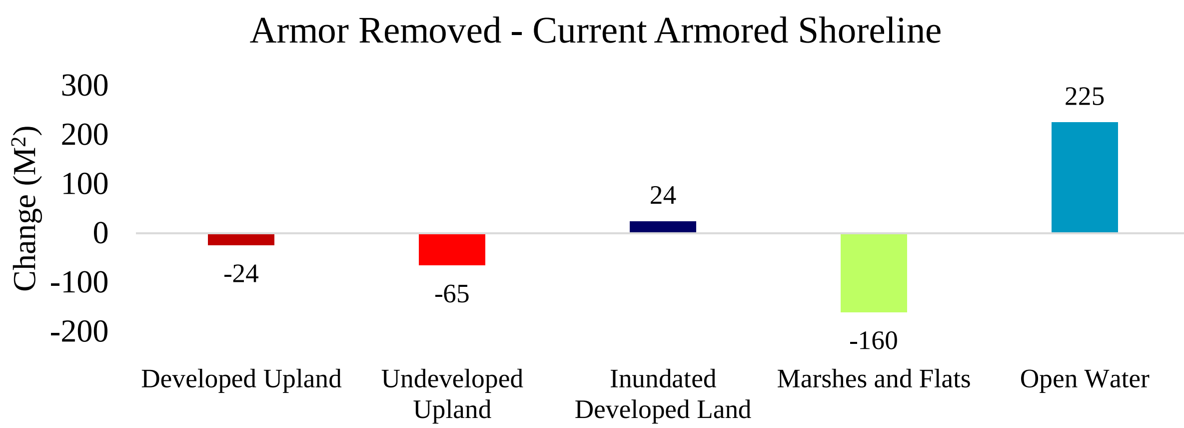

FIGURE 62: SURFSIDE BEACH'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

The changes in AR and CAS are minimal but do reflect how the system would be expected to respond to SLR. There was more Open Water in AR while the CAS armoring protected more Developed and Undeveloped Uplands in CAS. There was slightly more Marshes and Flats in the CAS scenario. Thus, the CAS armorings protected uplands and Marshes and Flats from conversion and erosion.

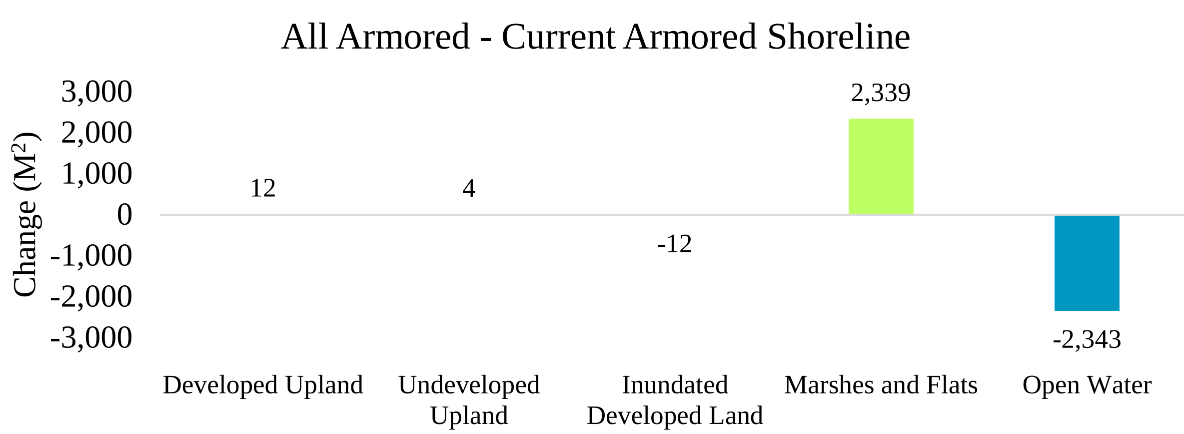

FIGURE 63: SURFSIDE BEACH'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

These two scenarios are very similar. AA protected the uplands and Marshes and Flats from inundation by Open Water, which aligns with how SLAMM has been responding to the armorings located seaward of the Open Water and non-Open Water boundary.

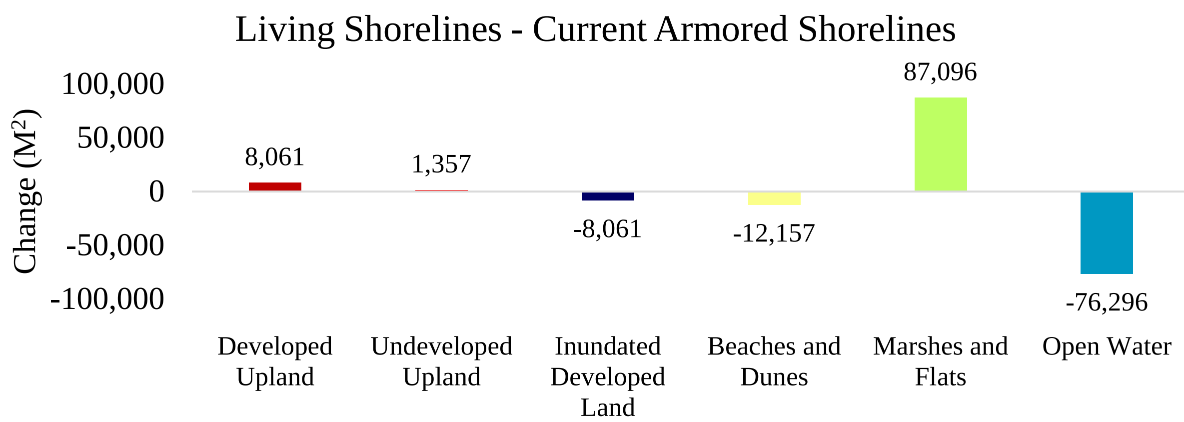

FIGURE 64: SURFSIDE BEACH'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

The sill in the LS scenario makes a larger difference than the CAS armorings in protecting non-Open Water from the Open Water. The LS outputs for Marshes and Flats are greater than the extent in the CAS output, and LS has less Open Water than CAS. The sill also protects more Developed and Undeveloped Uplands. CAS has more Beaches and

Dunes.

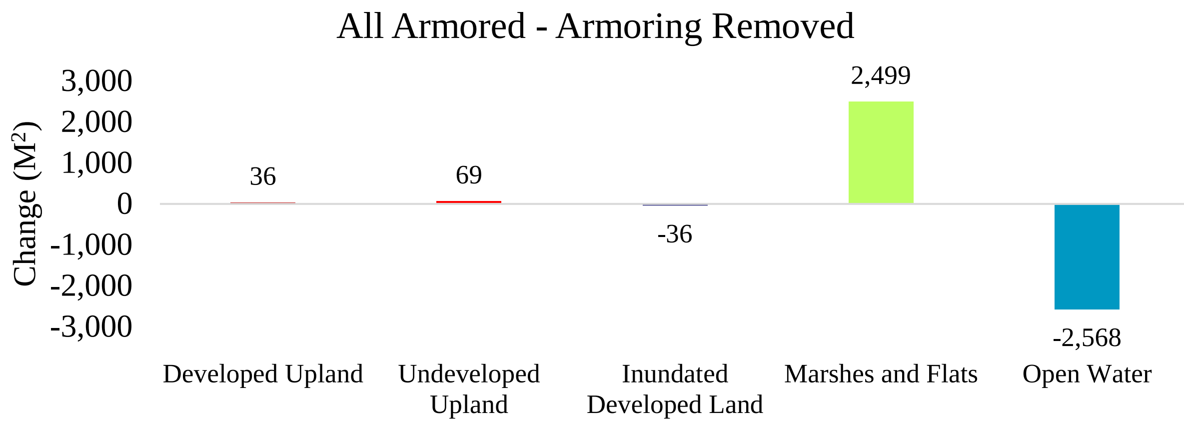

FIGURE 65: SURFSIDE BEACH'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMORING REMOVED 2100 OUTPUT UNDER THE MEDIUM SLR SCENARIO.

The difference between the AA and AR scenarios within Surfside are minimal. AA protected more Marshes and Flats, because the armoring limited the amount of water that could inundate inland. AR has more Open Water whereas AA protected slightly more uplands.

HIGH SLR- 1.8 M

If 1.8 m SLR occurs by 2100, human life will be massively affected. SLAMM indicates that regardless of human intervention, many changes will occur that will be extremely disruptive to human processes. Some habitats exhibit small areal changes but, because the habitats are so small in the site, it actually reflects a large percent change (please see Appendix). This has the potential to be particularly important in marsh habitats and their ecosystem services.

Anahuac

Anahuac is projected to be affected by 1.8 m of SLR, but it does not have the devastating results that some of the other sites are projected to have. Transitional marsh will migrate inland and convert many uplands, and the shoreline will erode inland.

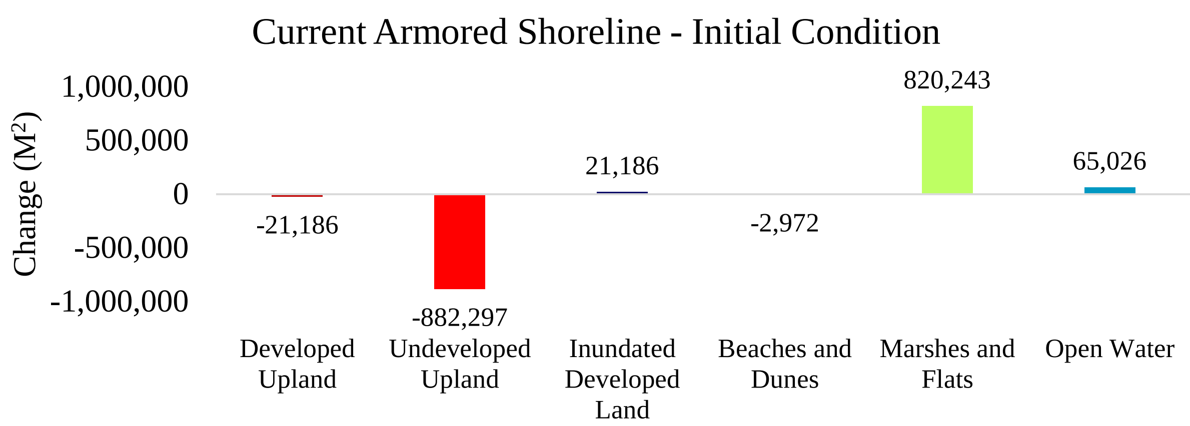

FIGURE 66: ANAHUAC'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO COMPARED TO ITS INITIAL CONDITION.

The biggest change that SLR is projected to have is a massive conversion of uplands to transitional marsh. The CAS output is expected to have many more Marshes and Flats than the Initial Condition did. SLR will cause the loss of Developed Uplands, Undeveloped Uplands, and Beaches and Dunes.

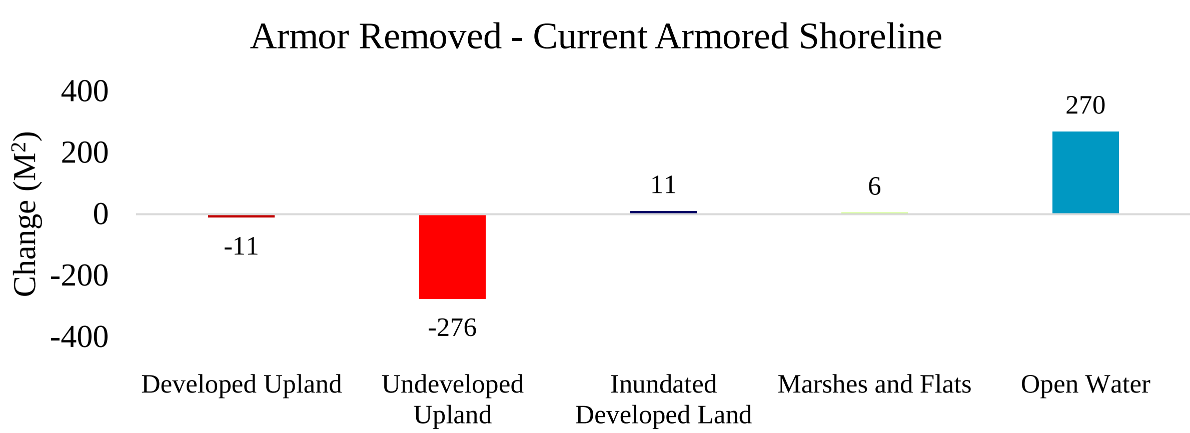

FIGURE 67: ANAHUAC'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

This represents an expected output of how the landscape will respond to SLR. CAS protects the uplands while AR allows edge erosion and the landward migration of Marshes and Flats. This indicates that human intervention will have limited effects given large magnitudes of SLR.

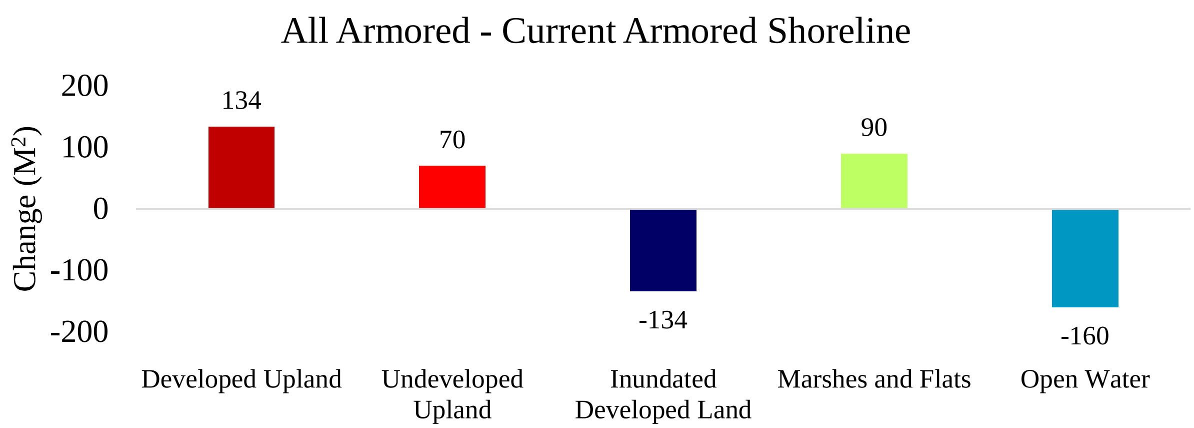

FIGURE 68: ANAHUAC'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

The AA armorings protected more uplands and Marshes and Flats than CAS. The breaks in the CAS armorings allowed Open Water to inundate inland and cause erosion.

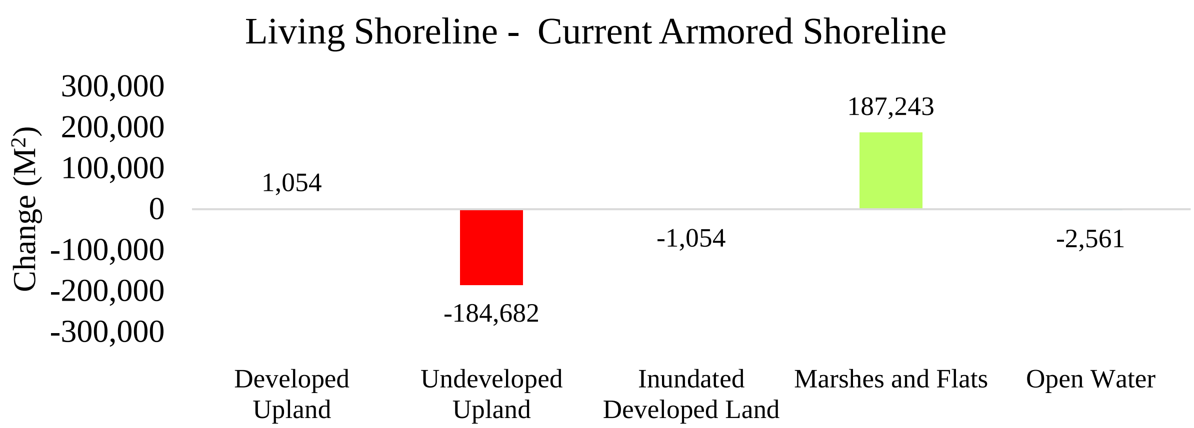

FIGURE 69: ANAHUAC'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

These outputs are fairly reflective of expected SLR-induced landscape changes. LS prevented the inundation of Open Water and protected more Marshes and Flats, Beaches and Dunes, and Developed Uplands. CAS protected more Undeveloped Uplands because some of those areas converted to Marshes and Flats in the LS scenario.

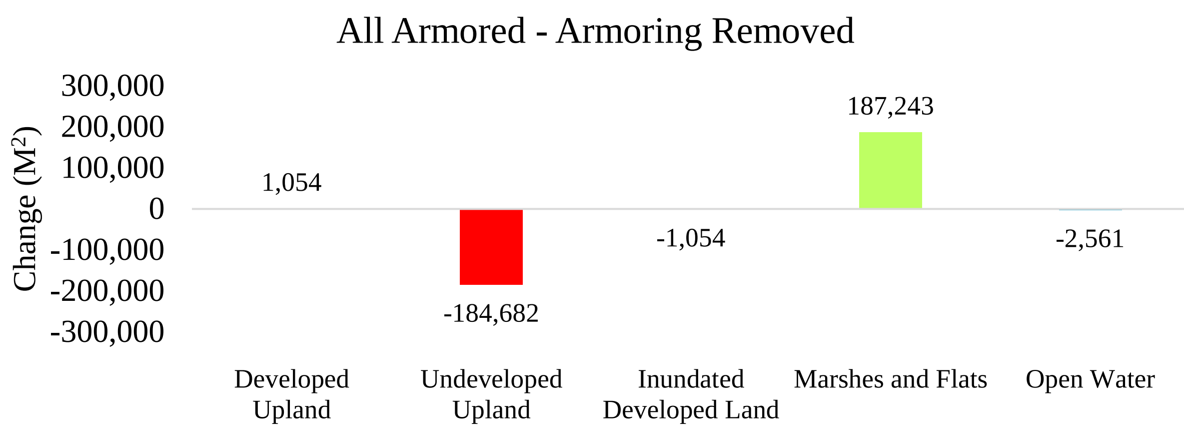

FIGURE 70: ANAHUAC'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMORING REMOVED 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

These outputs also reflect what would be expected from these policies, given knowledge of how SLAMM utilizes the armorings which are seaward of the non-water habitats. The AA armorings protect the uplands and Marshes and Flats from inundating water.

Texas City

1.8 m of SLR will have severe negative impacts upon Texas City's industry, and the area will probably have extreme vulnerabilities to storm-induced flood damage. Marshes and Flats are projected to migrate over nearly the entire extent of the site.

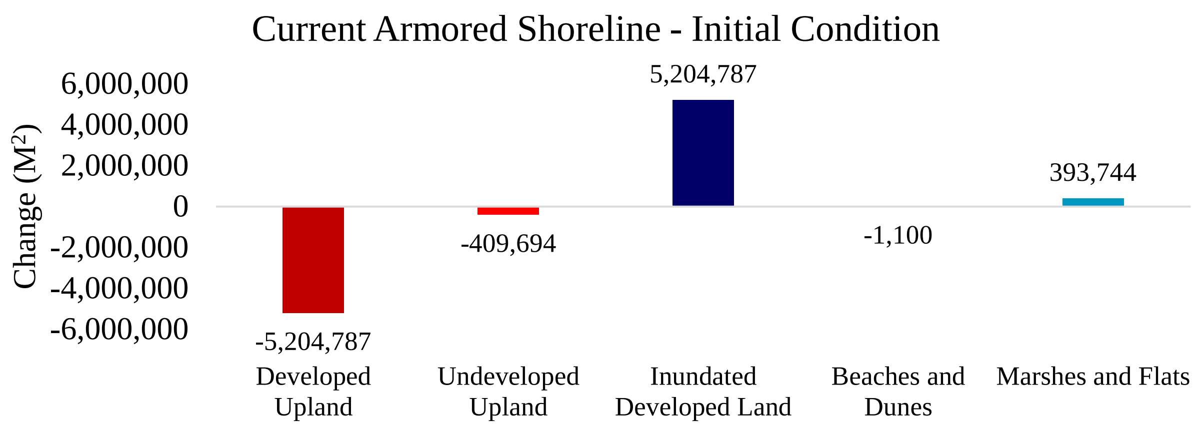

FIGURE 71: TEXAS CITY'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO COMPARED TO ITS INITIAL CONDITION.

Marshes migrated far inland due to SLR in the CAS scenario; there were more Marshes and Flats and Open Water under the CAS scenario compared to the Initial Condition. There were more Developed Uplands, Undeveloped Uplands, and Beaches and Dunes in the Initial Condition. The shoreline did not erode very much, but Marshes and Flats migrated onto many of the uplands.

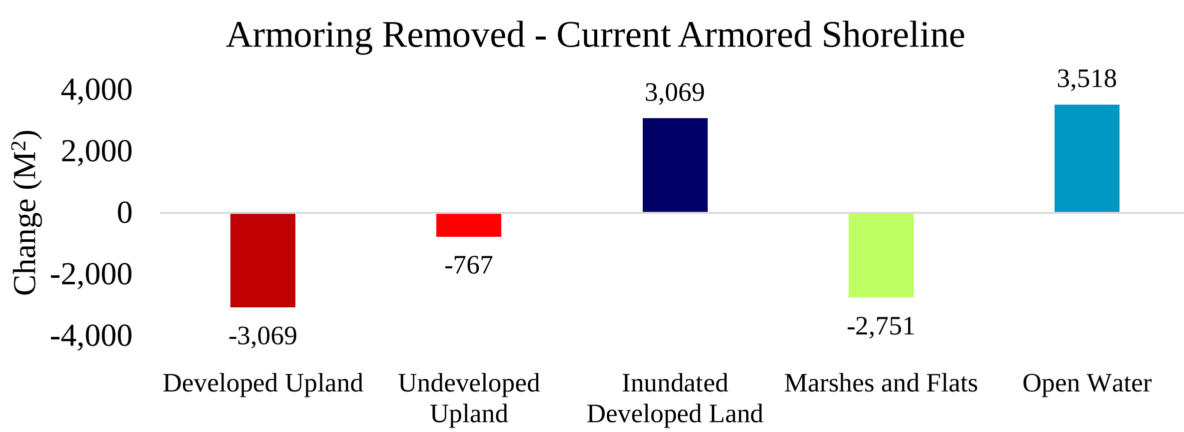

FIGURE 72: TEXAS CITY'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

Under a 1.8 m SLR, the policy option does not make much of a difference in the landscape; the changes probably equally disrupt human activities when one looks at the magnitude of landscape change. CAS had more Open Water while AR had more Marshes and Flats, more Undeveloped Uplands, and more Developed Uplands.

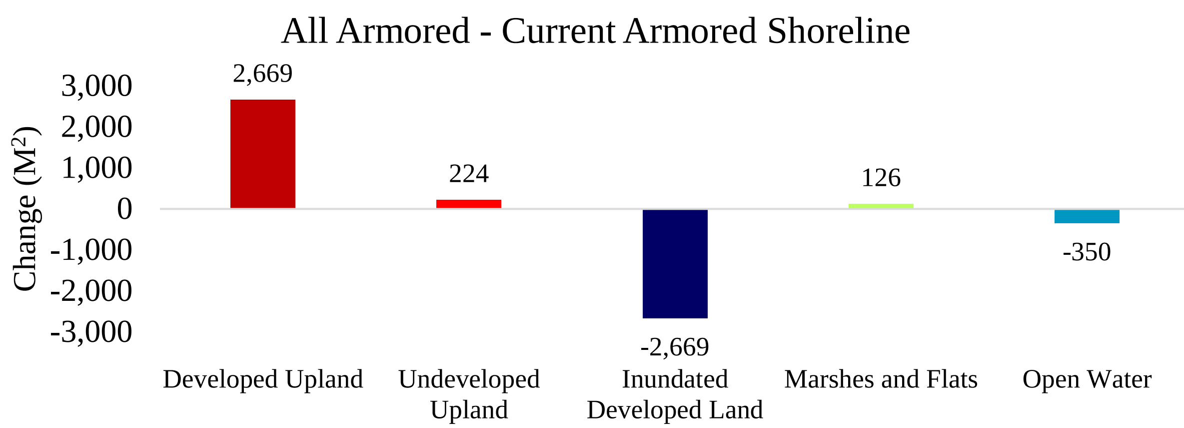

FIGURE 73: TEXAS CITY'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

As SLAMM has done with the armorings located seaward of the non-Open Water habitats, the AA scenario protects uplands from erosion and conversion. It also protects Marshes and Flats from inundation by Open Water. The percent difference between the two scenarios is not large, however; there was more Open Water in CAS than AA, and the percent difference for the other habitat types were all even less.

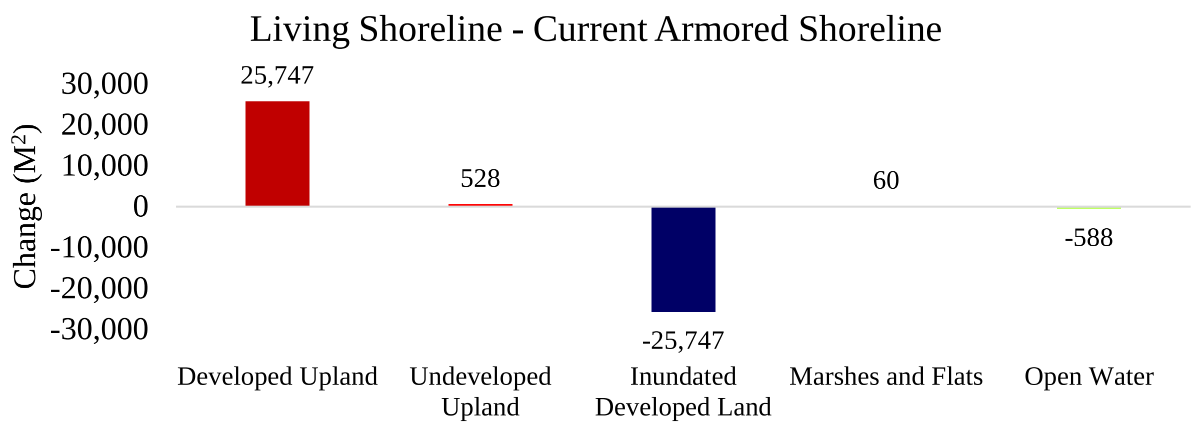

FIGURE 74: TEXAS CITY'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

The LS did a very good job of protecting Texas City from SLR. LS protected more Developed Uplands than CAS did. Because it protected more uplands, Marshes and Flats were not able to migrate inland as far, and thus there was a decrease in Marshes and Flats in the LS output compared to the CAS output. Erosion was greater in CAS, resulting in more Open Water.

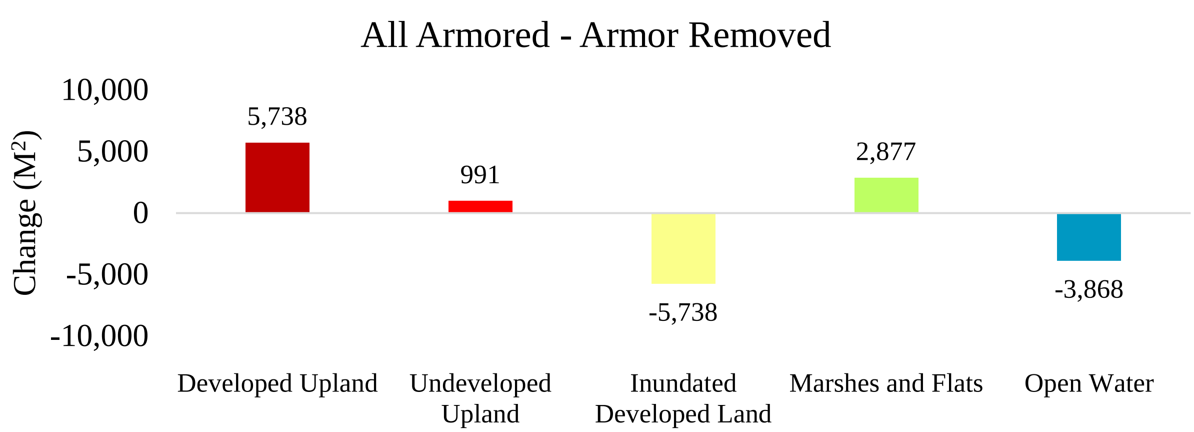

FIGURE 75: TEXAS CITY'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMOR REMOVED 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

These results are just like the prior comparisons of AA and AR. The AA armorings are seaward of non-water habitats, and so they protect the uplands and

Marshes and Flats from inundation by Open Water. When the armorings are removed, the Open Water inundates inland.

Galveston

Galveston would be completely changed under a 1.8 m rise in sea level. The shoreline is not projected to erode very far, especially relative to the Surfside site, because of the artifacts of the armorings within the DEM. Marshes and Flats, particularly transitional marsh, are projected to migrate into much of the uplands.

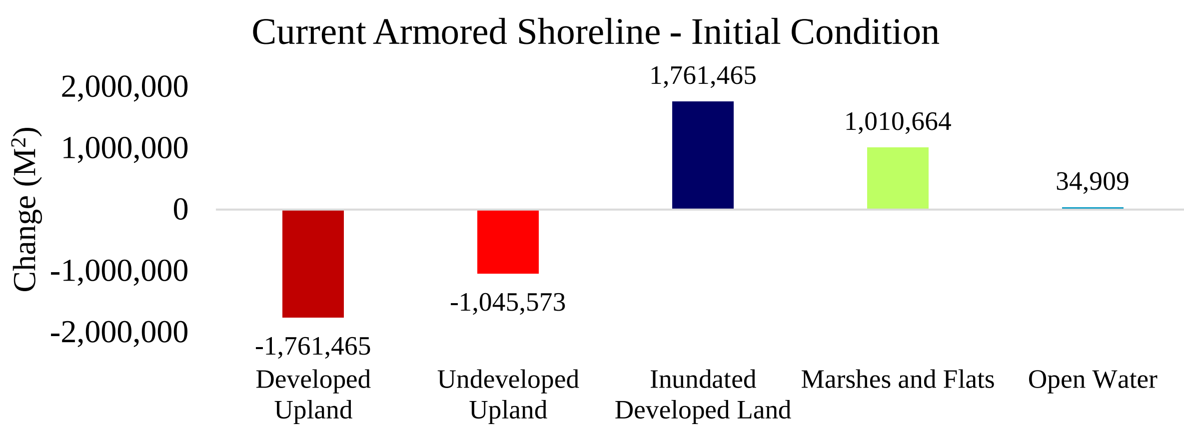

FIGURE 76: GALVESTON'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO COMPARED TO ITS INITIAL CONDITION.

The landscape in Galveston changed dramatically from the Initial Condition to CAS, given a 1.8 m rise in sea level. While the shoreline did not erode much, hence there is slightly more water in CAS than the Initial Condition, there was a loss of Developed Uplands and loss of the Undeveloped Uplands. CAS had more Marshes and Flats, most of which was transitional and regularly flooded marsh, than Initial Condition did. At the northwest portion of the study site, there was an inland marsh in the Initial Condition which was largely converted to transitional marsh. The southern portion of the study site had areas that were originally uplands which were converted to tidal flats in CAS.

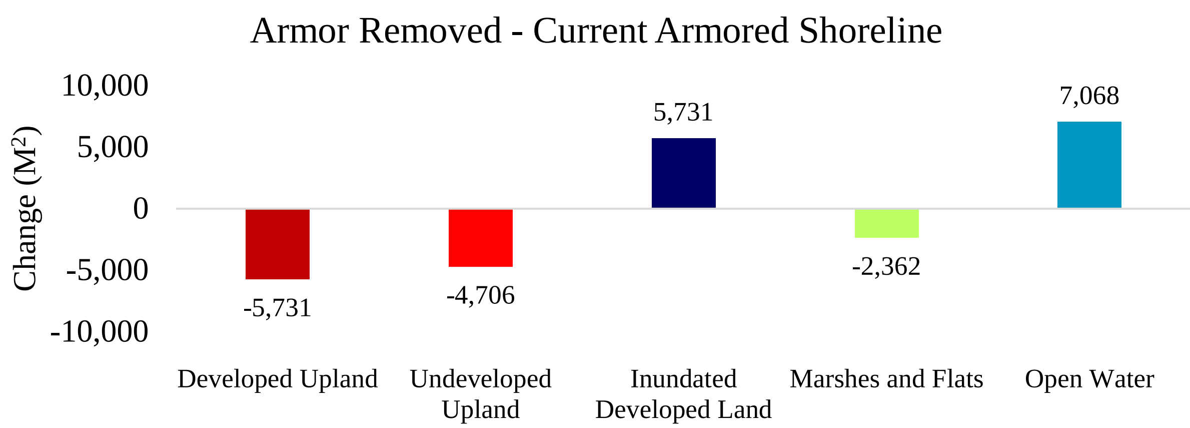

FIGURE 77: GALVESTON'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

The differences between AR and CAS were not large. CAS had more Developed Uplands and AR had more Open Water, and the Undeveloped Uplands and Marshes and Flats both had less than change. This comparison does represent what would be expected from SLR-induced landscape changes in response to the presence and absence of armorings.

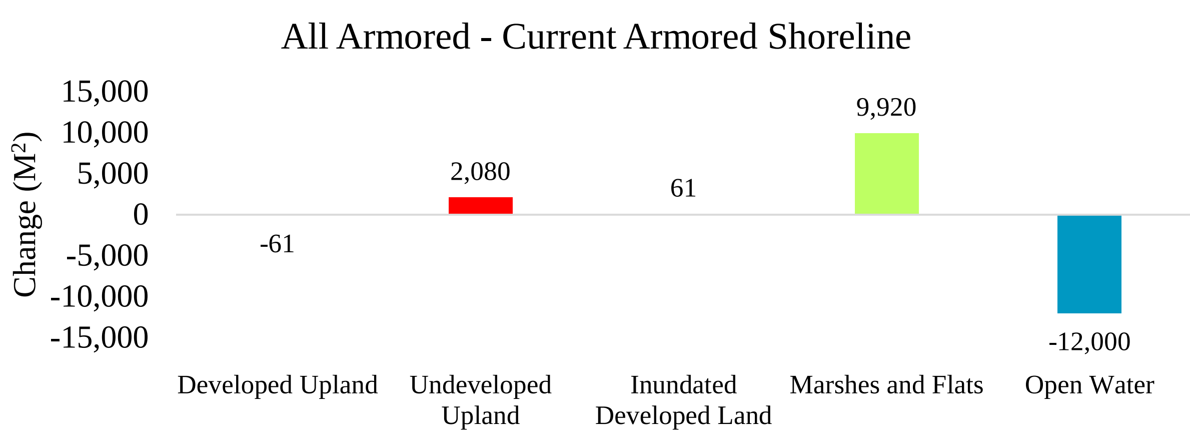

FIGURE 78: GALVESTON'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

AA protected more uplands and Marshes and Flats than CAS did. The gaps in the CAS armorings allowed more Open Water to inundate inland which caused shoreline erosion and inland land class conversions.

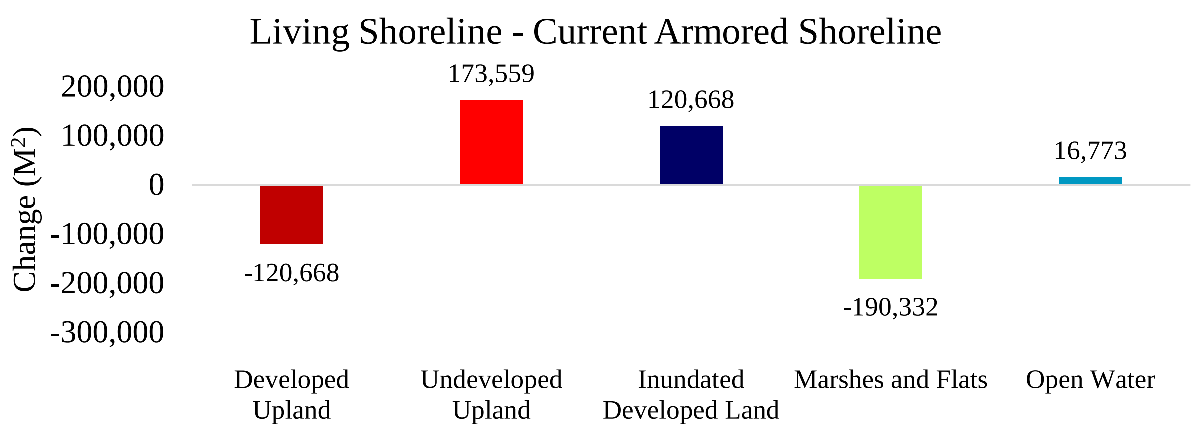

FIGURE 79: GALVESTON'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

The sill in the LS scenario did a much poorer job of protecting the docks than the CAS armorings did. Docks in the site are classified as Developed Uplands which is a factor as to why the CAS scenario has more Developed Uplands. LS, however, minimized the land conversions of Undeveloped Uplands resulting in more than CAS. There was more erosion in the LS scenario, thus areas that were classified as Marshes and

Flats in the CAS outputs were classified as Open Water in the LS output.

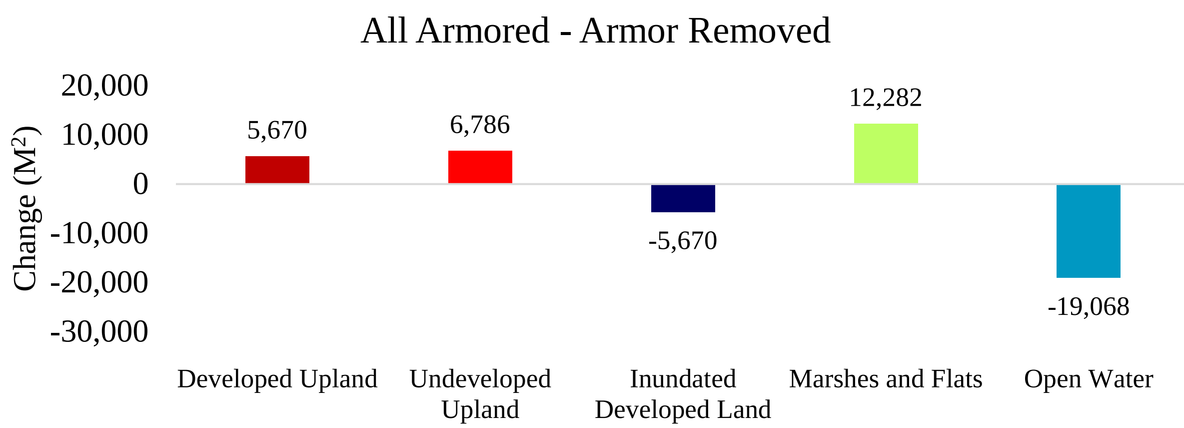

FIGURE 80: GALVESTON'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMOR REMOVED 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

AA protects more uplands and Marshes and Flats than AR because the armorings were seaward of the non-Open Water habitats. Erosion is worse under the AR scenario; more Open Water is present in the AR output than the AA output. The AA scenario protected the Marshes and Flats and uplands, including more Developed Uplands. However, because of the large magnitude of changes under both scenarios triggered by a 1.8 m rise in sea level, these outputs are virtually the same.

Surfside Beach

Surfside Beach would be completely devastated by a 1.8 m rise in sea level. It is predicted that there would be no usable uplands. The areas that would not be inundated would be primarily Marshes and Flats, and there would be some Beaches and Dunes in other areas of the site. While there are slight changes between the scenarios, living or working in the site would be extremely difficult under any of the scenarios.

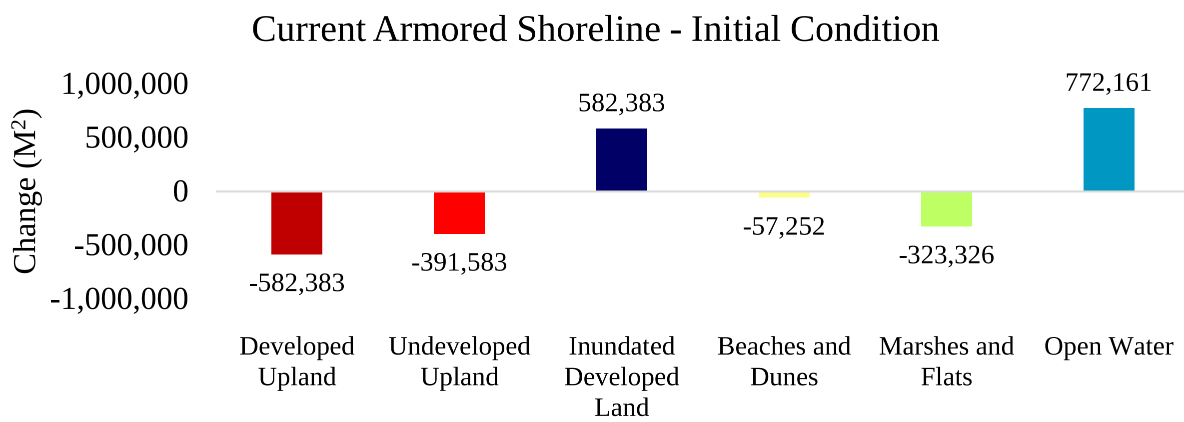

FIGURE 81: SURFSIDE BEACH'S CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO COMPARED TO ITS INITIAL CONDITION.

The difference between the Initial Condition and CAS outputs for the high SLR scenario is extreme. The barrier island broke up almost completely except for some Marshes and Flats. From the Initial Condition to CAS, Developed and Undeveloped Uplands were lost. Beaches and Dunes and Marshes and Flats were lost as well. There was more Open Water in CAS than the Initial Condition. This represents an expected landscape change in response to SLR.

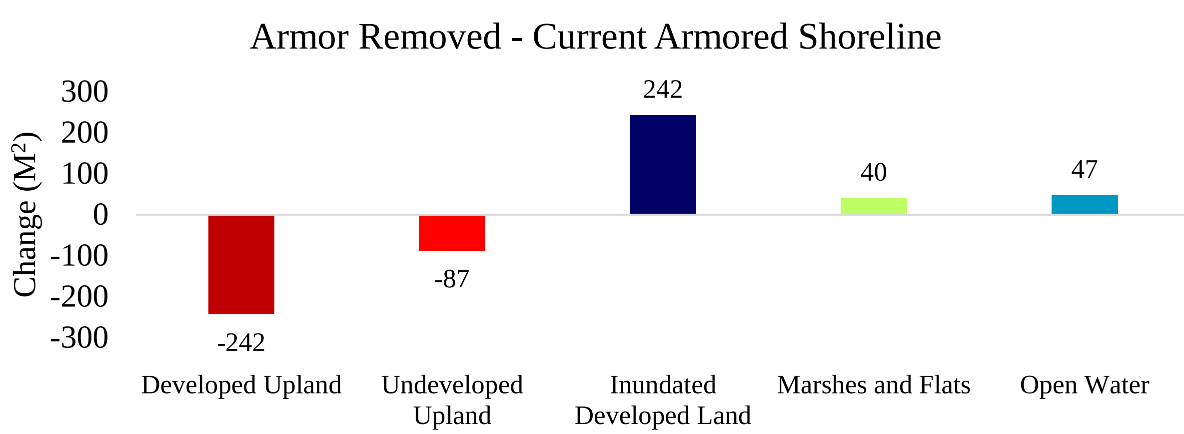

FIGURE 82: SURFSIDE BEACH'S ARMOR REMOVED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

There were less Undeveloped Uplands under the AR scenario than the CAS. AR, conversely, has more Marshes and Flats and slightly more Open Water than CAS. If the island hadn't already broken up, this would be an example of a site where it would be worth armoring, because armoring would have such a huge effect on uplands while the percent change is next to nothing for Marshes and Flats. In other words, its ecologic cost would not be very large. However, by this point, Surfside is projected to be largely flooded and uplands broken apart by Marshes and Flats. Humans will probably not be living on the site because of SLR issues, so armoring would not be needed.

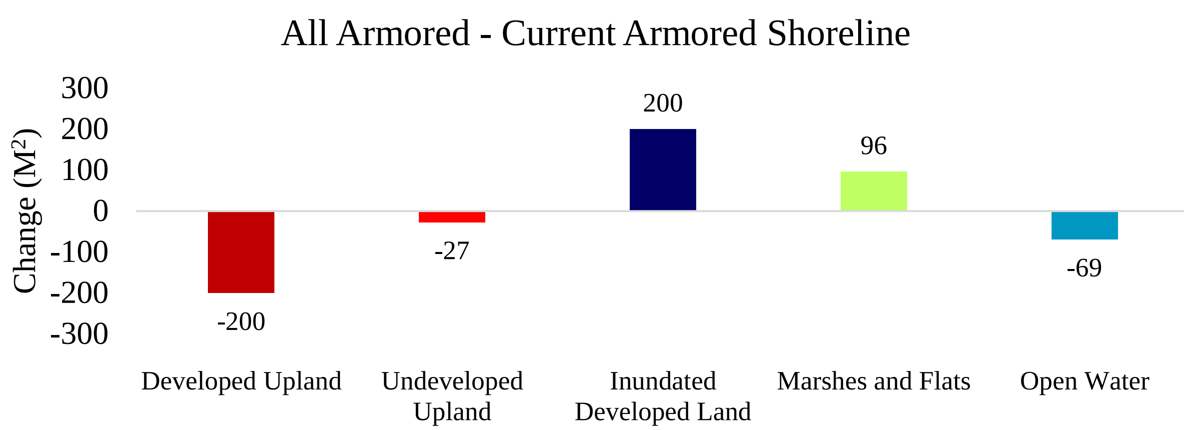

FIGURE 83: SURFSIDE BEACH'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

These outputs are expected given SLAMM's utilization of the armorings seaward of the Open Water and non-Open Water boundary. The AA armorings protect uplands and Marshes and Flats from inundation from Open Water, whereas the Open Water does drown out the other habitat types in CAS.

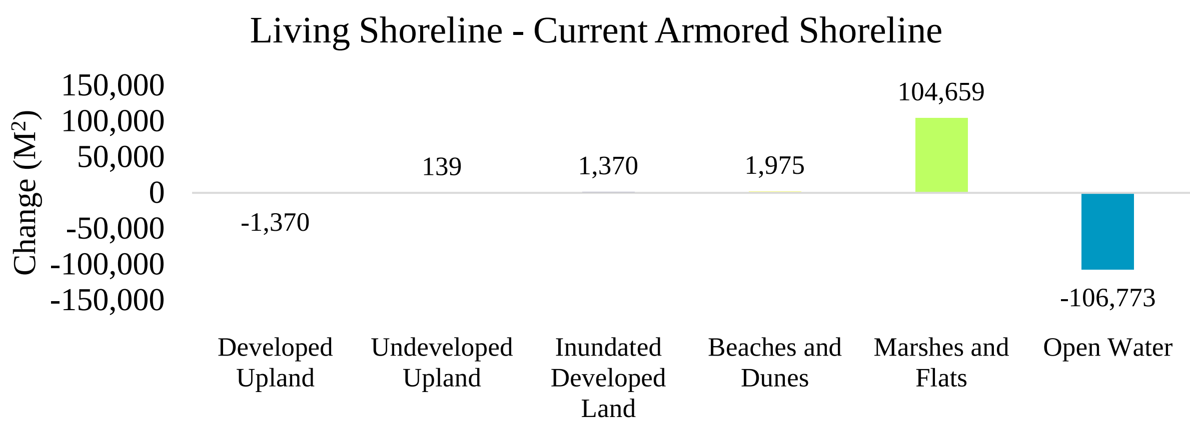

FIGURE 84: SURFSIDE BEACH'S LIVING SHORELINE 2100 OUTPUT COMPARED TO ITS CURRENT ARMORED SHORELINE 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

The LS protected more Undeveloped Uplands, Beaches and Dunes, and Marshes and Flats. CAS protected more Developed Uplands and allowed more Open Water to inundate inland. Some areas that were Developed Uplands in the CAS scenario were classified as Marshes and Flats in the LS scenario.

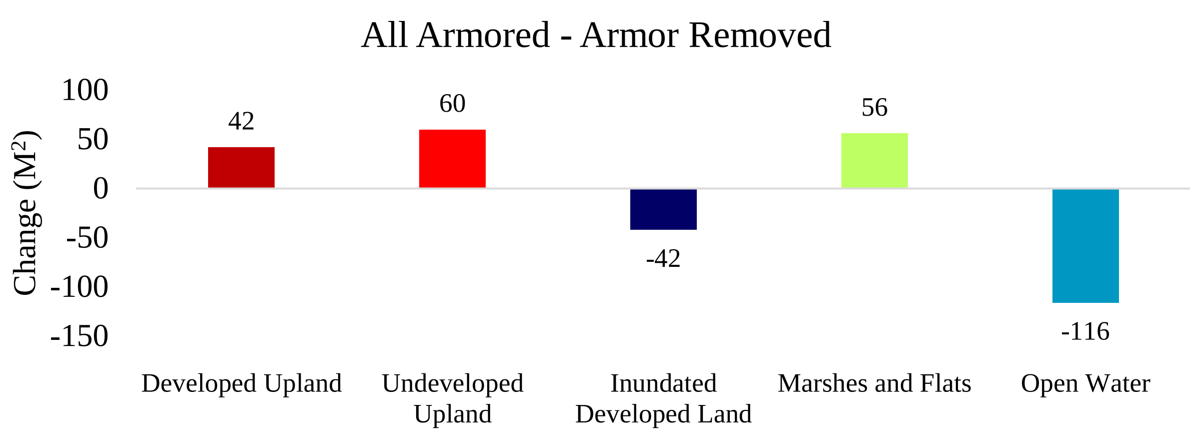

FIGURE 85: SURFSIDE BEACH'S ALL ARMORED 2100 OUTPUT COMPARED TO ITS ARMOR REMOVED 2100 OUTPUT UNDER THE HIGH SLR SCENARIO.

SLAMM's output for the AA scenario again reflects how the placement of armorings seaward of non-water habitats serves to protect them instead of resulting in the coastal squeeze that would be expected. AA had more Undeveloped Uplands and more Developed Uplands than AR did. The change between AA and AR for Marshes and Flats and Open Water was slight.

DISCUSSION

In this study, the shoreline was defined as the boundary of Open Water and non-Open Water habitats. Oftentimes in the "real world," armorings are installed landward of this location which results in the loss of marshes through coastal squeeze. Surprisingly, SLAMM actually predicted that armorings protected marshes from SLR in most instances. Because armorings prevented water from inundating so far inland and there were no marshes seaward of the armorings which could be lost to coastal squeeze, SLAMM predicted that the areal extent of 2100 outputs for the Marshes and Flats land cover class was generally greatest in the AA scenario. Comparatively, the rate of marsh inundation in the AR scenario was greater than the rate at which marshes were able to migrate inland. Furthermore, AA protected more marshes than CAS did; where there were breaks in the CAS armorings, the water inundated inland and flooded more marshes whereas AA armorings were continuous along the entire shoreline and prevented Open Water from inundating inland. AA, therefore, effectively prevents edge erosion and thus shoreline retreat. However, a real-world project such as this would likely have negative environmental impacts because it would be so disruptive to the system through interrupted along-shore currents and coastal squeeze which would result in the loss of wetland habitats and their ecosystem services.

The shoreline location that was used is a hole in this project, and it would have benefitted the study if satellite data that aligned with the DEM had been used instead.

Another option for addressing this problem is to utilize SLAMM's Protect Dry Land option; coastal squeeze would have certainly been witnessed, but that does not fully represent reality either. In reality, uplands will be lost due to SLR-induced migration of wetlands. Furthermore, structures will most likely be abandoned if they are not worth the required costs to save them from the rising sea. The actual response of the landscape to SLR will probably be somewhere in the middle of these two extremes; resources will be spent to protect some structures from SLR while others will be abandoned, demolished, or destroyed.

It is evident that human intervention will have limited degrees of influence on the geography of future wetland distribution. It appears that human actions to protect against SLR does not have as great of an effect as purely the rate of SLR. Thus, this study indicates that while human development should certainly be minimized along vulnerable sections of the shoreline, humans may derive the most benefits from actions to limit greenhouse gas emissions in hopes of avoiding higher rates of SLR altogether. Due to greenhouse gas emissions to date, there is a commitment to change where sea level will continue rising. To have the greatest certainty of limiting negative effects, policies should emphasize reducing greenhouse gas emissions immediately (Paris Agreement, 2015). Of additional benefit would be the development of technology that is able to remove greenhouse gasses like carbon from the atmosphere.

Anthropogenically manipulated shorelines will have minimal effects compared to the natural processes caused by large magnitudes of SLR, and the installation of armorings oftentimes results in the loss of marsh habitats and the ecosystem services they provide. This loss can range in the millions of dollars per year (Yoskowitz, 2009). Next steps in this study would be incorporating ES and seeing how they compare to the cost of armorings. The author hypothesizes that the armoring's negative costs plus their actual cost and maintenance would be more than the cost of retreating over a period of several decades; indeed, for the town of North Topsail Beach, NC, to buy out six hotels and demolish them would be cheaper than beach renourishment projects over a thirty-year span (Whose job is it to save North Topsail Beach?, 2016). Such actions have an additional benefit of ensuring that a beach exists for the public to enjoy which is imperative for the sustainability of coastal towns. Without a beach for the public to enjoy, will tourists frequent coastal towns and support the local economy through hotel and beach house reservations, small boutiques, and restaurants? Evidence suggests that they will not (Ali, 2014).

There are many factors to consider when determining what type of shoreline protection is best for a given community; priorities of the region and what is valued by its people are two of them. The four sites in this study have very different community structures and economic goals. They also have very different built environments. Because of this, different SLR protection strategies are appropriate for each. Below is an outline of actions that may be best suited to each site given their varying regional activities and priorities.

Texas City is a very industrial, unincorporated city that borders Galveston Bay. Because it has the largest concentration of petrochemical processing centers in the United States, it is vital to the national economy (Ryerson et al., 2013). 78 million net tons pass through the Port of Texas City annually. Its refineries and other infrastructure is absolutely necessary to the entire nation, and damages to it from natural disasters such as

Hurricane Ike can be catastrophic to the nation. Damages from future storms could be worse as a result of SLR. As such, its protection is a priority. Texas City probably does not prioritize the areal extent of coastal ecosystems or their services as evidenced by the installation and subsequent upkeep of their levee system and dike. Therefore, a continuation of hardening its shorelines and installing other grey infrastructure may very well be the best option for Texas City and other highly industrialized coastal cities like it.

Conversely, Anahuac has a small population- approximately 2,000 as of 2010- and very little infrastructure beyond private homes. This is an area that may prioritize the protection of coastal ecosystems. Because it is a fairly rural area with little to no infrastructure of national importance, Anahuac may be an excellent choice to install green infrastructure and thus protect the natural shoreline interface. Since coastal habitats such as marshes attenuate floodwaters, keeping Anahuac's shorelines natural may protect the surrounding regions in Galveston Bay by allowing the water to go somewhere instead of overtopping armorings that are located in other locations throughout the bay. Other ecosystem services that could be taken advantage of include ensuring habitats for juvenile fish; the preservation of wetland habitats in Anahuac would potentially benefit all of Galveston Bay since commercial and recreational fishing is a huge industry in the region. A combination of a building setback requirement and the encouragement of living shorelines as a protection strategy may be the best option for Anahuac and other rural, undeveloped areas around Galveston Bay.

Galveston is an example of an area that might most benefit from hybrid infrastructure. It is highly developed and has an economy driven by tourism, but it is vulnerable to erosion and land subsidence. Except for the area around the Bolivar jetties, Galveston has a long-term erosion average of 1.5 m/year. Galveston's needs include protection from erosion in a way that also is not an eye sore for tourists. Hybrid infrastructure which uses armoring in conjunction with natural materials may thus be the best option for their needs. The combination of green and grey infrastructure may best balance Galveston's draw to tourists with protection against erosion and storm surges.

Surfside Beach is another coastal town whose primary industry is tourism; the preservation of the beach system is paramount because without it, tourists will not visit the city. Surfside is in need of immediate and extreme action to mitigate its erosional issues because anthropogenic perturbations have resulted in a nearly complete loss of incoming sediment (Watson, 2003). Because it is a Gulf-facing beach, living shorelines are unable to be used under TOBA. Because of this, Surfside partakes in regular beach renourishment projects. This is probably the only way the extent of the beach can stay in a similar location as it is now. An arguably better and certainly more sustainable long term solution for Surfside, however, is to retreat from the rising Gulf. By retreating, Surfside would avoid projects that spend millions on renourishment and quickly erode. A retreat would also increase the safety of the residents by moving them further inland away from the extremely hazardous coastline, and insurance claims would certainly decrease due to a fewer number of structures in the vulnerable shoreline locations. Although a retreat is typically an extremely unpopular response to SLR, it may be the best option for Surfside as it was for the neighborhood of Brownwood. If the community of Surfside decides to stay in place, it will almost certainly be required to continue regular beach renourishment projects. By initiating a retreat, however, Surfside could be a model for other municipalities in the region with erosional issues, such as Sargent, TX, as well as other communities with similar issues across the United States.

LIMITATIONS

SLAMM is the best model that is currently available for studies dealing with SLR, but like all models it has some limitations. SLAMM does not incorporate hydrodynamics and how it interacts with ecology ("What Can SLAMM Do for You?", 2016). It also does not incorporate variable transport. For instance, if a large storm occurs, waves will move sediments from some areas and deposit it in others. SLAMM does not incorporate that sediment transport through variable erosion and accretion rates. Another drawback is that SLAMM's erosional module oversimplifies reality. SLAMM's designers, however, note that beach erosion is "ephemeral" and is difficult to quantify.

SLAMM was designed to give broad overviews of what changes can be expected to occur for a given area due to SLR. It is not designed for projects such as this with high resolution and relatively small study sites, nor is it designed to incorporate response options to SLR, and thus its sensitivity does not always represent what would be expected in reality. For example, there are feedbacks and relationships that occur when armorings are removed which are not taken into account by SLAMM. Generally, when armorings are removed, the landward area will erode until an equilibrium with the sea is met. SLAMM does not incorporate that process and rather treats the elevation change as a bluffed shoreline. As such, the outputs from this study represent the best estimate of what may happen given the current knowledge, but it is not perfect. The outputs from this study lend itself well to next steps which may include a valuation of ecosystem service changes under these SLR and policy scenarios. It would be interesting to see how the cost of these response strategies- both initially and that of their long term maintenance- compares to the gain or loss of ecosystem services and the protection or loss of properties located in the coastal zone.

CONCLUSION

Sea level is rising, and coastal counties are vulnerable. Due to its history of subsidence from groundwater and petrochemical extractions and its heavily populated coastal areas, Galveston Bay is at particular risk to SLR-induced hazards. As such, it is imperative that considerations are taken now to plan for these hazards and steps are taken immediately to mitigate future threats. Reactive strategies generally ignore the issue until a natural disaster strikes and extreme measures must be taken to minimize human harm and suffering. By researching the issues and the related benefits and constraints of potential proactive actions, human suffering can be minimized and the associated costs can be far less than those of a reactive strategy. As Benjamin Franklin famously stated, an ounce of prevention is worth a pound of cure. The four sites in this study can be used as examples for similar communities on and around Galveston Bay.

The optimal protection strategy for a given problem is one that best balances social, economic, political, and ecologic factors. Therefore, the optimal solution for SLR protection in communities around Galveston Bay will vary because the priorities and values of the individual communities vary. Armoring may be best for areas such as Texas City which has preexisting vital infrastructure while areas such as Galveston, which are still economically important, can be protected in areas with armorings while other areas are left with a natural land/sea interface. Green infrastructure may be best for communities like Anahuac which are not very densely developed while communities such as Surfside Beach may best protect resources by migrating away from the rising seas.

Community values and priorities will determine which response strategies are most appropriate for their given jurisdiction. The future "fate" of wetlands is intrinsically linked to socio-economic conditions, policy decisions, and perceptions about their value, and their future areal extent- whether they decrease, stay constant, or even increase- are directly affected by today's "complex economic and sociological decisions" (Kirwan and Megonigal, 2013). The effects of these relevant decisions may even have a bigger extent on the marshes than the rates and magnitude of SLR itself. Human perspectives, then, may be the most important factor regarding marshes' future extent. A paradigm that protects marshes and allows them the room to migrate upland can increase the resilience of coastal communities, preserve ecosystem services, and can cost less in the long-term (Pilkey and Young, 2009). This coupled with the long residence time of greenhouse gas emissions and the negative feedback loop that can occur from marsh degradation and released carbon means that the strategies made in the short-term can have huge consequences on the global climate and built and natural environments far into the future. Thus, it is important to find a sustainable solution which balances current needs with the needs of future generations.

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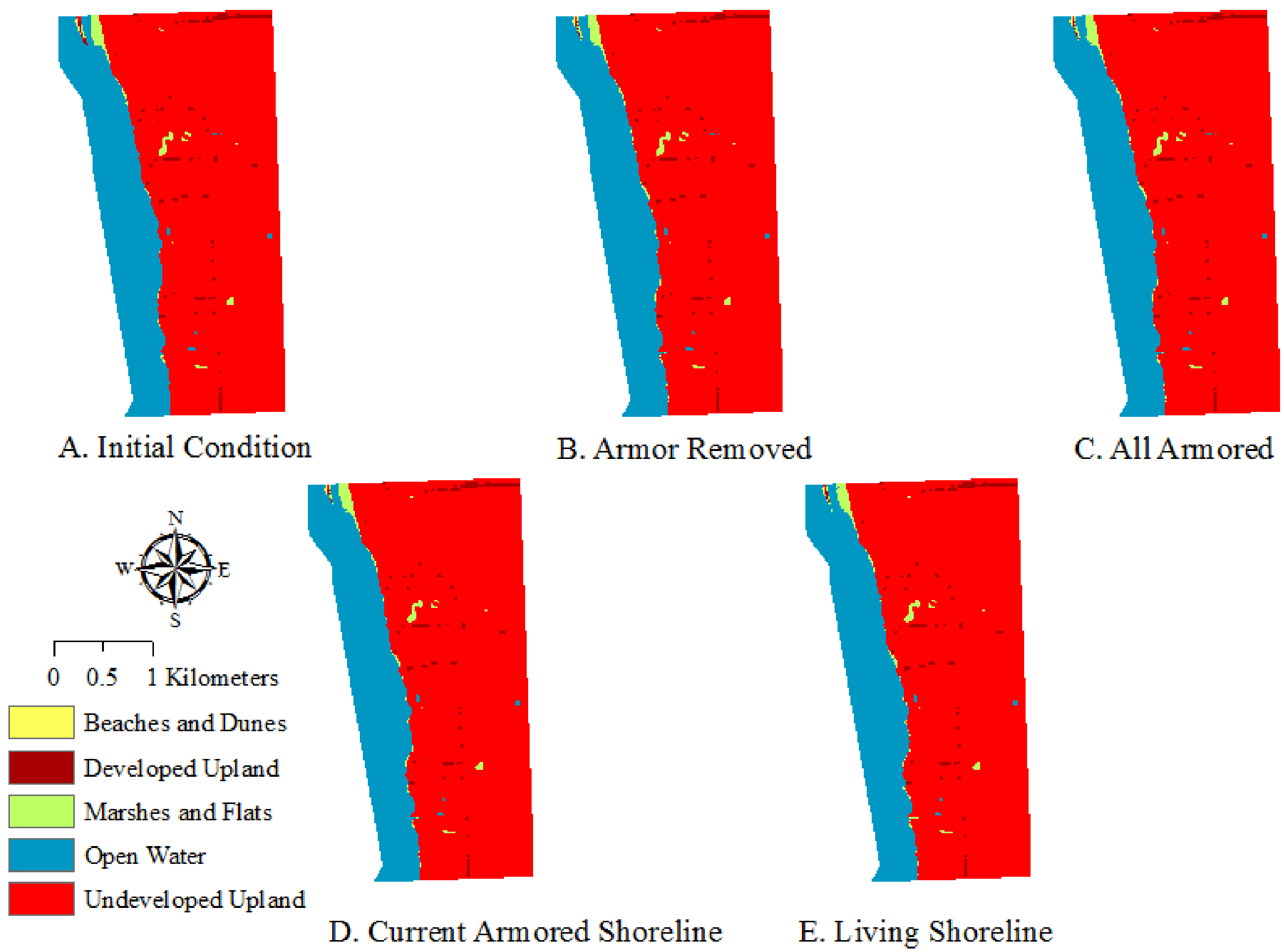
APPENDIX

LOW: 0.206 M OF SLR BY 2100

Anahuac- 0.206 m SLR

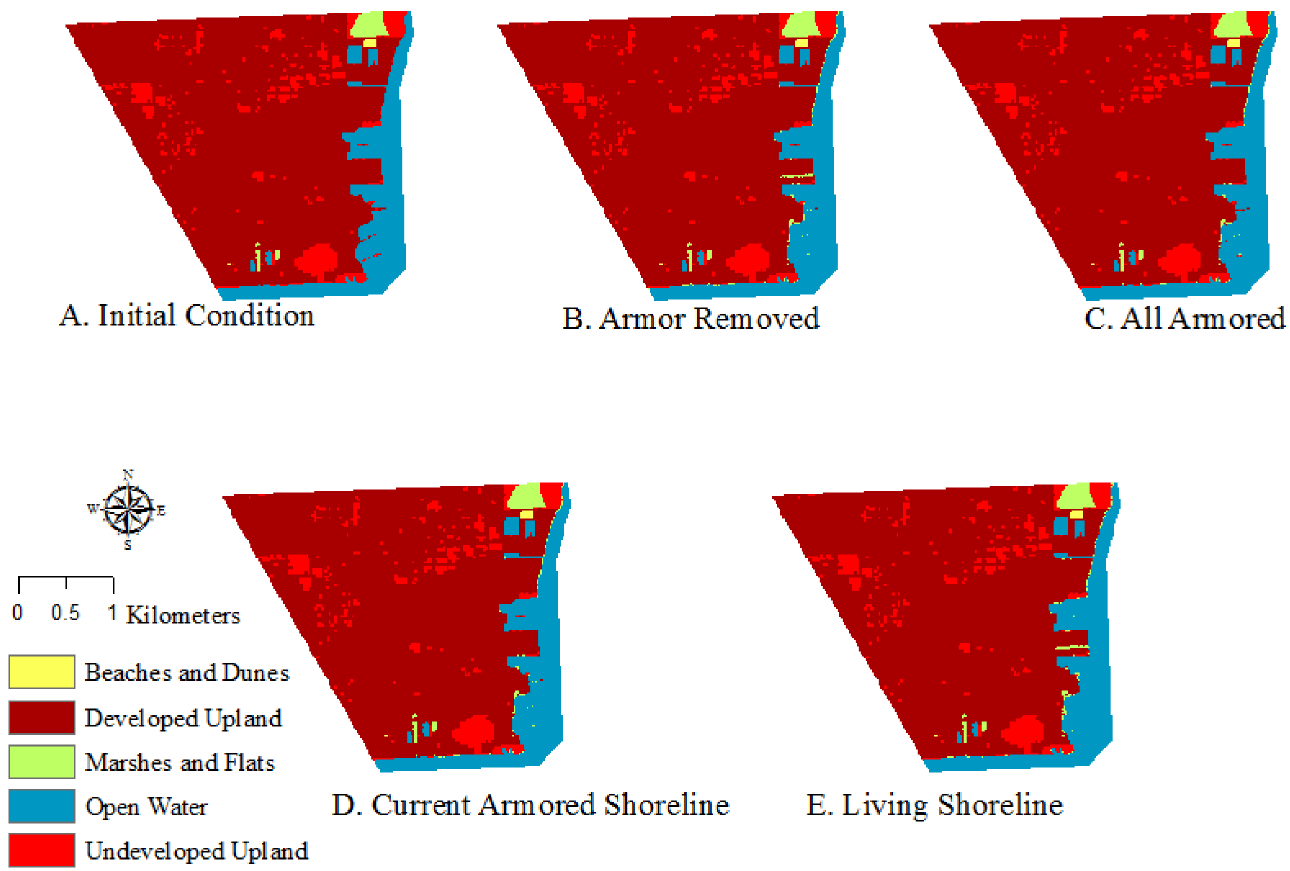


Anahuac:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	91,154	91,178	91,298	91,931
Undeveloped Upland	5,307,825	5,308,778	5,308,378	5,306,490
Inundated Developed Land	3,458	3,434	3,314	2,681
Beaches and Dunes	795	795	795	795
Marshes and Flats	82,193	82,834	83,017	86,117
Open Water	1,841,451	1,839,857	1,840,074	1,838,862

	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-3.65%	-3.63%	-3.50%	-2.83%
Undeveloped Upland	-0.25%	-0.23%	-0.24%	-0.28%
Beaches and Dunes	-34.96%	-78.90%	-78.90%	-78.90%
Marshes and Flats	0.62%	3.49%	3.72%	7.60%
Open Water	0.78%	0.69%	0.70%	0.64%

Texas City- 0.206 m SLR

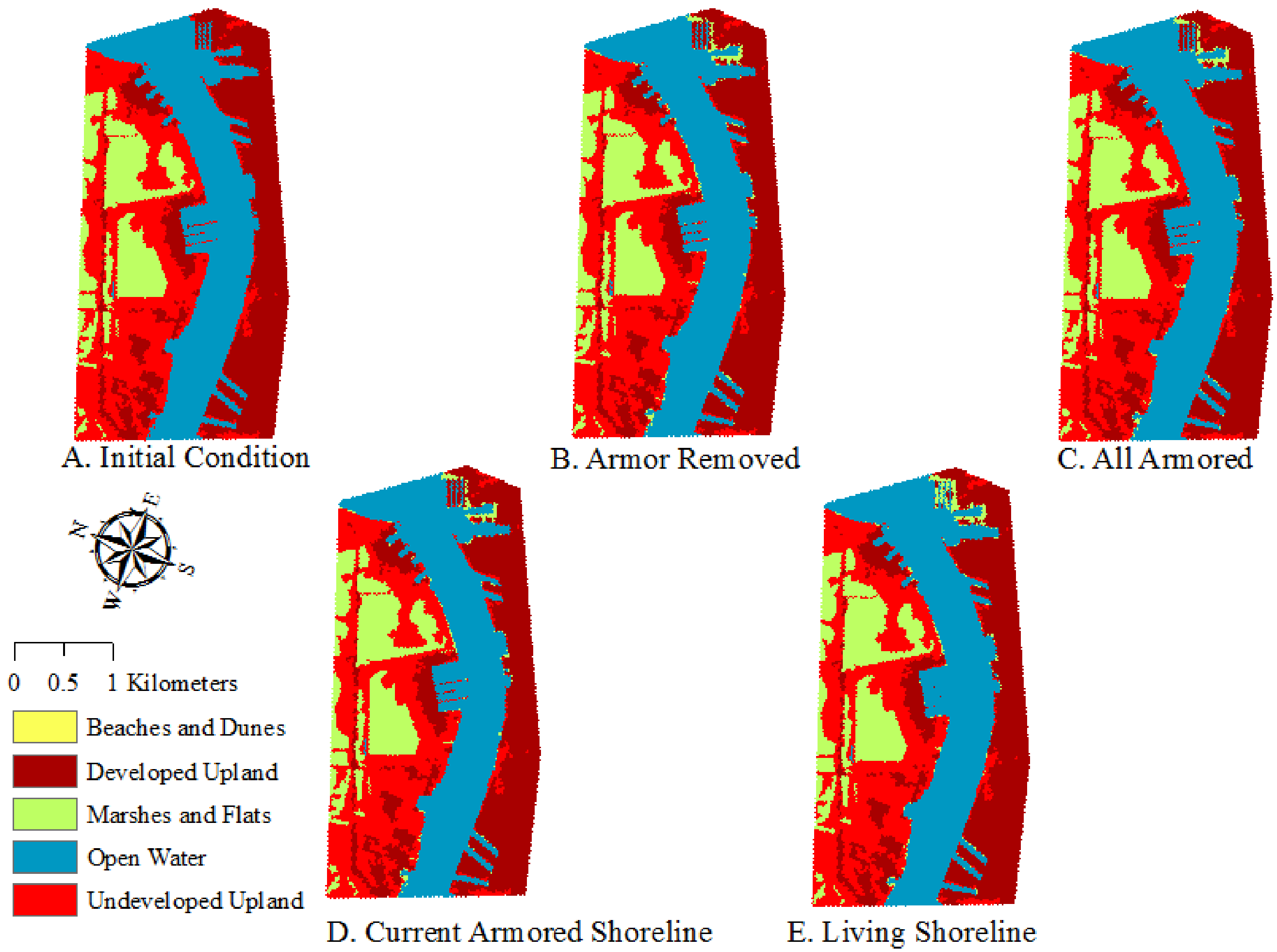


Texas City:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	6,274,444	6,287,354	6,288,941	6,273,055
Undeveloped Upland	578,044	580,036	581,217	578,253
Inundated Developed Land	44,476	31,566	29,979	45,865
Beaches and Dunes	11,800	11,800	11,800	11,800
Marshes and Flats	107,797	106,854	106,214	104,819
Open Water	1,116,975	1,115,926	1,115,385	1,119,744

	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-0.70%	-0.50%	-0.47%	-0.73%
Undeveloped Upland	-3.11%	-2.78%	-2.58%	-3.07%
Beaches and Dunes	0.00%	0.00%	0.00%	0.00%
Marshes and Flats	11.97%	10.99%	10.33%	8.88%
Open Water	0.63%	0.54%	0.49%	0.88%

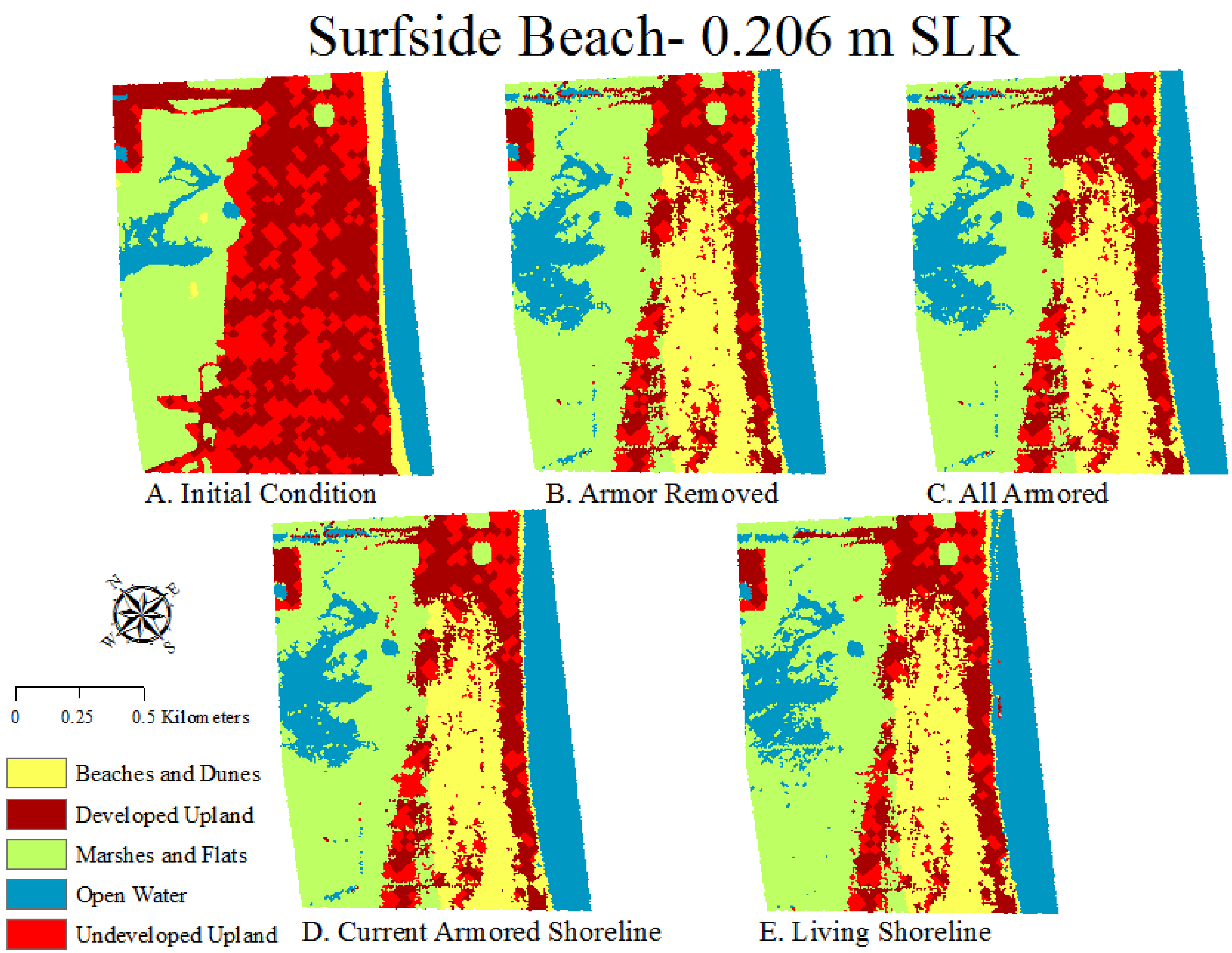
Galveston- 0.206 m SLR



Galveston:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	2,414,412	2,420,093	2,420,476	2,390,696
Undeveloped Upland	2,360,864	2,366,303	2,378,018	2,352,171
Inundated Developed Land	49,693	44,012	43,629	73,409
Marshes and Flats	1,193,044	1,190,122	1,180,945	1,187,258
Open Water	2,720,432	2,717,915	2,715,377	2,734,911

	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-2.02%	-1.79%	-1.77%	-2.98%
Undeveloped Upland	-2.04%	-1.82%	-1.33%	-2.40%
Marshes and Flats	3.77%	3.52%	2.72%	3.27%
Open Water	0.22%	0.12%	0.03%	0.75%


Surfside Beach- 0.206 m SLR
A. Initial Condition
B. Armor Removed
C. All Armored
D. Current Armored Shoreline
E. Living Shoreline
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W
0
0.25
0.5 Kilometers
Beaches and Dunes
Developed Upland
Marshes and Flats
Open Water
Undeveloped Upland

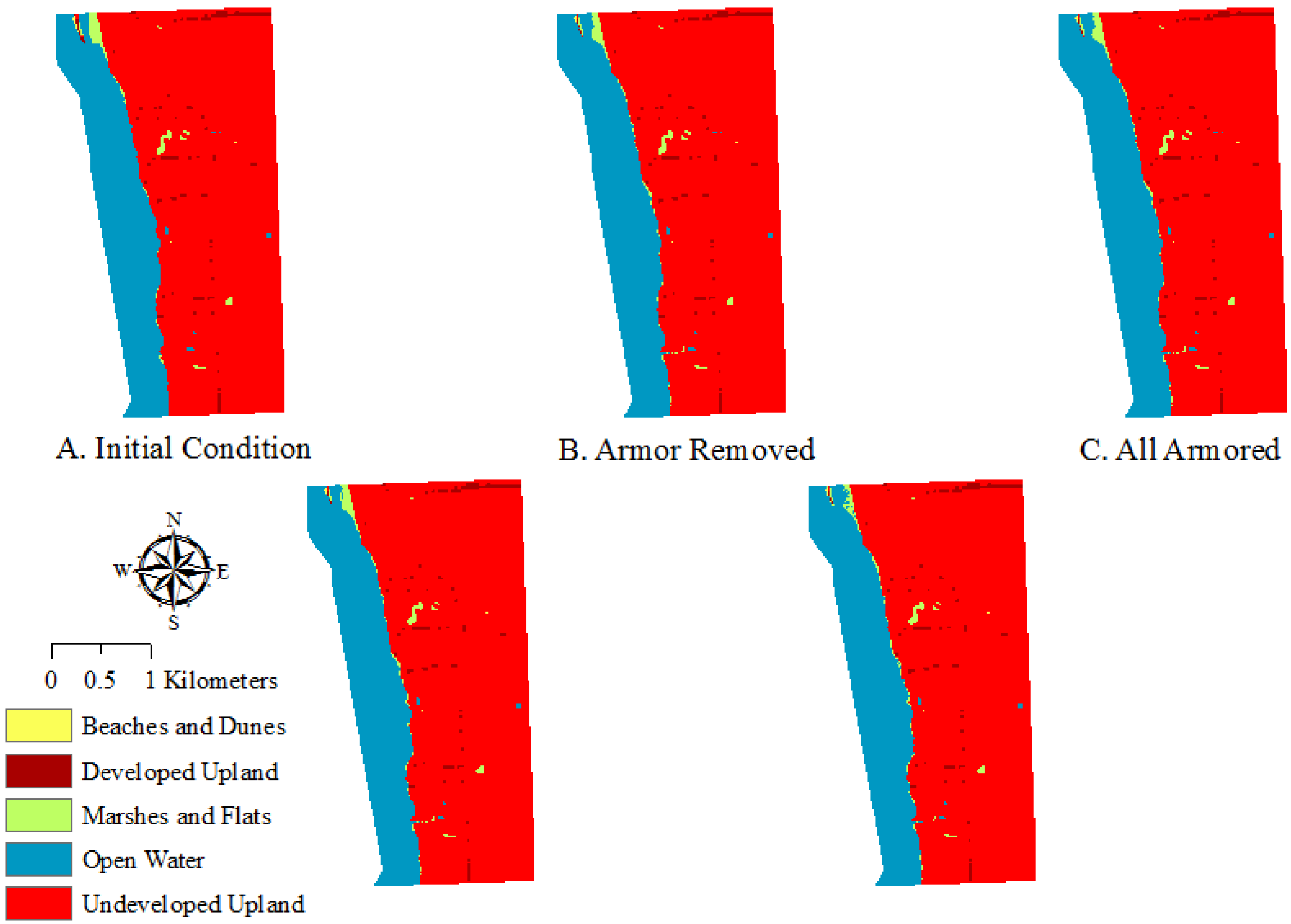
Surfside:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	266,608	266,614	266,614	266,608
Undeveloped Upland	153,520	153,568	153,580	153,520
Inundated Developed Land	322,065	322,059	322,059	322,065
Beaches and Dunes	123,158	123,158	123,158	123,158
Marshes and Flats	500,794	500,756	502,770	500,794
Open Water	345,052	345,042	343,016	345,052

	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-54.71%	-54.71%	-54.71%	-54.71%
Undeveloped Upland	-60.81%	-60.79%	-60.79%	-60.81%
Beaches and Dunes	98.92%	98.92%	98.92%	98.92%
Marshes and Flats	6.62%	6.61%	7.04%	6.62%
Open Water	73.22%	73.21%	72.19%	73.22%

MEDIUM: 0.74 M OF SLR BY 2100

Anahuac- 0.74 m SLR



A. Initial Condition

B. Armor Removed

C. All Armored

D. Current Armored Shoreline

E. Living Shoreline

Anahuac:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	90,633	90,644	90,780	90,860
Undeveloped Upland	5,298,864	5,299,272	5,299,545	5,296,042
Inundated Developed Land	3,979	3,968	3,832	3,752
Beaches and Dunes	795	795	795	795
Marshes and Flats	78,716	78,862	79,380	74,300
Open Water	1,853,889	1,853,335	1,852,544	1,861,127

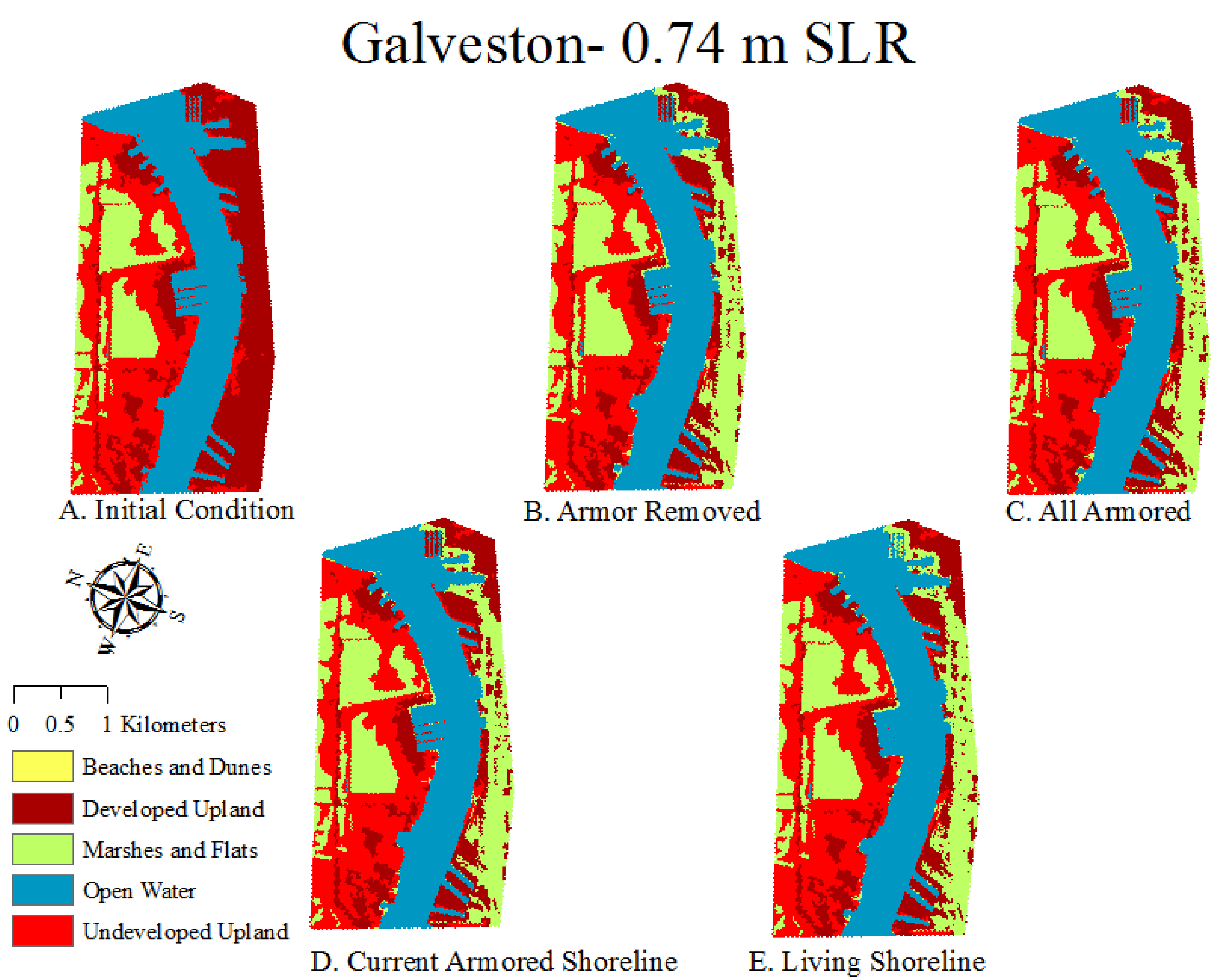
	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-4.21%	-4.19%	-4.05%	-3.97%
Undeveloped Upland	-0.42%	-0.41%	-0.41%	-0.47%
Beaches and Dunes	-78.90%	-78.90%	-78.90%	-78.90%
Marshes and Flats	-1.65%	-1.47%	-0.82%	-7.17%
Open Water	1.46%	1.43%	1.39%	1.86%

Texas City- 0.74 m SLR

Texas City:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	4,477,909	4,482,169	4,484,078	4,448,984
Undeveloped Upland	533,597	535,724	537,005	533,256
Inundated Developed Land	1,841,011	1,836,751	1,834,842	1,869,936
Beaches and Dunes	10,763	10,763	10,763	10,775
Marshes and Flats	145,388	145,556	145,447	145,541
Open Water	1,124,868	1,122,573	1,121,401	1,125,044

	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-29.13%	-29.07%	-29.04%	-29.59%
Undeveloped Upland	-10.56%	-10.20%	-9.99%	-10.62%
Beaches and Dunes	-8.79%	-8.79%	-8.79%	-8.69%
Marshes and Flats	51.02%	51.19%	51.08%	51.18%
Open Water	1.34%	1.14%	1.03%	1.36%


Galveston- 0.74 m SLR
A. Initial Condition
B. Armor Removed
C. All Armored
D. Current Armored Shoreline
E. Living Shoreline
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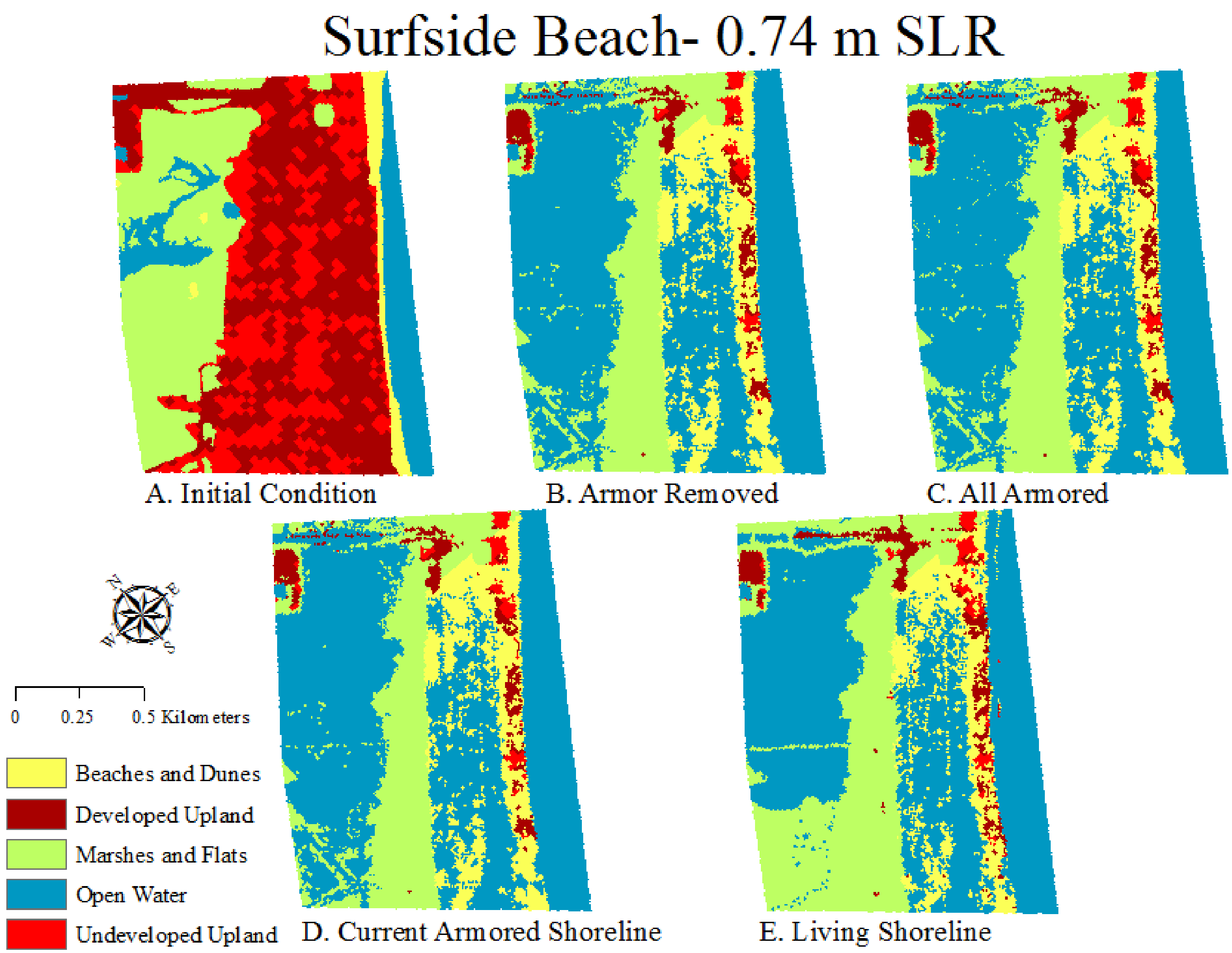
Beaches and Dunes
Developed Upland
Marshes and Flats
Open Water
Undeveloped Upland

Galveston:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	1,523,220	1,529,684	1,529,653	1,474,665
Undeveloped Upland	2,311,759	2,318,510	2,322,492	2,307,268
Inundated Developed Land	940,885	934,421	934,452	989,440
Marshes and Flats	1,223,757	1,223,982	1,226,817	1,217,219
Open Water	2,738,824	2,731,848	2,725,031	2,749,853

	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-38.18%	-37.92%	-37.92%	-40.15%
Undeveloped Upland	-4.08%	-3.80%	-3.64%	-4.27%
Marshes and Flats	6.44%	6.46%	6.71%	5.87%
Open Water	0.90%	0.64%	0.39%	1.30%


Surfside Beach- 0.74 m SLR
A. Initial Condition
B. Armor Removed
C. All Armored
D. Current Armored Shoreline
E. Living Shoreline
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W
0
0.25
0.5 Kilometers
Beaches and Dunes
Developed Upland
Marshes and Flats
Open Water
Undeveloped Upland

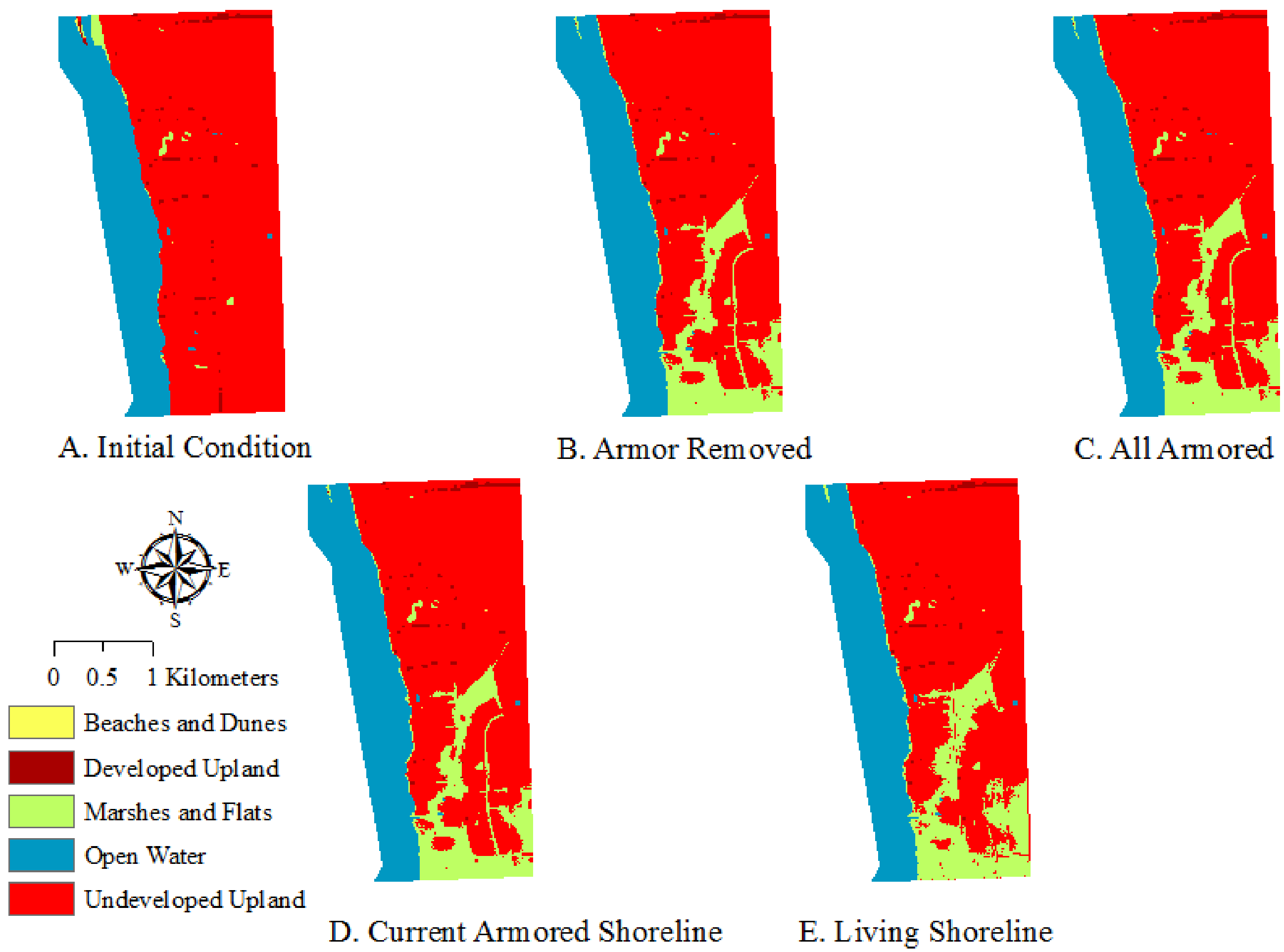
Surfside:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	59,355	59,379	59,391	67,440
Undeveloped Upland	25,126	25,191	25,195	26,548
Inundated Developed Land	529,318	529,294	529,282	521,233
Beaches and Dunes	79,271	79,271	79,271	67,114
Marshes and Flats	225,775	225,935	228,274	313,031
Open Water	792,352	792,127	789,784	715,831

	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-89.92%	-89.91%	-89.91%	-88.54%
Undeveloped Upland	-93.59%	-93.57%	-93.57%	-93.22%
Beaches and Dunes	28.03%	28.03%	28.03%	8.40%
Marshes and Flats	-51.93%	-51.90%	-51.40%	-33.36%
Open Water	297.76%	297.65%	296.47%	259.35%

HIGH: 1.8 M OF SLR BY 2100

Anahuac- 1.8 m SLR

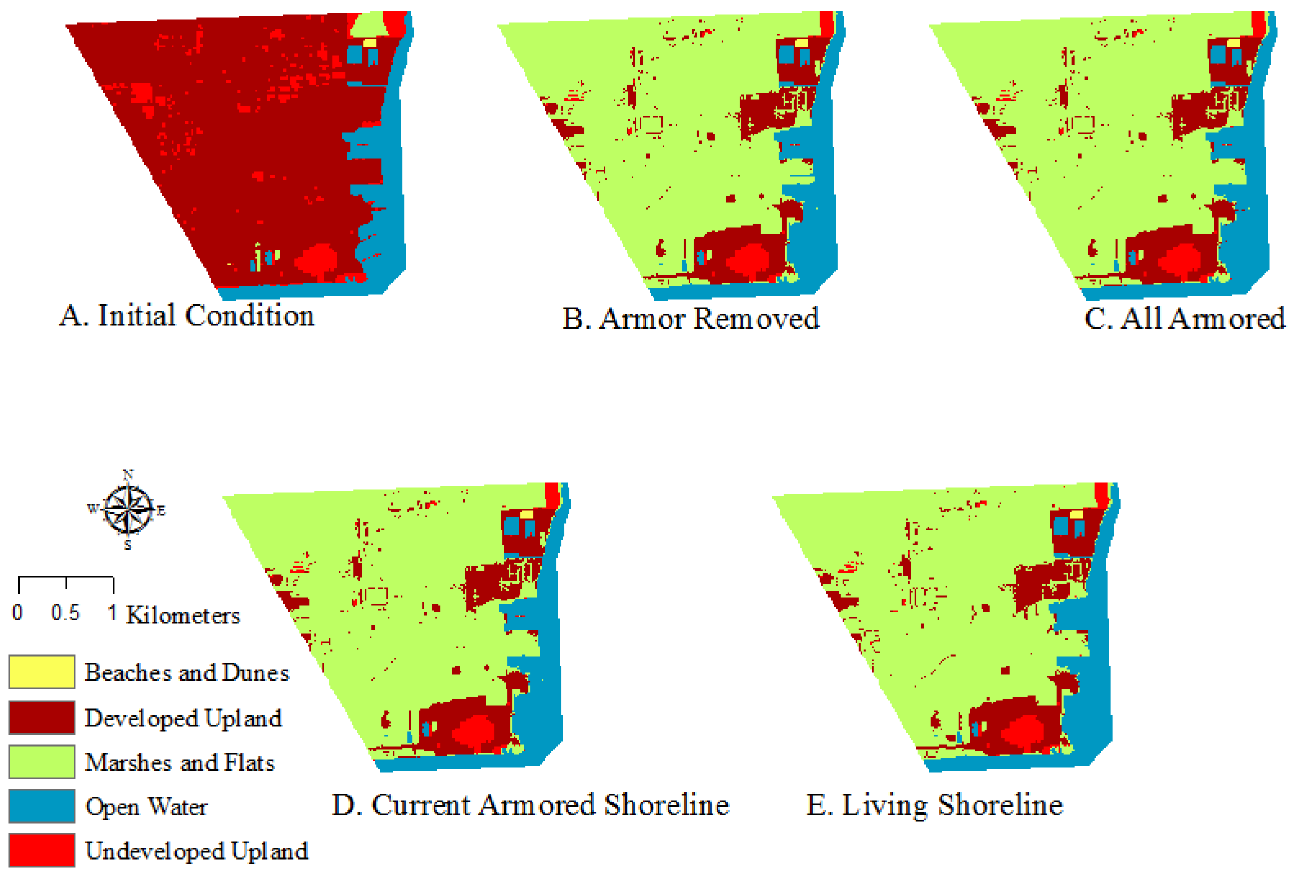


Anahuac:

Area (Meters^2)				
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	73,415	73,426	73,560	74,480
Undeveloped Upland	4,438,693	4,438,969	4,439,039	4,254,287
Inundated Developed Land	21,197	21,186	21,052	20,132
Beaches and Dunes	795	795	795	795
Marshes and Flats	900,287	900,281	900,371	1,087,524
Open Water	1,892,489	1,892,219	1,892,059	1,889,658

Percent Change from Initial Condition				
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-22.40%	-22.39%	-22.25%	-21.28%
Undeveloped Upland	-16.59%	-16.58%	-16.58%	-20.05%
Beaches and Dunes	-78.90%	-78.90%	-78.90%	-78.90%
Marshes and Flats	1024.82%	1024.82%	1024.93%	1258.76%
Open Water	3.57%	3.56%	3.55%	3.42%

Texas City- 1.8 m SLR

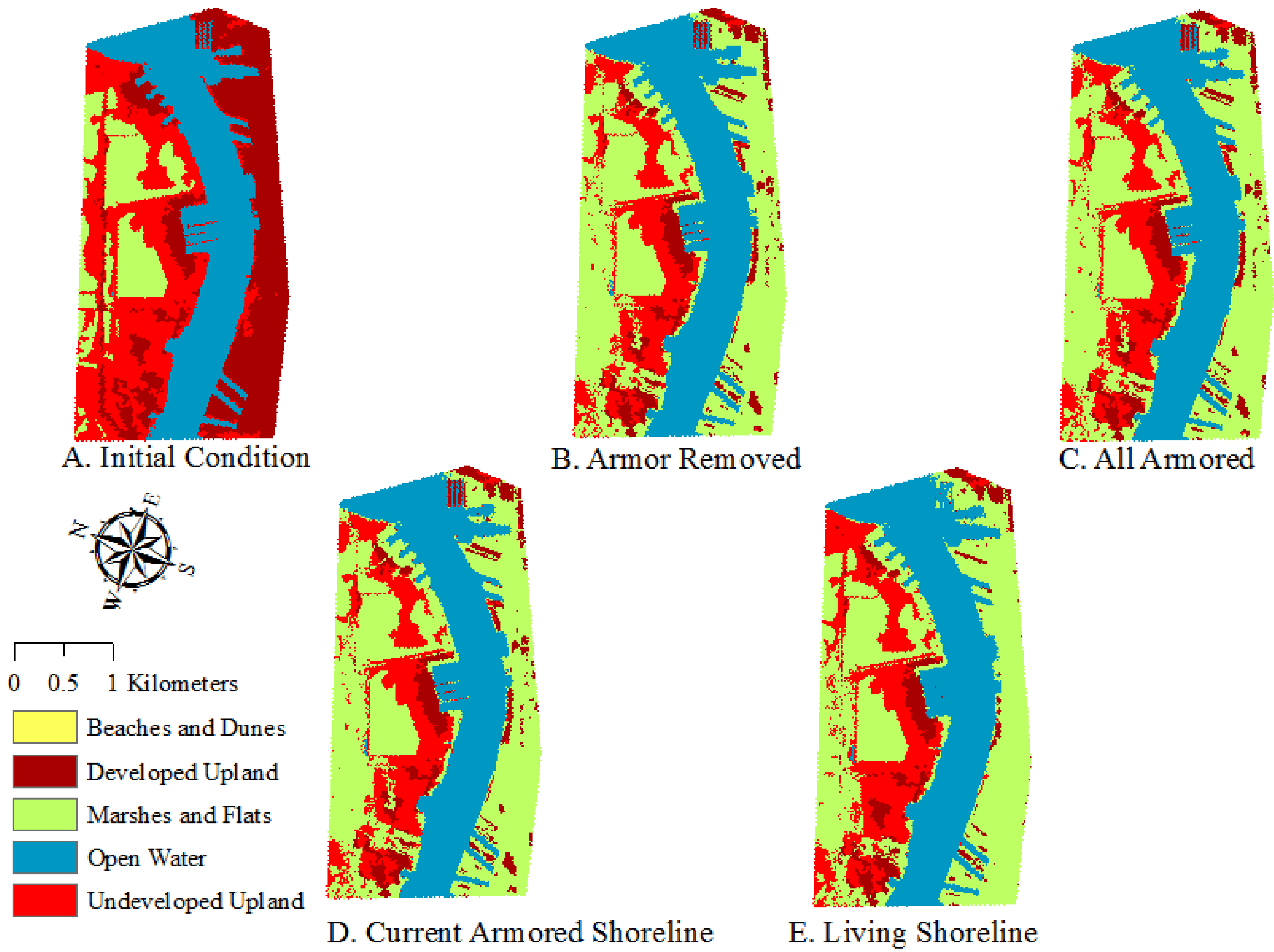


Texas City:

	Area (Meters^2)			
	Armor Removed	Current Armored Shoreline	All Armored	Living Shoreline
Developed Upland	1,111,064	1,114,133	1,116,802	1,139,880
Undeveloped Upland	186,135	186,902	187,126	187,430
Inundated Developed Land	5,207,856	5,204,787	5,202,118	5,179,040
Beaches and Dunes	10,700	10,700	10,700	10,700
Marshes and Flats	487,266	490,017	490,143	490,077
Open Water	1,130,515	1,126,997	1,126,647	1,126,409

	Percent Change from Initial Condition			
	Armor Removed	Current Armored Shoreline	All Armored	Living Shoreline
Developed Upland	-82.42%	-82.37%	-82.33%	-81.96%
Undeveloped Upland	-68.80%	-68.67%	-68.63%	-68.58%
Beaches and Dunes	-9.32%	-9.32%	-9.32%	-9.32%
Marshes and Flats	406.13%	408.99%	409.12%	409.05%
Open Water	1.85%	1.54%	1.50%	1.48%

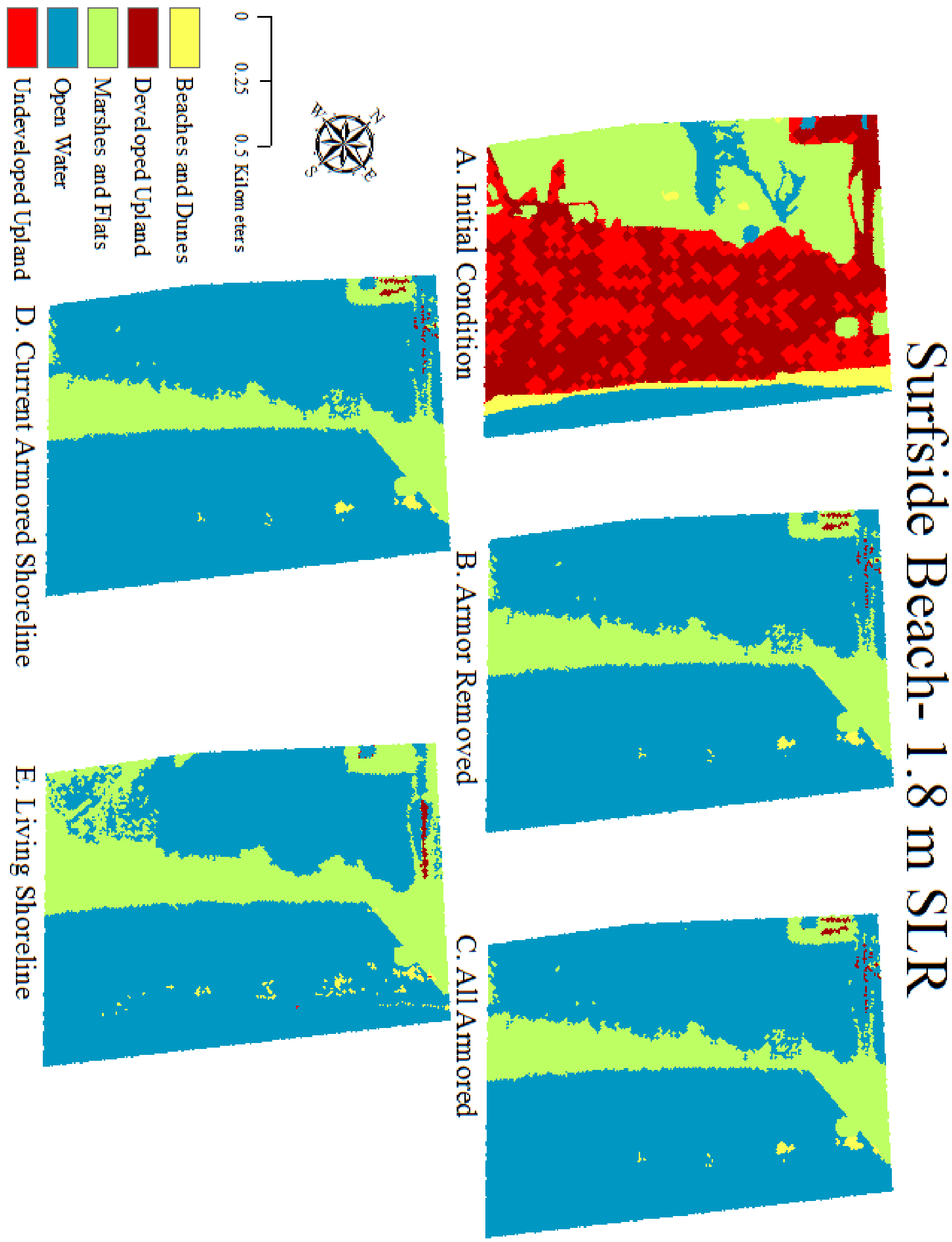
Galveston- 1.8 m SLR



Galveston:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	696,909	702,640	702,579	581,972
Undeveloped Upland	1,359,843	1,364,549	1,366,629	1,538,108
Inundated Developed Land	1,767,196	1,761,465	1,761,526	1,882,133
Marshes and Flats	2,157,995	2,160,357	2,170,277	1,970,025
Open Water	2,756,502	2,749,434	2,737,434	2,766,207

	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-71.72%	-71.48%	-71.49%	-76.38%
Undeveloped Upland	-43.58%	-43.38%	-43.30%	-36.18%
Marshes and Flats	87.70%	87.91%	88.77%	71.35%
Open Water	1.55%	1.29%	0.84%	1.90%



Note: The artifact at the northeast corner of the study area is due to the subsidence grid input. The grid's value at the most northeastern portion was -0.55 cm/yr which was converted to marsh whereas the value at the next pixel to the southwest was -0.56 cm/yr and was drowned.

Surfside:

	Area (Meters^2)			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	6,048	6,290	6,090	4,920
Undeveloped Upland	27	114	87	253
Inundated Developed Land	582,625	582,383	582,583	583,753
Beaches and Dunes	4,662	4,662	4,662	6,637
Marshes and Flats	146,424	146,384	146,480	251,043
Open Water	971,411	971,364	971,295	864,591

	Percent Change from Initial Condition			
	Armor Removed	**Current Armored Shoreline**	**All Armored**	**Living Shoreline**
Developed Upland	-98.97%	-98.93%	-98.97%	-99.16%
Undeveloped Upland	-99.99%	-99.97%	-99.98%	-99.94%
Beaches and Dunes	-92.47%	-92.47%	-92.47%	-89.28%
Marshes and Flats	-68.83%	-68.84%	-68.81%	-46.55%
Open Water	387.65%	387.63%	387.59%	334.03%