INCREASING RESILIENCE OF URBAN DEVELOPMENT ON TEXAS BARRIER ISLANDS

A Dissertation

by

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

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ABSTRACT

The purpose of the dissertation was to develop information, at a local scale, that can be incorporated into a spatial planning process to increase the resilience of urban development on Mustang and North Padre Islands, Texas. About 12% of U.S. barrier islands are completely urbanized, and 36% are heavily developed. This development trend is exposing more people, property, and infrastructure to coastal hazards. Therefore, coastal communities must plan for resiliency to remain functional and prosperous after a storm strikes or environmental conditions change.

Each chapter presents an element of the spatial planning process, including the following: a geohazards map, an ecosystem services valuation, and a land-use policy analysis. The geohazards map describes the effect of ongoing geologic processes and future evolution of a barrier island as a geomorphic system in response to relative sea-level rise (RSLR). The assessment and monetary valuation of the storm protection provided by beaches and foredunes informs decision-making regarding beach-dune management alternatives and supports their preservation. Land-use policies are analyzed and recommendations made to preserve current and future critical environments and guide future urban growth towards safer and more stable areas.

Results of the study show that RSLR could cause 50% of the study area to change by 2072. About 55% of the assessed beach-foredune areas provide overwash protection against at least a 100-year storm. Beaches and foredunes cover 6.9 sq. km; however, they save an estimated $141.4 million/year (2013 USD) in storm protection expenditures. It was found that 26% of the study area can accommodate higher density development, 23% should be left undeveloped or planned for lower density development, and 51% includes public spaces and preservation areas. Current state and federal regulations offer only limited protection to present and future locations

of critical environments, with beaches and dunes receiving the most protection compared to bay-margin wetlands. A transfer of development rights program may be a sensible land-use policy for addressing the realities of a dynamic coastal environment and balancing private and public interests.

While coastal vulnerability continues to increase, this dissertation provides actionable information and a process to follow for increasing the resilience of human activities on barrier islands.

DEDICATION

I fell in love with barrier islands back in 2004, when I first visited Port Aransas, Texas. I still remember driving on State Highway 361 and being stunned by the beauty of the sunlight reflecting on perfectly calm wetlands that blue sky, summer morning. That day was also my first time swimming in the warm waters of the Gulf of Mexico. My mind, used to Pacific Ocean beaches, was a little bit confused as the sun was setting on the wrong side of the beach. I was, to say the least, exhilarated by the experience of a different coastal setting. After that day, Mustang Island has become a special place where I have formed some of my most cherished memories.

This dissertation is dedicated to everyone who is concerned about the future of barrier islands around the world.

ACKNOWLEDGMENTS

I am greatly indebted to my advisor and mentor, Dr. Jim Gibeaut, for believing that an engineer/planner could be a good Ph.D. student to conduct research on Texas barrier islands. During the first couple of years of my studies, his rigorous classes helped me gain the knowledge and develop the skills of a coastal geoscientist. Later on, his trust and support of my work empowered me to persevere through the challenges of this academic pursuit. Without his mentorship, I could not call myself a scientist today. I would also like to thank Drs. Richard McLaughlin and David Yoskowitz for their excellent classes and agreeing to serve on my committee. Their time and advice have proven invaluable, especially during the most challenging moments of my Ph.D. journey. I greatly appreciate the mentorship and friendship of Dr. Michael Starek, which came at a crucial time in my research. His expertise and genuine curiosity helped improve my work significantly. I would like to thank Dr. Fritz Steiner for graciously agreeing to serve on my committee after the untimely passing away of my masters' advisor, Dr. Kent Butler. I appreciate his insights regarding land-use planning topics and the opportunities he facilitated for me to reconnect with my planning background. Furthermore, I thank Thomas Calnan for his mentorship since my time as an intern with the Texas General Office. His encouragement and vision were instrumental in my decision to pursue this doctoral degree.

The Ph.D. journey offered me the opportunity to connect with many people. I would like to thank the original CMGL crew, Anthony Reisinger, Diana Del Angel, Luz Lumb, John Wood, and Boris Radosavljevic, as well as Jeff Francis, Kate Lavelle, Carlota Santos, Michael Reuscher, Lauren Hutchison, and Jason Williams, for their friendship and support these past years. William Nichols, thank you for solving 99% of my computer problems by just coming in close proximity to my workstation. Thank you to the CMSS faculty and classmates for sharing your knowledge and experiences inside and outside the classroom. I am very grateful for the support and funding provided by the Harte Research Institute for Gulf of Mexico Studies and TAMUCC to pursue this doctoral degree. Additionally, I would like to thank Gail Sutton, Allison Knight, Roland Dominguez, and Luke Eckert for their all their help whenever needed.

To conclude, I would like to thank my parents, brother, and my Mexico and Texas families who have been very supportive of my dreams and academic pursuits. Ultimately, the successful completion of this journey could not have been possible without the love, support, and encouragement of my husband.

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1. Introduction

1.1 Human development on barrier islands

For centuries, humans have settled on barrier islands taking advantage of the fishing, transportation, and recreational opportunities that they offer; barrier islands in the United States are no exception. Many barrier islands along the Atlantic and Gulf coasts are home to towns, cities, and resort developments (Pilkey, 2003). According to Stutz and Pilkey (2005), about 12% of the U.S. barrier islands on Atlantic and Gulf coasts are completely urbanized, and 36% are heavily developed. In spite of all the risks involved with living in such a dynamic environment, coastal communities on barrier islands continue growing and rebuilding, even after major storm disasters (Bush et al., 1996; Pilkey and Neal, 2009; Riggs et al., 2009). Urban development is a major driver of environmental degradation and habitat loss on barrier islands (Davis and Fitzgerald, 2004). It has been extensively documented that residential and commercial development along with stabilization projects have not only created hazardous conditions, but also contributed to water quality problems, wetland losses, and detrimental sediment and geomorphic changes (Bush et al., 1996; Nordstrom, 2000; Davis and Fitzgerald, 2004; Stutz and Pilkey, 2005; Crozier, 2009; Pilkey and Neal, 2009; Riggs et al., 2009). In the past few decades, disaster-related losses and environmental problems have been escalating; however, these issues have not slowed down development and are not expected to do so in the next few decades (Bush et al., 1996). Due to the changing nature of barrier islands, most barrier island communities in the near future will be presented with the challenge of either to defend their shore, retreat, or abandon it. Whichever direction is chosen, costly economic, social, political, and environmental trade-offs will be unavoidable.

1.2 Resilience

Discussions about the concept of resilience first started in the 1970s. It was not until recent years, however, that resilience has gained prominence in the dialogue about the sustainability of coastal communities (Beatley, 2009). The term resilience refers to the ability of a system to persist in a particular state or configuration without major changes in its functions, feedbacks, and structure, as well as to its capacity to reorganize or rebound to a similar state after disturbances (Walker et al., 2002). In the context of coastal communities, resilience has to do with the ability of a community to remain functional and prosperous after disasters or external conditions change (Cone and Brown, 2011). Resilience has become a central theme for barrier island communities as concerns mount regarding the devastation left by recent hurricanes and increasing evidence of the potential impacts of sea-level rise (SLR) and changes in storm activity in the future (Cone and Brown, 2011).

The terms stability, resiliency, and adaptability are widely used to describe the goals and characteristics coastal communities aspire to attain (Sempier et al., 2010). A system, in theory, would be sustainable if: (1) it is stable in the presence of small frequent perturbations (e.g. cold fronts); (2) has some resilience to large rare disturbances (e.g. hurricanes); and (3) has the ability to adapt to permanent changes in conditions (e.g. SLR) (Levin et al., 1998). Following this idea, a barrier island (the system), in order for it to harbor a "sustainable" community, its geomorphology and natural ecosystems should be to a certain extent stable, resilient, and hopefully able to adapt to major environmental changes. Therefore, planning accounting for changes in different temporal and spatial scales need to be included in current and future efforts directed to make coastal communities more resilient and sustainable.

The degree of resilience of a coastal community also depends on its social, economic, and environmental vulnerability. Vulnerability, in this sense, can be described as the potential social, economic, or environmental assets that could be impacted by hazardous events or conditions while counteracted by protective and adaptation measures against such hazards (McFadden et al., 2007). The physical vulnerability of a coastal community is a function of the ability of a forcing agent (e.g. storm, SLR) to induce a change in the coastal setting and the resilience capacity of the landscape. Barrier island communities can enhance resilience and thus reduce their physical vulnerability to coastal hazards by (1) strengthening coastal protective structures; (2) promoting the preservation of natural defenses and sediment dynamics; and/or (3) limiting the exposure of vulnerable assets to hazards (Orford et al., 2007). The approach taken by each community to increase its resilience will ultimately be influenced by political, social, economic, and technological factors.

1.3 Planning for a dynamic coastal environment

Barrier islands are one of the most dynamic landforms on Earth, experiencing continuous changes by geologic processes and other forces taking place at different spatial and temporal scales. This characteristic of being in a state of constant flux poses a unique set of challenges for urban planning on barrier islands. First, a barrier island setting demands attention to physical forcings on two fronts: from the ocean side and bay (or lagoon) side. Second, conventional urban development on barrier islands includes buildings and infrastructure that are often designed to remain in place for their entire service lives. However, the rigidity of urban development clashes with the physical realities of a barrier island. Slight changes in sea-level, sediment availability, and storm frequency coupled with the construction of shore protection structures can have major impacts on how barrier islands behave as geomorphic systems. Third, the increasing development pressure on barrier islands is pushing these ever-changing landscapes and their associated ecosystems to the point of becoming rigid, human-dominated places, which are not able to provide the same quantity and quality of ecosystem services and resiliency dynamics as the original natural setting (Levin et al., 1998; Stutz and Pilkey, 2005). Finally, a growing coastal urban population presents a twofold challenge: dealing with more people and infrastructure exposed to coastal hazards, as well as an exacerbated pace of environmental consumption and degradation (Crosset et al., 2004; McGranahan et al., 2007; Nicholls et al., 2007; Brommer and Bochev-van der Burgh, 2009).

1.4 Barrier islands and SLR

One of the main drivers of change on barrier islands is sea level. Most barrier islands in the U.S. were formed in the last ~5000 years as eustatic SLR slowed down after increasing quite rapidly in the early Holocene (Stutz and Pilkey, 2011; Hayes, 2005). This gradual sea-level rate has been conducive for the development of modern barrier islands (Stutz and Pilkey, 2011). In contrast, accelerated increases in sea level may quickly outpace the sedimentary processes that build and maintain barrier islands, ultimately drowning them. Data records collected from tide gauges indicate that global sea level rose about 1.7 ± 0.3 mm/yr from 1870 to 2004 (Church and White, 2006). However, the analysis of recent global satellite data shows that the rate of SLR almost doubled (3.3 ± 0.4 mm/yr) from 1993-2009 (Nicholls and Cazenave, 2010). This acceleration trend is expected to continue through the 21st century, thus raising concerns about the impact of SLR on coastal areas, including barrier islands (Nicholls and Cazenave, 2010). By 2100, global sea level is expected to rise 0.26 – 0.98 m and tropical storm activity is projected to decrease in frequency, but increase in intensity (IPCC, 2013; Knutson et al., 2010; Woodruff et al., 2013). SLR is bound to become a major driver of coastal flooding, increasing the frequency of small and large flood events regardless of climate-induced variations in tropical storm activity (Warner and Tissot, 2012; Woodruff et al., 2013). Storms cause major erosive events on barrier islands; however, storms coupled with accelerated SLR and sediment supply deficits can exacerbate long-term erosion trends (Woodruff et al., 2013).

As mentioned before, barrier islands are subject to physical forces coming from the ocean and bays (or lagoons). Fringing environments, such as beaches, dunes, and wetlands, are continuously exposed to tides and waves. Inland environments, on the other hand, are exposed to these forces during extreme events such as storms and hurricanes. Extreme events can cause flooding and enable wave energy to reach sheltered inland areas. In some cases, storms can overwash or breach an island. Although barrier islands are constantly impacted by oceanographic and meteorological forcings, they are in a state of dynamic equilibrium that has been maintained for millennia (Leatherman et al., 2000). Fringing barrier island environments, however, would be some of the first places where the influence of an accelerated SLR rate would be seen. Beaches and dunes are expected to recede as waves are able to reach further up the beach profile (Fitzgerald et al., 2008; Leatherman et al., 2000). Similarly, marshes are expected to gradually migrate inland as their hydroperiod changes with SLR (Fitzgerald et al., 2008; Morris et al., 2002). The effects of SLR are offset by sedimentary processes that allow beaches to recover from erosion and marshes to build up and not drown. Nevertheless, concerns are mounting over projected SLR rates outpacing these natural sedimentary processes and urban development obstructing the inland migration of beaches, dunes, and marshes; thus, leading to chronic shoreline erosion and marsh loss (Fitzgerald et al., 2008; Leatherman et al., 2000; Morris et al., 2002; Nichols and Cazenave, 2010). As a result, barrier island communities need to plan and adopt measures that will allow them to adjust to a new set of future environmental conditions.

2. Purpose

The purpose of this dissertation is to develop transferable information and analyses regarding coastal hazards, ecosystem services, and land use policy that can be integrated into a spatial planning process to increase the physical resilience of urban development on Texas barrier islands. First, a geohazards map is created and proposed as a tool to inform planners, decision-makers, and the public about challenges and limitations of living on a barrier island. The map focuses on showing in a spatially explicit manner ongoing geologic processes and future evolution of a barrier island as a geomorphic system in response to relative sea-level rise (RSLR) in the next 60 years. Second, an assessment and monetary valuation of the storm protection function provided by beaches and dunes, at a site level, is conducted to better inform decisions regarding beach-dune management alternatives and support the preservation of these critical environments. Finally, a transfer of development rights program (TDR) is explored as a land-use policy tool to increase resilience of barrier island communities by preserving current and future critical environments locations and guiding future urban growth towards safer and more stable areas on the islands. The results of this study are intended to serve as inputs for coastal planning and SLR adaptation efforts on the Texas coast.

3. Relevance

Following the economic, social, and environmental losses that have occurred after hurricanes in the past decade, there has been a surge of interest in the subject of resilience of coastal communities. This interest has become even more heightened in the light of the potential effects of climate change, SLR, and an ever-increasing coastal population. In support of this concern, government, academic, and non-governmental organizations have produced research and documents to help communities become more resilient; however, the responsibility to act upon this information falls ultimately in the hands of local governments. As a result, there is a growing need for coastal science knowledge that can be integrated into the planning process and is readily actionable at the local level. The work developed in this dissertation seeks to address this need by presenting research to enhance the physical resilience of barrier island communities, along with its application and possible implications in a local context.

4. Research objectives

1. Create a geohazards map for Mustang and North Padre Island.
2. Classify beaches and foredunes according to their level of storm (overwash) protection.
3. Value the storm protection function of beaches and foredunes using a replacement cost approach.
4. Explore the implementation of a TDR program on Mustang and North Padre Island as a land-use policy to increase physical resilience of urban development.
5. Create a land suitability map for the development of Mustang and North Padre Islands that minimizes exposure to the effects of RSLR, erosion, and storms, and preserves current and future location critical barrier island environments.

6. Analyze current federal and state regulations that affect coastal development and the potential implementation of a TDR program on Texas barrier islands.

5. Study approach

The work presented in this dissertation has been developed as inputs that can be integrated into a spatial planning process to increase the physical resilience of urban development on Texas barrier islands. Each of the chapters presents research findings in a spatially explicit manner that can be readily incorporated to coastal and land-use planning activities. The approach taken in this study, to promote the physical resiliency and adaptability of barrier island communities through planning, hinges on the integration of the following principles:

1) *Understanding the physical landscape* by acquiring knowledge about short- and long-term geological processes, as well as episodic flooding events, that shape barrier islands to understand potential hazards and future evolution of the landscape.
2) *Developing information to support decision-making* by assessing and valuing a representative ecosystem service function currently under development pressure.
3) *Analyzing the implementation of land-use policy based on scientific information* by examining current regulatory frameworks and integrating scientific knowledge into land-use policy considerations.

The geohazards map provides a starting point by providing a picture of how the barrier island may look in the next 60 years in response to the effects of RSLR and other geological processes. The map shows hazardous areas and information about the future spatial location of critical barrier island environments. The development of this map involved detailed mapping of the different geo-environments currently present on the islands, resulting in a comprehensive geo-environment spatial inventory. Next, the assessment and valuation of the storm protection function uses this geo-environment spatial layer to initially identify beaches and dunes areas, and later on assign replacement cost values to beach-dune profiles across Mustang and North Padre Islands (Figure 1.1). The final chapter examines the implementation of a TDR program as a land-use policy to direct development away from risky areas as well as present and future critical environments locations. The proposed TDR program implementation is based on a land suitability analysis that takes into account the geohazards map and storm flooding information to identify areas that are not expected to change in the 60 years and less likely to be inundated during a 100-year flood (storm) event (Figure 1.1). Finally, information about the level and value of the storm protection function of beaches and dunes could further support the argument for the preservation of these critical environments.

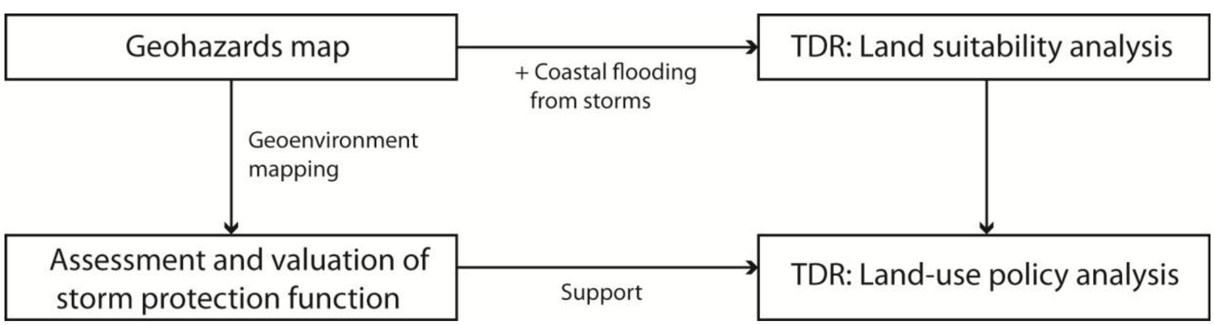

Figure 1.1. Integration of spatial planning elements.

6. Organization of the manuscript

This dissertation consists of five chapters. Chapter I includes a brief introduction, purpose, relevance, research objectives, and study approach, followed by a comprehensive description of the study area. Chapter II presents the geohazards map of Mustang and North Padre Island. Chapter III presents an assessment and monetary valuation of the storm (overwash) protection function of beach and foredunes. Chapter IV explores a TDR program as a land-use policy tool to increase physical resilience of urban development on Texas barrier islands. Finally, an overall summary and conclusions are presented in chapter V. A complete list of the literature cited throughout the dissertation can be found at end of this document.

7. Study Area

The study area includes Mustang and North Padre Islands, Texas, extending from Aransas Pass to the northern boundary of the Padre Island National Seashore (Figure 1.2). This study area was selected because it represents a typical wave-dominated sandy barrier island characteristic of most of the Atlantic and Gulf coasts. In addition, several scientific studies and data are available for this location. Finally, the impending urban development on Mustang and North Padre Islands embodies the challenge of balancing conservation and sustainability shared by many coastal communities around the world.

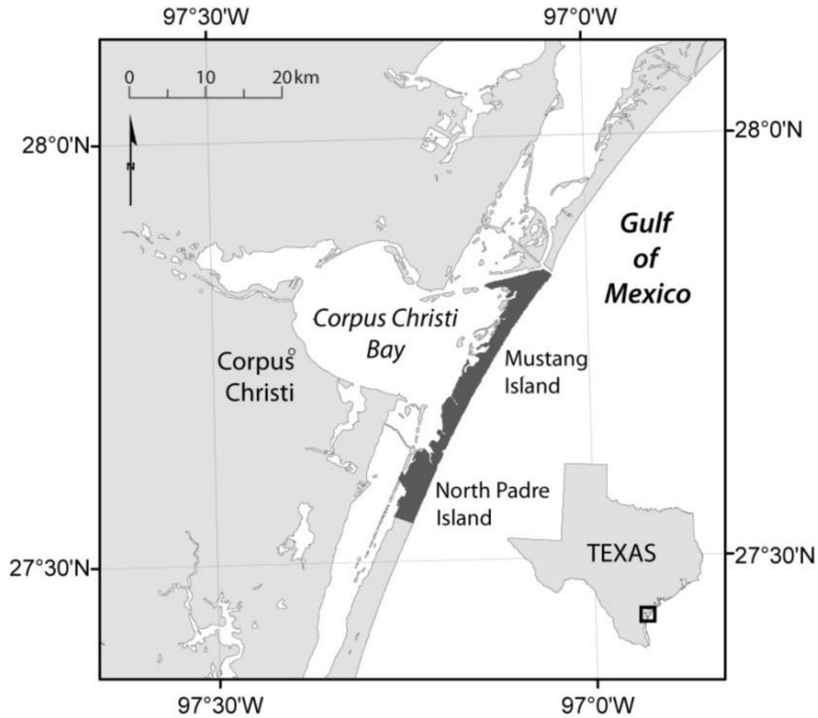

Figure 1.2. Location map of Mustang and North Padre Island

7.1 Physical setting

Mustang and North Padre Islands are sandy barrier islands located on the central Texas coast. These barrier islands shelter the waters of Corpus Christi Bay and the upper Laguna Madre from the Gulf of Mexico. Mustang and North Padre Islands began developing, over the ancient Nueces River valley, in the early Holocene (Simms et al., 2006). About 5,000 - 6,000 years ago the rate of sea-level rise slowed, Pleistocene headlands eroded, and incipient island sediments coalesced by spit accretion to form the barrier-island system as we know it today (Brown et al., 1976; Morton and McGowen, 1980; Simms et al., 2006). High-profile, aggradational barrier islands, such as Mustang and North Padre Islands, are relatively wide and have high, densely vegetated foredunes and few washover channels (Morton and McGowen, 1980; Simms et al., 2006).

The Texas central coast is a microtidal, mixed-energy (wave-dominated) coast that is periodically influenced by the passage of cold fronts and less frequent tropical storms (Hayes, 1979; Morton, 2010; Morton and McGowen, 1980). Tides along Mustang and North Padre Islands are predominantly of a diurnal nature, oscillating within a range of 0.50 m on the Gulf coast and 0.11 to 0.24 m on the bay side (Williams et al., 2007; TCOON, 2013). Waves breaking on the coast are of relatively low energy under fair-weather conditions, tending to be larger in the winter and smaller during spring and summer seasons (Watson and Behrens, 1976). The significant wave height for the area ranges from 0.54 to 1.25 m throughout the year (Kraus and Heilman, 1997).

Mustang and North Padre Islands are situated within a dry subhumid climatic zone (White et al., 1978). Annual precipitation (760-800 mm/year) is often surpassed by evaporation (~ 760 mm/yr), thus creating dry conditions in which aeolian processes have a great influence over the barrier islands' landscape (White et al., 1978). Wind direction in this area exhibits a bimodal behavior, shifting between southeast and northeast directions every five to six months. The resultant annual wind direction is from the southeast, with predominant speeds ranging from 4.5 to 8 m/s (Watson, 1971; Kraus and Heilman 1997).

Longshore sediment transport along Mustang and North Padre Islands has been estimated to be 726,000 m^3/yr, with a net rate of 66,000 m^3/yr in a southwest direction with occasional seasonal reversals (Watson and Behrens, 1976). The long-term shoreline change trend is erosional (-0.83 ± 0.7 m/yr, 1937-2011), characterized by short-term cycles of accelerated retreat due to tropical storms and beach recovery during years with slow hurricane activity (Taylor and Gibeaut, 2013; Morton & Pieper, 1977). The average return period for hurricanes in the vicinity of Port Aransas is 12 years (Keim et al., 2007).

From 1948 to 2006, relative sea level in the area rose an average of ~5.12 mm/yr as recorded by the Rockport tide gauge (Zervas, 2009). Sea level has also risen elsewhere along the Texas coast. To the north at Galveston Pier 21 station, relative sea-level rise (RSLR) from 1908-2006 was 6.4 mm/yr; while to the south, the Port Isabel gauge recorded an average of 3.6 mm/yr from 1958-2006 (Zervas, 2009). Paine (1993) reported rates of subsidence of 3 to 7 mm/yr for Texas coastal areas without significant groundwater extraction. A subsidence rate of about 2-3 mm/yr has been used as a good estimate for Mustang and North Padre Island (Gibeaut et al., 2010).

7.2 Barrier-island environments

Various natural barrier-island environments can be found on Mustang and North Padre Islands (Figure 1.3). These environments provide many ecosystem services that support human activities and well-being (Defeo et al., 2009). Marine-influenced environments include beaches, vegetated foredunes and secondary dunes, actives dunes, blowouts, and washover areas. Fresh water marshes and ponds found in vegetated barrier flats comprise palustrine environments on the islands. Estuarine environments include wind-tidal flats, salt marshes, and seagrass beds.

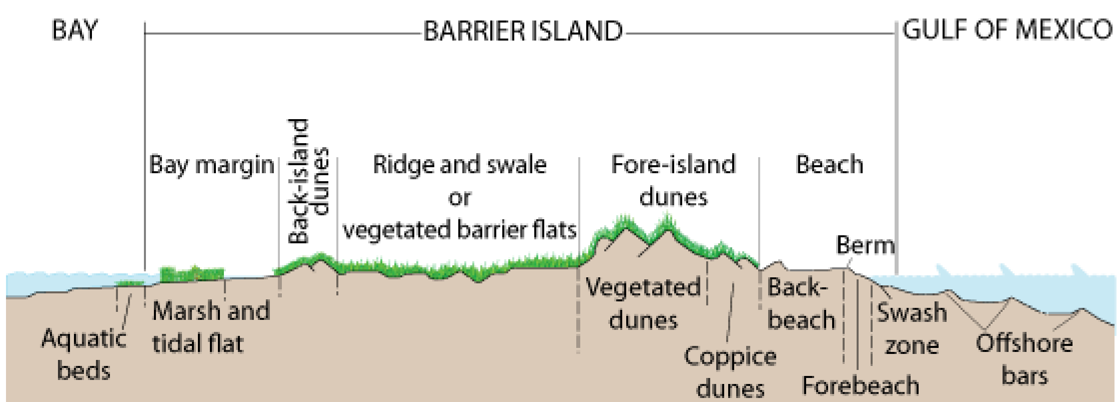

Figure 1.3. Generalized cross-section profile for Mustang Island indicating relative location of major barrier island environments. (Modified from Paine et al., 2003, Credit: Radosavljevic, 2011).

Mustang and North Padre Island beaches have an average width of 75 m, including the forebeach and backbeach. Coppice mounds are present on the backshore, and are sparsely vegetated with plants tolerant to salt-spray such as *Croton punctatus* (beach tea) and *Sesuvium portulacastrum* (sea purslane) (White et al., 1978). Coppice mounds along the island are constantly impacted by beach maintenance activities and vehicular traffic. Beaches are a highly dynamic area where the influence of waves, tides, and wind is ever present. Because of their sediment composition, beaches can buffer and absorb wave energy and shelter back-shore environments (Anthony, 2005). Beaches also provide the physical structure for water filtration (McLachlan and Brown, 2006). Although largely unvegetated, beaches serve as habitat to many invertebrate organisms, which feed from phytoplankton on the surf zone (McLachlan and Brown, 2006). Birds and turtles use beaches as foraging, nesting, and breeding grounds (McLachlan and Brown, 2006). Beaches provide many ecosystem services, such as disturbance regulation, water filtration, sediment storage and dynamics, and habitat for some coastal species. However, the most recognizable is the recreational use of the shore. (Defeo et al., 2009; Yoskowitz et al., 2010). It has been calculated that a day of closure of beaches around Padre Island, Texas in July may cause up to $172,000 (USD 2001) in recreation-related revenue losses (Parsons and Kang, 2007).

The landward boundary of the backshore is the toe of the foredunes. Along Mustang and North Padre Island, the foredune complex can be up to 10 m high and generally stable due to dense vegetation cover (White et al., 1978). In contrast, swales within the complex are low and may become inundated during rain events and storms. Some of the plants found on foredunes are grasses such as *Uniola paniculata* (sea oats), *Panicum amarum* (bitter panicum), and *Paspalum monostachyum* (gulfdune paspalum) (White et al., 1978). The topographic and vegetative complexity allows foredunes systems to perform numerous ecological functions (Everard et al., 2010). Dunes act as sediment storage for adjacent beaches and inland landforms. The shore-parallel pattern of foredunes makes effective barriers providing protection against salt spray, wave action, and storm surge (Davis and Fitzgerald, 2004). Foredunes serve as habitat for different insects, birds, and mammals (McLachlan and Brown, 2006). Moreover, dunes are places of ground water recharge and retention of freshwater, which buffer saltwater intrusion (Martínez and Psuty, 2004). Coastal dunes provide many services to humans such as sediment storage and dynamics, disturbance regulation (storm surge), groundwater storage and recharge, scenic views, and recreational opportunities (Defeo et al., 2009; Yoskowitz et al., 2010). As an example, Brenner et al. (2010) assigned a value of $67,400 hectare/year (2004 USD) to disturbance regulation services provided by dunes along coastal Spain.

Vegetated barrier flats are found in the central section of the islands interspersed with ephemeral freshwater ponds and marshes (White et al., 2006). These interior upland areas form a low-relief, hummocky terrain that extends over most of the island core. Plants in the vegetated flats include *Paspalum monostachyum* (gulfdune paspalum) and different *Panicum* species (White et al., 1978). Due to their relative location within the barrier-island system, vegetated barrier flats are the environment less affected by active physical processes (White et al., 1978). Flats serve as habitat for a variety vascular plants, small mammals, seed-eating birds, and reptiles (White et al., 1978; Smith, 2001). Birds, rodents, and coyotes use freshwater ponds and marshes as water sources (Britton and Morton, 1989). Vegetated flats also provide other ecosystem services such as groundwater storage and recharge, sediment storage and dynamics, developable land, and recreational opportunities (Smith, 2001). The value of these upland areas as potential real estate property was estimated to be $4,713.8 ha/yr on Galveston Island (Feagin et al., 2010).

Active dunes can be found towards the back of the island migrating in a bayward direction, especially in the vicinity of washover areas. These dunes are affected by wind action and are typically not vegetated until they stabilize. There are a few washover areas on Mustang and North Padre Islands. Corpus Christi Pass, Newport Pass, Fish Pass, and the now stabilized Packery Channel are low-lying areas that have been eroded and inundated during tropical storms. During these storms, sediment from these areas is transported to the back of the island. Washover areas are usually devoid of vegetation and are highly susceptible to wind modification (White et al., 1978).

Wind-tidal flats are found on the bay margins of the islands. As their name implies, these flats are periodically inundated by wind, storms, and astronomical tides. Vegetation on wind-tidal flats consists mostly of blue-green algae mats that form after inundation. *Monanthochloe littoralis* (shoregrass), *Salicornia* spp. (glassworts), and *Batis maritima* (saltwort) can also be found in these areas (White et al., 2006). Infrequent flooding, low freshwater inflow, and high summer temperatures make conditions on flats too extreme for mash plants to thrive (Withers, 2001).The elevation of wind-tidal flats ranges from 0.2m to 0.01m above MSL (Gibeaut et al., 2010). Wind-tidal flats serve as habitat for filter-feeding organisms and invertebrates (Paterson et al., 2009). They also provide habitat and feeding opportunities for shorebird species (Smith, 2001). Microalgae and detritus are primary producers for the rest of the intertidal ecosystems. Blue-green algae and algal mats fix nitrogen and other nutrients that are released when flooding occurs (Smith, 2001). Some of the ecosystem services provided by intertidal flats include net primary productivity, coastal protection, nutrient cycling, habitat for commercially important species, and recreational opportunities (Paterson et al., 2009). In a recent study, Feagin et al.

(2010) estimated the value of birding/hunting recreational services of intertidal flats on Galveston Island to be $4,540.2 hectare/year (2006 USD).

Salt marshes also fringe the bay margin of the barrier islands. They are found in elevations ranging just a few inches above and below MSL, and in areas sheltered from high wave energy and strong currents (White et al., 1978). Salt marshes can be differentiated into low marsh and high marsh based on their relative elevation to the high tide mark (how frequently they are inundated) and the different plant species that populate these areas. *Spartina alterniflora* (smooth cordgrass), *Batis maritima* (saltwort), and *Distichlis spicata* (seashore saltgrass) are prevalent in low marshes, while *Schoenoplectus* (formerly Scirpus), *Paspalum vaginatum* (seashore paspalum), and *Spartina patens* (saltmeadow cordgrass) characterize high marshes (White et al., 2006). Vegetation and soil in salt marshes perform water quality improvement functions, such as the denitrification of runoff and other nutrient removal (Zedler and Kercher, 2005). Waterfowl, fish, and certain benthic species use salt marshes as habitat. Salt marshes promote sedimentation as its vegetation traps suspended sediment during high tide flooding and buffers wave action (Davis and Fitzgerald, 2004). Moreover, salt marshes protect inland areas from flooding by storing and slowing floodwaters (Zedler and Kercher, 2005).

During the past 50 years, black mangroves (Avicennia germinans) have been extending their coverage, occupying areas previously dominated by low-marsh vegetation, especially in sheltered areas. This trend has been attributed to warmer climatic conditions (Tunnell et al., 2007). Finally, seagrass beds are the outermost environment on the bay side of the barrier islands. They are submerged shallow flats covered mostly by *Halodule wrightii* (shoalgrass) and *Thalassia testudinum* (turtlegrass) (White et al., 2006). Dense seagrass beds extending along

Mustang Island trap suspended sediment and provide habitat for juvenile fish (White et al., 1978).

7.3 Development on Mustang and North Padre Islands

Evidence of the first inhabitants on Mustang and North Padre Islands dates back to 2700 to 1500 B.C. (Garza, 1980). The Indians of the Aransas culture led a nomadic, primitive life based on subsistence from the island's limited resources (Garza, 1980). This changed in the 1800's with the introduction of cattle raising and ranching activities on the island (Garza, 1980). Early resorts and residential homes started to appear in the early 1900's; drilling for oil and gas also began during the first half of the 20th century (Garza, 1980). Since World War II, the focus of development on Mustang and North Padre Islands has been towards residential, commercial and recreational uses.

The study area is located mostly within Nueces County; a small uninhabited section falls under the jurisdiction of Kleberg County. Most of Mustang Island remains undeveloped except for a few resorts and condominiums scattered along the Gulf shore and the city of Port Aransas, which is located at the north end of the island. Similarly, North Padre Island is only developed from Packery Channel to the boundary between Nueces and Kleberg County. Several parks are within the study area, including Mustang Island State Park, Nueces County Park, Packery Channel Park, and Padre Balli Park. According to the Nueces County Appraisal District (2008), there are 6769 properties classified as single-family homes and condominiums, 258 as multi-family housing units, and 868 as commercial premises. About 12,624 people live within the study area, which constitutes 3.7% of the total population in Nueces County for the year 2010

(US Census Bureau, 2011). The population in the study area grew roughly 30% from 2000-2010 (US Census Bureau, 2011).

The character of residential development on North Padre Island is mostly of a bedroom community for people who commute daily to Corpus Christi and Flour Bluff for work and school. Most of residential stock is comprised of upscale detached single-family homes and a small number of multi-family units. North Padre Island is home to the well-established Padre Isles residential community, which was developed in the 1970s by dredging canals and filling and leveling back-barrier flats (Garza, 1980). Service-related businesses such as restaurants, gift shops, medical offices, and gas stations line the main access road to the island. On the other hand, Port Aransas is a small fishing and tourist town that dates back to the early 1900s. The residential stock is more varied than North Padre Island, ranging from modern luxury residences to older small homes. There are a few condominium complexes as well. Similar to North Padre Island, Port Aransas has a few businesses; most of them are tourism-related such as gift shops, restaurants, tackle shops, and a supermarket. Development in Port Aransas extends from behind the foredunes to the back of the island, with a couple of marinas, The University of Texas Marine Science Institute complex, and an upscale finger-canal residential community.

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CHAPTER II

Geohazards map of Mustang and North Padre Islands, Texas

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Abstract

Barrier island communities face the unique challenge of living and planning for a dynamic coastal environment. One of the most effective steps a community can take to enhance its resilience is to assess the vulnerability of existing development and guide future growth away from hazardous areas through sensible land-use planning. From a hazards mitigation perspective, land-use planning on a barrier island requires knowledge about short- and long-term geologic processes as well as episodic events. In Texas, information on coastal flooding resulting from storms, erosion rates, and historic washovers has been available for the Gulf coast for quite some time; however, integrated, practical information about ongoing geologic processes and future evolution of the barrier islands has been scarce. In response to this need, a geohazards map has been developed for Mustang and North Padre Islands. The geohazards map shows areas on the barrier islands according to their relative susceptibility to, and mitigation of, the effects of geological processes including relative sea-level rise, erosion, historic washover locations, and present and future location of critical environments, such as dunes and wetlands. The total mapped area covers 97.1 sq. km. About 34% of the area was categorized as having the highest geohazard potential levels (extreme and imminent), most of which is along the bay shoreline of Mustang Island, where the largest extent of wetlands is located, and the beach/foredune system strip on the Gulf side. While 27% of the area falls in the lowest geohazard potential category, which includes developed areas on North Padre and the northern end of Mustang Island, as well as undeveloped areas where the ground elevation is generally higher. The geohazards map for Mustang and North Padre Islands is presented as an interactive online tool to inform planners, decision-makers, and the public about current and future geologic challenges and limitations of living on a barrier island. Information about how the coastal landscape may evolve in the future,

in conjunction with sound regulations and policies, can effectively aid communities to lay out a tangible blueprint for future adaptation efforts.

1. Introduction

In the wake of economic, social, and ecological losses left by recent major storms, discussions about rebuilding, protecting, and living on the coast take center stage in the public opinion, at least for a couple months after the event. However, the dynamic geologic nature of coastal areas is often not given the prominence it deserves, or at best, it is relegated to a second plane. Coastal areas, including barrier islands, are shaped continually by geologic processes occurring at different spatial and temporal scales (Heinz Center, 2000). These processes have been shaping barrier islands for millennia, but these processes only become hazardous when they intersect vulnerable infrastructure, property, or population. The idea of an ever-changing coastal setting often clashes with conventional, fixed development patterns; nevertheless, acknowledgment of this reality and acting upon it are imperative if coastal communities want to thrive in the future.

2. Coastal hazards mapping

One of the most effective steps a community can take to enhance its resilience is to assess the vulnerability of existing development and guide future growth outside of hazardous areas through sensible land-use planning (Burby, 1998; Jacob and Pacello, 2011). From a hazards mitigation perspective, land-use planning requires knowledge about short- and long-term geologic processes as well as episodic events. Identifying and documenting the geologic landscape and its inherent hazards is essential for planning. Examples of coastal hazards mapping exist in Oregon and California, where hazards such as erosion, flooding, and landslides, have been documented (Ross and Morgan, 1986; Moore et al., 1999). These coastal hazards maps provided enough detail to be successfully incorporated into comprehensive plans, facilitating rezoning and imposition of site-specific requirements in hazardous areas (Ross and Morgan 1986). In Texas, information on coastal flooding, erosion rates and coastal vulnerability to sea-level rise has been available for the Gulf coast for quite some time (FEMA, 2013; Paine et al. 2011; Thieler and Hammar-Klose, 2000). However, practical information about ongoing geologic processes and future evolution of the barrier islands as a geomorphic system has been scarce. Provisions in the Texas Open Beaches Act (OBA) and Dune Protection Act (DPA) provide some across-the-board guidance for the preservation of protective coastal features, such as a beachfront construction certificate requirement for any construction activity taking place within 1,000-ft (304.8 m) of the mean high tide mark or the nearest public road, a public beach easement from the mean low tide to the line of vegetation, and a dune protection line to preserve dunes and dune complexes (TNRC Sec. 61.013 and 63.011, 1991; Sec. 61.011, 2009). However, both of these provisions apply only to the Gulf -facing shoreline, leaving bay shorelines unprotected (McLaughlin, 2011). These measures are intended to preserve beaches and dunes as well as providing public access; incidentally, they have also kept new development in safer areas behind the dunes.

In response to the need for guiding development toward safer areas, a series of geohazards maps have been created for three of the most populated barrier islands on the Texas coast: Galveston, Mustang and North Padre, and South Padre Islands. The geohazards maps show areas on the barrier islands according to their relative susceptibility to, and mitigation of, the effects of geological processes including relative sea-level rise (RSLR), erosion, historic washover locations, and present and future location of critical environments, such as dunes and wetlands (Gibeaut et al., 2010). These maps present a synthesis of knowledge on barrier-island dynamics in an accessible manner, ready to be used in land-use planning or incorporated as a guide in policy-making decisions. The geohazards maps differ from coastal flooding maps in that they not only delineate hazardous areas, but also paint a picture on how the island may look in the near future; thus allowing identification of critical areas to avoid or preserve.

3. Study area

This chapter focuses on Mustang and North Padre Islands. Both are microtidal, wave-dominated, sandy barrier islands located on the central Texas coast (Hayes, 1979; Morton, 1994, 2010; Figure 2.1A). These barrier islands shelter the waters of Corpus Christi Bay and the upper Laguna Madre from the Gulf of Mexico. They are relatively wide barrier islands (~2.6 km) with high, densely vegetated foredunes and secondary dunes, beaches, blowouts, and few washover channels (Morton and McGowen, 1980). The central area of the islands is mostly comprised of vegetated barrier flats with interspersed fresh water marshes and ponds. The bay-edge environments include wind-tidal flats and salt marshes. Approximately 85% (58.2 sq. km) of Mustang Island remains undeveloped except for a few resorts and condominiums scattered along the Gulf shore and the city of Port Aransas, located on the north end of the island. Similarly, North Padre Island is only developed from Packery Channel to the boundary between Nueces and Kleberg counties; the developed area covers ~18.2 sq. km (Figure 2.1B).

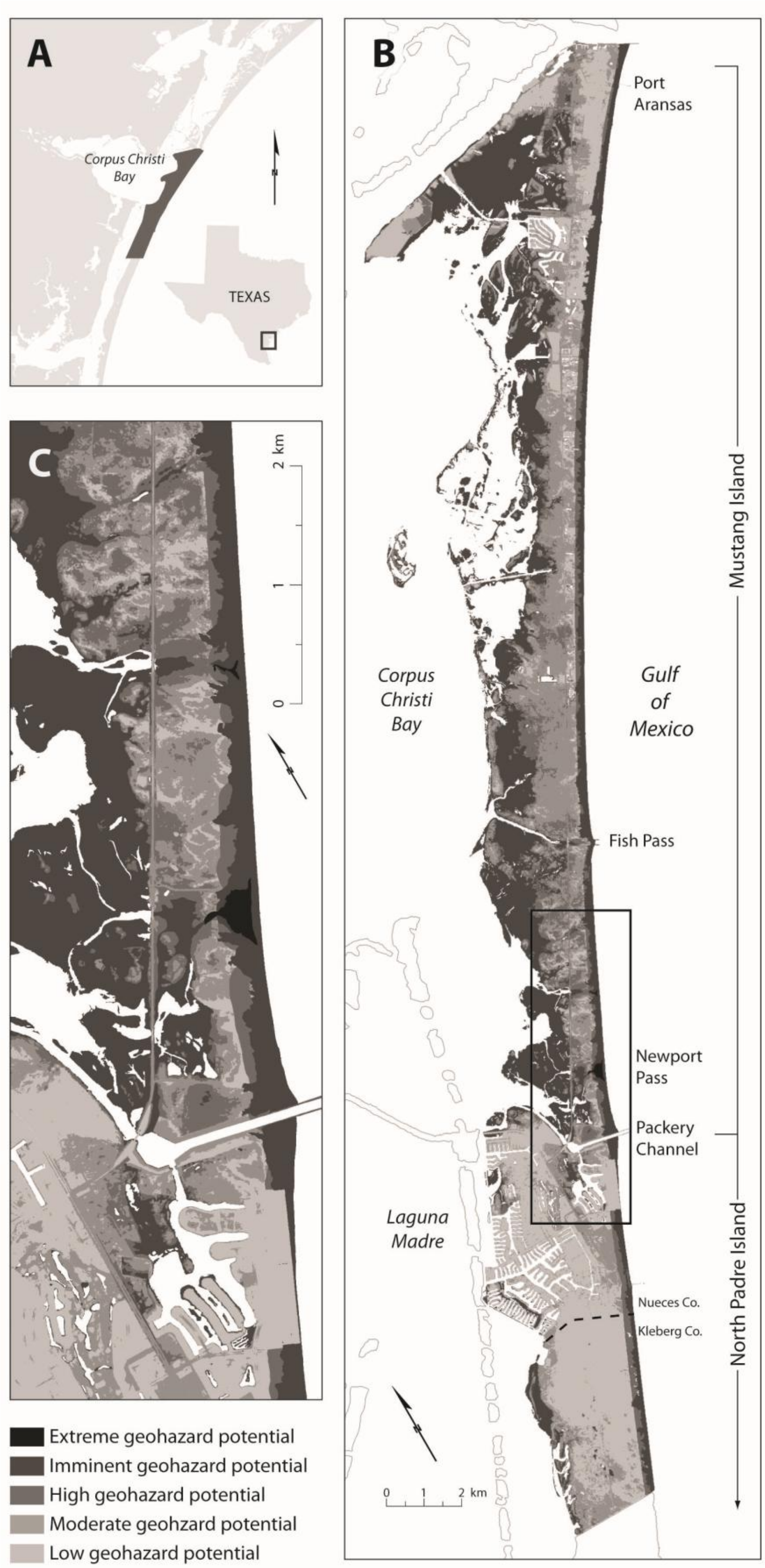

Figure 2.1. Maps showing (A) the study area, (B) the geohazards map, and (C) a detailed view of the geohazards map in the vicinity of Packery Channel and Newport Pass. An interactive color version of the map is available at http://geohazards.tamucc.edu

4. Development of the geohazards map

The development of the geohazards map follows the methodology used by Gibeaut et al. (2007) to create a similar map for Galveston Island, that shows hazardous areas coupled with information about the future spatial distribution of critical environments, such as wetlands, dunes, and beaches. The projection horizon for the geohazards maps is 60 years to allow for predictions that are most reliable for the data and projection methods used, as well as presenting results at a relatable human-scale. It is assumed that the observed RSLR rate of ~5.2 mm/yr will continue during the 60 years (Gibeaut et al., 2010; NOAA, 2013). First, a geo-environment classification layer was mapped for the entire study area. It identifies estuarine, upland, and marine-influenced environments (Appendix A Table A.1). This layer builds on previous wetland mapping done by White et al. (2006). This previous wetland map was revised, updated, and augmented by adding upland classes using high-resolution aerial imagery, a 1-m resolution lidar-derived digital elevation model (DEM), as well as current parcel data. The geo-environment classification layer and the DEM are used to compute elevation range statistics for different geo-environments including wetland types. Next, a wetland transition model is used to simulate how wetlands migrate inland in response to RSLR (Gibeaut et al., 2010). The model requires the wetland elevation range statistics to reclassify an elevation grid that is subject to RSLR inundation and vertical accretion adjustments in 1-year increments (Gibeaut et al., 2010). Intermediate and final output grids from the wetlands transition model for the northern section of the study area are included in Appendix A (Figure A.1-6).

To simulate the inland migration of beaches and dunes due to RSLR, long-term shoreline-change rates and an estimation of the width required for the development of beaches and foredunes are used to project the position of the shoreline, beaches, and foredunes in 60 years. A projected 2071 shoreline was developed using long-term shoreline-change rates along the study area (-0.83 ± 0.7 m/yr). The shoreline-change rates calculations included digitized shorelines from 1937-2011. The future location of critical beach and dune environments was identified as an area extending 173 m landward of the projected shoreline, which corresponds to the current average beach and foredune complex width along Mustang and North Padre Islands. Finally, the original geo-environments layer was reclassified into five geohazard level categories by combining elements from the wetland transition model output, future shoreline position, historic washover locations, and DEM.

4.1 Geohazards map

The geohazards map shows five geohazard potential categories: extreme, imminent, high, moderate, and low (Figure 2.1B & 2.1C). Historic storm washover channels were designated as extreme geohazard potential areas. Areas mapped as having imminent geohazard potential include the presently existing critical environments of regularly flooded estuarine wetlands, freshwater wetlands, and the beach/foredune system. Areas of future critical environments are designated as having a high geohazard potential and include uplands projected to become critical environments in 60 years. Areas designated as having moderate geohazard potential are uplands that are neither currently, nor are expected to become, critical environments during the next 60 years but are less than 1.5 meters in elevation causing them to be inundated during a tropical storm or category-one hurricane. Remaining upland areas have a low geohazard potential because of their elevation greater than 1.5 m NAVD88 and interior location to the island, making them overall less susceptible to geohazards. The distinction between moderate and low geohazard potential classifications is based on ground elevation. Areas below 1.5 m NAVD88 are more likely to be inundated by a 10- or 20-yr storm that has a theoretical storm surge elevation ranging from 1.34-1.91 m NAVD88 (Krecic et al., 2011). As a result, these areas are deemed more hazardous than areas above 1.5 m NAVD88.

5. Results

The total mapped area covers 97.1 sq. km. Close to 0.1% of the mapped area was assigned the extreme geohazard potential category, this includes historic washover locations at Newport Pass and Fish Pass. About 34.3% of the mapped area falls in the imminent geohazard potential category most of which is along the bay shoreline of Mustang Island, where the largest extent of wetlands is located, and the strip of beaches and foredunes on the Gulf side. The high geohazard potential category, which are areas projected to become imminent geohazard areas in 60 years, covers 12.3% of the mapped area, concentrated on the low-lying areas between Packery Channel and Fish Pass (Figure 2.1B) as well as a buffer landward of the beach and foredune system. About 26.6% of the mapped area falls in the moderate geohazard potential category, found mostly in the central area of Mustang Island. The remaining 26.8% of the mapped area was categorized as having a low geohazard potential and includes developed areas on North Padre and the northern end of Mustang Island, as well as undeveloped areas where the ground elevation is generally higher. Results are summarized by geohazard potential category in Table 2.1.

Table 2.1. Summary by geohazard potential category.

Geohazard potential category	Area (sq. km)	Percentage (%)
Extreme	0.1	0.1
Imminent	33.4	34.3
High	11.9	12.3
Moderate	25.8	26.6
Low	26	26.8
Total mapped areas	97.1	100

An interactive version of this geohazards map is available online at http://geohazards.tamucc.edu/. The interactive mapping tool, in addition to displaying geohazard areas, has the option to overlay different information including historic and projected shoreline-change rates, geo-environments, upland land-use classes, platted parcels, and a lidar-derived DEM. The goal of this tool is to present geohazards and coastal change information in one place and in the spatial context that planning decisions usually take place.

6. Discussion

Close to half of the mapped area is classified as current critical environments or future critical environments. In other words, an extent of ~45 sq. km is expected to be either inundated or transitioned into a different environment in 60 years if development does not obstruct the landward migration of wetlands, beaches, and dunes. This expectation of change not only has profound implications in terms of how the community will prepare and address the impending transformation of the barrier island landscape, but also highlights the magnitude of the situation. On the other hand, a little over half of the total mapped area is not expected to become a critical environment in 60 years and some sections are high enough to escape flooding from at least low-intensity storms. These areas are generally more stable and safer for urban development. However, we must emphasize that with the right storm or slight changes in future erosion, sedimentation, or RSLR rates, the vulnerability of relatively less hazardous areas can be adversely impacted. Overall, barrier islands are a hazardous place to develop.

With information such as the geohazards map, communities can start looking into strategies that will better help them preserve critical environments and adapt in the near future. For example, the state of Florida is currently encouraging the inclusion of "adaptation action areas" into local comprehensive plans (FDEO, 2013). These "adaptation areas" are an optional designation that local governments can use to highlight areas that are prone to experience coastal flooding and likely to be impacted by RSLR (FDEO, 2013). This designation prioritizes areas in need of adaptation planning and actions, such as protection, accommodation, or retreat. A similar designation, complementing the current OBA and DPA provisions, could stem from the Mustang and North Padre Islands geohazards map. The map could be used to identify areas likely to change, and therefore in need of an adaptation plan or strategy to provide hazards protection as well as future preservation of these environments.

Both geohazards maps for Galveston and South Padre Island have been used and incorporated in local planning activities and documents. The City of Galveston uses the map as background information to evaluate new development permits and support planning decisions in critical dune areas (within 1,000 feet from the mean high tide) on the west end of the island (D. Henry and C. Sanchez, pers. comm., June 2013). Moreover, the City of Galveston has cited the map in its recently adopted comprehensive plan as a primary reference to complement existing zoning regulations for the protection of beaches, dune, and bay wetlands, as well as to develop and implement an open space preservation program (HDR Engineering, 2011). The Galveston geohazards map has also been used in the preparation of the City's Hazard Mitigation Plan (City of Galveston, 2011). In addition, the South Padre Island geohazards map has been used to evaluate alternative beachfront development practices as part of the Cameron County Erosion Analysis report (Worsham and Ravella, 2013).

7. Conclusions

The geohazards map for Mustang and North Padre Islands is an accessible tool to inform planners, decision-makers, and the public about current and future geologic challenges and limitations of living on a barrier island. The geohazards map integrates information about geological processes and future spatial distribution of coastal environments to present a picture of how Mustang and North Padre Islands may look in the near future along with the associated hazards potential of different sections of the islands. Such a map provides valuable input to land-use planning activities that require site-specific information to identify areas and plan for their appropriate use or future conservation. Information about how the coastal landscape may evolve, in conjunction with sound regulations and policies, can effectively aid communities to lay out a tangible blueprint for future adaptation efforts.

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CHAPTER III

Assessment and monetary valuation of the storm protection function of beaches and foredunes

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Abstract

Beaches and dunes can dampen wave energy and protect against storm surge; however, this protection function is not uniform and varies according to geomorphic characteristics. Barrier island communities should identify these features and the protection afforded by them to better assess their vulnerability and manage these areas. This chapter presents a classification that identifies a theoretical level of protection that beaches and foredunes, in Mustang and North Padre Islands, Texas, could provide against overwash resulting from a tropical storm or hurricane along with a monetary valuation of this protective function at a site-level scale. The theoretical level of storm protection was determined by assessing the response of representative beach-dune profiles to a set of synthetic storms and identifying the storm level at which profiles are overwashed. A monetary value was assigned to the storm protection function of beach-dune profiles using a replacement cost approach. The level of protection afforded by beaches and foredunes varies across the islands, making some areas more vulnerable to overwash and inundation during lesser-intensity storms. About 50% of the assessed beach-dune profiles provide overwash protection against at least a 100-yr storm. Areas with the highest protection level (100- and 200-yr) share the following characteristics: (1) have high dunes (> 4 m); (2) are largely undeveloped, or buildings are at least 150-200 m landward of the line of vegetation; and (3) generally have a wider beach-foredune complex width. The total expected average annual value of the storm protection function of beaches and foredunes is estimated to be $141.4 million (replacement cost equivalent: USD 2013).

1. Introduction

Due to their geologic setting, barrier islands are exposed to the action of waves, tides, wind, storms, and changes in sea level. These natural processes and events have shaped barrier islands for thousands of years and only became hazardous when humans began to permanently occupy these coastal areas (Bush et al., 1996). Recent hurricanes and major storms have made landfall near barrier island communities, damaging infrastructure and buildings, as well as bringing about coastal change. The extent of the physical damage or change resulting from major storms varies depending on storm characteristics, local geomorphology, and vulnerability of the local built environment (Doran et al., 2009; Morton, 2002). During a storm, the presence or absence of protective natural features such as beaches and dunes can determine the fate of inland features and development (Houser et al., 2008; Stockdon et al., 2012). Beaches and dunes can dampen wave energy and protect against storm surge; however, these features can be eroded or overtopped, giving way to flooding, overwash, and in extreme cases, barrier breaching (Morton and Sallenger, 2003; Sallenger 2000; Sherman et al., 2013; Stockdon et al., 2012). The protection provided by beaches and dunes is not uniform and varies according to their geomorphic characteristics such as width and height (Houser et al 2008; Stockdon et al., 2012). Therefore, it is important for barrier island communities to identify these features and the protection afforded by them to better assess their vulnerability and manage these critical areas. Although the protective function of beaches and dunes has been recognized to be very valuable, it has rarely been estimated and represented in the monetary terms that planning and, sometimes, conservation decisions are usually based upon (Daily et al., 2009).

This chapter presents a classification that identifies a theoretical level of protection that beaches and foredunes could provide against overwash resulting from a tropical storm or hurricane along with a monetary valuation of this protective function at a site-level scale. This classification indicates the relative level of protection among profiles in Mustang and North Padre Islands, Texas and does not consider wind damage, the type of built or natural environment being protected, potential bay return flow, or alongshore sediment transport effects during a storm. Combined with information on priority areas for protection and restoration, this classification could help determine the location and scope for projects to mitigate future storm damage as well as serve to inform about costs and benefits of beach-foredune areas management alternatives.

A similar study, except for the monetary valuation section, has been conducted by the U.S. Geological Survey for the Gulf of Mexico as part of the National Assessment of Hurricane-Induced Coastal Erosion Hazards (Stockdon et al., 2012). The analysis is a storm-impact scale presenting the probability of three types of coastal change –collision, overwash, and inundation – in response to extreme conditions for category 1-5 hurricanes (Sallenger, 2000; Stockdon et al., 2012). Although both studies are similar in principle, this study differs in that it seeks to assess the response of the entire subaerial profile –from the seaward boundary of the beach to the landward edge of the foredune complex– using an empirical numerical model as opposed to comparing parameterized beach and storm characteristics to a conceptual model (Plant and Stockdon, 2012). In addition, our study focuses on lower-intensity storm conditions to evaluate the response of beaches and foredunes to less intense, but more frequent events.

2. Study Area

Mustang and North Padre Islands are microtidal (0.5 m), wave-dominated sandy barrier islands located on the central Texas coast, sheltering Corpus Christi Bay and the upper Laguna

Madre from the Gulf of Mexico (Hayes 1979; Morton 1994, 2010; TCOON, 2013; Figure 3.1). Both Mustang and North Padre are relatively wide (~2.6 km), high-profile, aggradational barrier islands with foredunes and secondary dunes, beaches, blowouts, and few washover channels (Morton and McGowen 1980; Simms et al., 2006). The foredune complex along the islands has an average width of 142 m (± 68) and dunes that are in average 3.4 m (± 0.6) high, with some exceeding 10 m NAVD88. In some sections, the foredune complex is a multi-ridge and swale system with 2-3 ridges. The dry beach along the islands has an average width of 31m (± 27) and an elevation of 0.9 m (± 0.1) NAVD88. There are 3 historic washover channels: Newport Pass and Fish Pass which are currently closed, and Packery Channel (formerly Corpus Christi Pass) which has been dredged and stabilized as of 2006 (Williams and Kraus, 2011). Newport Pass and Fish Pass are located in southern Mustang Island, while Packery Channel is the feature that separates Mustang from Padre Island.

The average return period for major hurricanes, category 3 and above, in the study area is 105 years (Keim and Muller, 2007). The islands have been spared from a direct storm hit since 1970 when Celia, a category-3 hurricane, made landfall just south of Port Aransas (McGowen et al., 1970). In 1980, Hurricane Allen made landfall ~120 km south of North Padre Island, but had a 2.6 m surge that severely damaged the seawall (Morton, 1988). More recently, the effects of other hurricanes hitting on or close to the Texas coast have not been severe, but certainly noticeable in the weeks after the storms. For instance, the surge and waves brought by Hurricane Ike (2008) temporarily inundated low-lying beach areas and scarped the seaward-most dune ridge along the islands.

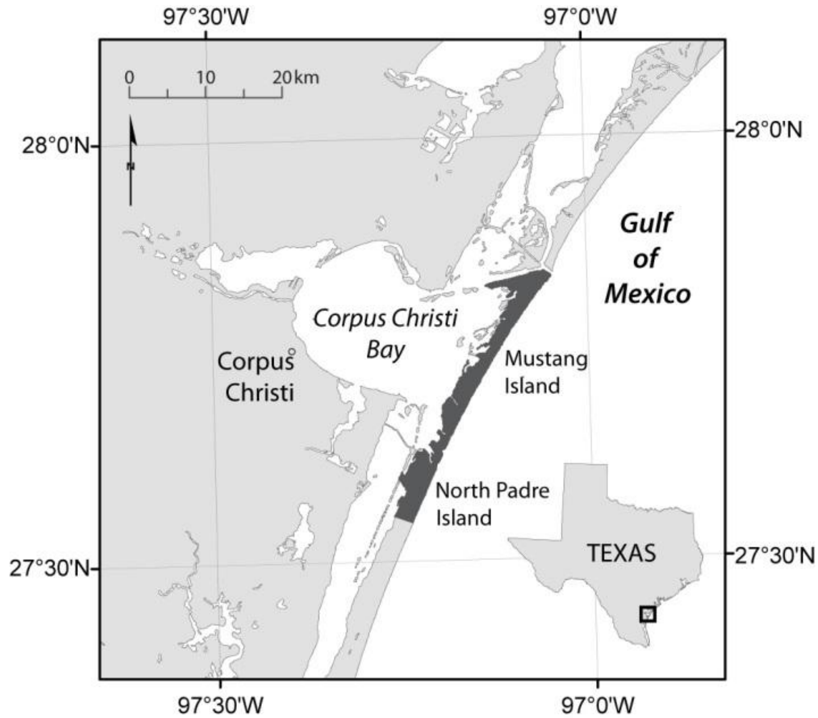

Figure 3.1. Location map of study area: Mustang and North Padre Islands, Texas.

3. Methods

Changes in the representative profiles resulting from a storm event were simulated using the SBEACH (Storm-induced BEAch CHange) model. SBEACH is a two-dimensional empirical model that simulates beach profile response to storm events in sandy beaches (Larson and Kraus, 1989). The theoretical level of storm protection was determined by assessing beach-dune profile changes after simulating a set of synthetic storms and identifying the storm level at which profiles are overwashed. Results of the assessment were extrapolated along the study area by matching representative pre-storm profiles to areas with similar beach-dune profile characteristics. A monetary value was assigned to the storm protection function of beach-dune profiles using a replacement cost approach.

3.1 Storm protection level assessment

3.1.1 SBEACH calibration

SBEACH is an empirical model designed to predict short-term beach and dune erosion resulting from storm events (Larson and Kraus, 1989). It is a two-dimensional model based on the assumption that profile change results from cross-shore processes and longshore wave, current, and sediment transport effects are not considered (Rosati et al, 1993). SBEACH uses cross-shore beach and dune profiles which are subjected to storm conditions defined by the user to produce a post-storm cross-shore profile. Initial profiles and storm characteristics can be derived from actual field measurements or synthetically created; whereas sediment transport parameters are derived from calibration of the model if actual pre- and post-storm data are available. SBEACH was selected because it has been used in local studies and other areas, extensive documentation is available, and it allowed for the modeling of multiple storms using our local computing resources.

In this study, SBEACH parameters were calibrated with beach profiles and storm data for Mustang and North Padre Island acquired for Hurricane Ike in September 2008. Even though Hurricane Ike did not make a direct hit on the study area, it still impacted local dunes and beaches with elevated water levels and increased wave energy. Hurricane Ike made landfall north of Galveston Island on September 13th as a upper-end Category 2 storm (Berg, 2009). Pre- and post-storm profiles for the study area were provided by the Conrad Blucher Institute's Packery Channel Monitoring Project (PCMP). Profiles were collected on September 5^{th} and 23^{rd}, 2008 about 8 km north and 5 km south of Packery Channel (Figure 3.). These profiles include topographic and bathymetric measurements. Six of these profiles were selected for calibration purposes.

Storm water levels were determined from primary water level measurements at the Bob Hall Pier tide gauge every six minutes starting on September 10th-15th. Local significant wave heights and period time series at a depth of 8.2 m NAVD88 were provided by Dr. Andrew Kennedy from the University of Notre Dame. Dr. Kennedy's group developed both wave heights and periods from a tightly-coupled, depth-averaged, SWAN+ADCIRC wave and circulation model using buoy measurements deployed during Hurricane Ike along the Texas coast (Bender et al., 2010).

Initial beach and sediment transport parameters used in the calibration process were taken from previous technical reports that used SBEACH to model beach and dune storm response in South Padre Island and Galveston Island, Texas (King, 2007; Krecic et al., 2011). A sensitivity analysis was conducted, and the chosen parameters combination had the smallest root mean squared error between the simulated and measured post-storm profiles. The resulting calibration parameters are close in range to the parameters from King (2007) and Krecic et al. (2011) (Table 3.1).

Table 3.1. Locally calibrated SBEACH parameters.

Parameter	Value
Transport rate coefficient	2.25 x 10-6 m4/N
Overwash parameter	0.005
Coefficient for slope-dependent term	0.002 m2/s
Transport rate decay coefficient multiplier	0.5
Max. slope prior to avalanching	30°
Landward surf zone depth	0.5m
Effective grain size	0.15 mm

3.1.2 Representative profiles

The Mustang and North Padre Island study area extends approximately 38 km. 732 cross-shore profiles were cast every 50 m alongshore starting at the local mean sea-level (MSL) contour extending to the landward edge of the foredune complex. Elevation points were extracted every 2 m along each profile from a 1-m resolution digital elevation model (DEM) covering beach and dune environments. The DEM was derived from lidar point data collected in 2010 by the Coastal Studies Group at The University of Texas at Austin Bureau of Economic Geology. The foredune complex in this study is defined as an area with stable, mostly vegetated sandy features located at the seaward boundary of the barrier island including coppice mounds, foredunes, and the foredune ridge. The average width of the beach-foredune complex is 190.6 m (±66.6 m). Profiles that intersected piers, jetties, and seawall were excluded. A cluster analysis was used as a data reduction method to select the representative profiles to be modeled in SBEACH. Cluster analysis sorts data into groups based on the degree of similarity and difference among observations (Wilks, 2006). De Souza Pereira et al. (2010) applied cluster analysis along with multidimensional scaling to a dataset of profile morphometric parameters to group beaches with similar morphodynamic characteristics at a regional scale. In this study, we selected a k-means clustering method using as input a data matrix with cross-shore elevation values as the input variables data (columns) from cast profiles (rows), similar to the approach described by Houser et al. (2008). To find the optimal number of clusters (k), we applied the Bayesian Information Criterion (BIC) adapted for the k-means problem by Pelleg and Moore (2000). The BIC is a scoring function commonly employed in model selection problems, such as linear regression, that provides a compromise between model complexity (number of parameters) and model fit (likelihood function). By increasing the number of parameters, a model's fit can be improved at the potential cost of overfitting. BIC addresses this problem by penalizing the model's likelihood function based on the number of parameters (in this case the k clusters).

The k-means algorithm is sensitive to the choice of initial cluster centroids. A Monte Carlo approach was applied in MATLAB to compute the BIC score for a range of k (e.g. 1 to 40 clusters) over several thousand replications. The k with the lowest average BIC score was then selected resulting in a k of 31. The cluster allocation that minimized the sum of the elevation points-to-centroid distance over the thousands of replications for k = 31 was selected. The centroid (mean) for each of the clusters is then considered a representative profile. All representative profiles were assigned the same mean bathymetry section derived from the 2008 PCMP pre-Ike survey data.

3.1.3 Synthetic storms

Storm conditions used in SBEACH simulations were synthetically created using wave and water level measurements collected during Hurricane Ike near Galveston Island, Texas – where it made landfall– as the reference. Eight different storms representing different return periods were created by scaling tide gauge and buoy measurements during Ike for primary water level, wave height, and peak wave period at a 6-minute time step. Measurements for the reference conditions were made by instruments located in the right-front quadrant area of the storm from September 11th - 14th, 2008. Primary water level measurements were collected by NOAA's tide gauge 87770570 in Sabine Pass; wave height measurements were collected by Kennedy Station Z buoy close to Sabine Pass; and peak wave periods were taken from a post-Ike STWAVE simulation at Kennedy Station Z (Bender et al., 2010). Eight reference time series curves were derived from the actual measurements, making each point a percentage of the maximum measured value. The percentage curves were then multiplied by maximum values for each storm return period and smoothed using a mixture of Gaussians curve fitting algorithm within MATLAB. All maximum synthetic values for water level, wave height, and wave period curves were taken from Krecic et al. (2011); except for the 200-year storm, which was calculated as an extrapolation from these values. The eight synthetic storms with return periods of 1, 2, 5, 10, 20, 50, 100, and 200 years were used to represent a wide range of conditions. All synthetic storms were designed to have a duration of 72 hours (Figure 3.2).

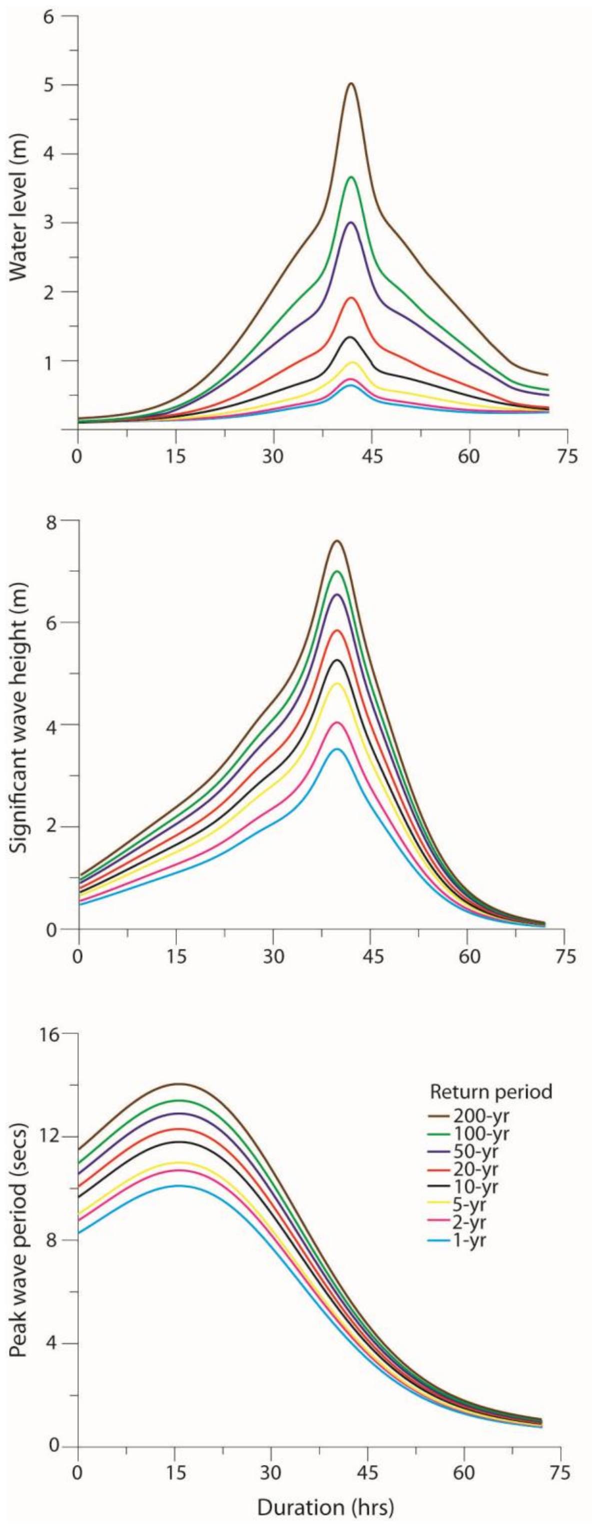

Figure 3.2. Synthetic storms water level, significant wave height, and peak wave period hydrographs.

3.1.4 Level of protection provided by beach-dune environments

The theoretical level of storm protection was determined using a quantitative assessment of the beach-dune representative profile change after simulating the set of synthetic storms. The goal was to identify the storm level at which the profiles are overwashed. Using SBEACH simulation outputs, we focused on the maximum water depth value reached during the simulation along the profile. A beach-dune representative profile is considered to have been overwashed, and thus not offering protection, if the maximum water depth hydrograph indicates that water was present landward of mean beach-foredune complex width of that representative profile's cluster during the simulation. The level of protection for each representative profile is then assigned to all of the on-the-ground profiles that belong to the same cluster.

3.1.5 Results from protection level assessment

The 31 modeled representative profiles were found to withstand a 5-, 20-, 50-, 100-, or 200-yr storm or less before being overwashed. One representative profile was assessed as protective against a 5-yr storm or less, 3 were protective against a 20-yr storm or less, 8 were protective against a 50-yr storm or less; 13 were protective against a 100-yr storm or less, and 6 were protective against a 200-yr storm or less (Table 3.2; Figure 3.3).

Table 3.2. Level of protection assessment results.

Level of protection (return period years)	**Representative profiles (number)**	**Cast profiles (number)**	**Percentage (%)**
5	1	19	2.6
20	3	137	18.7
50	8	210	28.7
100	13	294	40.2
200	6	72	9.8
Total	31	732	100

Different representative profile characteristics including maximum foredune crest elevation, beach-foredune complex width, cross-sectional area, and location of center of mass, were analyzed to evaluate their influence on the assessed level of protection derived from SBEACH simulation results. First, a correlation matrix was produced to identify correlations among the four representative profile characteristics. The least correlated pair was maximum foredune crest elevation and beach-foredune complex width (R=0.32). Next, ordinal logistic regression (OLR) models were used to evaluate the influence of this pair of representative profile characteristics on the assessed level of protection. OLR models were selected because the response variable (level of protection) is an ordinal categorical variable with five ($r=5$) response levels (5-, 20-, 50-, 100-, and 200-yr) (Long and Freese, 2006). An ORL estimates the cumulative probability of observations being at a response level or below, with levels modeled by $r-1$ logistic curves (PSDS, 2014; SAS, 2014). Maximum foredune crest elevation and beach-foredune complex were used as the independent variables and the assessed level of protection was the dependent (response) variable in all three models:

(1) *Level of protection* = $b_0 + b_1$ * *Beach-foredune complex width*
(2) *Level of protection* = $b_0 + b_1$ * *Maximum foredune crest elevation*
(3) *Level of protection* = $b_0 + b_1$ * *Maximum foredune crest elevation* + b_2 * *Beach-foredune complex width*

Performance of the ORL models was evaluated by comparing McFadden's R^2 (a linear regression R^2 analog) and BIC scores amongst models (Wilks, 2006; Williams, 2013a). The McFadden's R^2 ratio indicates the reduction in deviance by the model that includes independent variables as predictors ($b_1 x_1 \ldots b_n x_n$) over a model that only includes the intercept term (b_0) (Williams, 2013b). A considerable improvement in performance is seen in the model that includes maximum foredune crest elevation as a predictor compared to the one with only the beach-foredune complex width. The MacFadden's R^2 increases from 0.0976 to 0.5669, while the BIC scores decrease from 93.74 to 53.92 (Table 3.3). The lower the BIC score for a model, the better a model fits the observed data (Wilks, 2006; Williams, 2013a). Further improvement is observed when including both profile characteristics in the model (3); however, the improvement is not as dramatic compared to going from model (1) to (2) (Table 3.3). Therefore, it can be concluded that maximum foredune crest elevation better explains the variation in level of protection (based on SBEACH simulation results) among representative profiles than the beach-foredune complex width.

Table 3.3. OLR models performance measures.

Performance measure	Model (1)	Model (2)	Model (3)
McFadden's R^2	0.0976	0.5669	0.6511
BIC Score	93.74	53.92	50.21

Generally, profiles with higher foredune crest elevations have a higher protection level irrespective of the beach-foredune complex width (Figure 3.4). However, profiles with similar dune crest elevation can have different protection levels depending on their beach-foredune complex width – a profile with a wider beach-foredune complex will have a higher protection level. There was only an instance of a pair of profiles, both close in dimensions and classified as 100-yr protection level, that have slightly lower or equal dune crests elevations and narrower beach-foredune complex widths than another pair of profiles classified as 50-yr protection level. This discrepancy may stem from the fact that in the profiles with higher protection, more sand is distributed, or the centers of mass are, closer to the shoreline (Figure 3.5). Beach-foredune complex width is highly correlated (R^2=0.8) with the location of the maximum foredune crest elevation along the profile; suggesting that in long profiles, high dunes are located further inland than in short profiles.

Out of all 732 cast profiles, about 2.6% were deemed as protective against a 5-yr storm or less, 18.7% were protective against a 20-yr storm or less, 28.7% were protective against a 50-yr storm or less, 40.2% were protective against a 100-yr storm or less, and 9.8% were protective against a 200-yr storm or less (Table 3.2). The different levels of protection are interspersed along Mustang and North Padre Islands (Figure 3.6). Profiles with lowest level of protection were located at the throat of the Newport Pass historic washover channel, in front of the Lost Colony subdivision, at the entrance of access roads, and in areas where the beach was wide but dunes were low (< 2 m) or absent. In contrast, profiles with the highest level of protection were found in areas with high dunes (> 4 m) and that are undeveloped, or where buildings are at least 150-200 m landward of the line of vegetation. A random sample of 31 on-the-ground profiles was modeled on SBEACH to test the accuracy of the profile protection level classification based on the modeled response of their cluster's representative profiles. Only 6.5% (2) of the sample profiles were found to overestimate the level of protection compared to the storm response of their cluster representative profile. In both cases, the overestimation was of one protection level; the sample profiles indicated a 50-yr storm protection level while the representative profile had a 100-yr storm protection level.

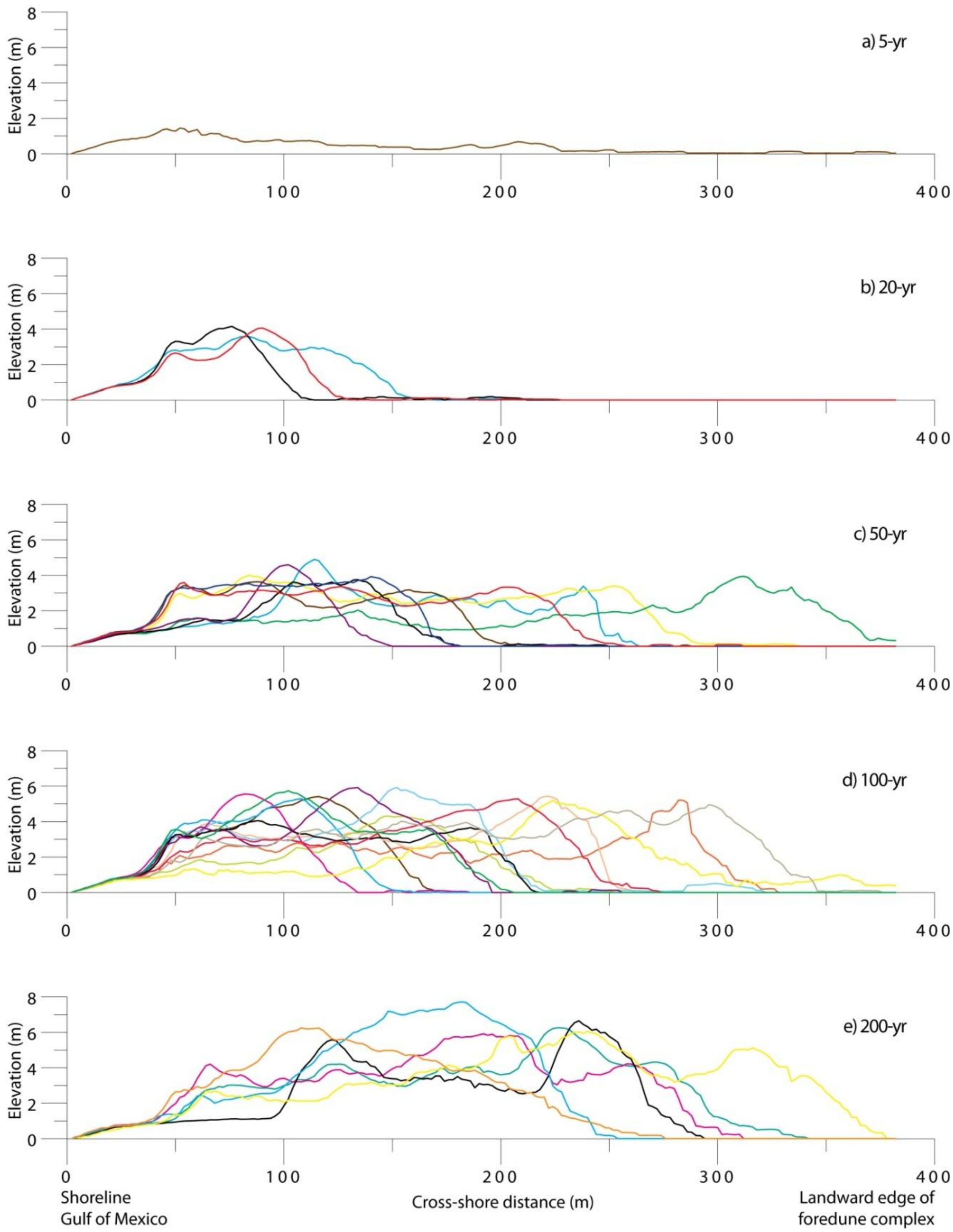

Figure 3.3. Representative profiles grouped by level of protection: a) 5-yr, b) 20-yr, c) 50-yr, d) 100-yr, and e) 200-yr.

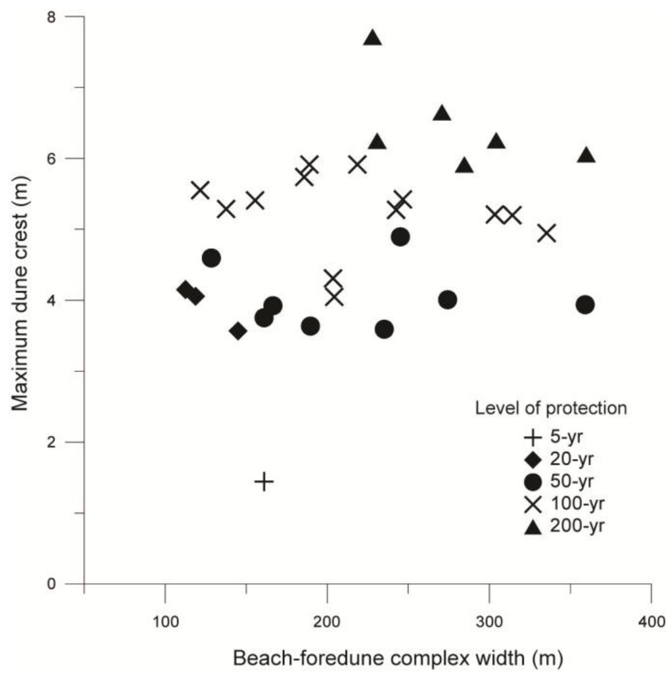

Figure 3.4. Scatter-plot of beach-foredune complex width and maximum foredune dune crest elevation for representative profiles by level of protection.

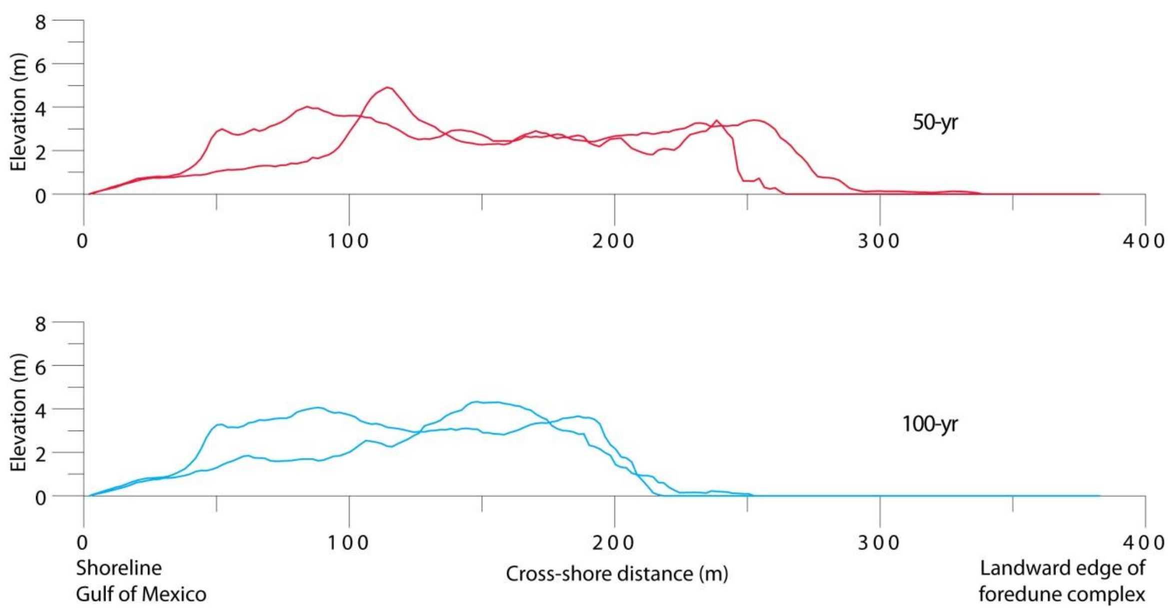

Figure 3.5. Comparison of representative profiles with 50-yr and 100-yr protection levels. In this case, more sand is distributed closer to the shoreline in the profiles with a higher level of protection.

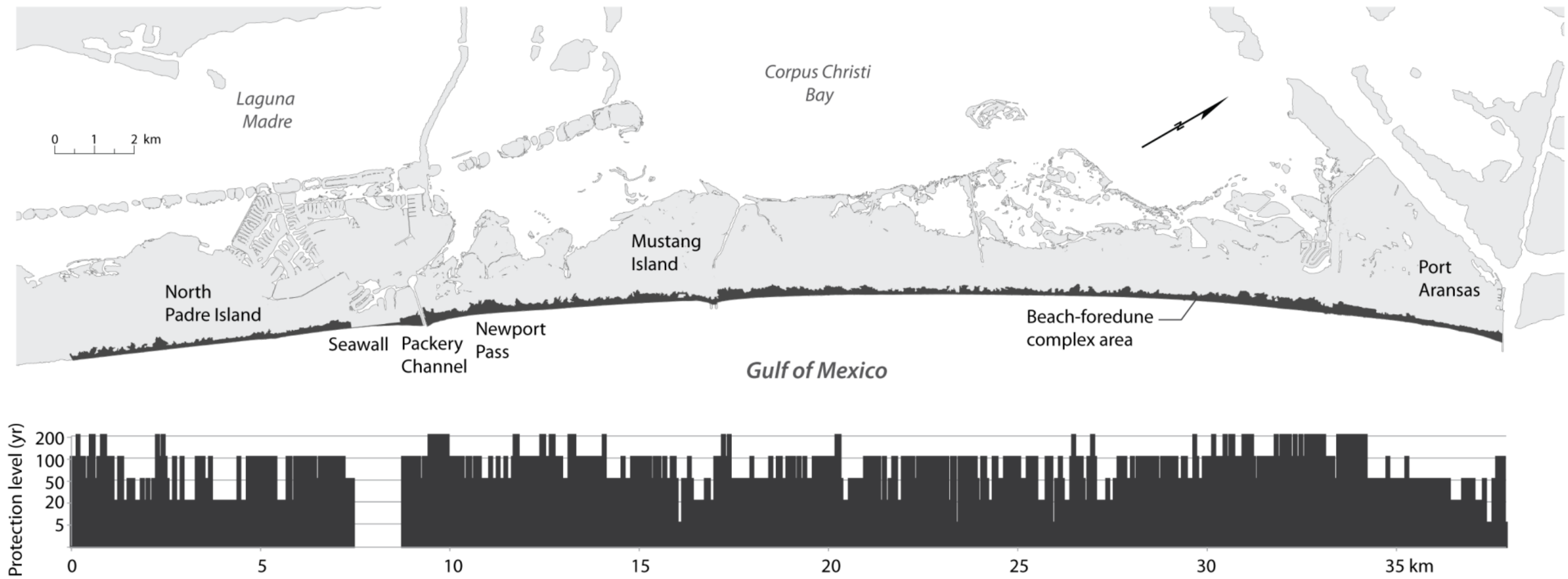

Figure 3.6. Assesed levels of protection provided by beach-dune profiles along Mustang and North Padre Islands.

3.2 Valuation of storm protection function

Many of the services provided by beaches and dunes, such as recreation, storm protection, and aesthetics, are not traded and therefore not valued in the market (Pendleton et al., 2007). To capture an approximate monetary value of these ecosystem goods and services, different non-market valuation methods are used such as revealed-preference methods (travel cost, hedonic methods), stated-preference methods (contingent valuation), and cost-based methods (replacement cost, avoided cost) (Farber et al. 2006). In this study, we selected a replacement cost approach to value the storm protection ecosystem service, also referred to as disturbance regulation, provided by beaches and foredunes. The replacement cost method assumes that the cost of an alternative option that replaces an ecosystem or service can be used as an approximation of its value (King and Mazzotta, 2000). We propose estimating the monetary value of Mustang and North Padre's beaches and foredunes storm protection service by linking it to the construction cost of a concrete seawall that would provide a similar level of protection as the "replaced" beach-dune profiles. A seawall is a vertical protective structure intended to prevent or minimize wave overtopping and inland flooding by acting as a barrier against elevated water levels and large waves during major storms (Kraus and McDougal, 1996). The replacement cost approach was deemed appropriate in this case because it reflects a monetary value that is closely linked to the protective function resulting from the beaches and foredunes' morphology.

Some authors (Heal, 2000; King and Mazzotta 2000) have pointed out that replacement cost is an imperfect estimation of economic value and it is most useful in cases where there is, has been, or will be an interest in paying the cost to replace the ecosystem or service. Current Texas legislature prohibits the maintenance, repair, or construction of protection structures by private individuals or groups within 200 ft (~61 m) landward of the line of vegetation, but it does not prevent state or federal entities from doing so (TAC Title 31.1.15A Rule 15.6, 2010; TNRC Sec. 61.013, 1991; Sec. 61.022, 2009). Moreover, there has been a 1.3-km long seawall on North Padre Island for more than 30 years. Therefore, we find the replacement cost approach applicable to our study, as seawalls have been or could be used as a coastal defense strategy in the future.

Estimations of the storm protection value of coastal ecosystems, including wetlands, beaches, and dunes, can be found in the literature (Brenner et al., 2010; Feagin et al. 2010; King and Lester, 1995). Most of these estimates, however, have been presented as generalized values over large areas; thus assigning a uniform ecosystem service value to an entire ecosystem type. Studies using the replacement cost valuation usually interpret this monetary value as savings in shoreline and storm protection construction costs that would be, otherwise, incurred if the ecosystem or service was not available (King and Lester, 1995; Mangi et al., 2011). No previous study valuing the storm protection function of beaches and foredunes using the replacement cost method was found for the Texas Gulf coast.

The value of the storm protection function of beach-dune profiles was estimated by calculating an expected average annual storm protection value as adapted from the U.S. Army Corps of Engineers' methodology to calculate expected average annual damages from floods (Beard, 1997). This method has also been adapted to calculate savings in storm-induced damage costs due to beach nourishment projects (Krecic et al., 2011). In this study, the expected average annual storm protection value represents the benefits–or savings–provided by beaches and foredunes in terms of coastal protection replacement costs per year. The value is cumulative because it accounts for benefits derived from the full range of storms a particular beach-dune profile protects against. For instance, a beach-dune profile providing 100-yr storm protection would also be protective against 1-, 2-, 5, 10-, 20-, and 50-yr storms during the same year; assuming that only one storm would make landfall any given year. Construction (replacement) costs were calculated for seawalls designs providing protection for 10-, 50-, and 100-yr storms. The general structure design includes a concrete vertical wall anchored by driven piles, supported by counterfort wall braces (only for 50- and 100-yr designs), and sheet pile scour protection (Figure 3.7). The sole purpose of the structure is to mimic the storm-surge protection provided by a beach-dune profile to inland locations; no aesthetics or recreational aspects are taken into account. The seawall designs consider the following: (1) the structure does not prevent overtopping, but limits wave transmission to below 1.5 ft (0.45 m), which is the limit between FEMA's A and AE zones, now referred as the Limit of Moderate Wave Action (LiMWA) (FEMA, 2008); (2) flooding from the bay side of the islands is anticipated; and (3) fill material was not incorporated into the design to avoid confusion with a dune restoration replacement cost approach. Cost estimation for the three seawall designs incorporate variable (mobilization, earthwork and compaction, and structural elements) and fixed (engineering, geotechnical, administration, and contingency) construction costs for structures that are 50-m long. The construction cost for structures protecting against 1-, 2-, 5-, and 20-yr storms was estimated by interpolating values from a power function fitted to the designed seawalls costs. Whereas the construction cost value for a structure protecting against a 200-yr was extrapolated from the same power function.

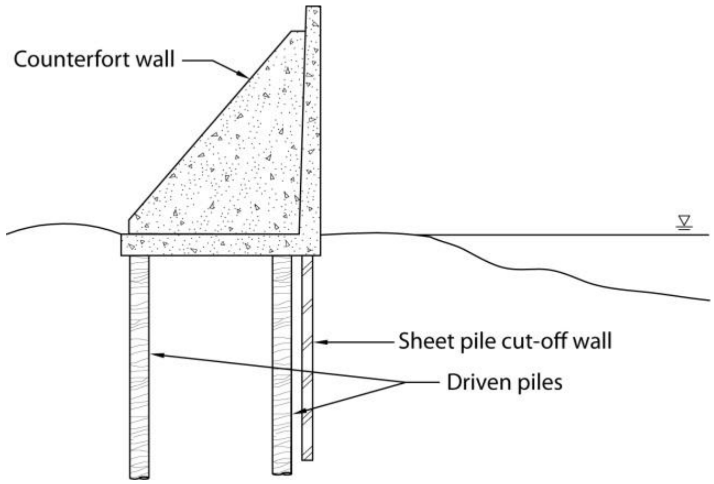

Figure 3.7. General structural design for seawalls.

The expected average annual protection value (replacement cost equivalent) for a profile is calculated as the area under a replacement cost-cumulative probability curve, up to assessed level of protection for the analyzed profile (trapezoidal approximation, Figure 3.8). The x-axis denotes the cumulative probability of cost occurrence for events greater than a 1-yr storm event, and the y-axis indicates the seawall construction costs (or replacement costs). The expected average annual protection value (replacement cost equivalent) of \$65,013 (2013 USD) for a profile that provides a 2-yr storm protection is derived from the area under the curve starting from 0 (cumulative probability of cost occurrence for a 1-yr storm, 1 – 1 = 0) to 0.5 (2-yr storm, 1 – 0.5 = 0.5) on the x-axis and from \$107,587 (seawall cost 1-yr design, baseline) to \$152,465 (2-yr design) on the y-axis. The area under the curve for a profile providing a 200-yr storm protection is \$209,644. This area is calculated from 0 (cumulative probability of cost occurrence for a 1-yr storm, 1 – 1 = 0) to 0.995 (200-yr storm, 1 - .005= 0.995) on the x-axis and from \$107,587 (seawall cost 1-yr design, baseline) to \$1,765,172 (200-yr design) on the y-axis.

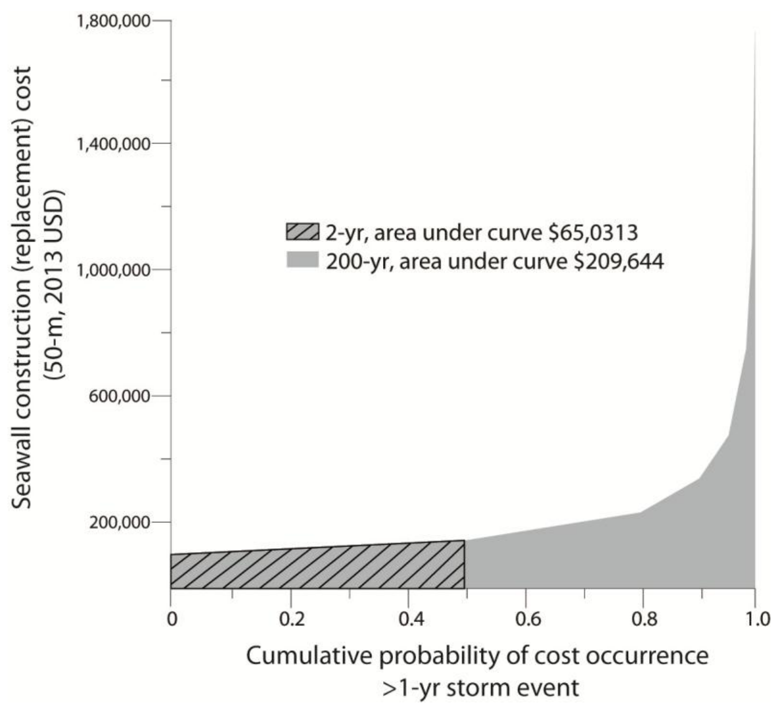

Figure 3.8. Replacement cost-cumulative probability curve.

The previous expected average annual storm protection value (replacement cost equivalent) calculation can also be represented in a tabular form (Table 3.4). The expected average annual storm protection value (replacement cost equivalent) of profile is the product of multiplying the average seawall construction costs of contiguous levels of protection by the probability interval between cumulative probabilities of cost occurrence for the same contiguous levels, and then adding these values for each interval up to the level of protection provided by the profile (Krecic et al., 2011). Marginal cost calculations show the increase in construction costs, or storm protection value, of going up a level of protection. The expected average annual storm protection value was spatially represented as a raster grid that covers the mapped beach-foredune complex area along Mustang and North Padre Islands. A 25-m buffer was created around each of the cast profiles. These features were rasterized and the resulting raster grid was reclassified by assigning the monetary value to cells according to the protection level of the corresponding representative profile. The expected average annual storm protection value (replacement cost equivalent) is assigned to every 50-m section (Figure 3.9).

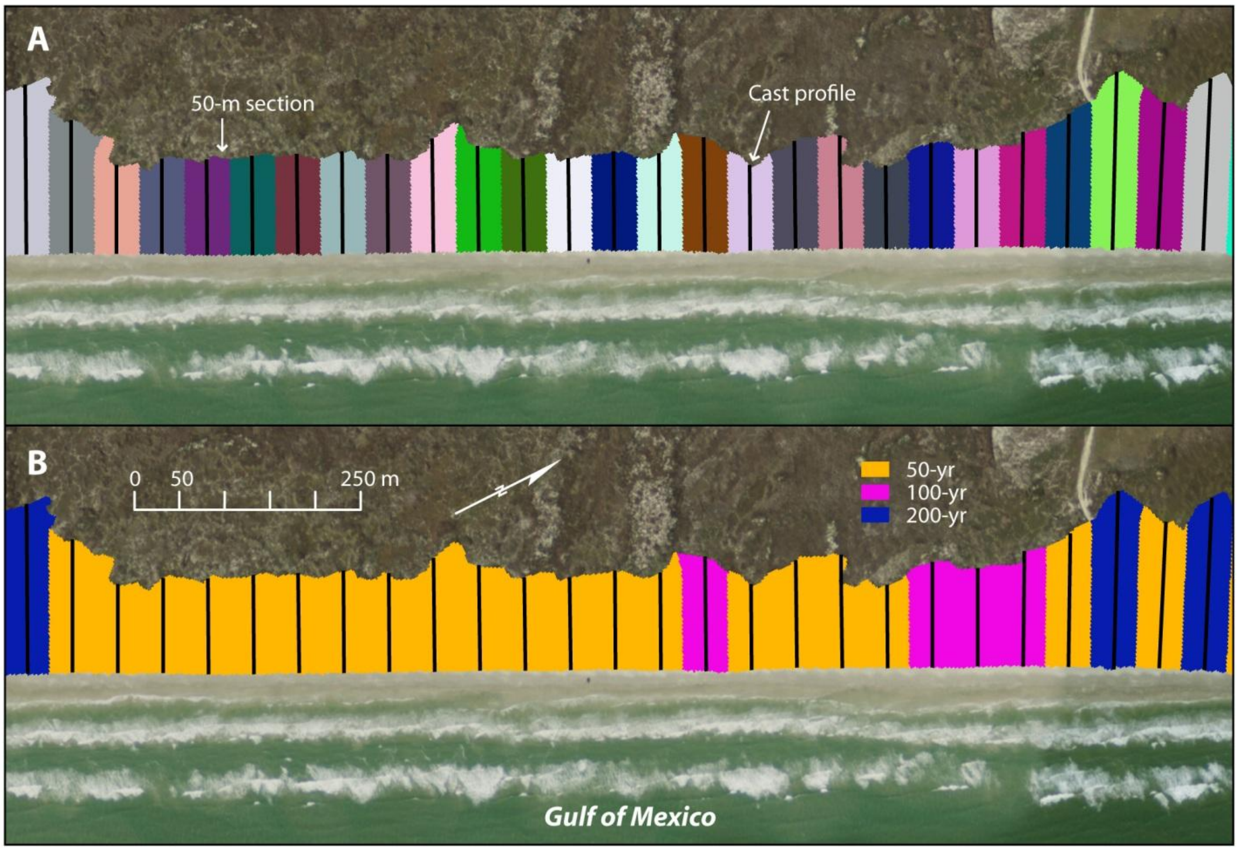

Figure 3.9. Spatial representation of expected average annual storm protection value, area located in North Padre Island. A) 50-m sections from cast profiles; and B) 50-m sections classified according to profiles' protection levels.

Table 3.4. Expected average annual protection value (replacement cost equivalent) calculation for a 50-m section at the 200-yr storm protection level (Based on Krecic et al., 2011).

Return period (years)	Annual occurrence probability	Seawall cost (50-m wall: 2013 USD)	Marginal seawall cost (50-m wall: 2013 USD)	Average seawall cost (2013 USD)	Cumulative probability of cost occurrence > 1-yr storm event	Interval probability	Expected average annual storm protection value - interval (replacement cost equivalent: 2013 USD)	Annual marginal expected protection storm value (replacement cost equivalent: 2013 USD)
1	1	107,587	-	-	-	-	-	-
2	0.5	152,465	44,878	130,026	0.5	0.5	65,013	22,439
5	0.2	241,725	89,260	197,095	0.8	0.3	59,129	26,778
10	0.1	348,853	107,128	295,289	0.9	0.1	29,529	10,713
20	0.05	485,446	136,593	417,150	0.95	0.05	20,857	6,830
50	0.02	760,338	274,892	622,892	0.98	0.03	18,687	8,247
100	0.01	1,095,283	334,945	927,811	0.99	0.01	9,278	3,349
200	0.005	1,765,172	669,889	1,430,228	0.995	0.005	7,151	3,349
				Expected average annual storm protection value (2013 USD)			**209,644**	

3.2.1 Results from storm protection function valuation

The total mapped beach-foredune complex area is 6.89 sq. km and provides close to $141.4 million (USD 2013) per year in storm protection services (savings in seawall construction cost equivalent). About 14.4% of this area was classified as protective against a 200-yr storm with an annual storm protection value of $15.1 million/yr, 41.3% against a 100-yr storm with a value of $59.5 million/yr, 29.8% against a 50-yr storm with a value of $40.6 million/yr, 12.2% against a 20-yr storm with a value of $23.9 million/yr, and 2.3% against a 10-yr storm with a value of $2.3 million/yr (Table 3.5).

Table 3.5. Total value (replacement cost equivalent) of the storm protection function of beaches and foredunes in Mustang and North Padre Islands, Texas.

Protection level (return period years)	Cast profiles (number)	Expected average annual protection value per profile (replacement cost equivalent: 2013 USD)	Storm protection value (replacement cost equivalent: 2013 USD)	Area (sq. km)	Percentage area (%)
5	19	124,142	2,358,698	0.16	2.3
20	137	174,528	23,910,336	0.84	12.2
50	210	193,215	40,575,150	2.06	29.8
100	294	202,493	59,532,942	2.85	41.3
200	72	209,644	15,094,368	0.99	14.4
Total	732		141,471,494	6.89	100

4. Discussion

The level of protection against overwash provided by beach-dune profiles appears to be primarily determined by the maximum foredune crest elevation, agreeing with findings from previous studies –higher dunes are more protective than lower dunes (Sallenger 2000; Houser et al. 2008; Stockdon et al., 2012). Although the profile's beach-foredune complex width by itself is not indicative of the level of protection, it can be assumed that generally a wider beach-foredune complex enhances protection against overwash. It has been shown that the inclusion of beach and foredune widths improves predictions of morphologic response to storms (Plant and Stockdon, 2012; Starek et al., 2012).

About 50% of the profiles along Mustang and North Padre Islands were assessed as providing protection against at least a 100-yr storm. This can be attributed to the presence of relatively high dunes, a multi-ridge foredune complex, and the mostly undeveloped landscape of both islands with few structures encroaching upon foredunes and beaches. The fact that beach-dune profiles providing the highest protection are in mostly undeveloped areas or where buildings are at least 150-200 m landward of the line of vegetation supports current state and county dune protection regulations requirements that seek to preserve these valuable geomorphic features. The Dune Protection Act requires a permit for activities that may damage, destroy, or remove sand dunes or vegetation covering them from areas within 1,000 ft (~300 m) from the mean high tide mark (TNRC Sec. 63.012, 1977; Sec. 63.091, 1991). In addition, the recently adopted Joint Erosion Plan for Nueces County and the City of Corpus Christi restricts new development landward of 200-350 ft (~ 60-100 m) from the line of vegetation (Nueces County and City of Corpus Christi, 2012).

The data reduction approach (clustering) used in this study has both advantages and disadvantages. The k-means clustering technique allowed us to identify representative profiles (cluster centroids) by sorting cast profiles into clusters with similar geometries and cross-shore elevations, and then assign the protection level of representative profiles back to on-the-ground profiles that belong to the same cluster. A shortcoming of this approach is the inherent variability within clusters, which can result in over- or underestimation of the washover protection level as the storm response of profiles grouped into the same cluster may vary. Depending on the objective of the analysis, over- or underestimation of the level of protection can be problematic.

In the case of this study, underestimation is less of a concern than overestimation, as we would like to minimize the risk of communicating higher levels of protection that may give a false sense of security. Our accuracy test shows that the classification approach used here is more likely to match or underestimate the protection level of a profile in reference to its cluster's representative profile than to overestimate it.

Finally, the storm protection function of beaches and foredunes was valued using a replacement cost method. The construction cost of a concrete seawall that would provide a similar level of protection as the "replaced" beach-dune profiles was used as a proxy for the value of their storm protection services. The total area mapped as beaches and foredunes in Mustang and North Padre Islands covers 6.89 sq. km and provides close to \$141.4 million/yr (replacement cost equivalent: USD 2013) in storm protection services. In other words, beaches and foredunes in this section of the Texas coast could produce savings of ~\$141.4 million annually in seawall construction expenditures. Our exercise shows that beaches and foredunes are valuable because they have the potential to protect inland areas from overwash and flooding; however, this monetary figure does not reflect the value of recreation, aesthetics, and sediment dynamics functions inherent to these geo-environments. Therefore, it is safe to assume that the overall of value of the ecosystem services provided by beaches and foredunes is significantly higher than the value presented in this study. It must be noted that demand for this storm protection service will most likely only come about if buildings and infrastructure are placed behind beaches and foredunes.

5. Conclusions

Beaches and foredunes in Mustang and North Padre Islands provide protection against surge and wave action resulting from storms. The level of protection afforded by these features varies across the islands, making some areas more vulnerable to overwash and inundation during lesser-intensity storms. About 50% of the assessed beach-dune profiles provide overwash protection against at least a 100-yr storm. Areas with the highest protection level (100- and 200-yr) share the following characteristics: (1) have high dunes (> 4 m); (2) are largely undeveloped, or buildings are at least 150-200 m landward of the line of vegetation; and (3) generally have a wider beach-foredune complex width. The total expected average annual value of the storm protection function of beaches and foredunes is estimated to be $141.4 million (replacement cost equivalent: USD 2013). The findings in this study highlight the importance of preserving and restoring beaches and dunes as barrier island communities benefit from their protective services. In the light of recent sea-level rise predictions, it is critical to plan for beaches and dunes to migrate inland and avoid losing them to coastal squeeze (Anderson et al., 2010; IPCC, 2013; Overpeck and Weiss, 2009). When beaches and dunes are lost, we not only lose coastal landforms, but also the services that they provide.

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CHAPTER IV

Transfer of development rights as a tool to increase resilience of urban development on Texas barrier island communities

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Abstract

Resilience, in the context of coastal communities, has to do with the ability of a community to remain functional and prosperous after a storm hits or environmental conditions change. Current development pressure is eroding away barrier island communities' resilience by increasingly exposing more people, property and infrastructure to coastal hazards. Although coastal development seems inevitable, communities can increase their resilience by restricting current development and guiding future growth away from the most hazardous and vulnerable areas through land-use planning. This chapter explores the idea of a transfer of development rights (TDR) program as a land-use policy tool to increase resilience of Mustang and North Padre Islands, Texas through preservation of current and future critical environments locations and guidance of future urban growth towards safer and more stable areas on the islands. A TDR program is a land policy instrument whereby a market is created for the trading and transferring of severed development rights from sending to receiving areas, thus transferring the right to build or develop from one location to another. Through a land suitability analysis to determine TDR sending and receiving areas, including spatial information regarding the response of barrier island environments to future relative sea-level rise, coastal storm flooding, and future land use maps, it was found that 26% of the study area is suitable to receive more and higher density development, 23% of the area should be left undeveloped or planned for lower density development, and parks, public spaces, and land indicated for preservation cover about 51% of the study area. The analysis of current state and federal regulations that affect coastal development shows that present regulations and policies offer only limited protection to present and future locations of critical barrier island environments, with beaches and dunes areas receiving the most protection compared to bay-margin wetlands; therefore, a TDR program

could serve as complementary policy. TDR programs are often referred to as a way to provide compensation to affected property owners in sending areas and increase the chances of avoiding a regulatory takings claim. Yet, TDR programs can be challenged as there is no clear-cut legal guidance on how to consider TDRs in a takings assessment. A TDR program may be a sensible land-use policy tool capable of addressing the realities of a dynamic coastal environment and balancing, to a certain extent, private and public interests. However, aside from the administrative complexity of managing such a program, its implementation usually poses economic and regulatory challenges that some barrier island communities may not be ready to undertake.

1. Introduction

Following the economic, social, and environmental losses that have occurred after recent storms, there has been a surge of interest in the subject of resilience. This interest has become even more heightened in light of the predicted effects of climate change on storms, sea-level rise (SLR), and increasing coastal population. Resilience refers to ability of a system to persist, reorganize itself, or rebound after a disturbance (Walker et al., 2002). In the context of coastal communities, resilience has to do with the ability of a community to remain functional and prosperous after a storm hits or environmental conditions change (Cone and Brown, 2011). Unfortunately, current development pressure is eroding away barrier island communities' resilience by increasingly exposing more people, property and infrastructure to coastal hazards, and exacerbating habitat loss and environmental degradation; thus, making barrier island communities more vulnerable in all fronts. Although coastal development seems inevitable, communities can increase their resilience by restricting current development and guiding future growth away from the most hazardous and vulnerable areas through land-use planning (Burby

1998; Jacob and Pacello, 2011). In the case of barrier islands, where the entire island is prone to hazards, what gets built, where it is built and how, can make a difference in the recovery after a storm or adaptation to SLR (Bush et al., 1996). The responsibility of regulating land-use falls under the jurisdiction of state and local governments, which can enact regulations that promote and enhance the resilience of coastal communities. However, even when these regulations intend to advance the public's health, safety, and welfare, they are often met with resistance and sometimes are challenged in court as regulatory takings. As a result, local and state governments are left to find feasible, equitable, and yet legally defendable solutions that balance private and public interests.

This chapter explores the idea of a transfer of development rights (TDR) program as a land-use policy tool to increase resilience of Texas barrier island communities through preservation of current and future critical environments locations and guidance of future urban growth towards safer and more stable areas on the islands. Besides being a policy tool that can target multiple objectives at once, TDR programs are attractive because they can create a monetary incentive for preservation of environmentally sensitive areas while providing a compensation mechanism for impacted landowners. Thus, allowing local governments to use the market to fund land preservation and drive future development. TDR programs are complex policy instruments composed of planning, legal, administrative, and financial elements, such as specific rezoning ordinances, conservation easements, creation of TDR banks and assessment of TDR credits among others (Barrows and Prenguber, 1975; Pruetz and Standridge, 2009; Hanly-Forde et al., n.d.). Therefore, the scope of this chapter will be limited to identifying sending and receiving areas for North Padre and Mustang Islands, Texas and analyzing current regulations that affect coastal development and the implementation of a TDR program.

2. TDR and its applications

2.1 TDR concept

A transfer of development rights program is a land policy instrument whereby a market is created for the trading and transferring of development rights (Grannis, 2011; Kaplowitz et al., 2008). Property owners in a sending area can sever the development rights of their land and sell them to others for use in receiving areas, thus transferring the right to build or develop from one location to another. Generally, sending and receiving areas are designated through zoning overlays following the objective of the TDR program (Nelson et al., 2012). The property owner of the sending area retains all of the remaining property rights in addition to the private ownership of the land. Development rights are treated as a tradable commodity; landowners in sending areas are entitled to monetary compensation that results from selling these rights (Nelson et al., 2012). Once the development rights are transferred, a conservation easement is placed on the sending area in perpetuity. Developers may buy these available TDRs and apply them in receiving zones to increase density, lot coverage, or get exemptions from building permit quotas (Nelson et al., 2012). The main purpose of a TDR program is to redirect development from one area to another where it is preferred by using market incentives to finance such a redistribution of building/development potential. TDR programs also address some of the issues present in traditional zoning, such as inflexibility, case-by-case determinations, lack of compensation for affected landowners, and uneven economic and development impacts across the community (Miller, 1999; Nelson et al., 2012).

TDR programs are enabled through local or state legislation (Nelson et al., 2012). Sending and receiving areas are designated and documented in comprehensive plans. Some communities choose to establish a TDR bank to facilitate buying, holding, and selling of development rights (Pruetz and Standridge, 2009). The process of transferring the rights can be conducted by a local planning agency or TDR bank. TDR programs have been successfully used in the U.S. to preserve open space (King County, Washington), farmland (New Jersey Pinelands), historic structures (New York City), and environmentally sensitive areas (Tahoe Regional Planning Agency, California and Nevada) (Nelson et al., 2012). As with other tools, TDR programs have advantages and shortcomings. Some of the advantages include: (1) compensation to owners in sending areas; (2) easier implementation than other zoning regulations; (3) the use of private funding for preservation of land; (4) predictability of development; and (5) greater permanence than zoning regulations (Hanly-Forde et al., n.d.; Nelson et al., 2012). Shortcomings of TDR programs are: (1) the amount of planning, administration, and oversight required; (2) the need of intensive public outreach and education; and (3) future inflexibility of the preserved land (Bailey and Ogg, 1977; Hanly-Forde et al., n.d.).

2.2 Components of successful TDR programs

Pruetz and Standridge (2009) conducted a literature review in search of the most important components of successful TDR programs. Their findings point at TDR demand and viable receiving areas as essential for success. Developers should be interested in seeking this bonus density or benefits offered through TDRs. In addition, receiving areas should be attractive and able to accommodate incoming growth without much opposition from adjacent areas. Strong sending areas designations, few alternatives to bypass TDR requirements in receiving areas, and an efficient pricing market are listed as very important success factors. Lastly, other helpful components include certainty for developers, community support for preservation, simplicity of TDR program, outreach and education, and TDR banks.

2.3 Takings and TDRs

Government agencies have the duty to protect public health, morals, safety, and welfare. Sometimes, this entails imposing regulations to fulfill these constitutional responsibilities. Regulatory actions may hinder the use and enjoyment of private property; in some cases, the effects of these regulations may appear so onerous that they can be compared to the government seizing the property. The Fifth Amendment to the U.S. Constitution states that the government cannot take private property for public use without just compensation. Thus, regulatory takings claims may be brought up when the government has restricted the use of private land through regulations, and if awarded, landowners may be entitled to compensation. The conservation of open space and protection of environmentally sensitive areas, both legitimate public interests that benefit society at large, present a challenge due to the restrictive nature of the regulations needed to carry out these goals. Since the 1960s, government agencies have used TDR programs as a planning instrument that allows for privately funded compensation to mitigate the economic burden imposed on landowners whose development expectations are impacted by these regulations (Burke, 2009; Kaplowitz et al., 2008). This market-based compensatory scheme provides agencies with some leverage against a regulatory taking claim or compensation due to one.

In 1978, the U.S. Supreme Court first decided on a case involving TDRs. In *Penn Central Transportation Co. v. New York City*, Penn Central brought a takings claims triggered by the Landmark Preservation Commision's rejection of plans to construct a multi-story building on top of Grand Central Station (Burke, 2009). Penn Central was not allowed to use the air space above the terminal, but was offered TDRs to transfer this development potential to other properties in the vicinity. The Supreme Court found no unconstitutional taking and in the majority opinion, Justice Brennan stated the following: *"While these rights* [TDRs] *may not well have constituted "just compensation" if a "taking" had occurred, the rights nevertheless undoubtedly mitigate whatever financial burdens that law has imposed on appellants, for that reason, are to be taken into account in considering the impact of regulation"* (Penn Central). Justice Brennan's analysis has been interpreted as (1) giving TDRs weight in the determination of a regulatory taking; (2) suggesting that TDRs offer an off-site use of the land; and (3) conferring value to TDRs to mitigate economic burdens imposed by regulations (Nelson et al., 2012).

Once again, in 1997, the U.S. Supreme Court addressed TDRs in the case *Suitum v. Tahoe Regional Planning Agency (TRPA)*. Suitum was denied a building permit because her property was located in an area designated as stream environment zone (Nelson et al., 2012). Even though the TRPA offered Suitum several transferrable rights credits valued in excess of $50,000 to mitigate her loss, she filed a takings claim arguing that the allocation of these credits did not change the fact that she could no longer reap meaningful benefits from her land (Lazarus, 1997). Moreover, Suitum argued that the U.S. Supreme Court had not clarified if TDRs were relevant in a takings determination (Nelson et al., 2012). The U.S. Supreme Court decided the case based on the issue of ripeness for adjudication and did not answer the question of whether TDRs should be considered as a factor in a takings analysis or as a compensation mechanism for a taking (Hitchcock, 2010; Nelson et al., 2012). In his concurring opinion, Justice Scalia argued that TDRs do not constitute an alternative or off-site use of the land, thus not reducing the occurrence of a taking; instead, they should be viewed as compensation for a taking as they allow the affected landowners to receive remuneration for the extinguished rights (Suitum at 747). Due to the reticence of the U.S. Supreme Court to provide clear guidance on takings jurisprudence regarding TDRs, governments should not rely on these programs as their only defense to avoid or confront a takings challenge (Nelson et al., 2012).

TDR programs may also be vulnerable to challenges as exactions from individuals required to buy these rights to develop property in receiving areas (Miller, 1999). An exaction is a condition or payment required from developers to offset the impacts and costs associated with urban growth (Evans-Cowley, 2006). Exactions are legal land-use regulation instruments available to local governments through their police power (Evans-Cowley, 2006). The U.S. Supreme Court has provided guidance to determine the legality of exactions that are akin to physical appropriations in the landmark cases: *Nollan v. California Coastal Commission* (1987) and *Dolan v. City of Tigard* (1994) (Burke, 2009). Exactions must (1) have an “essential nexus” between the imposed permit condition and the government interests sought to advance with the exactions; and (2) must be “roughly proportional” in both extent and nature to the impact of the proposed development (Burke, 2009). The issue with TDR programs stems from (1) the difficulty to prove the existence of an “essential nexus” between the purchase of a right from a sending area and the conditions imposed to develop the receiving area, and (2) establishing “rough proportionality” because the price paid for the required TDRs is, ideally, dictated by the market and not by the impact of the new development in the receiving area (Miller, 1999). Although TDRs are rarely contended as exactions, TDR programs can be defended arguing that the exaction does not compare to a physical appropriation and that TDRs are enacted by legislation and not applied as individualized determinations (Miller, 1999). However, the physical appropriation distinction argument in favor of TDRs has recently been weakened by the U.S. Supreme Court’s ruling in *Koontz v. St. Johns River Water Management District* (2013), which extended the *Nollan* and *Dolan* scrutiny standards to monetary exactions and denials of permits (Hansen, 2013).

2.4 TDR programs in coastal areas

Several TDR programs have been established in the Pacific, Atlantic, and Gulf coasts with the objective of preserving valuable coastal resources. Among the most successful coastal TDR programs are the ones in Collier County, Florida which has preserved 54,692 acres (2010) of land including wetlands, groundwater recharge zones, and wildlife habitat; Miami-Dade County, Florida, which seeks the protection of the Everglades as a supply of freshwater, flood control, recreational opportunities, and wildlife habitat; and Malibu, California which made possible the preservation of large tracts in the Santa Monica Mountains (Nelson et al., 2012). Florida is also the home of two TDR programs that encompass land on barrier islands: the Brevard County and Charlotte County programs. Brevard County included TDRs incentives as part of its zoning ordinances in 1979; the TDRs are intended to further the County's preservation of agricultural lands and natural resources as well as an instrument to guide development away from Coastal High Hazards Areas (CHHA) (Brevard County, 2011.; Pruetz, 2013a). The State of Florida requires local governments to identify CHHAs on their future land-use maps and limit public expenditures and subsidies for development in these areas (Florida Statutes Sec. 163.3177, 2012). CHHAs are defined as zones prone to storm surge inundation caused by a category 1 storm as delineated by the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model output (Florida Statutes Sec. 163.3178, 2012). Brevard County has not seen much TDR activity due to the program's inconvenience, the ability to obtain density bonuses without purchasing TDRs, and the voluntary nature of the incentive (Pruetz, 2013a). In 2004, Charlotte County adopted the ordinance establishing a Transfer of Development Units (TDU) Code program. Similar to other TDR programs, the Code's objective is to redirect growth to more suitable areas, while protecting environmentally sensitive areas, historic and agricultural uses, and the public's health, safety, and welfare (Charlotte County, 2007; Pruetz, 2013b). Sending areas include areas with environmentally-sensitive resources, historic sites, properties in CHHAs, and substandard lots (Charlotte County, 2007). Participation in the TDU program is voluntary. TDUs can be sold and purchased between private parties or through the County's Land Acquisition Trust Fund (Charlotte County, 2007). As of 2009, close to 1700 acres had been preserved in designated sending areas (Charlotte County, 2009).

2.5 Current TDR programs in Texas

Texas has no state legislation enabling TDRs, yet existing TDR programs have been established by local governments using police powers delegated through the state's home rule (Nelson et al., 2012). Currently, Texas has TDR programs operating in four home-rule cities: San Marcos, Austin, San Antonio, and Dallas. The San Marcos Code of Ordinances as amended in 2011 includes provisions for the transfer of residential density or impervious cover area through a development transfer petition (SMCO Sec. 1.5.4.1; Pruetz, 2013c). The transfer of development ordinance's objective is the conservation of open space in residential and non-residential properties within the Edwards Aquifer recharge zone, the San Marcos River corridor, buffer zones, floodplains, and other zones with environmentally-sensitive resources (SMCO Sec. 4.2.7.1). Transferred rights can be applied to land with no significant environmental characteristics; the incoming development should be compatible with neighboring uses as well as the city's master plan (SMCO Sec. 1.5.4.5). Sending and receiving areas are designated by overlay zoning districts created when a petition is recommended for approval (SMCO Sec. 1.5.4.4). Participation in the San Marcos TDR program is voluntary and treated as a conservation incentive (J. Foreman, pers. comm. August 2013). Most of the transfers to date have been done as transfers of density within the sites, and not to off-site locations (J. Foreman, pers. comm. August 2013). The city allocates rights only in terms of residential density or impervious cover; however, private parties can negotiate monetary transactions as the city code does not prohibit the sale and purchase of rights (J. Foreman, pers. comm. August 2013).

Since 1980, the City of Austin has adopted several ordinances that seek to protect water quality through the restriction of density and impervious cover in critical water quality zones (City of Austin, n.d.). These ordinances include the Transfer of Development Intensity (TDI) as an incentive for property owners to conserve valuable watershed areas in exchange of bonus impervious cover to be applied in uplands areas (ALDC Sec. 25-8-395). The Water Quality subchapter of the Land Development title in the Austin City Code is currently being amended, the information presented here summarizes some of the proposed amendments as related to TDI requirements (M. Hollon, pers. comm. August 2013). Sending areas include Suburban Watershed upland areas in critical water quality zones, 100-yr floodplains, or dedicated to the city for parkland, as well as upland areas in critical water quality zones, water quality transition zones, or dedicated to the city for parkland within Water Supply Suburban Watershed and Water Supply Rural Watershed zones (City of Austin, 2013). Receiving sites include upland areas in Suburban Watershed, Water Supply Suburban Watershed, and Water Supply Rural Watershed zones, but no transfers are allowed to Urban Watershed or Barton Spring Recharge Zones (City of Austin 2013). Transfers can be made between two tracts within the same watershed zone; however, this requirement does not apply to contiguous tracts under the same ownership (City of Austin, 2013). TDI participation is voluntary and rights are allocated strictly on an impervious cover area basis. Current amendments to TDI-related ordinances seek to facilitate the use of the incentive by changing the requirement of concurrently filing sending and receiving areas at a subdivision tract level to a site plan level (M. Hollon, pers. comm. August 2013).

The San Antonio Unified Development Code in its Flexible Zoning division mentions TDRs as a regulatory incentive to encourage permanent protection of natural resources and provision of parks and open space (SAUDC Art.III Div. 6). The severing and application of rights are voluntarily requested by landowners in both sending and receiving areas. Sending areas include critical areas (natural resource or environmentally-sensitive), agricultural preservation areas, and transportation corridors (SAUDC Sec. 35-361). The rights severed in sending areas are expressed as percentages of the development potential in dwelling units per area or just land area. Receiving areas are classified as districts: traditional neighborhood development, transit-oriented development, and infill development (SAUDC Sec. 35-361). The City of San Antonio has also included TDR provisions in the Form-Based Zoning Development District (FBZD) adopted in 2007 (Pruetz, 2013d). Transfers of rights within the FBZD are made from sites classified as Reserved Open Space (floodplains, steep slopes, land over aquifers, wildlife habitat, woodlands, viewsheds) and Restricted Growth sectors to Restricted, Controlled, and Intended Growth sectors (SAUDC Sec. 35-209). The TDR Code provision allows for the purchase, sale, and exchange of rights between private parties as well as the right for the city to purchase and hold TDRs for resale at a later date (SAUDC Sec. 35-361).

The City of Dallas through its Historic Development Program promotes the preservation of historic structures and revitalization of neighborhoods (City of Dallas, 2005). The program provides tax abatements, conservation easements, and TDRs as incentives (City of Dallas, 2005). TDRs may be transferred from historic property that is in an urban historic district, listed in the National Register of Historic Places, or has been extensively rehabilitated within the past five years (DCD Sec. 51A-11.302). The transferable rights correspond to the difference between the current floor area of the building and the maximum permitted floor area ratio of the site (DCD Sec. 51A-11.302). This transferable bonus floor area can only be applied to receiving sites designated as central area districts. TDRs are rarely used as the developers can reach high levels of density in receiving areas as a matter of right or through other means (Pruetz, 2013e).

2.6 An alternative to TDRs: Purchase of development rights

Purchase of development rights (PDR) entails buying development rights from landowners in exchange for a conservation easement that effectively restricts development on the property according to the stipulations of the easement (Crompton, 2009; Daniels, 1991). PDR differs from TDR in that the severed development rights are bought outright and not transferred to any other property. Thus, the need to create a market for the trade of development rights and specify receiving areas is non-existent. In general, a PDR program is less complex than a TDR program in administrative, financial, and legal terms; however, PDR programs are subject to the availability of funds for buying out the development rights. Yet, the initial substantial investment in purchasing development rights may be less costly than the long-term cost of administering a full-fledged TDR program. PDR programs are voluntary, meaning that landowners are not obligated to participate even when their property falls within the program's boundaries (Crompton, 2009). PDRs, similar to the TDRs, offer monetary compensation to property owners for the restrictions imposed on their land and lend more permanence to the state of the preserved land (Daniels, 1991). From a state and local government perspective, benefits of a PDR program include: (1) the cost of conserving land is usually less than a fee simple acquisition; (2) conserved land remains taxable according to its post-easement use; and (3) landowners retain maintenance/management responsibilities of their property (Buckland, 1987; Crompton, 2009;

Whyte, 1962). The major challenges of a PDR program are the availability of funds to conduct the purchases, the willingness of property owners to participate in such a program, and in some cases, rapid urbanization trends (Daniels, 1991). Overall, PDR programs offer a middle-of-the-road alternative, between acquisition of land at full market price and stringent land use regulation, for the conservation of open space and environmentally significant areas.

PDRs have been used in many states across the U.S. for the preservation of farmland and open space since the 1970s (Buckland, 1987; Crompton, 2009; Daniels, 1991). At least 20 states have or have had major PDR programs, with the most extensive and active programs taking place in northeastern states (Crompton, 2009). Other land acquisition programs include the purchase of conservation easements as a preferred strategy to carry out their goals. For example, Florida boasts "the largest public land acquisition program of its kind", Florida Forever, which has accumulated more than 707,740 ac. (2864 sq. km) with an investment of $2.81 billion since 2001 (FDEP, 2014). Under this program, Florida can acquire land in fee simple or conservation easements over land that has been targeted due its natural and cultural heritage (FDEP, 2014). Protected areas through Florida Forever include coastline acreage, functional wetlands, natural floodplains, and areas that minimize flood damage (FDEP, 2014). Moreover, Maryland has recently included the purchase of "Coastal Resilience Easements" in its statewide open space acquisitions program (MDNR, n.d; 2013). The easements are intended to reduce vulnerability and increase resilience of property and coastal habitats by protecting areas that minimize the impact of storm surge, ensure future wetland migration in response to SLR, limit impervious cover, and preserve important coastal habitats (MDNR, n.d; 2013). The first "Coastal Resilience Easement" of 221 ac. (~ 0.9 sq. km) was acquired in 2013 in Dorchester County, Maryland (MDNR, 2013). Public and private land trusts, such as the North Carolina Coastal Land Trust, and non-profit organizations, such as The Nature Conservancy, also employ conservation easements as tool for land conservation (NCLT, n.d.; TNC, 2014).

3. TDR as applied to Texas barrier islands

3.1 State and federal laws and policies pertinent to coastal development in Texas

3.1.1 Wetlands protection

Wetlands in Texas are protected by federal and state regulations. The federal government derives its regulatory authority from Section 404 of the Clean Water Act (CWA), which regulates the discharge of dredged and fill material into the waters of the United States including wetlands (ELI, 2008a; USFWS, n.d.; USEPA, 2013). The U.S. Army Corps of Engineers (USACE), in cooperation with the U.S. Environmental Protection Agency (EPA), administers the program (USFWS, n.d.). USACE is in charge of permitting activities, while EPA provides general oversight (USFWS, n.d.). Other agencies, such as the U.S. Fish & Wildlife Service, provide advice in permitting determinations (USFWS, n.d.). Section 401 of the CWA requires permit applicants to obtain a state certification that indicates that proposed projects meet water quality standards of the state where the project takes place, regardless of the state's requirements being more stringent than federal standards (ELI, 2008a). Construction in wetlands areas is also regulated through Section 10 of the Rivers and Harbors Appropriation Act which prohibits obstruction to the navigable capacity of water of the U.S. (USEPA, 2012). In Texas, activities taking place in coastal wetlands are regulated through Sec. 401 certification and the federal consistency requirement with the Texas Coastal Management Program (TCMP) triggered by construction within the Texas Coastal Zone Boundary (ELI, 2008b; TGLO, 2012a). One of the goals of the TCMP is the coordination of state agencies' efforts to manage activities that may be detrimental to Coastal Natural Resources Areas (CNRAs) (TNRC Sec. 33.202, 1995). Coastal wetlands are considered CNRAs (TNRC Sec. 33.203, 2013). Permits for activities potentially impacting coastal wetlands are jointly reviewed by USACE, Texas General Land Office (TGLO), Texas Commission for Environmental Quality (TCEQ), and other state agencies part of the Coastal Coordination Advisory Committee (CCAC) (ELI, 2008b; TGLO, 2013). Permits are granted based on determinations of the severity of the impacts to CNRAs and measures presented to minimize them (TRCC, n.d.). Texas has adopted a policy seeking "no net loss" of state wetlands; thus, mitigation is mandatory as required by federal and state laws (ELI, 2008b; TCEQ, 2002). Wetland mitigation and monitoring are carried out by the USACE with input from state agencies (ELI, 2008b; pers. comm. Jesse Solis, September 2013). In summary, activities affecting coastal wetlands are regulated by federal and state laws, which also provide mechanisms for the mitigation of losses and adverse effects but do not effectively prevent development in these areas. As a result, many coastal wetlands could still potentially be modified or lost (Figure 4.1; Appendix B Figure. 4.10A-D).

3.1.2 Beaches and dunes protection

Beaches and dunes of the Texas coast are protected by state and local regulations. Across-the-board beach and dune protection is afforded by the Open Beaches Act (OBA) and the Dune Protection Act (DPA). The OBA addresses issues regarding the preservation and enhancement of access to public beaches along the Gulf of Mexico, while the DPA seeks the preservation of dunes features (TAC Title 31.1.15A Rule 15.3, 2010). The OBA declares that the public shall have unrestricted access to Gulf-facing beaches from the mean low tide mark to the line of vegetation (LOV) (TNRC Sec. 61.001 and 61.013, 1991). The public area of the beach is protected through an easement, which effectively bans any private construction and other types of obstruction in this area (TNRC Sec. 61.013, 1991). The OBA explicitly regulates construction and other activities occurring within the public easement up to 1000-ft (304.8 m) landward from the mean high tide mark or the nearest public road, whichever distance is greater (TNRC Sec. 61.011, 2009). Construction in this area triggers the requirement of a Beach Construction Certificate, issued by local entities and reviewed by the TGLO to guarantee consistency with OBA and DPA statutes (TAC Title 31.1.15A Rule 15.5, 2006; TGLO, 2012b). Beaches and dunes are considered CNRAs; therefore, CCAC has oversight authority over these resources as well (TNRC Sec. 33.203, 2013). The TGLO has also the responsibility of protecting critical dune areas, these areas are deemed “essential to the protection of state-owned land, public beaches, and submerged land […] from nuisance, erosion, storm surge, and high wind and waves” (TNRC Sec. 63.121, 1991; TAC Title 31.1.15A Rule 15.3, 2010). Critical dune areas have been identified as dunes and dune complexes located within 1,000-ft landward from the mean high tide mark (TNRC Sec. 63.121, 1991). Moreover, local governments are required to define a dune protection line, and, most recently, establish a building setback line (TNRC Sec. 63.011, 1977; TAC Title 31.1.15A Rule 15.7, 2010). The dune protection line delimits the area where a dune protection permit is required for construction and other activities that may damage, destroy, or remove sand dunes or vegetation covering them (TGLO, 2012b; TNRC Sec. 63.051 and 63.091, 1991). Nueces County, the City of Corpus Christi, and the City of Port Aransas have adopted the definition of critical dune areas as their dune protection line (Nueces County and City of Corpus Christi, 2012; Mahoney, 2012).

In 2010, local governments were required to develop Erosion Response Plans (ERP) to “reduce public expenditures for erosion and storm damage losses to public and private property”

(TAC Title 31.1.15A Rule 15.17, 2010). One of the salient features of these plans is the inclusion of a building setback line delineation. The statute prohibits new construction seawards of the setback line established by local entities. The Joint Nueces County/City of Corpus Christi ERP establishes a 350-ft (106.7 m) setback line from the LOV for new residential and commercial dwellings and restricts development that may still occur within 200-350 ft from the LOV to recreational amenities, such as pools or decks (Nueces County and City of Corpus Christi, 2012). Meanwhile, the City of Port Aransas ERP calls for a 200-ft (61 m) setback line from the LOV for new construction (Mahoney, 2012). Approved construction permits may require mitigation for impacted dunes (TNRC Sec. 63.1813, 2007). Overall, beaches and dunes are protected through various regulations, which have been formulated and are enforced, at the state and local levels (Table 4.1; Figure 4.1; Appendix B Figure 4.10A-D). Beaches are afforded more protection due to the stringent nature of the OBA; on the other hand, dunes enjoy less protection as development can still occur in critical dune areas.

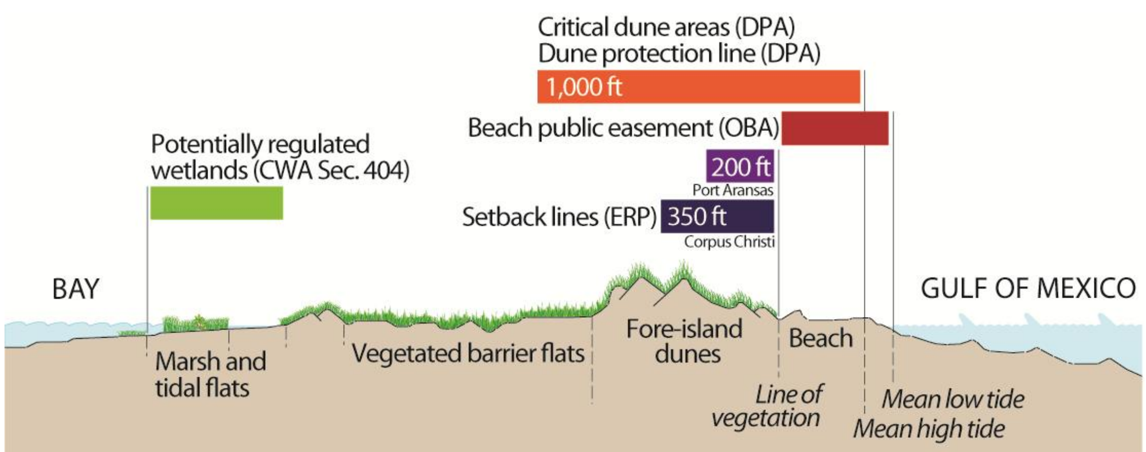

Figure 4.1 Local, state, and federal regulated areas on Mustang and North Padre Islands, Texas. (Modified from Radosavljevic, 2011).

Since 1959, the OBA established a provision granting the public access to the dry beach up to the LOV through a public easement (McLaughlin, 2011). In the past, this provision had been unsuccessfully challenged by private landowners, as courts have upheld the traditional interpretation of the OBA that the public easement shifts following changes in the LOV (McLaughlin, 2011). However, in 2010 the Texas Supreme Court decided in *Severance v. Patterson* that the beach public easement moves due to gradual and imperceptible erosion, but does not roll landwards as a result of an avulsive event, such as a hurricane. Thus, making Severance's takings claim valid if the State of Texas was to enforce the OBA's public easement through her property and remove the homes that obstructed the public beach after Hurricane Rita. The case was reheard by the Texas Supreme Court in 2011 and by the U.S. Court of Appeals for the Fifth Circuit in 2012. The U.S. Court of Appeals relied on the Texas Supreme Court's final ruling to assert Severance's "unreasonable" seizure claim under the Fourth Amendment and reverse and remand the case to a lower court to address this issue. Even though the decision of this case only applies to beaches in Galveston's West Beach, the precedent can potentially open the door to future litigation challenges between the State and coastal landowners (McLaughlin, 2011).

Table 4.1. Summary of local and state regulatory boundaries.

Regulatory boundaries	**General definition**	**Notes**
Beach public easement	Mean low tide mark to line of vegetation	
Critical dune areas	1000-ft from mean high tide mark	
Setback lines		* Corpus Christi exceptions: In front of seawall and Mustang Island State Park. * Setback line should not be further inland than the dune protection line.
Corpus Christi City Limits	350-ft from the line of vegetation	
Port Aransas City Limits	200-ft from the line of vegetation	
Dune protection line	1000-ft from mean high tide mark	Does not apply to Mustang Island State Park and Padre Island National Seashore.

3.1.3 Coastal Barrier Resources Act

The Coastal Barrier Resources Act (CBRA) was passed by Congress in 1982 as response to federal programs that indirectly encouraged development on coastal barriers (Heinz Center, 2000; USFWS, 2013a). The Act established the Coastal Barrier Resources System (CBRS) which included relatively undeveloped areas in coastal barriers along the Atlantic and Gulf coasts. Areas in the CBRS are ineligible to receive federal funding for major capital projects and expenditures that encourage further development or modification of coastal barriers, such as coastal defense projects or federal flood insurance, unless activities or properties are grandfathered in (Heinz Center, 2000; USFWS, 2013b). The CBRA seeks to cut incentives for private and public investment in risk-prone areas. In 1990, the Coastal Barrier Improvement Act increased the number of areas subject to the CBRA (USFWS, 2013a). Currently, the CBRS has two types of units: System Units, mostly relatively undeveloped private lands before 1982; and Otherwise Protected Areas (OPAs), which include parks, wildlife reserves, and other conservation areas (USFWS, 2013a). While most federal expenditures are prohibited on System Units, federally subsidized flood insurance is the only subsidy prohibited in OPAs (USFWS, 2013b). There are six CBRS units in the study area, three in Mustang Island and three in North Padre Island. Only one unit in NPI is a System unit, the rest are OPAs.

3.1.4 National Flood Insurance Program

The National Flood Insurance Program was first authorized by Congress in 1968 (FEMA, 2010). The program was created to encourage the recognition and inclusion of flood hazards into land-use planning activities and decisions at the state and local levels, thus minimizing flood-related risks and losses (FEMA, 2010). The NFIP is currently administered by the Federal

Emergency Management Agency (FEMA) and has three main components: (1) Hazard identification and mapping flood hazard areas; (2) Floodplain management criteria and guidance; (3) Flood insurance as a financial protection against potential losses (FEMA, 2010). Although the NFIP seeks to decrease risk in flood-prone areas, it has been argued that the program has had quite the opposite effect in coastal areas – acting as an incentive and a subsidy for development in hazardous or environmentally sensitive areas (Bagstad et al., 2007; Dolan and Wallace, 2012). Landowners may perceive the availability of flood insurance as an incentive because the potential return of investment on coastal property is protected while the risk is transferred to the NFIP. Moreover, several coastal properties are eligible for subsidized flood insurance rates that do not reflect the full risk and costs of insuring in such hazardous locations. There are instances where the market is willing to build and invest in hazardous coastal areas without the safety net of the NFIP, such as Hatteras Island, North Carolina and Tortuga Dunes on Mustang Island, Texas. Currently, the NFIP is deemed by the U.S. Government Accountability Office as a "high risk" program to the government due to insolvency issues (USGAO, 2013). In 2010, the NFIP had a debt $18.5 billion to the U.S. Treasury and approximately $3 billion in annual revenues (Conrad, 2010). After Sandy, the debt has gone up nearing $20 billion (USGAO, 2013). In response to this problem, Congress recently passed the Biggert-Waters Flood Insurance Reform Act (2012) which extends the NFIP for five more years; but incorporates comprehensive reforms, such as increases and readjustments to premiums charges and improved flood maps, to reduce the program's deficit (FEMA, 2013a). The effects of the Biggert-Waters Act on coastal development trends are still unknown; however, coastal landowners affected by the act's provisions are already facing hard financial decisions such as whether to comply with new elevation and building requirements or pay significantly higher actuarial premium rates

(Leitsinger, 2013). Some landowners affected by Superstorm Sandy have decided not to rebuild in the light of the new NFIP requirements (Leitsinger, 2013).

3.1.5 Texas Windstorm Insurance

In response to the significant losses suffered from Hurricane Celia hitting Corpus Christi in 1970, the Texas Legislature created the Texas Wind Insurance Association (TWIA) (TDI, 2013). The purpose of the TWIA is to provide windstorm and hail insurance to property owners who are unable to obtain coverage in the market, serving as a "last resort" option after other protection coverage alternatives have been exhausted (TDI, 2013). TWIA policies do not cover damages resulting from flood or storm surge, even if the property is not eligible to participate in the NFIP. TWIA policies are available for property in the 14 counties along the Gulf Coast and some areas of Harris County (TWIA, 2013).

The TWIA has become the coastal region's largest windstorm insurer with $74.8 billion in directly insured assets (TDI, 2013; Woods, 2013). Lately, the state-backed program has been struggling to meet its financial obligations following payouts close to $2.7 billion in damage claims and litigation from Hurricane Ike (Serrano, 2013). According to recent reports, the TWIA only had $182 million in its Catastrophe Reserve Trust Fund to respond to potential excess losses from the 2013 hurricane season (TDI, 2013). The influence that the TWI program has had on coastal development is unclear; yet, it has been pointed out that the program has inadvertently created a moral hazard for development on barrier islands (Todd and Weisman, 2010). Property owners and developers build in risky coastal areas because they are able to transfer some of the risk through the TWI program (Anthony, n.d.).

3.2 Study Area

This study focuses on Mustang and North Padre Islands, located on the Texas central coast, extending from Aransas Pass to the northern boundary of the Padre Island National Seashore (Figure 4.2). The study area was selected because the impending urban development on Mustang and North Padre Islands embodies the challenge of balancing conservation and sustainability shared by many coastal communities around the world. Also, Mustang and North Padre represent typical wave-dominated sandy barrier islands characteristic of most of the Atlantic and Gulf coasts. Various natural environments can be found on the islands including marine-influenced environments such as beaches, vegetated foredunes and secondary dunes, blowouts, and washover areas; fresh water marshes and ponds interspersed within vegetated barrier flats; and estuarine environments such as wind-tidal flats, salt marshes, and seagrass beds. The long-term shoreline-change trend along Mustang and North Padre is erosional (-0.83±0.7 m/yr, 1937-2011), characterized by short-term cycles of accelerated retreat due to storms and beach recovery during years with low hurricane activity (Morton and Pieper, 1977; Taylor and Gibeaut, 2013). The average return period for tropical storms and hurricanes in the area is 5 years and 12 years for all hurricane categories 1-5 (Keim et al., 2007). From 1948 to 2006, the closest long-term tide gauge to the area recorded a relative sea-level rise averaging 5.16 ±0.67 mm/yr (NOAA, 2013; Zervas, 2009).

Most of the study area is located within Nueces County; a small uninhabited section falls under the jurisdiction of Kleberg County. Most of Mustang Island remains undeveloped except for a few resorts and condominiums scattered along the Gulf shore and the city of Port Aransas, which is located at the north end of the island. Similarly, North Padre Island is only developed from Packery Channel to the boundary between Nueces and Kleberg County. Several parks are within the study area, including Mustang Island State Park, Nueces County Park, Packery Channel Park, and Padre Balli Park. The character of residential development on North Padre Island is mostly of a bedroom community, for people who commute daily to Corpus Christi and Flour Bluff for work and school, dotted with vacation rentals. Most of the residential stock is comprised of upscale detached single-family homes and a small number of multi-family units. North Padre Island is home to the well-established Padre Isles residential community, which was developed in the 1970s by dredging canals and filling and leveling back-barrier flats (Garza, 1980). Service-related businesses such as restaurants, gift shops, medical offices, and gas stations line the main access road to the island. On the other hand, Port Aransas is a small fishing and tourist town that dates back to the early 1900s. The residential stock is more varied than North Padre Island, ranging from modern multi-story residences to older small homes, in addition to condominiums and a few trailer parks. Similar to North Padre Island, Port Aransas has few businesses; most of them are tourism-related such as gift shops, restaurants, tackle shops, and a supermarket. Development in Port Aransas extends from behind the foredunes to the back of the island, with a couple of marinas, The University of Texas Marine Science Institute complex, a golf course, and an upscale finger-canal residential community. About 12,624 people live within the study area, which constitutes 3.7% of the total population in Nueces County for the year 2010 (U.S. Census Bureau, 2011). The population in the study area grew roughly 30% from 2000-2010 (U.S. Census Bureau, 2011).

Figure 4.2. Study area: Mustang and North Padre Islands, Texas.

3.3 Methods

The designation of TDR sending and receiving areas was done through an overlay analysis of different geographic layers. The first layer is a geohazards map of Mustang and North Padre Islands, Texas (Taylor and Gibeaut, 2013). The geohazards map identifies areas on the barrier islands according to their relative susceptibility to, and mitigation of, the effects of geological processes including RSLR, erosion, historic washover locations, and present and future location of critical environments, such as beaches, dunes, and wetlands (Taylor and Gibeaut, 2013). Five geohazard potential categories are shown in the map: extreme, imminent, high, moderate, and low (Table 4.2; Appendix B Figure 4.9A-D). The second layer is the draft version of preliminary FEMA Flood Insurance Rate Maps (FIRM) (FEMA, 2013b) covering the study area. The FIRM maps identify areas likely to be inundated by 1 and 0.2 percent annual chance flood events, also known as 100- and 500-year floods (NRC, 2009). In coastal areas, FIRMs include VE and AE special flood hazard categories that indicate areas subject to wave action (Table 4.2; Appendix B Figure 4.8A-D). This updated version of the FIRM maps also includes the delineation of the landward limit of areas that could be affected by waves equal or higher than 1.5 ft (0.45 m) known as Limit of Moderate Wave Action (LiMWA). The inclusion of the LiMWA is the result of findings in post-storm assessments and laboratory tests indicating that structures can experience severe damage when exposed to breaking waves as small as 1.5 ft (0.45 m) (FEMA, 2008). The LiMWA is not a regulatory boundary, but rather an informative feature to promote risk awareness and encourage communities to adopt building requirements closer to those for VE areas (FEMA, 2008). The final layers are the City of Corpus Christi and the City of Port Aransas future land use maps, which spatially reflect the cities' policies, goals, and objectives regarding future use of the land within their jurisdiction (Table 4.2, Appendix B Figure 4.4 &4.5).

Sending areas are defined as present critical environments or areas expected to change due to short- and long-term geological processes and likely to be affected by episodic coastal flooding. In other words, sending areas resulted from the geometric union of areas in the extreme, imminent, and high geohazard potential categories and areas in the VE zone (Table 4.3). Conversely, receiving areas comprise areas not expected to change in the next 60 years (low and moderate geohazard potential) and are landward of the LiMWA boundary (Table 4.3). Areas classified as having low and moderate geohazard potential but located in the AE zone outside of the LiMWA boundary were designated as special sending areas. Parks, public spaces, and other land currently indicated for conservation or preservation in the future land-use maps (FLUM) were classified as reserved areas.

3.3.1 Proposed TDR sending and receiving areas design

Sending areas should not be developed any further (Table 4.3). The objective is to minimize risk exposure of real property and infrastructure in hazardous areas. Also, the preservation of sending areas is intended to protect and provide critical environments such as wetlands, beaches, and dunes space to migrate inland in response to dynamics of RSLR or recover from damage brought by tropical storms and hurricanes. Special sending areas should be downzoned or planned for low density development with stricter building requirements as suggested by FEMA's LiMWA recommendation (Table 4.3). Development in special sending areas is not expected to jeopardize present or future critical environments, but it is still considered highly vulnerable due to exposure to moderate wave action during a 100-year storm or higher. Although most of the receiving areas within Nueces County fall in the FIRM's AE zone, development should be directed to areas less likely to experience severe over-land wave damage, such as areas landward of the LiMWA or areas in the X zone. Therefore, receiving areas are considered relatively safer and more adequate to accommodate higher density development than special sending areas. Development that would occur in receiving areas is also less likely to impact present and future critical environments.

Table 4.2. Summary of overlay analysis geographic layers.

Layer	Source	Explanation	Units
Geohazards map for Mustang and North Padre Islands, Texas	Taylor and Gibeaut (2013)	Identifies areas according to their relative susceptibility to, and mitigation of, the effects of geological processes including RSLR, erosion, historic storm washover locations, and present and future location of critical environments, such as beaches, dunes, and wetlands	Geohazard potential *Extreme*: Historic washover storm channel *Imminent*: Presently existing critical environments of regularly flooded estuarine wetlands, freshwater wetlands, and beach/foredune system. *High*: Future critical environments, includes uplands projected to become critical environments in the next 60 years. *Moderate*: Uplands that are neither currently, nor are expected to become critical environments in the next 60 years but are less than 1.5 m (~5 ft) NAV88 in elevation. *Low*: Uplands with an elevation greater than 1.5 m (~5 ft) NAVD88.
FIRM maps	FEMA (2013)	Identifies areas likely to be inundated by 1 and 0.2 percent annual chance flood events	Special flood hazards areas (SFHA) *Zone VE*: Coastal flood zone (1% annual chance flood) with velocity hazard, wave heights equal to or greater than 3 ft (0.91 m). *Zone AE*: Flood zone (1% annual chance flood), wave heights less than 3 ft (0.91 m). *Zone AO*: Flood zone (1% annual chance flood, sheet flow). Other areas: *Zone X*: Areas of 0.2% annual chance flood. Limit of Moderate Wave Action: landward reach of waves equal or higher than 1.5 ft (0.45 m).
Corpus Christi Future Land Use Map	City of Corpus Christi (2010)	Spatial representation of policies, goals, and objectives regarding future use of land.	Relevant land-use categories: Low Density Residential, Medium Density Residential, Park, Tourist, Public Semi-Public, Conservation/Preservation, Commercial.
Future Land-use Map Port Aransas, Texas	City of Port Aransas (2006)	Spatial representation of policies, goals, and objectives regarding future use of land.	All land-use categories.

Table 4.3. Proposed TDR area designations.

TDR area category	Expected to change in next 60 years?	Geohazard potential category	FEMA FIRM zone	LiMWA boundary	Development recommendation
Sending	Yes	Extreme, imminent, & high	VE	Outside	No more development
Special sending	No	Low & moderate	AE / X	Outside	Low density
Receiving	No	Low & moderate	AE / X	Inside	Higher density
Reserved	Parks, public spaces, and land indicated for conservation or preservation				

4. Results

The study area covers 97.1 sq. km of which 72.9 sq. km are within the City of Corpus Christi's extraterritorial jurisdiction (ETJ) and 24.2 sq. km within the City of Port Aransas' ETJ (Table 4.3). The proposed TDR area designations results in the following distribution: 17% (16.8 sq. km) of the study area classified as sending areas, 8.7% (8.4 sq. km) as special sending areas, 23.5% (22.8 sq. km) as receiving areas, and 50.6 % (49.1 sq. km) as reserved areas. Most of the receiving areas within Corpus Christi's ETJ (15.2 sq. km) are evenly distributed in North Padre Island, while most of the receiving areas within Port Aransas' ETJ (7.6 sq. km) are narrowly clustered towards the north end of Mustang Island. The majority of the special sending areas are concentrated in the middle section of Mustang Island. The reserved areas class is the largest, with most of the land classified as such falling within Corpus Christi's ETJ (Table 4.3). Reserved areas include the Port Aransas Nature Preserve, the University of Texas Marine Science Institute campus, Shamrock Island and nearby wetlands, Mustang Island State Park, public-owned premises, city and county parks, and a large extension of land located south of Corpus Christi's city limits.

Table 4.4. Results of TDR sending and receiving areas designation.

TDR area category	Corpus Christi ETJ (sq. km)	Port Aransas ETJ (sq. km)	Total (sq. km)
Sending	9.9	6.9	16.8
Special sending	5.7	2.7	8.4
Receiving	15.2	7.6	22.8
Reserved	42.1	7.0	49.1
Total	72.9	24.2	97.1

4.1 Corpus Christi ETJ

About 4 sq. km of potential receiving areas located south of the Nueces/Kleberg County boundary are intended for low density residential development (up to 8 Dwelling Units/Acre; Appendix B Figure 4.4 & 4.7A). This land-use designation helps the TDR implementation as TDR credits could be required to increase density of the area. This part of North Padre Island is currently undeveloped; however, it is in a CBRA CBRS unit which will preclude the city or county from receiving any federal subsidies to offset infrastructure costs or spur future development. From Nueces/Kleberg County boundary to Packery Channel, sending areas and receiving areas cover 1.8 sq. km and 10.6 sq. km, respectively. Close to half of the receiving areas are platted and developed as low density development zones; the other half is identified in the FLUM as a “Tourist” land-use (multifamily apartment tourist; City of Corpus Christi, 2013). Both land-uses in this section of NPI are adequate to accept infill development from other sending areas within Corpus Christi’s ETJ (Appendix B Figure 4.7A). The area east of Park Road 22 between Whitecap Blvd and Packery Channel has been identified as a potential destination node for the island in the Corpus Christi Sustainability Plan (HDR Engineering, 2011).

In the FLUM, the area north of Zahn Road, east of State Highway 361, and before Newport Pass has been identified for “Medium Density Residential” (0.3 sq. km, 8-22 DU/AC) and “Tourist” (0.2 sq. km) land-uses. Although this area has some land classified as receiving and special sending zones, the planned future land-uses are discouraged. The proximity to a historic washover channel and extensive wetlands make potential development in this location vulnerable to coastal flooding and likely to impact environmentally sensitive land (Appendix B Figure 4.7B). Moreover, the southern section of Mustang Island extending to the northern boundary of Mustang Island Park is a CBRA OPA unit; therefore, development occurring in this section will not be able to participate in the NFIP.

The area between the northern boundary of Mustang Island State Park and Corpus Christi/Port Aransas ETJ has been identified for "Tourist" (west of State Highway 361), "Low Density Residential", (east of State Highway 361); and "Conservation/Preservation" (wetlands close to Shamrock Cove) land-uses. Sending areas flank the core of the island, receiving areas are concentrated toward the middle of the island east of State Highway 361; and special sending areas are mostly distributed west of State Highway 361 (Appendix B Figure 4.7C). Out of 4.6 sq. km intended for "Tourist" use, about 1.5 sq. km are receiving areas and 1 sq. km are special sending areas. Development in this section could be carried out in clusters, pushing development density back closer to the road and towards sending areas. The "low density residential" designation over special sending areas (4 sq. km) west of State Highway 361 could be used as is in the TDR program or reduced even further.

4.2 Port Aransas ETJ

The Port Aransas' FLUM points at largely undeveloped areas, located between the southern boundary of the ETJ up to Access Road 1-A, as growth areas where high density development and the Newport Dunes planned unit development would take place (Appendix B Figure 4.5). About 1.3 sq. km out of 4.1 sq. km regarded as "High Density Residential" land fall in receiving areas and 0.7 sq. km in special sending areas (Appendix B Figure 4.7C-D). The

"Newport Dunes/other P.D.'s" land-use category covers close to 4.7 sq. km with 2.7 sq. km in receiving and special sending areas. Pockets of land identified as receiving areas in "High Density Residential" zones are recommended to keep the current future land-use designation, while special sending areas should be reclassified for less intensive development uses.

Parts of some beachfront lots classified as "Mixed Use Residential" are identified as sending areas. In these cases, TDR credits could be used to increase lot coverage in the receiving sections of the lots, or credits could be transferred off-site to adjacent properties in the same land-use class. Close to the intersection of State Highway 361 and Avenue G, lots intended for office/retail uses on the west side of the highway are vulnerable to moderate wave action. Even though office/retail uses are appropriate for this location to take advantage of passing traffic, special considerations regarding building and structural requirements should be enforced to minimize risk in case of a storm. Other areas low lying zones between State Highway 361 and 6th Street are sending areas, undeveloped wetlands south of Avenue G should be preserved as such (Appendix B Figure 4.7D).

4.3 Current developed areas

An analysis of the currently developed parcels on Mustang and North Padre Islands reveals that, in theory, all of these parcels (19.8 sq. km) could be accommodated in receiving areas (22.8 sq. km) as indicated by the TDR area designation in this study (Table 4.5). Sections of these developed parcels (2 sq. km) are presently in sending areas. In other words, current development on the islands could be accommodated entirely in designated receiving areas and still have room for future development in relatively safe areas. Port Aransas' existing developed areas exceed the TDR receiving areas; however, growth could take place as infill in receiving areas or in lower densities in special sending areas (Table 4.5). Meanwhile, higher density growth could happen in about 5.4 sq. km of potential receiving areas within the Corpus Christi ETJ that remain undeveloped; most of them south of the Nueces/Kleberg county boundary.

Although the implementation of land-use policy measures, such as a TDR program, may restrict development potential, they do not necessarily thwart future growth. The reduced availability of developable land would, hopefully, encourage local stakeholders to take a hard look at the prevalent sprawling development patterns and think about safer and environmentally sound development alternatives.

Table 4.5. Current developed areas by TDR area category.

TDR area category	**Corpus Christi ETJ (sq. km)**	**Port Aransas ETJ (sq. km)**	**Total (sq. km)**
Developed sending	0.8	1.2	2.0
Developed special sending	0.7	0.9	1.6
Developed receiving	9.8	6.4	16.2
Total developed	11.3	8.5	19.8
* Total TDR receiving areas	15.2	7.6	22.8
* Total TDR special sending areas	5.7	2.7	8.4

5. Discussion

Mustang and North Padre Islands are still relatively undeveloped; however, according to Corpus Christi and Port Aransas' FLUM, both cities plan to continue growing into currently undeveloped areas. Much of the future growth is planned towards the middle section of Mustang Island, where urban development would be most vulnerable to the effects of RSLR and storm-surge flooding. This section of the island is also the narrowest, with extensive wetlands and exposed to the largest fetch from Corpus Christi Bay. Ideally, further development and high-intensity uses should not be planned for this area on Mustang Island. Instead, future development should be redirected south of the Nueces/Kleberg County boundary and as infill within the current footprint of the city Port Aransas. Both of these locations offer uplands that are more sheltered and have slightly higher ground elevations.

Current regulations and policies offer limited protection to present and future locations of critical barrier island environments. The most protective regulations are derived from the OBA, DPA, and recently adopted building setback lines (ERP). These acts include provisions that prohibit or restrict construction, destruction of natural features, and other human-made obstructions in beaches and critical dune areas. OBA- and DPA-regulated areas and setbacks lines shift according to natural changes in the positions of the mean high tide mark, mean low tide mark, and line of vegetation. Unfortunately, the protective power of the OBA has been undermined by recent court decisions applying *Severance v. Patterson*. Wetlands, although regulated at the state and federal level, receive less protection than beaches and critical dune areas. In theory, wetlands could be developed if evidence is presented that no other development alternatives are viable for the site, wetlands impacts have been minimized, and adverse effects could be mitigated off-site. The distribution of the CBRA designations is not uniform, allowing for federal assistance over large areas of Mustang and North Padre Islands. Lack of federal investment-backing can be a powerful hindrance for local and state governments to discourage development within a CBRA unit. However, if economic or political pressure is strong enough, development, as it has in the past, can occur regardless of the CBRA designation. The availability of subsidized NFIP policies has been regarded as a development incentive, even when the purchase of flood insurance may be mandatory. Consequently, the NFIP does not lend any protection to critical environments; on the contrary, it supports development and rebuilding in risky and environmentally sensitive areas. Recent reforms brought by the Biggert-Waters Act may dampen the influence of the NFIP on coastal development. Finally, the availability of the

TWI may have a similar effect on coastal development as the NFIP; however, to a lesser extent as participation is voluntary.

A TDR program is proposed as a potential land-use policy that would complement existing regulations to protect critical barrier island environments and redirect development to safer areas. The main goal of the program is to preserve land and restrict hazardous development through market-funded conservation easements. The TDR program could be instituted as a local ordinance due to the home-rule status of both Corpus Christi and Port Aransas. Proposed sending and receiving areas could be implemented by making the following zoning changes: sending areas downzoned to 0.5 - 1 DU/AC with low lot coverage (<50%) and low floor area ratios (FAR <0.5); special sending areas downzoned to 1-2 DU/AC with low lot coverage (<50%) but higher FARs (0.5-1) to allow for higher vertical density; and some receiving areas upzoned with increased lot coverage and even higher FARs (1-2) to accommodate mixed-use, high-density development. The proposed TDR areas zoning structure is intended to create an urban cross-section where density increases gradually from the gulf- and bay-shores to the core of the island. This gradient transfers density from the most vulnerable, hazardous areas to safer, more stable sections of the barrier island (Figure 4.3). Another benefit that could be derived from the proposed TDR urban cross-section would be the availability of water viewsheds for most buildings located in middle section of Mustang Island; which can have an across-the-board positive effect on property values in this area. Indirectly, the TDR program could spread a heavily waterfront-biased tax base across the island by increasing the intensity and density of uses towards the core. For instance, a mixed-development pattern in receiving areas could compensate the loss of tax base resulting from sending areas' decreased development potential

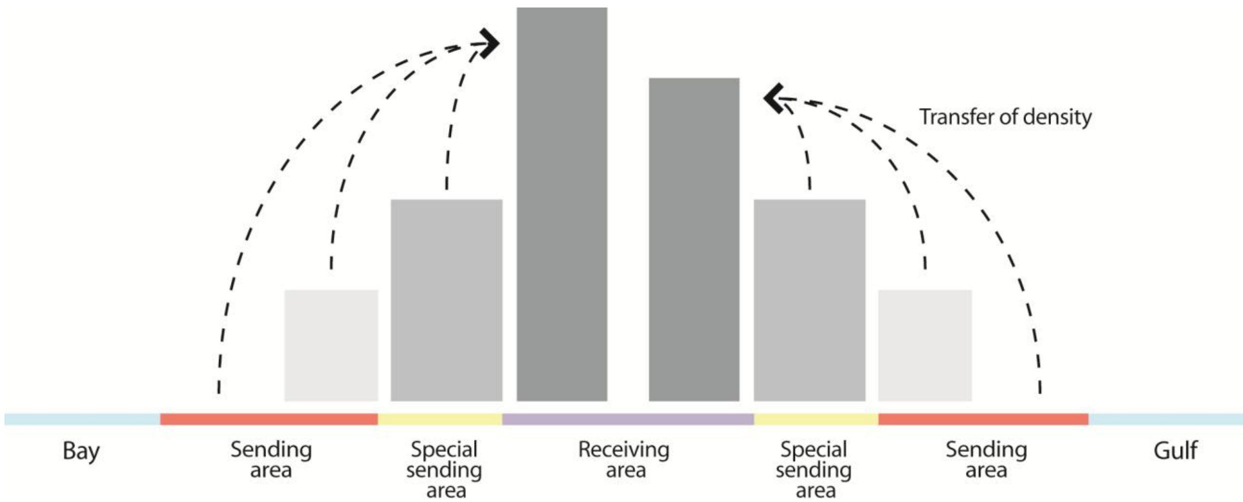

Figure 4.3. Proposed island urban cross-section.

Although a TDR program on Mustang and North Padre Islands may be a sensible land-use policy tool capable of addressing the realities of a dynamic coastal environment, its implementation would pose some complex economic and regulatory challenges to local governments. The first challenge is creating a demand for denser development on the barrier islands. Some coastal TDR programs in Florida and California have been successful because the market demanded denser development in receiving areas that were as profitable and attractive as the sending areas. This situation is presently not the case of Mustang and North Padre Islands, where much land remains available for development, low density is the dominant development pattern, and the greatest asset of real estate property is still based on its proximity to the water. A second challenge is the temporary erosion of the tax base as further development of sending areas is restricted and demand for denser development in receiving areas catches up. Both of these challenges, however, could be overcome in the next few decades. The amount of land available for development is projected to decrease as shorelines retreat and more land becomes inundated due to RSLR. The market's development pressure on the barrier islands may be then strong enough that developers and landowners would be willing to compromise and build wherever and in whatever form is permitted. From a regulatory perspective, TDR programs have been referred to as a way to provide compensation to affected property owners in sending areas and increase the chances of avoiding a regulatory takings claim. Yet, TDR programs can be challenged as there is no clear-cut legal guidance on how to consider TDRs in a takings assessment. In the case of Mustang and North Padre Islands, the current state coastal regulatory framework would support the proposed TDR sending and receiving designations. For example, sending areas intersect beaches and dunes which are protected by OBA and DPA rules and it can be argued that investment-backed expectations are impacted by preexisting regulations. Therefore, the impact of implementing the TDR program in these areas could be regarded as not so onerous as to amount to a regulatory taking. Alas, the same argument would be weaker for bay-side wetlands areas which are primarily protected through Sec. 404 of CWA and TCMP federal consistency requirement. On the other hand, if the implementation of the TDR program is regarded as a regulatory taking but TDR credits are used as compensatory payment for the claim, the value of TDR credits may come under attack. TDR credits may not be as valuable in early stages of the program if the market's demand for TDRs is weak. Consequently, the value of TDR credits by themselves may not constitute sufficient compensation and the local government would have to pay affected landowners in sending areas. Existing Texas TDR programs have eluded the regulatory takings issue altogether by treating their programs as "voluntary" incentives rather than "mandatory" rules. However, this approach has had a negative effect on participation in the programs, which as of this date have not been very active or successful.

An alternative to TDRs could be the implementation of a PDR program to acquire conservation easements in sending and special sending areas. Purchases of development rights on Mustang and North Padre Islands could be prioritized by the land's vulnerability to SLR and episodic coastal flooding, likeliness of being developed in the next 10 years or so, and level of current regulatory protection. For instance, areas that are present critical environments, with development likely to occur by 2020, and are past the 350-ft building setback would be at the top of the list of targeted acquisitions. According to the findings of this study, it would be advantageous to focus PDRs towards the middle of Mustang Island. The funds for PDRs could come from state and local government contributions and appropriations, bonds, private donations, or taxes (Crompton, 2009). Another possible source of funding for PDRs on Texas barrier islands could be NOAA's Coastal and Estuarine Land Conservation Program (CELCP), which matches state and local funds to purchase threatened, but valuable coastal and estuarine lands (NOAA OCRM, 2014a). Unfortunately, the funding for this program has declined from a high $50.6 million in FY 2004 to less than $5.1 million in FY 2012 (NOAA OCRM, 2014b). No additional funds for coastal areas were allocated for FY 2013 (NOAA OCRM, 2014b). Moreover, partnerships with public land trusts or organizations, such as The Nature Conservancy, could help leverage available resources and public support. The implementation of a PDR program may be more feasible than TDR program, provided that local governments are able to secure: (1) sufficient funding for the purchases; and (2) the participation of private landowners in target areas.

6. Conclusions

Barrier islands communities in Texas could implement TDR programs as a land-use policy tool to increase their resilience to the effects of storms and SLR. A TDR program would allow communities to further regulate the type and uses of the land in hazardous areas and preserve critical environments, such as dunes, beaches, and wetlands that protect inland areas. TDR programs are attractive because they can create a monetary incentive for preservation of environmentally sensitive areas while providing a compensation mechanism for impacted landowners. Thus, TDR programs allow local governments to use the market to fund land preservation and drive future development towards more desirable areas. Moreover, in the case of Texas, a TDR program would complement current coastal regulations to provide enough protection to present and future locations of critical barrier island environments.

A TDR program may be a sensible land-use policy tool capable of addressing the realities of a dynamic coastal environment and balancing, to a certain extent, private and public interests. However, aside from the administrative complexity of managing such a program, its implementation usually poses economic and regulatory challenges that some barrier island communities may not be ready to undertake. A less complex alternative to TDRs could be establishment of a PDR program. Land-use planning has long been suggested as an effective strategy to increase community resilience; yet, it is not always the first or the easiest alternative. Ultimately, the approach taken by each barrier island community to increase its resilience will be influenced by political, social, legal, and economic factors.

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CHAPTER V

Conclusions and Future research

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1. Conclusions

Corpus Christi and Port Aransas can effectively increase their physical resilience by guiding growth outside of hazardous areas and preserving current and future locations of critical environments that mitigate and protect inland areas from the effects of erosion, relative sea-level rise (RSLR), and storm-surge flooding. Through land-use planning, both communities can limit the amount of people and infrastructure exposed to hazards; thus, greatly reducing the risk of future losses or damage. Mustang and North Padre Islands are expected to experience profound changes in the next 60 years as barrier islands respond to ongoing erosion and RSLR. According to the geohazards map analysis, close to 50% of the study area is expected to change, meaning that both communities will need to consider taking action to protect, accommodate, or retreat from large areas on the islands. The remaining 50% of the study area is not expected to change; however, most of Mustang Island is vulnerable to flooding by 100-year flood (storm) event. The geohazards map presents only one possible scenario of the islands' response to RSLR and it is important to note that it may be a conservative one. For the development of the geohazards map, it was assumed that current RSLR, shoreline erosion, and vertical accretion rates would continue unchanged for the next 60 years; which, in reality, may not be the case. Studies project an acceleration of the global sea-level rate over the next century, which in turn, would likely accelerate local RSLR beyond 5.6 mm/yr and worsen erosion rates on bay and gulf shores (IPCC, 2013; Nicholls and Cazenave, 2010). Higher RLSR rates may have a short-term enhancing effect on marsh vertical accretion resulting in wetlands gains; however, sustained acceleration of RSLR rates may outpace vertical accretion and drown marshes leading to net long-term marsh losses. As a result, the area projected to be either inundated or have transitioned into a different environment may occur in a shorter period or may cover a larger extension than initially estimated. Moreover, the right storm, or slight changes in future erosion, sedimentation, or RSLR rates can adversely affect the vulnerability of less hazardous areas.

Beaches and foredunes in Mustang and North Padre Islands provide protection against surge and wave action resulting from storms. The level of protection afforded by these features varies across the islands, making some areas more vulnerable to overwash and inundation during lesser-intensity storms. Close to 55% of the assessed beach-dune areas provide overwash protection against at least a 100-yr storm. Beaches and foredunes in the study area cover roughly 6.9 sq. km; however, this narrow strip saves an estimated $141.4 million/yr in storm protection (seawall construction) expenditures. This monetary figure does not take into account other ecosystem services that beaches and foredunes provide, such as recreation and aesthetics; therefore, it is safe to assume that a more inclusive valuation study would yield an even higher monetary value for these geomomorphic features. Similar to the geohazards map, the assessment of the level of storm (overwash) protection represents a snapshot based on the state of beaches and foredunes in 2010. Thus, the level of protection of beaches and foredunes may change with the impacts of future erosion, RSLR, and tropical storms. Preserving beaches and foredunes is important for the physical resilience of barrier island communities as they act natural defenses and sand reservoirs that dampen wave energy and provide protection against coastal flooding and storm-surge.

In this study, a transfer of development rights (TDR) program was explored as a land-use policy tool capable of addressing multiple concerns of barrier island communities, including (1) guiding development away from hazardous areas; (2) preserving valuable present and future locations of critical environments; and (3) tending to public and private development interests. Currently, Mustang and North Padre Islands are relatively undeveloped; however, both Corpus

Christi and Port Aransas have planned future growth in hazardous areas towards the middle section of Mustang Island, and several properties have been platted in close proximity to dunes, wetlands, and other areas that would potentially transition into a different environment in the next decades. Even though current federal and state regulations offer some protection for these environments, development pressure is still a latent threat. The proposed TDR area designations based on the land suitability analysis results in: 17% (16.8 sq. km) of the study area classified as sending areas, 8.7% (8.4 sq. km) as special sending areas, 23.5% (22.8 sq. km) as receiving areas, and 50.6 % (49.1 sq. km) as reserved areas. Most of the receiving areas within Corpus Christi's ETJ (15.2 sq. km) are evenly distributed in North Padre Island, while most of the receiving areas within Port Aransas's ETJ (7.6 sq. km) are clustered towards the north end of Mustang Island. An analysis of current developed parcels reveals that, in theory, these parcels could be entirely accommodated in designated receiving areas and still have land available for future growth in relatively safe areas.

Although a TDR program on Mustang and North Padre Islands may be a sensible land-use policy tool capable of addressing the realities of a dynamic coastal environment, its implementation would pose some complex economic and regulatory challenges to local governments. Some of the issues include: (1) creating a demand for denser development; (2) the temporary erosion of the tax base due to restricted development in sending areas; and (3) ambiguous legal guidance on how to consider TDRs in a regulatory takings challenge. At the moment, these issues represent difficult obstacles for the implementation of a TDR program. Nevertheless, future conditions may ease these hurdles by restricting the amount of land available for development, forcing development to concentrate towards the core of the islands, and favoring higher densities to meet market demands.

Corpus Christi and Port Aransas are faced with important decisions regarding future growth on Mustang and North Padre Islands. Both communities are at a crucial point where the decisions they make today will impact their ability to adapt to changing environmental conditions over the next decades. The work in this dissertation focused on developing information and analyses that could inform these decisions and help these barrier island communities take action to increase their physical resilience and adaptability to sea-level rise (SLR) in coming decades.

2. Future research

The work in this dissertation can be further improved by expanding on the following topics: (1) modeling different SLR scenarios for the geohazards map; (2) using XBeach to model beach-dune profile response to storms; and (3) incorporating impacts to the property tax base and urban form considerations for a TDR program implementation. As mentioned before, the geohazards map shows only one possibility on how barrier island environments may transition due to the effects of RSLR. Hence, it would be informative to include maps presenting different outcomes, along with confidence intervals, based on the full range SLR predictions. The response of beach-dune profiles to storms was modeled using SBEACH, a two-dimensional empirical model developed from field and wave-tank experiments that relies mainly on cross-shore processes as drivers of change (Larson and Kraus, 1989; Rosati et al., 1993).

The SBEACH model assumes sediment conservation within the profile and neglects alongshore processes. In spite of these assumptions, SBEACH was selected because it has been used in local studies and other areas, extensive documentation is available, and it allowed for the modeling of multiple storms using our local computing resources. During the development of this dissertation, XBeach was fully released and quickly gained popularity within the scientific community. XBeach is a numerical model that solves 2HD equations for cross- and long-shore hydrodynamics and morphodynamic changes (McCall et al., 2010; Roelvink et al., 2009). The main improvement of using XBeach over SBEACH is the ability to incorporate the effect of alongshore variability on forcings and the morphologic response of nearshore features (McCall et al., 2010; Roelvink et al., 2009). Thus, outputs from XBeach could result in a more realistic representation of the level of protection provided by beaches and foredunes. Using XBeach would also eliminate the need for topographic data reduction, such as the profile clustering technique presented on chapter III, by allowing the use of the entire barrier island DEM as an input.

Finally, an analysis of the potential impacts to the property tax base resulting from a TDR program implementation could provide much needed insight to local governments considering more restrictive, but environmentally sound land-use policies. Plans and policies aimed at limiting development, even when the goal is to prevent further urbanization of hazardous locations, will likely be met with initial community and political resistance. However, if favorable economic arguments could be presented in support of more sensible land-use policies, there is the possibility of countering some of this initial resistance to even consider implementing policies such as a TDR program. Part of the success of a TDR program, at least on barrier islands, will depend on the ability to create the levels density and activity to support its economic viability. Therefore, discussions about the urban form required for the successful implementation of a TDR program would be informative. This urban form is very likely to be different from current low-density development patterns.

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APPENDIX A: Table and figures Chapter II

Table A.1 Geo-environments descriptions for Mustang and North Padre Islands.

Code	Habitat code	Environment	Description
1	E1AB3	sea grass	Estuarine, subtidal habitat with rooted, vascular aquatic beds.
2	E1UB	water	Estuarine, subtidal habitat with an unconsolidated bottom.
3	E2EM1N	low marsh	Estuarine, intertidal wetland with emergent vegetation that is persistent and regularly flooded.
4	E2EM1P	high marsh	Estuarine, intertidal wetland with emergent vegetation that is persistent and irregularly flooded.
5	E2SS	estuarine scrub shrub	Estuarine, intertidal wetland with scrub-shrub vegetation (not mangrove).
6	E2USN	low flat	Estuarine, intertidal wetland with an unconsolidated bottom that is regularly flooded.
7	E2USP	high flat	Estuarine, intertidal wetland with an unconsolidated bottom that is irregularly flooded.
8	M1UB	water	Marine, subtidal habitat with an unconsolidated bottom.
9	M2USP	shore-upper	Marine, intertidal habitat with an unconsolidated shore that is irregularly flooded.
10	PEM1A	temp. flooded	Palustrine (non-tidal) wetland with emergent vegetation that is persistent and temporarily flooded.
11	PSS1A	palustrine scrub shrub	Palustrine broad-leaved deciduous vegetation (scrub-shrub) that is temporarily flooded.
12	PUB	water	Palustrine wetland with an unconsolidated bottom.
13	PUS	fresh flat	Palustrine flat.
15	PEM1F	semi-perm. flooded	Palustrine wetland with emergent vegetation that is persistent and semipermanently flooded.
16	E2SS3	scrub shrub broad leaved evergreen	Intertidal estuarine wetland with broad-leaved evergreen, scrub-shrub vegetation (mangrove).
17	PEM1C	seasonally flooded	Palustrine wetland with emergent vegetation that is persistent and seasonally flooded.
18	M2USN	shore-lower	Marine, intertidal habitat with an unconsolidated shore that is regularly flooded
22	E2USM	irregularly exposed flat	Estuarine, intertidal unconsolidated shore which is irregularly exposed by tidal fluctuations
23	PUBHx	water, perm. flooded, excavated	Palustrine, unconsolidated bottom feature which is permanently flooded. Excavated feature.
27	E2USNs	low flat on spoil	Estuarine, intertidal wetland with an unconsolidated bottom that is regularly flooded. Wetland on dredged spoil material.
28	E2USPs	high flat on spoil	Estuarine, intertidal wetland with an unconsolidated bottom that is irregularly flooded. Wetland on dredged spoil material.
29	E2EM1Ns	low marsh on spoil	Estuarine, intertidal wetland with emergent vegetation that is persistent and regularly flooded. Wetland on dredged spoil material.
30	E2EM1Ps	high marsh on spoil	Estuarine, intertidal wetland with emergent vegetation that is persistent and irregularly flooded. Wetland on dredged spoil material.
35	E1AB1	algae	Estuarine, subtidal algal aquatic bed.
38	PUBKh	palustrine pond artificially flooded diked	Palustrine, unconsolidated bottom which has been artificially flooded, diked.
39	PUSh	palustrine flat diked	Palustrine flat, diked.

42	PUSCx	palustrine flat seasonally flooded excavated	Palustrine flat that is seasonally flooded within an excavated feature.
43	PEM1Ah	palustrine marsh temp. flooded, diked	Palustrine wetland with persistent emergent vegetation that is temporarily flooded, diked.
45	E2USNx	estuarine low flat excavated	Estuarine, intertidal wetland with an unconsolidated bottom that is regularly flooded within an excavated feature.
46	E1UBx	estuarine water excavated	Estuarine, subtidal habitat with an unconsolidated bottom. Excavated feature.
50	PEM1Ch	seasonally flooded marsh diked/impounded	Palustrine wetland with persistent emergent vegetation that is seasonally flooded, diked or impounded.
52	PUBCh	water, seasonally flooded diked/impounded	Palustrine unconsolidated bottom that is seasonally flooded, diked.
53	PFO1A	palustrine forest	Palustrine, broad-leaved deciduous trees.
55	E1RF2M	subtidal reef irregularly exposed	Estuarine, subtidal mollusk (oyster) reef irregularly exposed.
58	E1AB3x	sea grass excavated	Estuarine, subtidal habitat with rooted, vascular aquatic beds within an excavated feature.
61	E2AB1P	high algal flat	Estuarine, intertidal algal aquatic bed that is irregularly flooded by tidal fluctuations.
62	E2AB1N	low algal flat	Estuarine, intertidal algal aquatic bed that is regularly flooded by tidal fluctuations.
66	E2AB1Ns	low algal flat on spoil	Estuarine, intertidal algal aquatic bed that is regularly flooded by tidal fluctuations. Aquatic bed on dredged spoil material.
69	UVF	upland vegetated flat	Generally flat terrain found in the interior part of the barrier island, which is densely vegetated.
73	ML	modified land	Upland, undeveloped areas in which the land has been modified by mechanical means.
74	WC	washover channel	Low relief unvegetated features formed from the flow of water over the crest of the beach during high storm surge conditions.
76	FIDC	fore-island dune complex	Stable, mostly vegetated features formed from the accumulation of windblown sand located on the seaward boundary of the barrier island. The foredune complex is composed of coppice mounds, foredunes, and the foredune ridge. These are critical dune environments
81	MIDC	mid-island dune complex	Cluster or chain of dune features higher than 2 meters located in the interior part of the barrier island.
82	MID	mid-island dune	Dune features higher than 2 meters located in the interior part of the barrier island.
83	BO	dune blowout	Sandy depression devoid of vegetation, usually within or near other dune features.
84	UH	upland hummocky	Low relief, hummocky environment found in the interior part of the barrier island, which is densely vegetated.
101	UDRSS	upland developed within rural, suburban, and park settings	Includes blocks of developed parcels state tax code of residential within rural setting, low-density residential or with tax code of non-qualified lands within state or county park property.
102	UDUI	upland developed within urban and	Includes blocks of developed parcels with state tax codes of residential, commercial or utilities. Some vacant lots

		industrial	were included if located within developed blocks. Includes minor roads and parking lots.
103	URC	upland major corridor	Major road.
108	UDHR	upland developed high-rise	Includes blocks of developed parcels with building structures of 4 stories or higher and associated amenities, such as parking lots and pools.
109	UJ	jetties	Stone structures at navigational channels to prevent sand from depositing in the channel and provide wave protection for vessels.
110	UP	pier	Continuous wooden or concrete structure stretching from the beach into the surf that provides sightseeing opportunities.

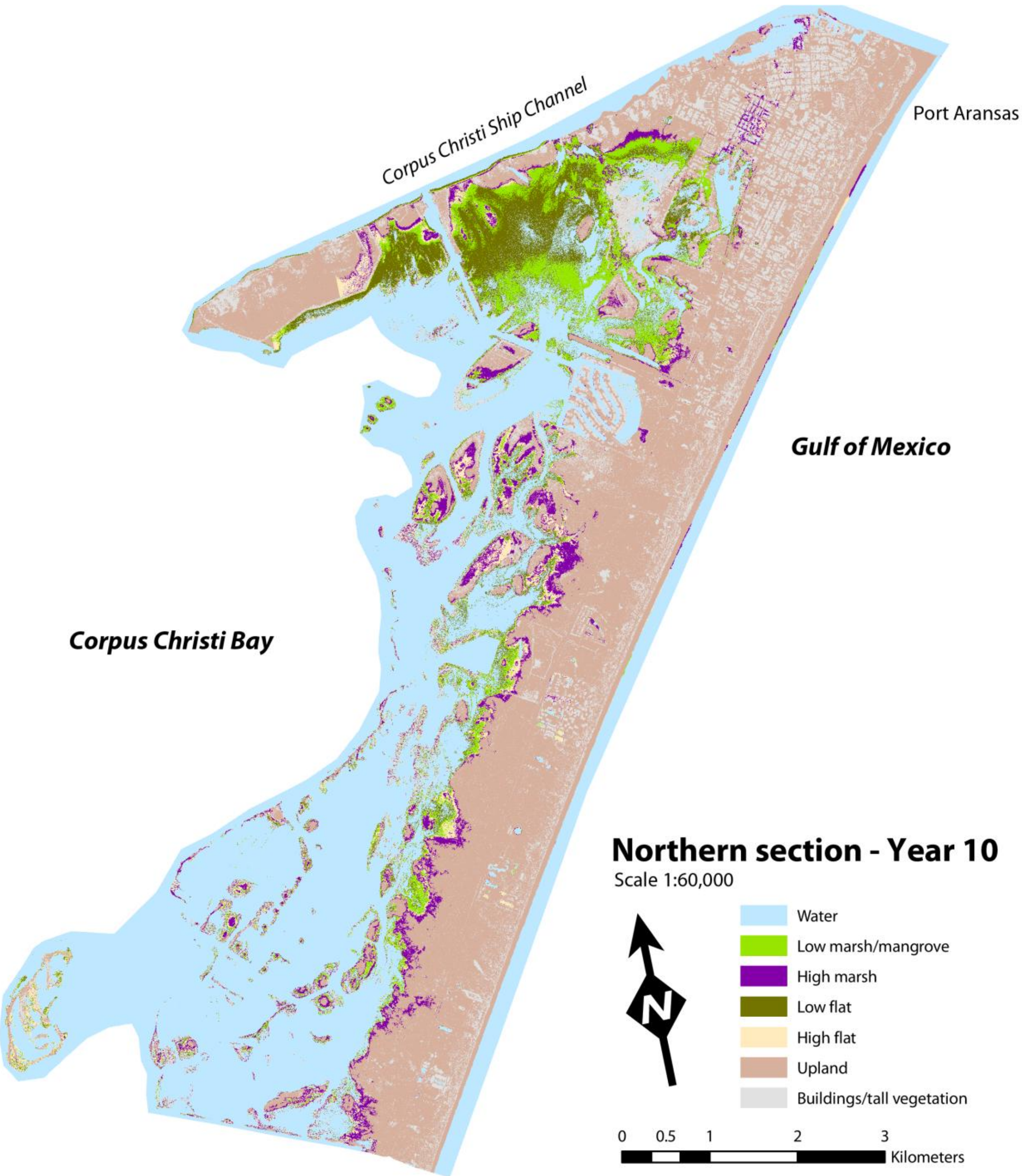

Figure A.1 Output from wetland transition model, northern section of study area, year 10. From Gibeaut et al., 2011.

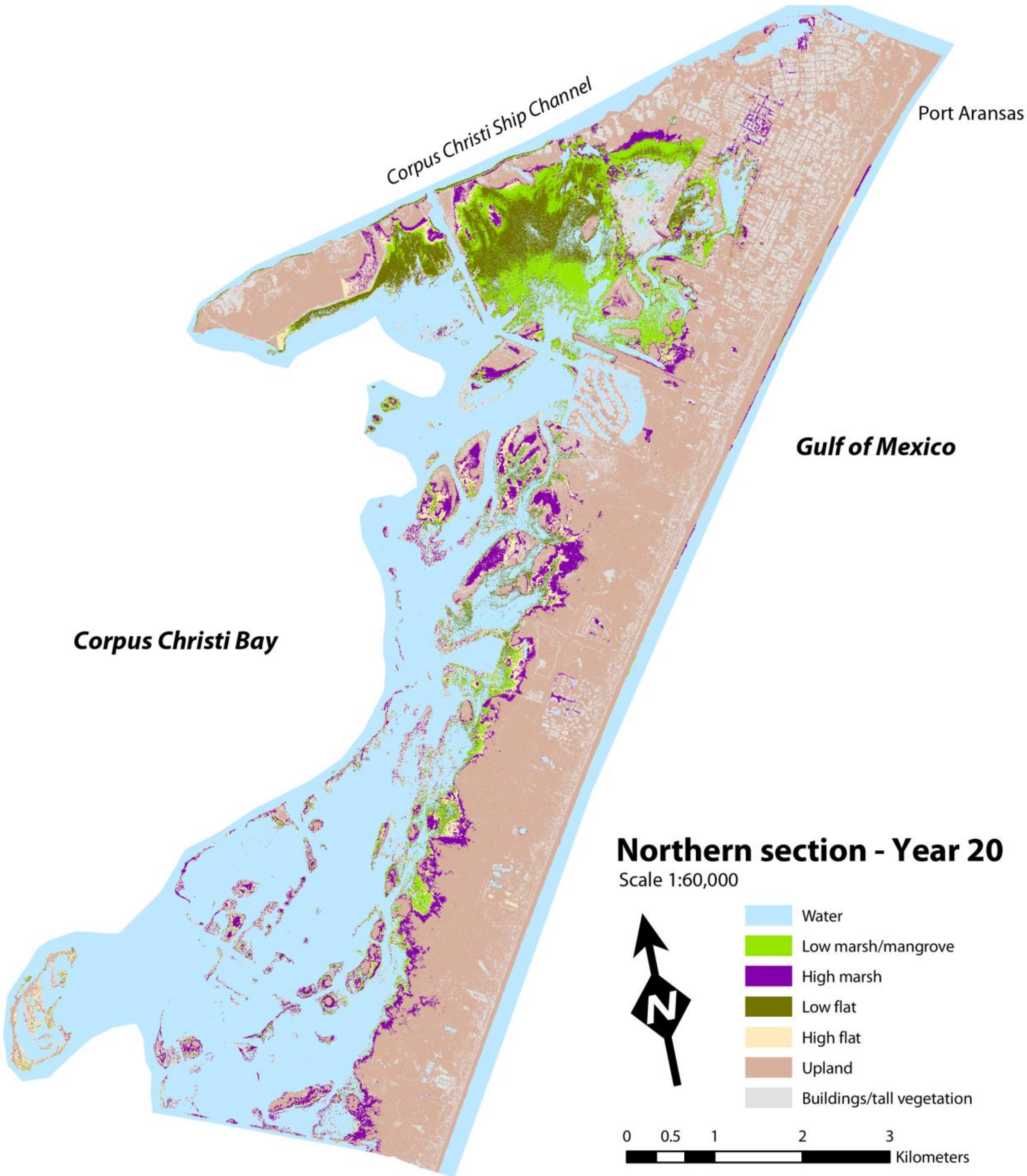

Figure A.2 Output from wetland transition model, northern section of study area, year 20. From Gibeaut et al., 2011.

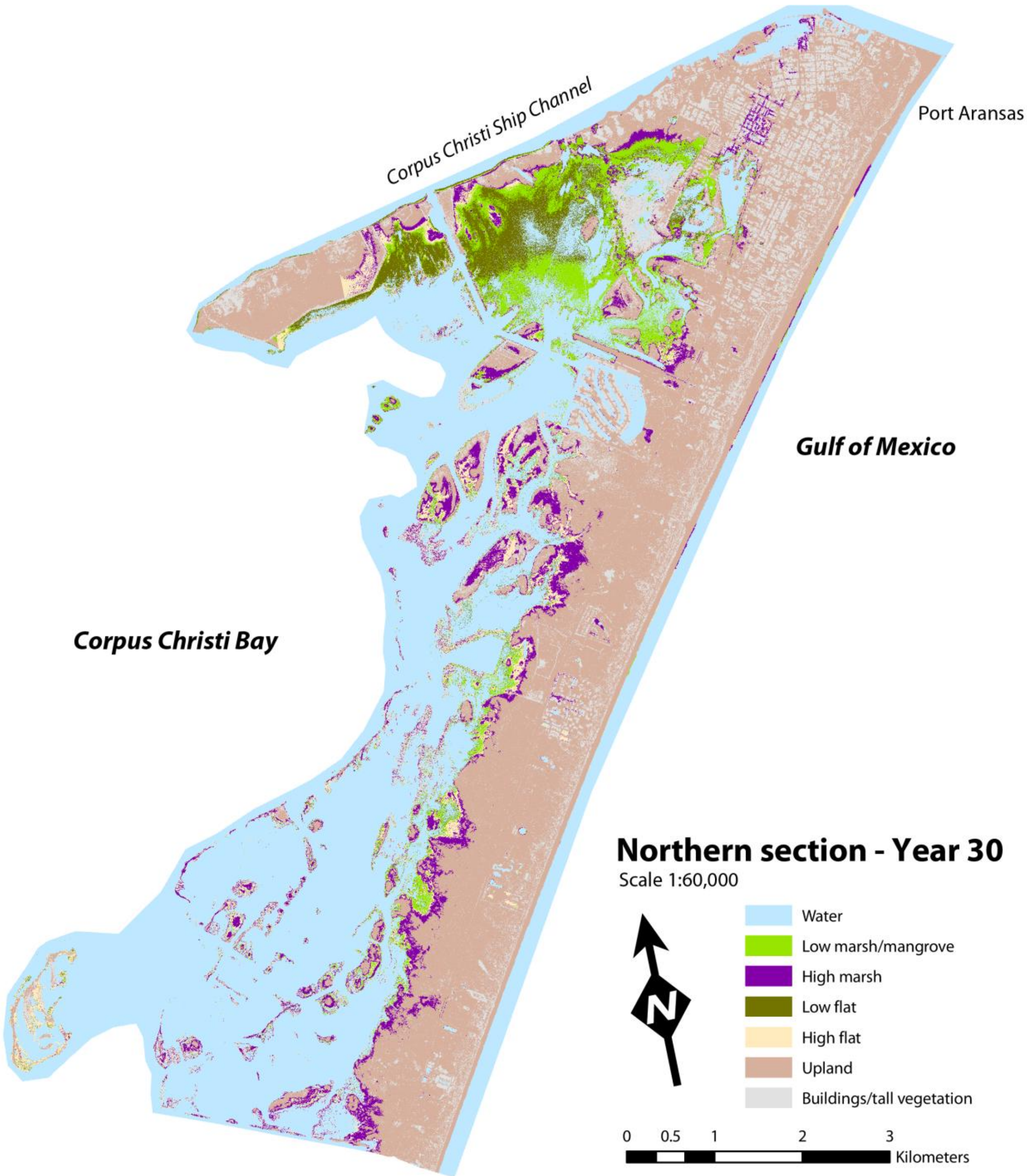

Figure A.3 Output from wetland transition model, northern section of study area, year 30. From Gibeaut et al., 2011.

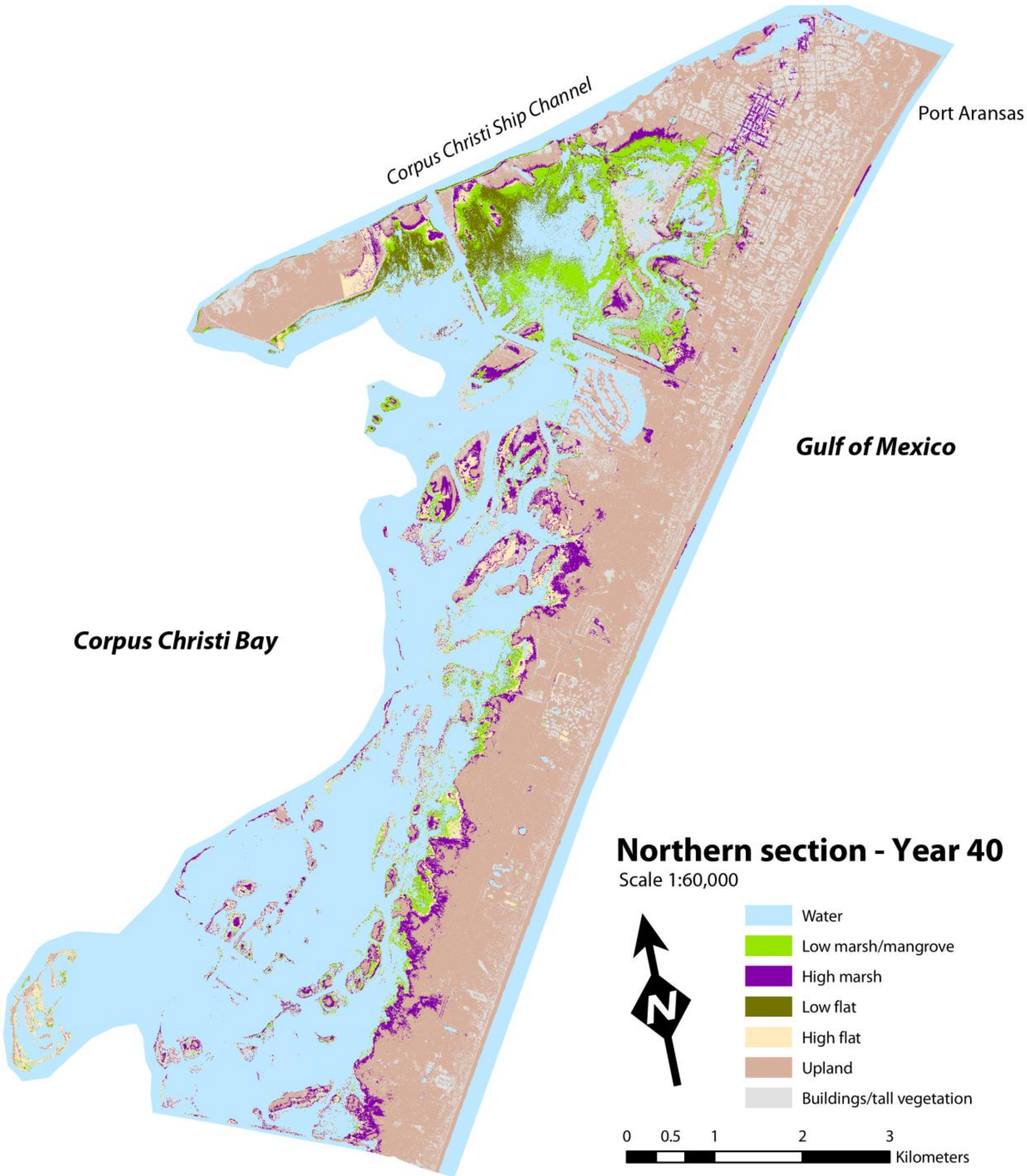

Figure A.4 Output from wetland transition model, northern section of study area, year 40. From Gibeaut et al., 2011.

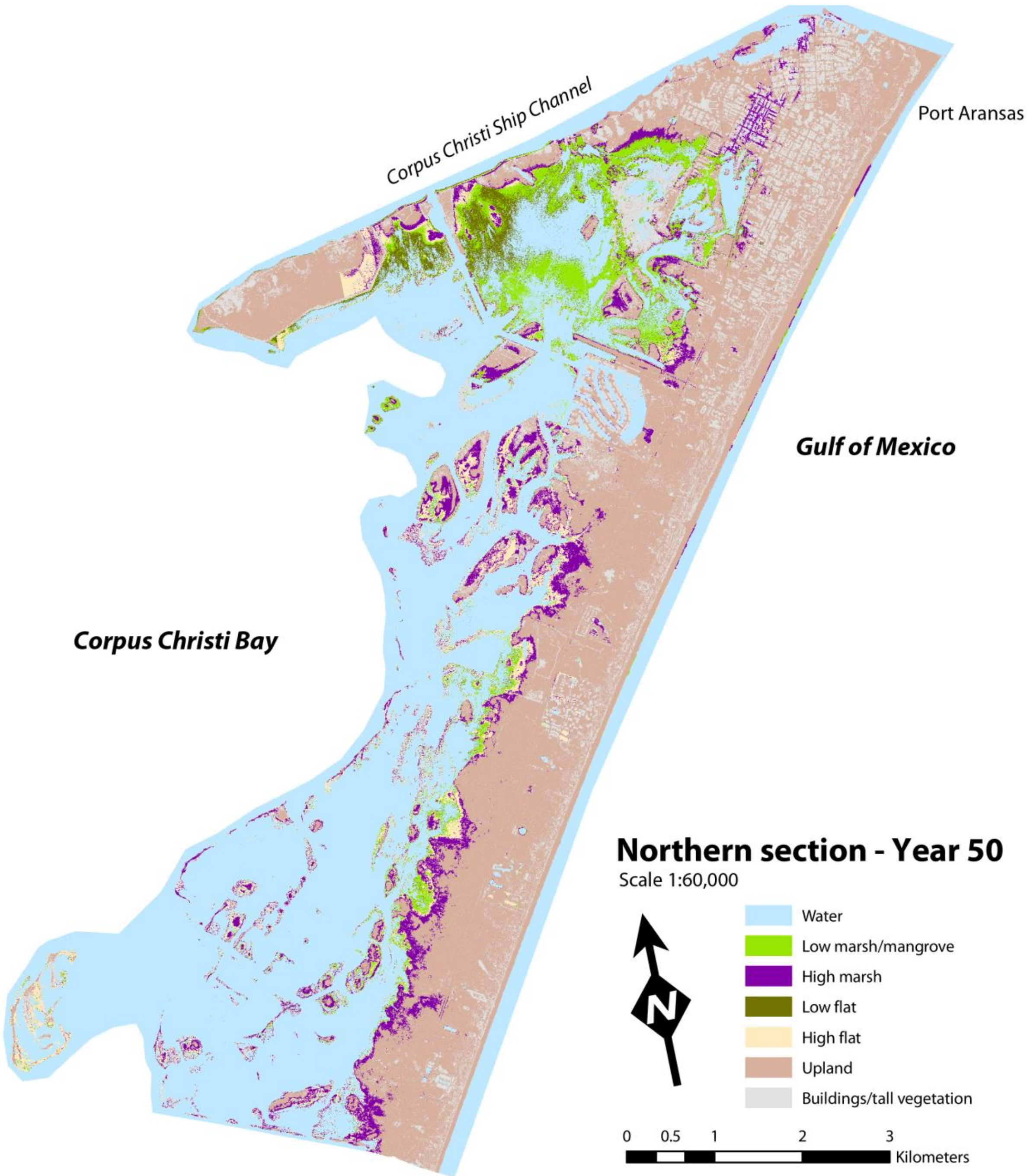

Figure A.5 Output from wetland transition model, northern section of study area, year 50. From Gibeaut et al., 2011.

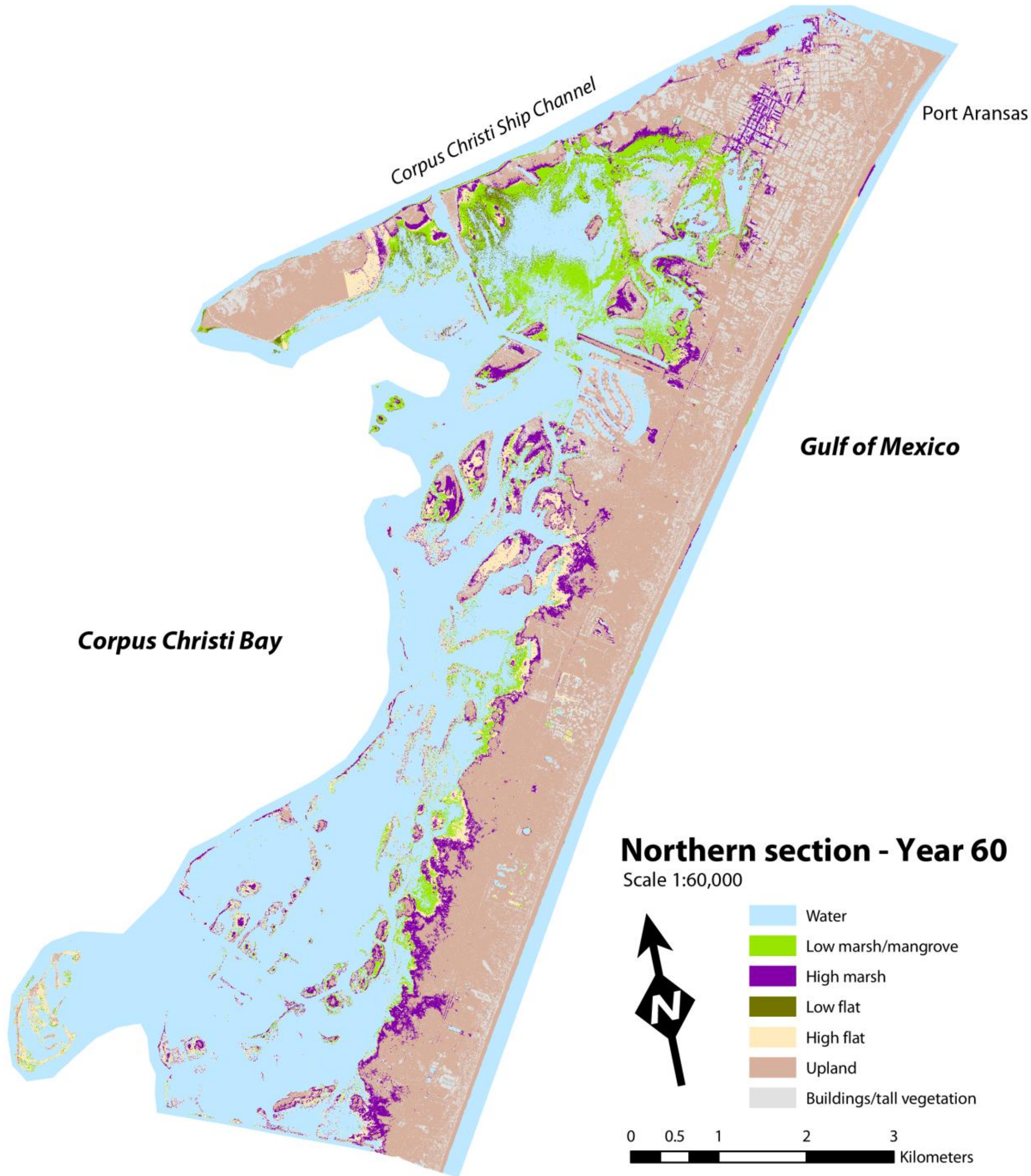

Figure A.6 Output from wetland transition model, northern section of study area, year 60. From Gibeaut et al., 2011.

APPENDIX B: Maps Chapter IV

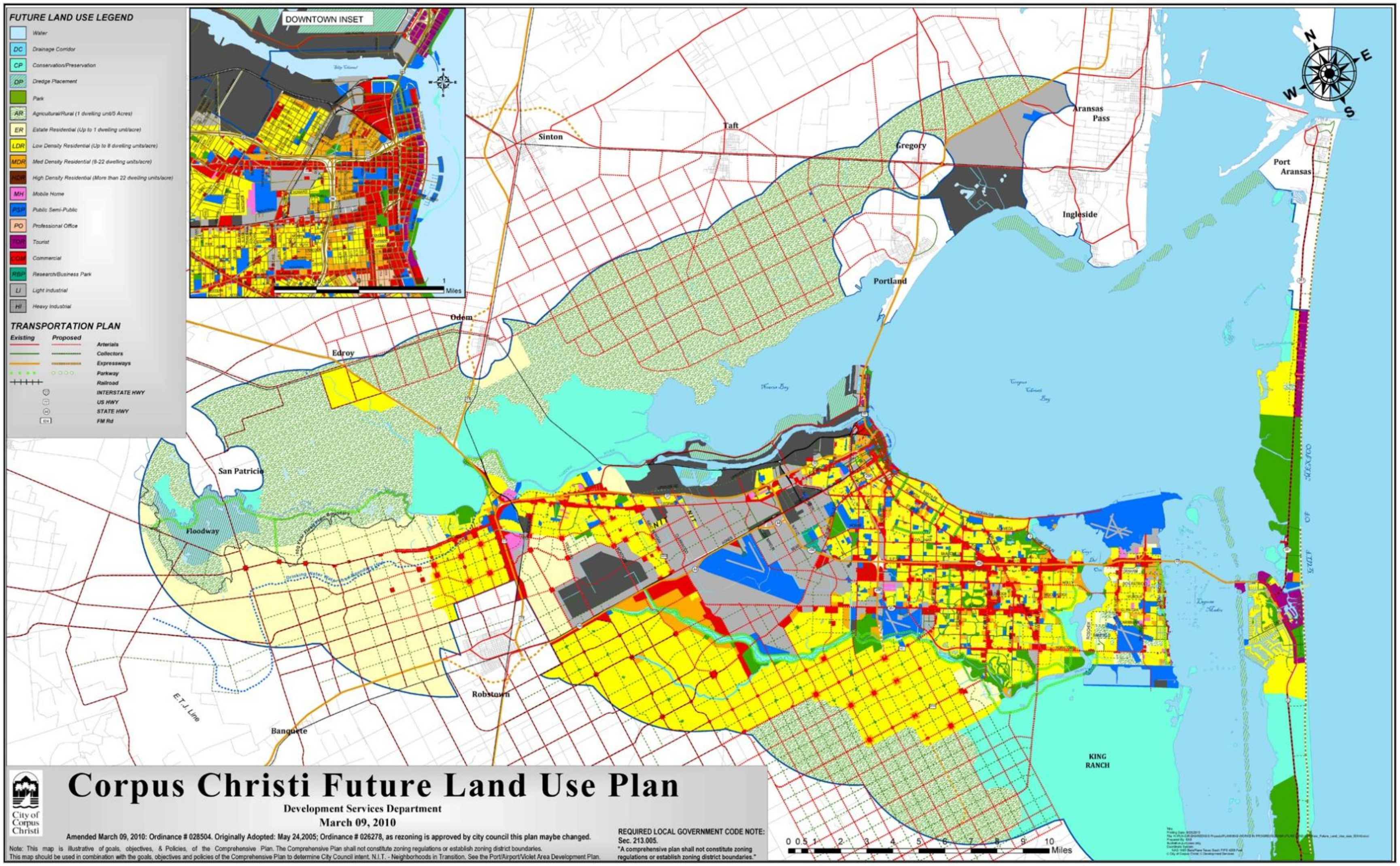

Figure 4.4. Corpus Christi Future Land Use Plan
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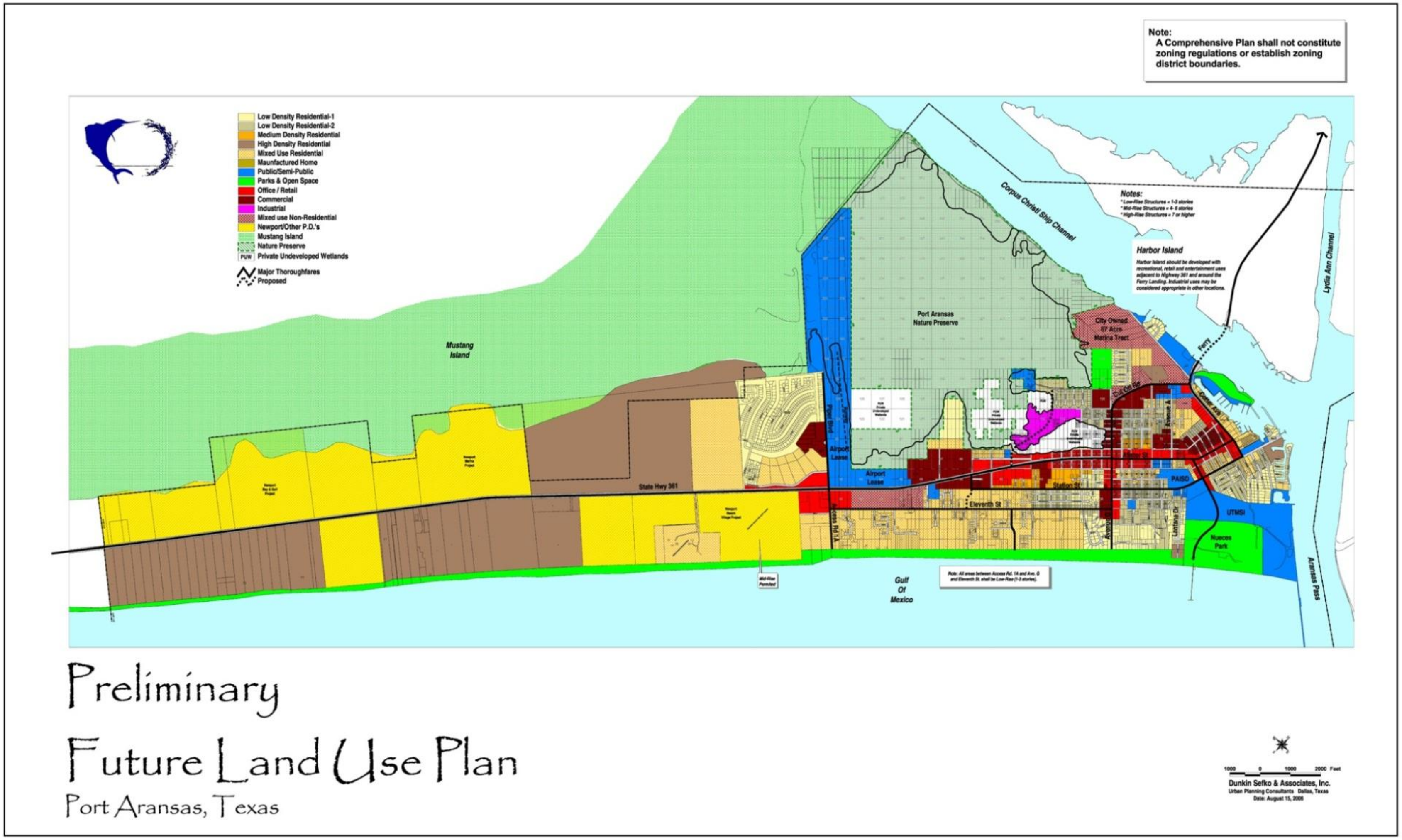

Figure 4.5. Port Aransas Future Land Use Plan
http://www.cityofportaransas.org/pdf/flup-all_08061.pdf

Figure 4.6. Mustang and North Padre Islands, Texas. Map sections.

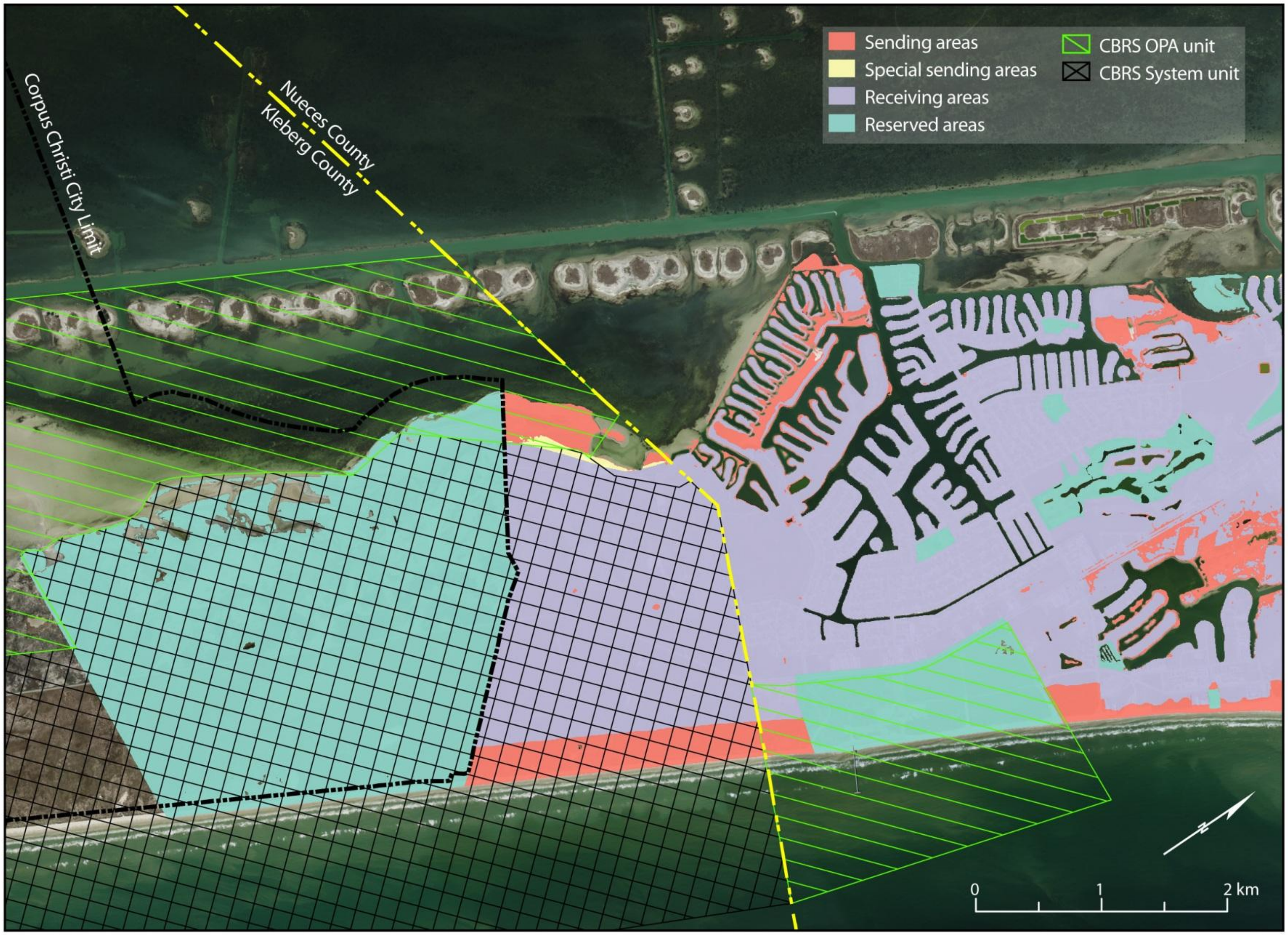

Figure 4.7A. TDR sending and receiving areas section A.
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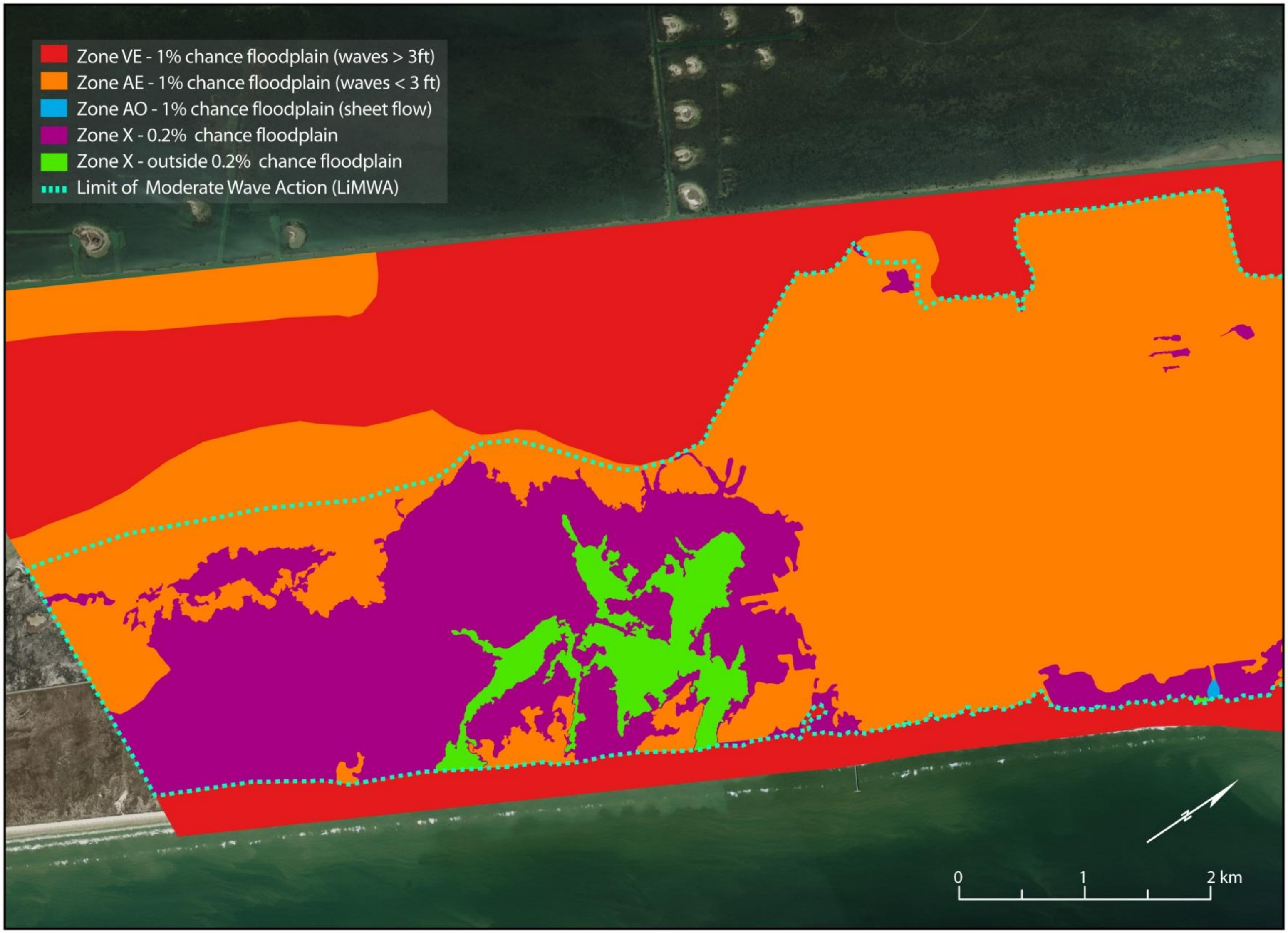


Figure 4.8A. FIRM map section A.
Map scale 1:50,000. Projection : NAD 1983 UTM 14N.

Figure 4.9A. Geohazards map section A.
Map scale 1:50,000. Projection: NAD 1983 UTM 14N.

Figure 4.10A. Regulatory map section A.
Map scale 1:50,000. Projection : NAD 1983 UTM 14N.

Figure 4.11A. Base map section A.
Map scale 1:50,000. Projection : NAD 1983 UTM 14N. Source: National Agriculture Imagery Program (2009).

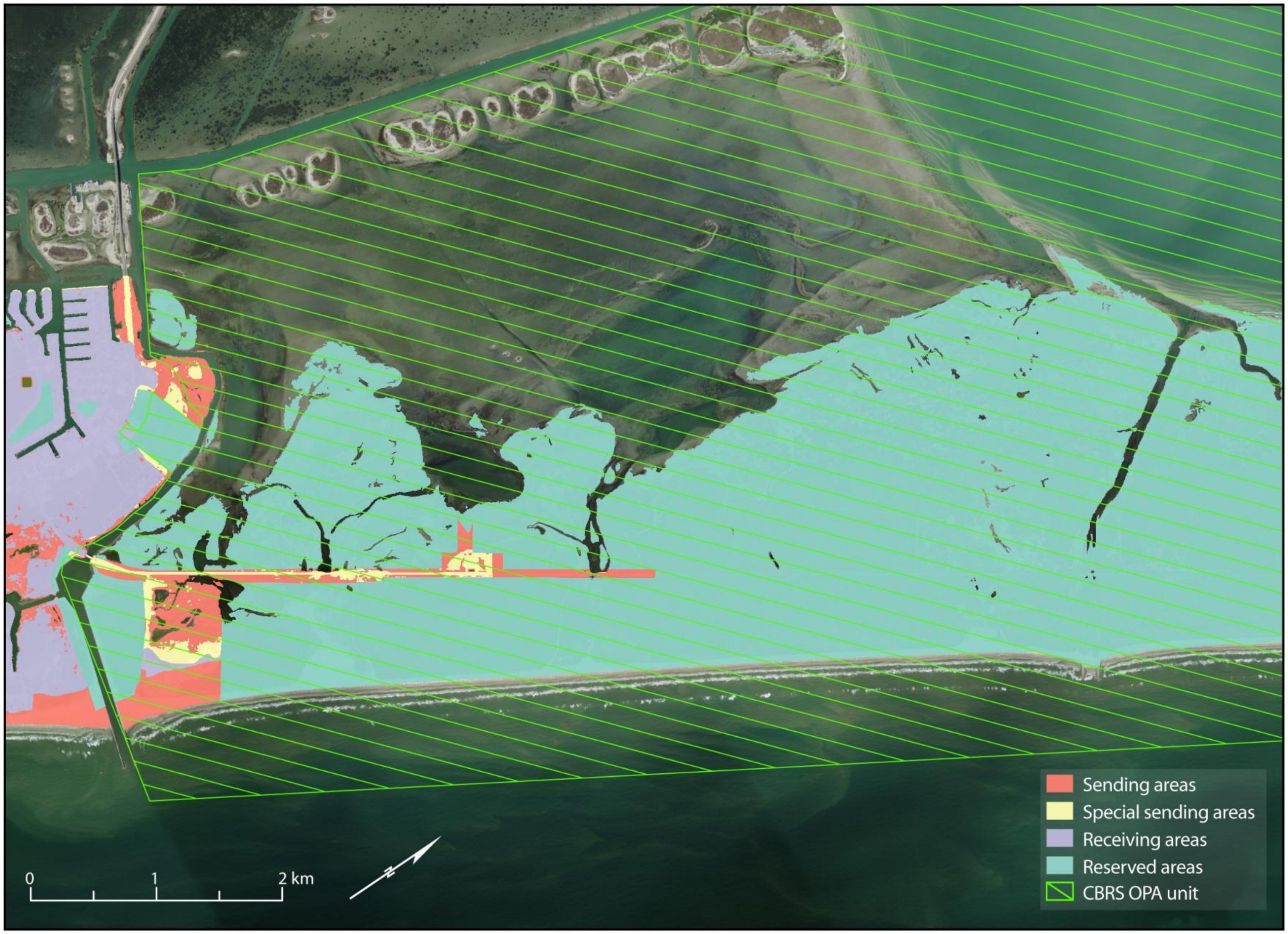
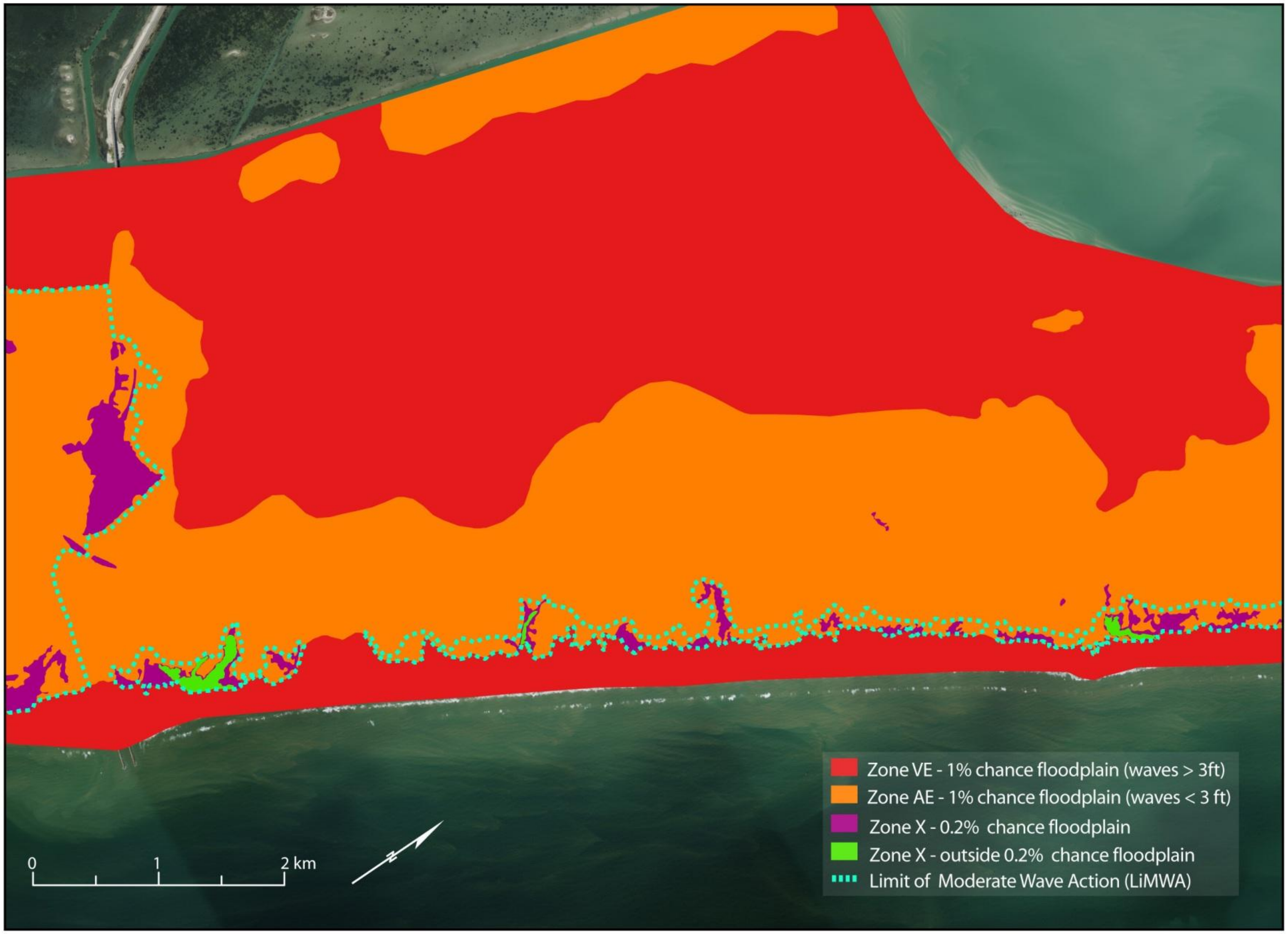


Figure 4.7B. TDR sending and receiving areas section B.
Map scale 1:50,000. Projection: NAD 1983 UTM 14N.



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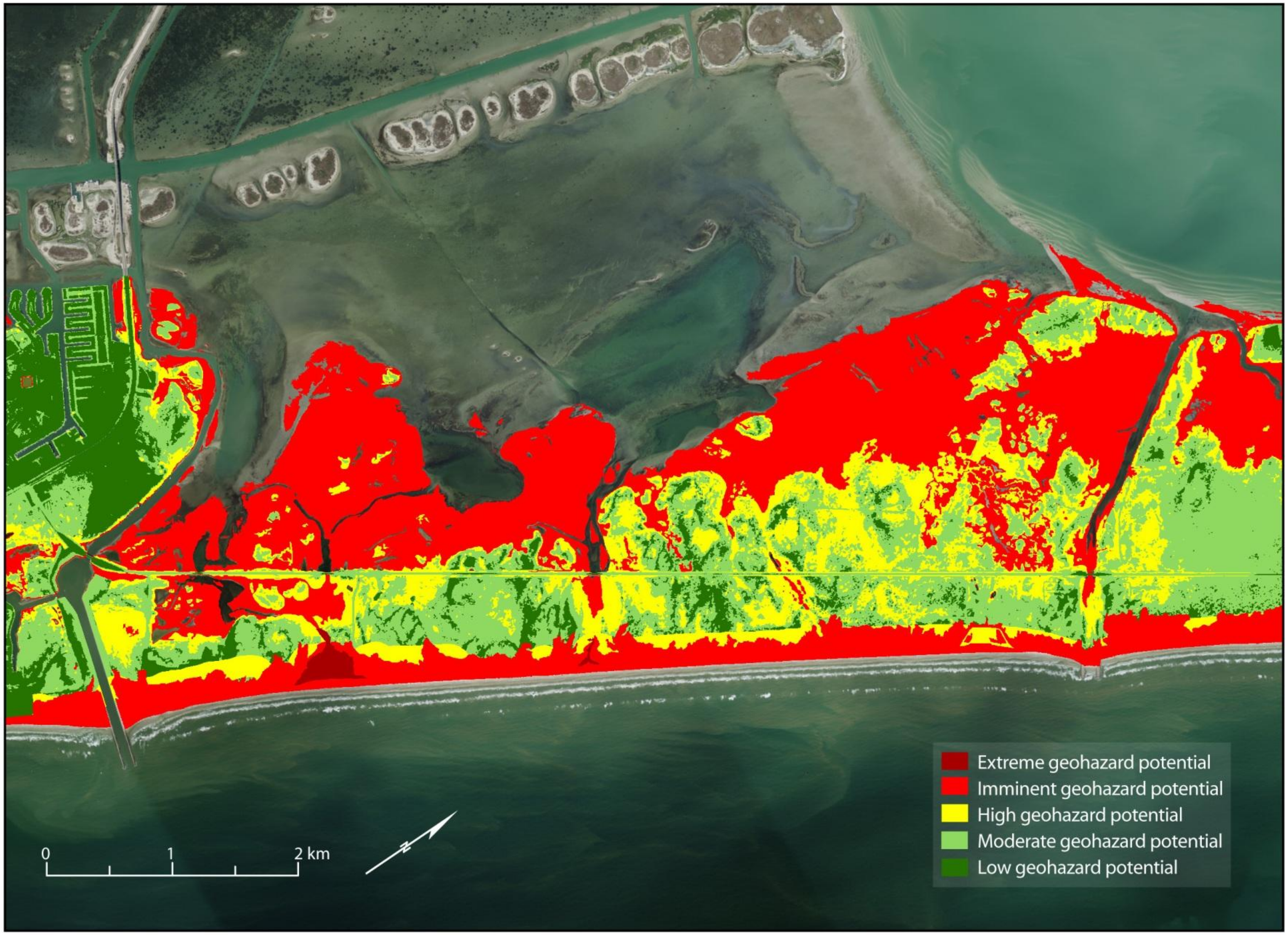

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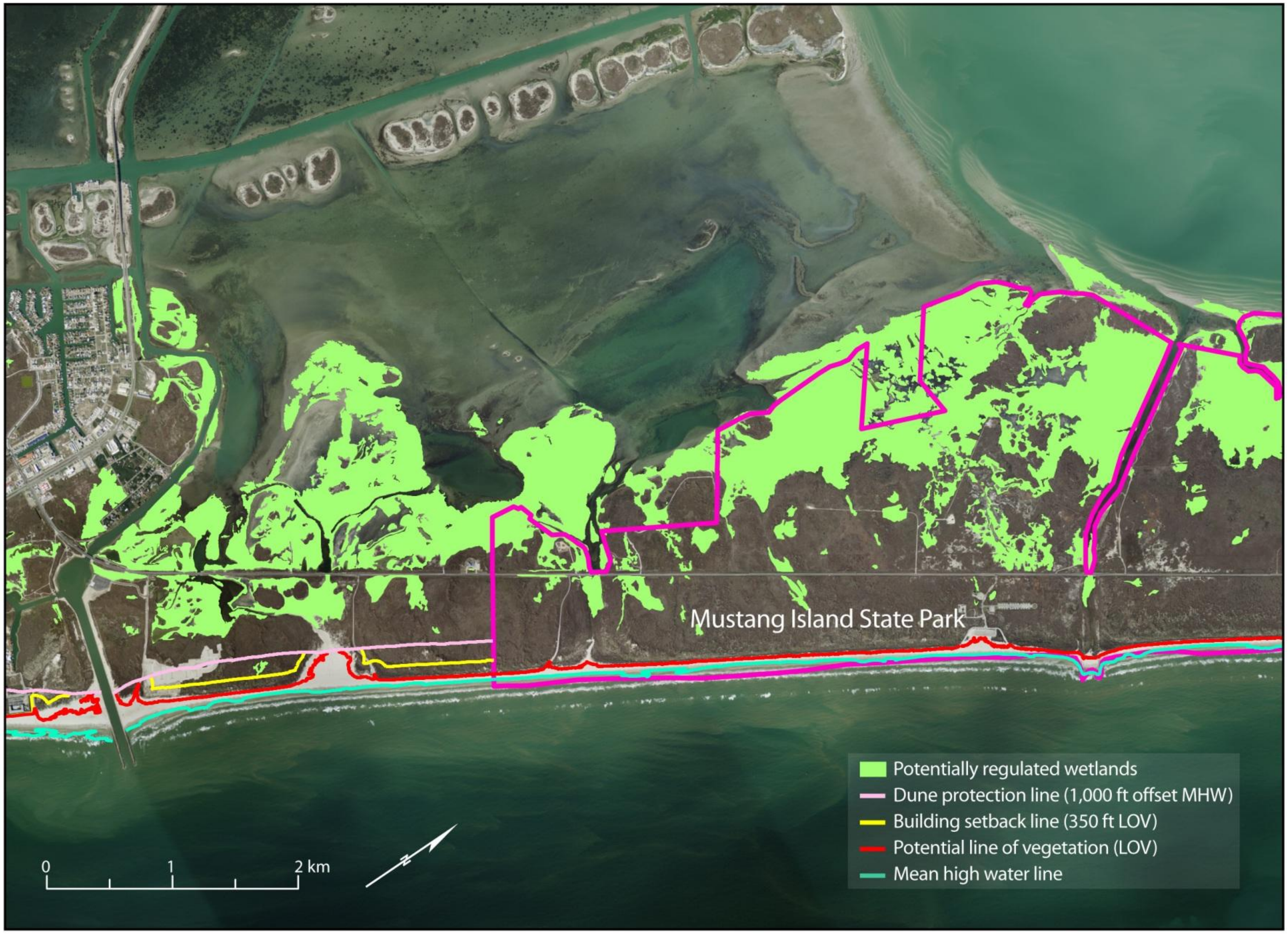

Figure 4.10B. Regulatory map section B.
Map scale 1:50,000. Projection: NAD 1983 UTM 14N.

Figure 4.11B. Base map section B.
Map scale 1:50,000. Projection : NAD 1983 UTM 14N. Source: National Agriculture Imagery Program (2009).

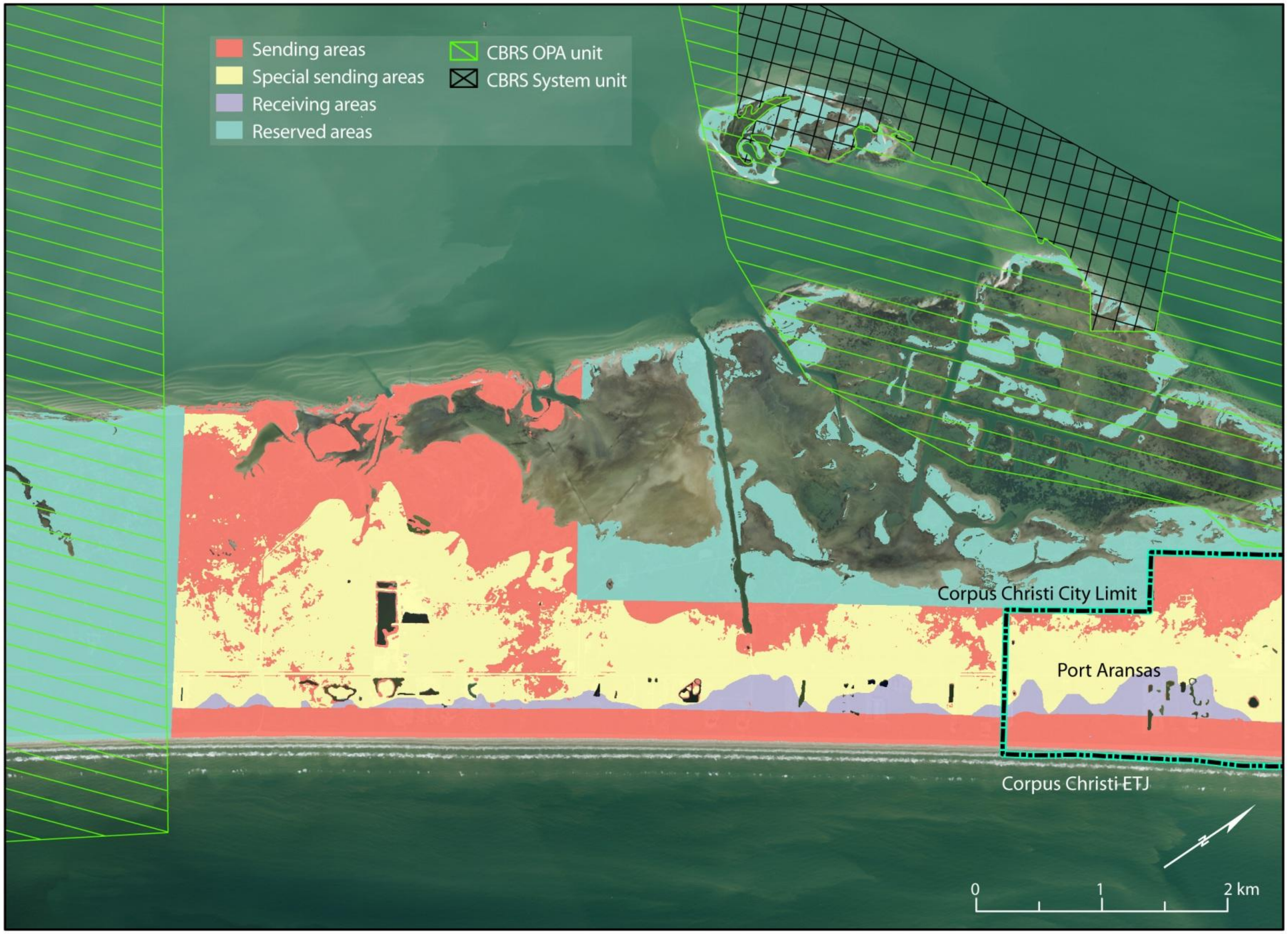

Figure 4.7C. TDR sending and receiving areas section C.
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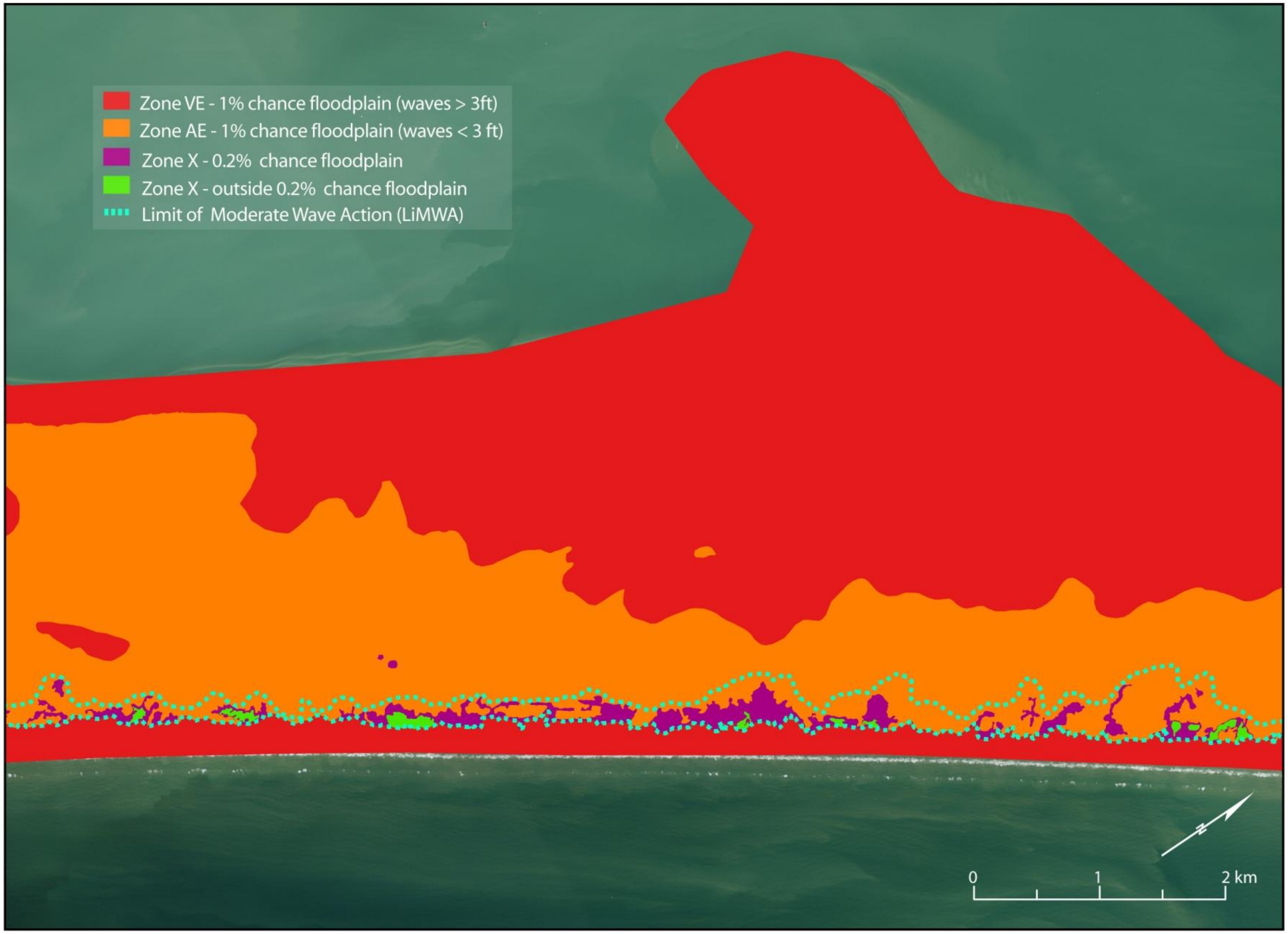

Figure 4.8C. FIRM map section C.
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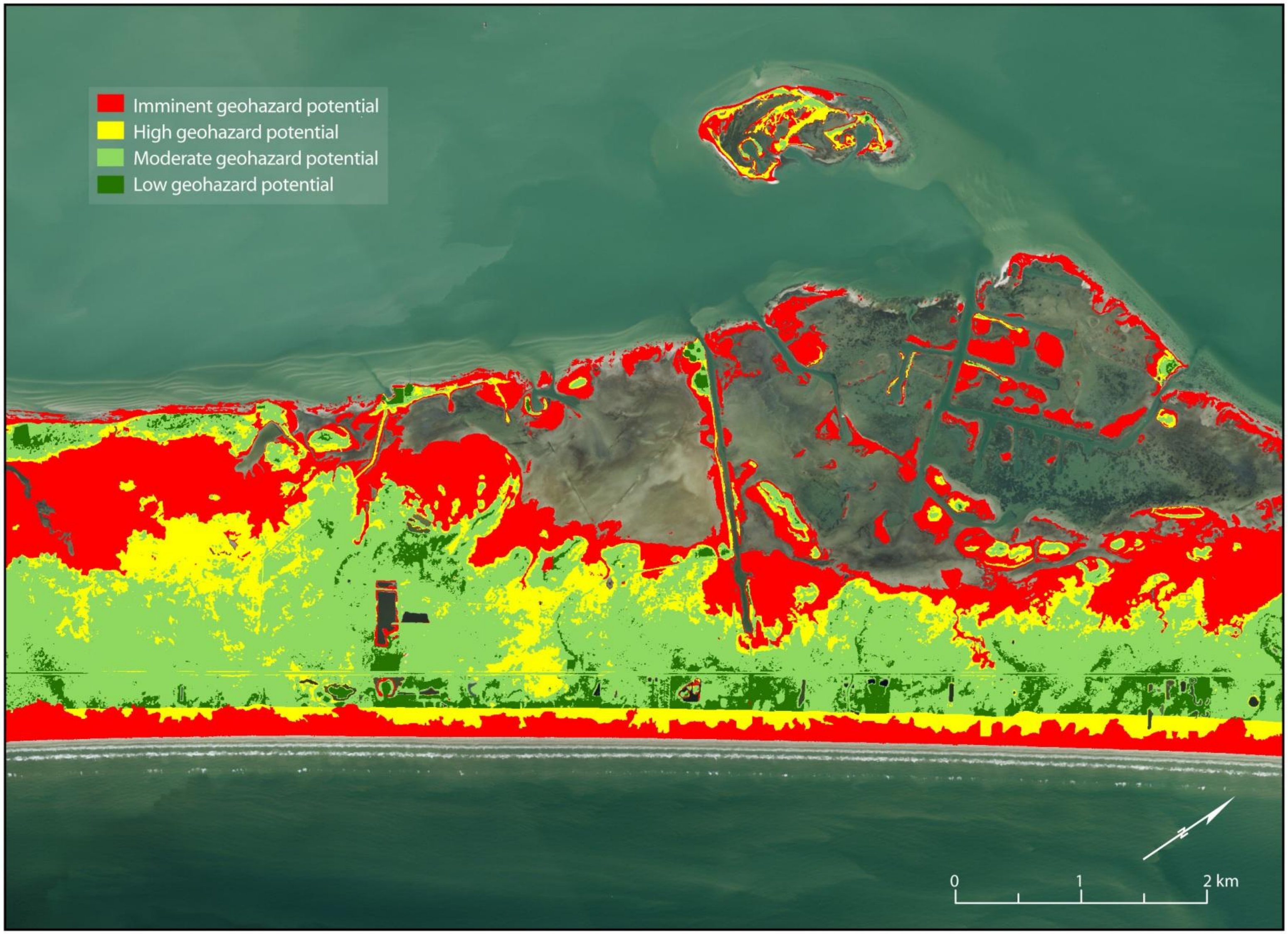

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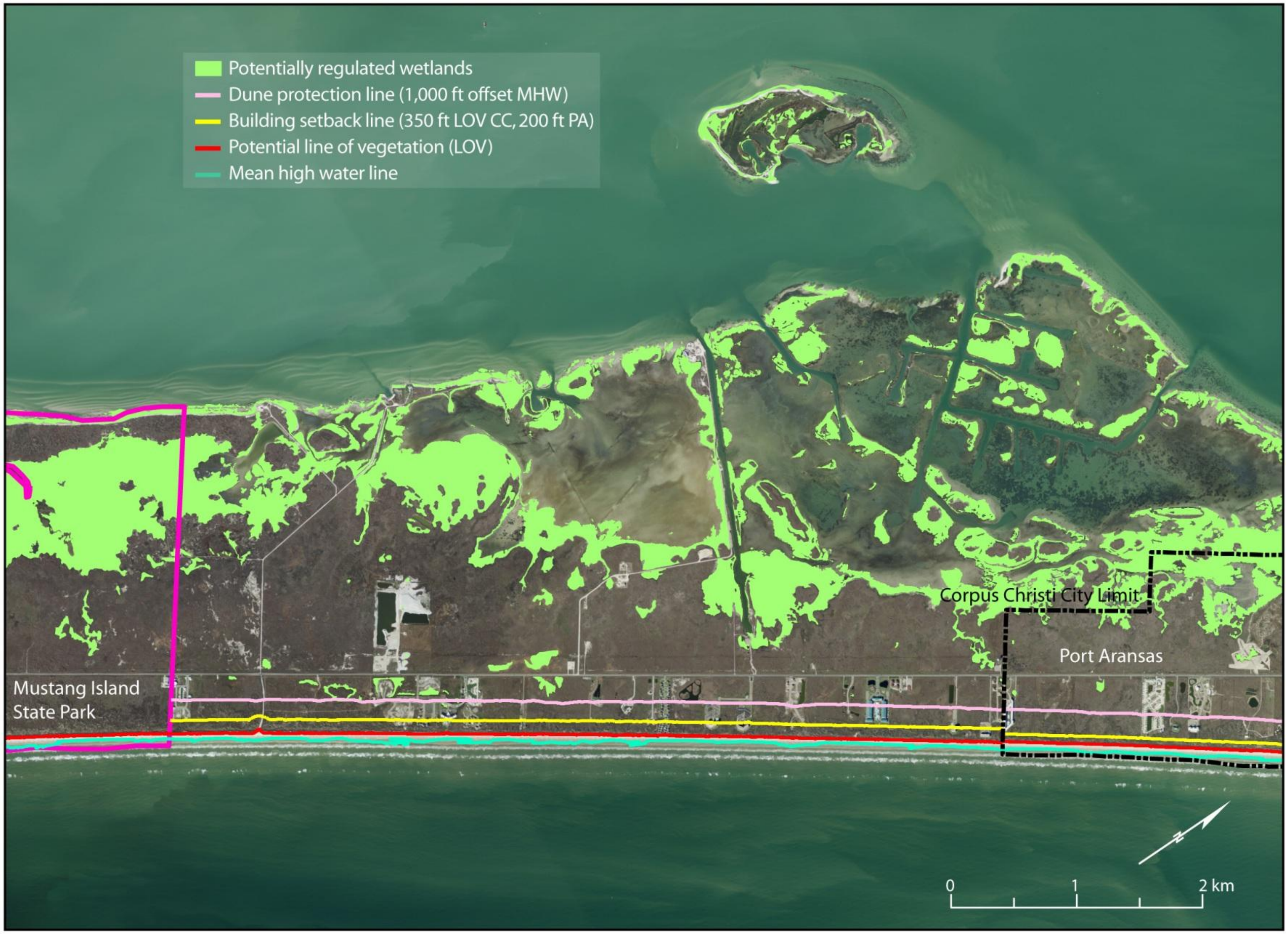

Figure 4.10C. Regulatory map section C.
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Figure 4.11C. Base map section C.
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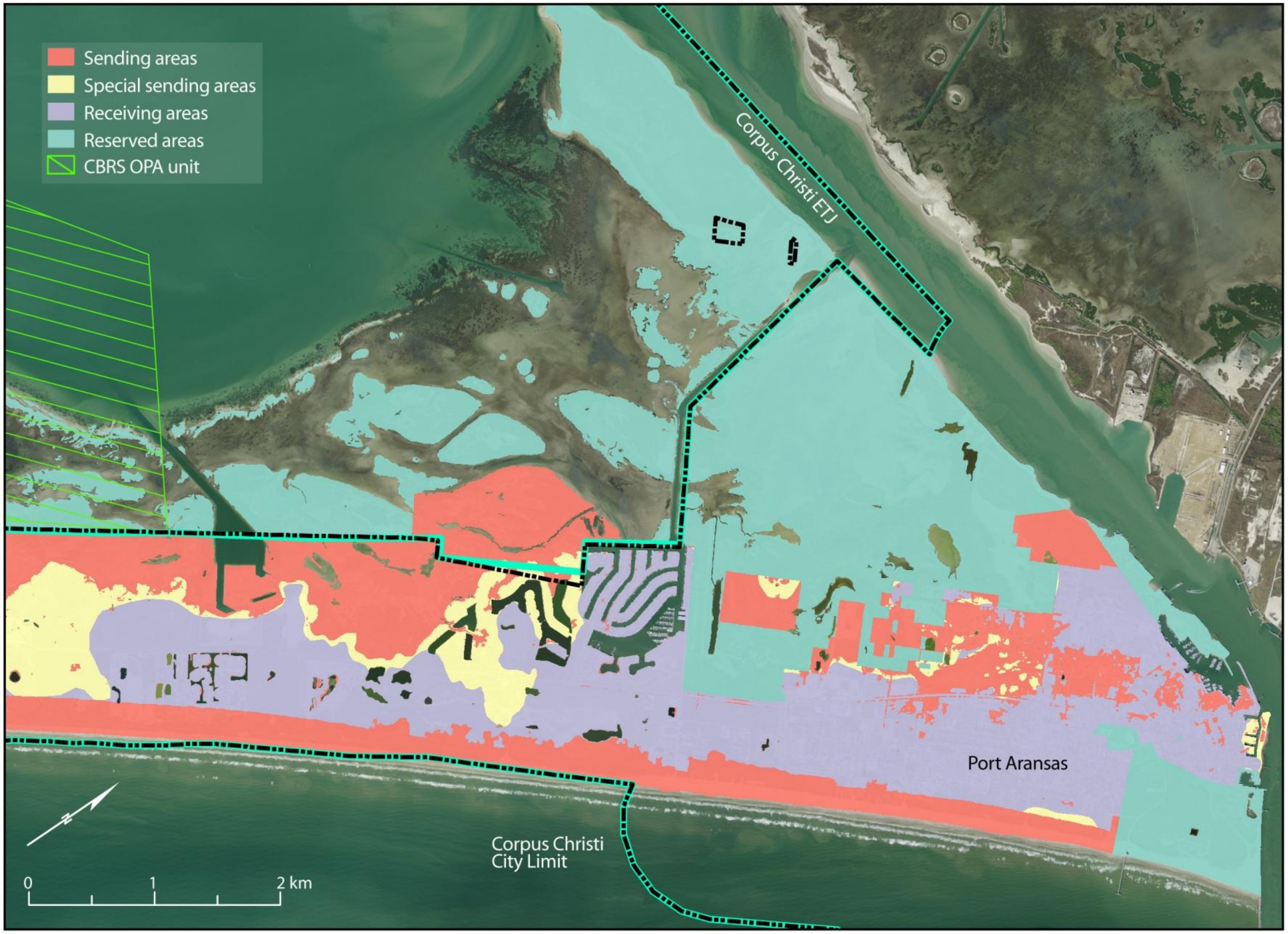

Figure 4.7D. TDR sending and receiving areas section D.
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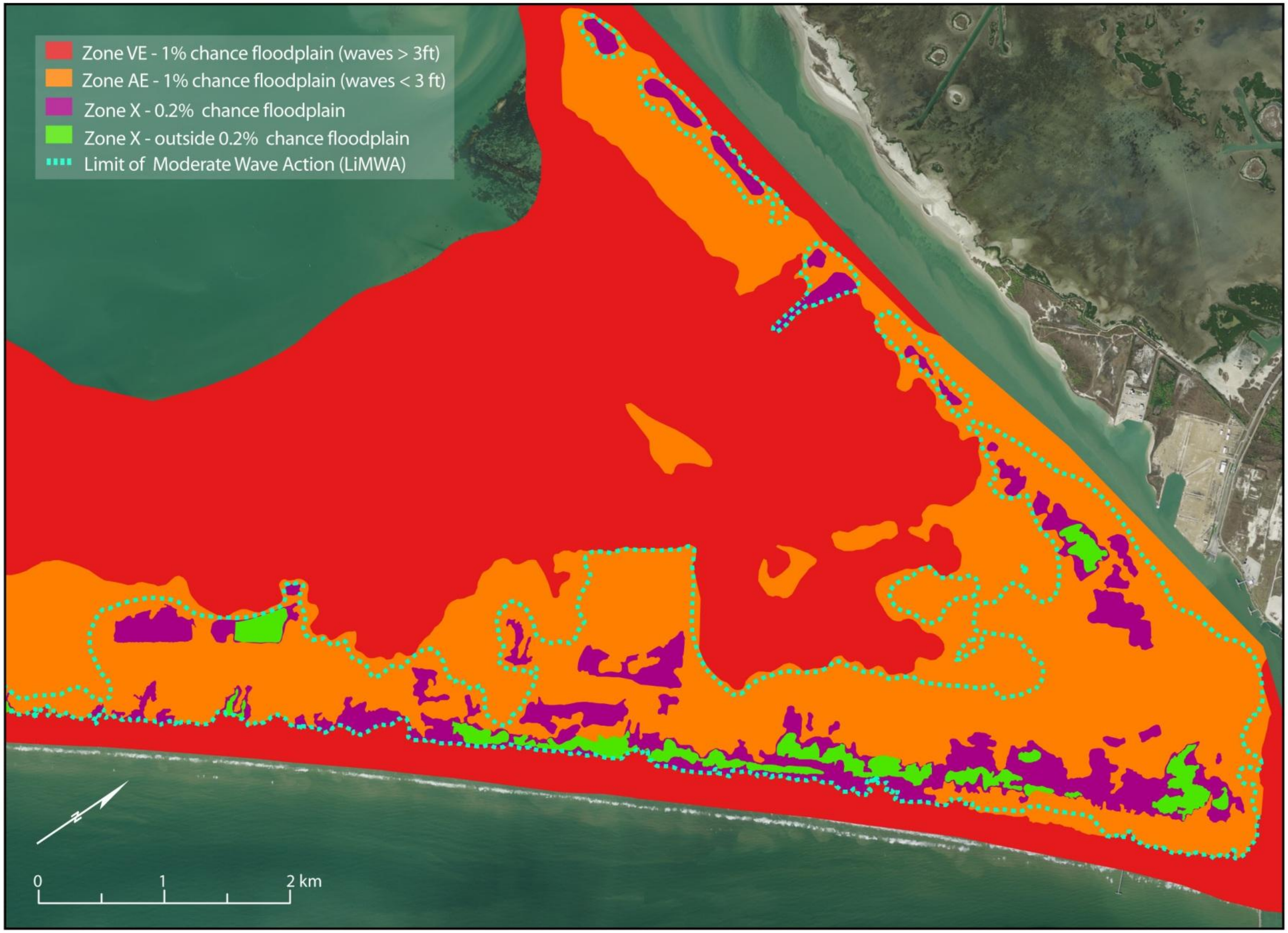

Figure 4.8D. FIRM map section D.
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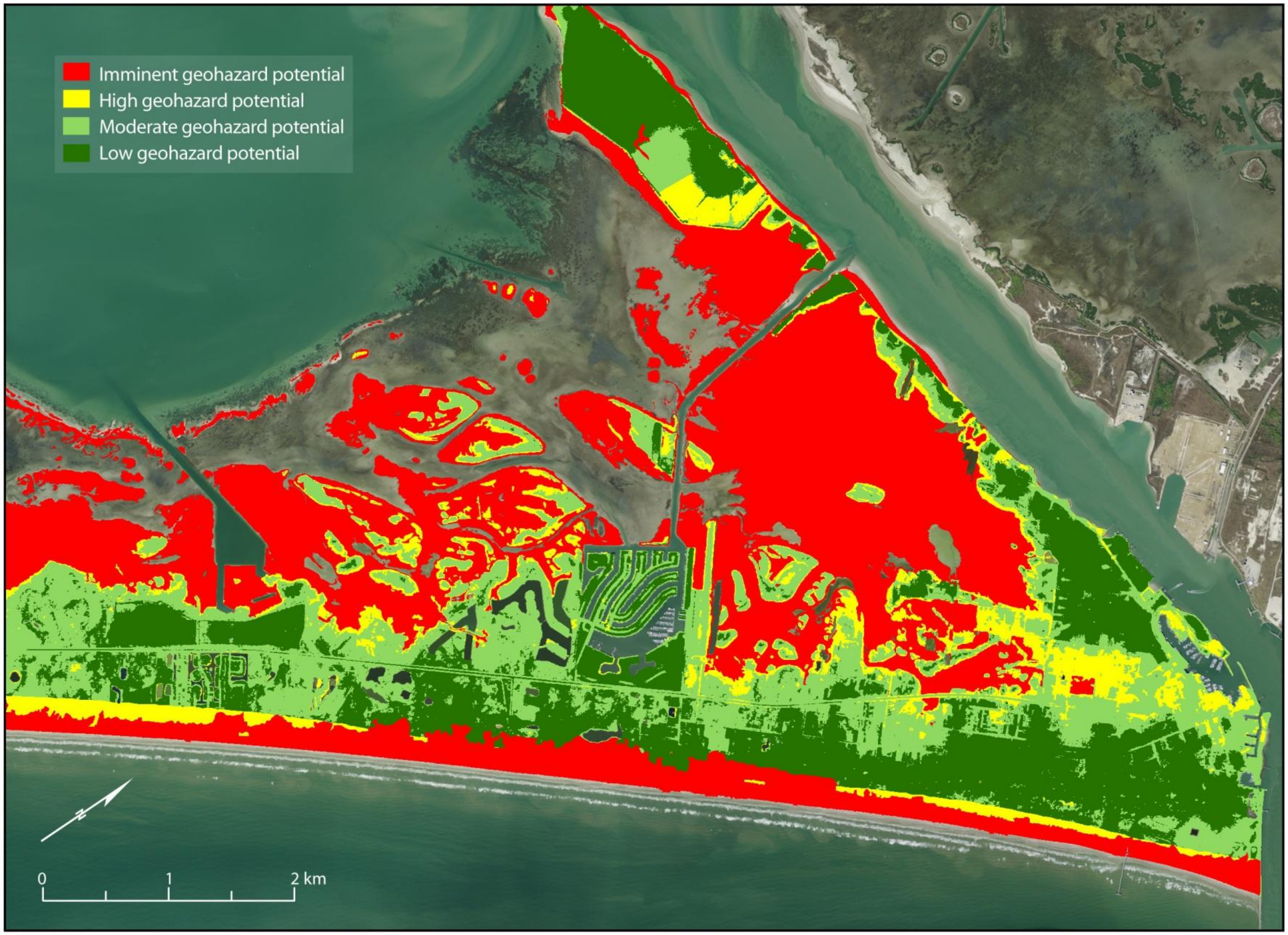

Figure 4.9D. Geohazards map section D.
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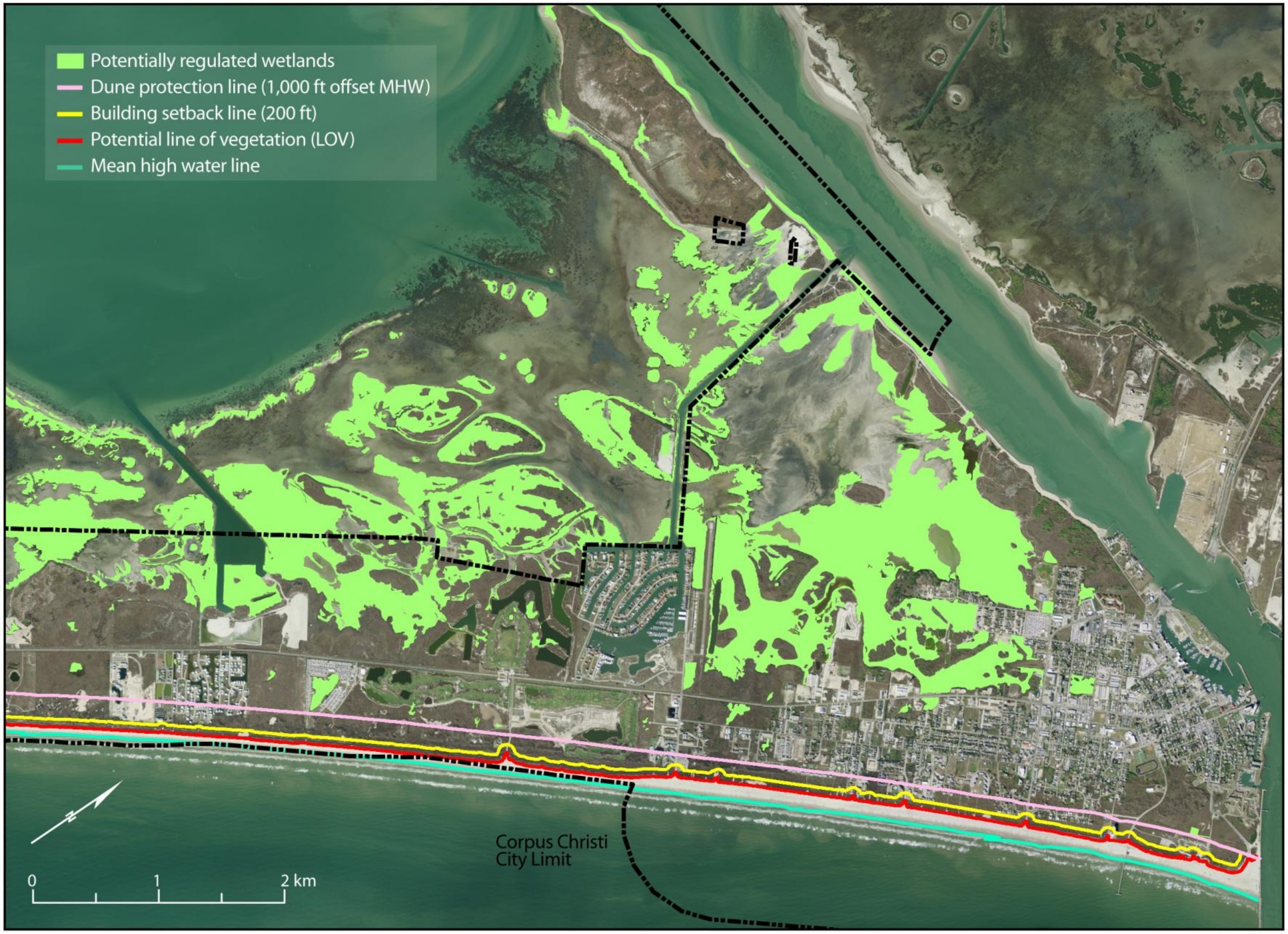

Figure 4.10D. Regulatory map section D.
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Figure 4.11D. Base map section D.
Map scale 1:50,000. Projection : NAD 1983 UTM 14N. Source: National Agriculture Imagery Program (2009).

BIOGRAPHIC STATEMENT

Eleonor B. Taylor was raised in Mazatlán, México. She attended the Instituto Tecnológico Estudios Superiores de Monterrey Campus Mazatlán where she obtained her Bachelor of Science in Industrial and Systems Engineering in 2003. Later, she was awarded a Fulbright scholarship to undertake graduate studies in the United States. She earned a master's degree in Community and Regional Planning, specializing in Environmental and Natural Resources Planning from The University of Texas at Austin in 2006. After working in coastal planning issues as an intern with the Texas General Land Office and private waterfront development firms in Mexico, she decided to pursue a Ph.D. to gain a deeper understanding of coastal environments. She joined the Coastal and Marine System Science program at Texas A&M University-Corpus Christi where she studied coastal change and land planning on Texas barrier islands under Dr. James C. Gibeaut.