SPATIAL AND STATISTICAL ANALYSIS OF THE CAUSES OF SALTMARSH LOSS ALONG THE TEXAS COAST

A Thesis

by

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ABSTRACT

In the state of Texas, cities and counties located along the coastline have all experienced an increase in population due to its navigable waterways and natural resources. Policy makers are faced with a difficult task to plan for the growth of urban development while using natural resources in a sustainable fashion. Despite efforts to protect valuable natural areas such as marshes, wetland loss continues to occur. In a study conducted in 2015 by Armitage et al., it was recently discovered that saltmarsh areas on the Texas coastline decreased by 77.8 km^2 from 1990-2010 within the Coastal Zone Management (CZM) boundary. When a formerly extensive area of salt marshes has been reduced by conversion to agricultural land, urban development or for industrial use and port facilities it can become quite a significant problem (Boorman,1999). Saltmarshes are given great value due to their ability to absorb impacts from storms, provide wildlife habitat, and provide social and economic benefits. It then becomes critical that analysis be conducted to identify the major causes of wetland loss along the Texas coastline.

This thesis aims to understand the major drivers of saltmarsh change throughout the 20-year time frame. Using the change in saltmarsh area for 1990-2010 as the dependent variable and watersheds as the unit of analysis, a regression model was estimated to evaluate drivers of saltmarsh change. Results indicate that if more saltmarsh area was present prior to 2010, then the change would decrease significantly. Additionally, Section 404 permits granted by the U.S. Army Corps of Engineers that permitted the alteration of wetlands indicated that as more permits were distributed, the

change that occurred from 1990-2010 increased significantly. Change in population proved quite the opposite. As population change occurred, it decreased the amount of area change in saltmarshes. Similarly, sea level rise also demonstrated to decrease the amount of change exhibited by saltmarsh area. Discussion of the results for all four statistically significant variables reveal that more studies will need to be conducted to further understand their effects on saltmarshes.

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The data analyzed for section 4.2.1.2 (Section 404 permits) was retrieved by the United States Army Corps of Engineers through the Freedom of Information Act.

All work for the thesis was completed by the student, under the advisement of Associate Professor Wesley E. Highfield of the Department of Marine Sciences.

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1. INTRODUCTION

Lying on the edge of land and water, saltmarsh ecosystems are placed all throughout the earth providing an abundance of habitat for wildlife and serving as an integral part of many economies and cultures. The state of Texas' livelihood and its success, like many other parts of the world, relies on its natural resources, which includes miles of wetlands that lie along the 373 miles of coastline. Wetlands cover about 7.6 million acres of Texas, 4.4 percent of the State's area. The most extensive wetlands are the bottom-land hardwood forests and swamps of East Texas; the marshes, swamps, and tidal flats of the coast; and the playa lakes of the High Plains. Wetlands provide flood attenuation, bank stabilization, water-quality maintenance, fish and wildlife habitat, and opportunities for hunting, fishing, and other recreational activities. Commercial fisheries benefit directly from coastal wetlands. Texas has lost a large percentage of its original wetlands as a result of agricultural conversions, overgrazing, urbanization, channelization, water-table declines, construction of navigation canals, and other cause (Yuhas, 1999). State and local entities aware of the value of wetlands lobby for management plans to better protect, and reduce human impact towards the environment. However, despite the increase in legislation aimed at protecting wetlands, saltmarshes are still subject to destruction and degradation (Adam, 2002). The question then becomes why is this still occurring? The remainder of this document will explore the importance of saltmarshes and their values and drivers behind their decline. I will then describe a methodology aimed at addressing these questions through the use of spatial and statistical analysis. Finally, the results and discussion of the analysis will be presented.

2. LITERATURE REVIEW

2.1 Review of Saltmarshes and their Value

Of all the complex ecosystems this world harbors, one of the most endangered ecosystems on the planet are its wetlands (Chiras, 2010). A wetland ecosystem is composed of a variety of plants and a wide array of biodiversity that is adapted for life in saturated soils. Biologists, and ecologists alike have come to understand that there are many different forms of these ecosystems, such as inland wetlands and estuarine (coastal) wetlands. Inland wetlands are common in areas near streams, lakes, rivers, and ponds. While, estuarine wetlands are commonly found along the U.S. Coastline. These estuarine emergent wetlands are dominated by grass or grass-like plants and are commonly referred to as "saltmarshes" or "brackish tidal marshes (Tiner,1984). In the state of Texas, saltmarshes are primarily composed of *Spartina alterniflora, Batis maritima, Salicornia spp., Distichlis spicata, Monanthochloe littoralis, Scirpus maritimus, Juncus roemerianus*, and at higher elevations *Spartina patens* (White, 1995). These saltmarshes characteristically are known to lie behind barrier islands and beaches along all coasts in relatively high saline waters and are normally flooded by tides for varying periods depending on elevation and tidal amplitude (Tiner,1984). Due to the characteristics that make up a saltmarsh and where they lie along stretches of land and water, they are extremely valuable for the success of the surrounding ecological and social systems. Today, saltmarshes are now widely recognized as contributors to fish and wildlife, environmental quality, and socio-economic values as can be seen in Table 1.

Table 1. Examples of services provided by wetlands.
Adapted from *Wetlands of the United States: current status and* recent trends (p. 13), by R.H. Tiner,1984

Fish and Wildlife Values	**Environmental Quality Values**	**Socio-Economic Values**
Fish and shellfish habitat	Water Quality maintenance	Flood Control
Waterfowl and other bird habitat	Pollution filter	Wave damage protection
Furbearer and other wildlife habitat	Sediment Removal	Erosion Control
	Oxygen Production	Groundwater recharge
	Nutrient Recycling	Timber and other natural products
	Chemical and Nutrient Absorption	Energy Source (Peat)
	Aquatic Productivity	Livestock grazing
	Microclimate Regulator	Hunting and Trapping
	World Climate Ozone Layer	Recreation
		Education and Scientific Research

The ecological value of tidal wetlands has been well documented by a number of researchers (Mitsch and Gosselink, 2007; Costanza et al., 2008; Harrington, 2008; USEPA, 2008). Wetlands, particularly shallow open water and marshes, have been found to provide food shelter, spawning sites and nursery areas for a wide variety of fish species (Bardecki, 1984). Because of their high productivity, tidal marshes are a large source of organic matter and nutrients for adjacent habitats (Boorman, 1999). The organic matter exported provides food for a wide range of commercially important fish and shellfish species such as adult stocks of commercially harvested shrimp, blue crabs, oysters, and other species of fish and shellfish, providing economic benefits to nearby communities (Boorman, 1999). Even avian wildlife benefit from wetlands as they provide crucial migratory habitat for the majority of shorebirds that breed in the United States (Dahl, 2011).

The second most cited reason for wetlands importance is their supposed role in flood control (Bardecki 1984). An extensive amount of simulated and field research has been conducted on mostly rainfall-based flooding, demonstrating that wetlands help to reduce flooding and associated losses because of their ability to hold, store, and slowly release accumulated runoff (Brody, 2015). In addition, saltmarshes are also seen as providing a dynamic buffer between the land and the sea as the high wave energy experienced during storm events can be dissipated by the vertical erosion of the front of the saltmarsh (Boorman, 1997). Besides flood protection, and storm resistance, saltmarshes help regulate the hydrological cycle, increase water quality, and other services as mentioned in Table 1. Yet, despite the abundance of ecological, economic, and social importance that saltwater intertidal wetlands provide (Dahl, 2011), wetland areas are still declining.

2.2 Causes of Saltmarsh Loss

In the United States and worldwide, saltmarsh loss has been occurring for many years. According to a US Fish and Wildlife report published in 2011, from 2004-2009 the largest acreage change in the saltwater system on the United States was an estimated loss of more than 111,500 acres (45,140 ha) of estuarine emergent wetland (salt marsh). This rate of loss was three times greater than estuarine emergent losses from 1998 to 2004 (Dahl, 2011). Loss of wetlands is commonly attributed to two reasons; the influence of human activities and the influence of the natural system.

2.2.1 Influence of Human Activities to Saltmarshes

The possibility of humans affecting nature is not a novel concept. When humans create changes there can be direct and indirect consequences that may affect the health of the natural system. These consequences are primarily driven by substantial population growth, ultimately leading to cities and urbanization.

According to McCauley, (2013) urbanization has occurred globally, mostly driven by growth in metropolitan areas. For the U.S., most of the nation's most densely populated areas are located along the coast. In fact, since 1980, population density has increased in coastal counties by 65 persons per square mile, or by 28% (Crosset et al., 2004). It is estimated that up to 53% of people in the U.S. now live in coastal counties (Crosset et al., 2004). As a result, scientists attribute coastal wetland decline to be associated with urban development along the coast (USGS, 1996). With rising population growth along the coastal margins, natural drainage patterns, hydrological systems are frequently compromised in order to accommodate coastal cities. According to (Blankespoor et al., 2014) alteration of land for urban and suburban environment includes but is not limited to:

- Constructing drainage for agriculture and forestry
- Dredging and stream channelization for navigation
- Flood protection
- Conversion for aquaculture and mariculture
- Construction of schemes for water supply
- Irrigation and storm protection
- Discharges of pesticides
- Herbicides, and nutrients
- Solid waste dispersal
- Sediment diversion by deep channels and other structures
- Mining of wetland soil, groundwater abstraction
- Hydrological alteration by canals, roads, and other structures

- Filling of wetlands for farming, residences, and mosquito control (Blankespoor et al., 2014)

Any of the alterations listed above, can have a ripple effects towards the nearby natural systems, but especially any alteration of water volume whether an increase, decrease, or timing of high and low water can threaten the area and the integrity of wetlands (Zedler, 2005). Such changes in the hydrological cycle are considered one of the most visible impacts of growth, affecting hydrodynamic variables within the systems, and strongly influencing water (Lee, 2006).

In addition to changing water volume input, an increase in nutrient levels whether sudden or steady gain can change the ecology and natural balance of wetlands. It was determined by (Deegan et al., 2012) that nutrient levels commonly associated with coastal eutrophication increased above-ground leaf biomass, decreased the dense, below-ground biomass of bank-stabilizing roots, and increased microbial decomposition of organic matter. Ultimately, reducing geomorphic stability, resulting in creek-bank collapse with significant areas of creek-bank marsh converted to non-vegetated mud (Deegan et al., 2012). Nutrient enrichment may also invoke a series of positive feedbacks by altering ecosystem processes that affect below-ground dynamics and creek-bank stability, leaving marshes more susceptible to the erosive forces of storms and sea-level rise and gravitational slumping.

Human induced wetland loss, is further aggravated by liquid resource extractions. In fact, areas off the Texas and Louisiana coast saturated with energy production facilities have experienced considerable subsidence due to its extraction of oil, gas and groundwater (Dahl, 2011). Coastal wetlands already under pressure by sea level rise, become further submerged as elevation levels drop. Not to mention, navigational routes needed to transfer energy resources and other commerce are continuously dredged to widen shipping routes, ultimately affecting natural processes and damaging the health of nearby coastal marshes.

2.2.2 Influence of Natural Factors to Saltmarshes

While significant losses credited by human actions are likely to continue into the future, it is projected that stresses on saltmarsh may be further aggravated by natural disturbances and rising global temperatures. Eustatic and relative sea level rise linked to global warming can cause inland migration of coastal marsh and mangrove species creating a shift in plant species distribution and fundamentally changing the ecology of an ecosystem (Armitage, 2015). For example, in the state of Texas, and in some places worldwide mangroves have expanded into saltmarshes, replacing low stature forbs and grasses into taller, woody vegetation, ultimately rendering the loss of ecosystem services provided by saltmarshes. Although landscape level shifts do not occur in large scales, it can regionally disrupt hydrological systems and biological cycles. In addition to changing landscapes, coastal habitats will likely continue to be stressed by climate change impacts that have resulted from sea level rise and coastal storms of increasing frequency and intensity (Dahl, 2011). For example, in the Gulf of Mexico, tidal wetlands have been recorded to have been lost from coastal erosion and inundation of salt water. Only to be further exacerbated by a series of hurricanes that damage property and natural resources in proximity to coastal areas.

Understanding the many factors potentially responsible for marsh area reduction is very complex especially when there are multiple feedback loop systems occurring within the system, but it is clear that both human and natural factors are the major driving forces for most coastal marsh loss. The following Table 2 seeks to categorize many of the drivers that are responsible for saltmarsh loss into human and natural derived factors.

Table 2. Human and natural impact to wetlands

	Factors	Effects	Source
Human Induced Factors	Urbanization	Decreases native species, eliminates habitats, increases fragmentation.	McCauley et al., 2013 Brody et al., 2015.
	Land Cover Land Use Change	Hydrological (surface and groundwater) alteration, increases run off, nutrients, urban sewage, water quantity and flow, etc.	Meyer et al., 1992 Armitage et al., 2015
	Increased Nutrients	Reduces geomorphic stability, decreases dense below ground biomass, invoking a series of positive feedback loops.	Deegan et al., 2012
	Groundwater Withdrawal	Excessive groundwater withdrawal has been known to cause subsidence leaving saltmarshes to be exposed to sea-level rise	White et al., 1995
	Dredging and Filling	Reduces light penetration, increases saltwater intrusion, low dissolved oxygen levels, altered tidal exchange, circulation change, etc.	Highfield & Brody 2006
	Sediment Accretion	Loss of sediment accretion rates cannot compete with relative sea level rise, causing wetlands to be submerged.	Ravens et al., 2009
Natural Factors	Sea Level Rise	Exposure to submersion risk	Kuhfuss et al. ., 2016
	Landscape Change	Introduction or proliferation of other species such as mangrove expansion displacing saltmarshes	Armitage et al. ., 2015
	Waves, Currents, and Storms	Vegetation submersion, physically high impact. Storm surge, high wind speed can impact intensive damage to already vulnerable saltmarsh.	Karimpour et al., 2015, Ravens et al., 2009, Roland, R. M., & Douglass, S. L. (2005). Paine 2011

It is important to note that not all human and natural impacts are listed in Table 2 above partly because causational factors are still being discovered.

2.3 Measuring Marsh Loss

Measuring and understanding all the possible causes of wetland loss can sometimes prove to be very tedious and costly especially if data needs to be acquired via field methods. Thankfully, technology backed by satellite remote sensing has several advantages for monitoring wetland resources, especially for large geographic areas, (Ozesmi et al., 2002). Because of its capabilities, speed, and cost effectiveness, the use of spatial data has garnered praise from state and national agencies often publishing new datasets, and creating decisions based on spatial information. Today, the use of remotely sensed imagery has even helped scientists and planners predict coastal marsh loss before it even happens, proving to be very beneficial for long term planning. For example, Kearney et al., (2010) used 7.5 minute orthophotoquads from the National Wetland Inventory to define upland boundaries of estuarine and saltmarshes, he then established a baseline for determining the relationship between distance upstream in estuaries and marsh degradation. Once the baseline was created, Kearney used a tool in Geographic Information Systems (GIS) to calculate the distance between the uplands layer and the boundary line, later to apply the values into a logistic regression model to identify what topographical variables caused marsh loss. In Kearney's case, he looked at distance from tidal creeks or shorelines to marsh loss, or loss to proximity of upland boundaries, and so on. Kearney's regression results indicated that the probability of encountering degraded marshes for his study area in North Carolina, was actually closest to tidal waters, while the interior areas of the marshes are least likely to be degraded. Based on the success of his work, Kearney concluded that the use of both satellite imagery and logistic regression models could be applied to other areas in the country to identify where marshes can be lost in the future.

In other cases, the use of satellite imagery can actually help scientists discover if wetland loss even occurred in the past. For example, while Armitage et al., (2015) was conducting a study to identity the extent of mangrove area in Texas from 1990-2010, using Landsat 5 Thematic Mapper Land Use Land Cover (LULC) images obtained from the United States Geological Survey government agency (USGS); it was discovered within the 20-year time frame, that saltmarshes decreased from 318.27 km^2 to 240.44 km^2, a net loss of 77.82 km^2, or 24% of the 1990 saltmarsh (Armitage et al., 2015). The study went on to explain that part of what caused marshes to be lost was mangrove expansion by 6%, the rest could have been lost to conversion of tidal flats or water, likely a result of relative sea level rise.

3. RESEARCH QUESTION

Based on the background literature on the natural and human drivers of saltmarsh loss, the methods obtained from Kearney et al., (2010), previous work and the findings obtained from Armitage et al. (2015) I seek to answer the following question: *what are the main causes of saltmarsh area change from 1990-2010 along the Texas coastline?*

While Kearney, sought to identify where marsh loss could occur in the future by using logistic regression analysis on a variety of variables, I propose using the same concept but applying variables from 1990-2010 to identify the main drivers of marsh loss in the past. By evaluating numerous variables across a large geographic area, results can be used to aid management and policy efforts to better target drivers that are reducing saltmarsh area on the Texas coastline.

4. CONCEPTUAL FRAMEWORK AND HYPOTHESIS

Based on the information presented in the literature review, saltmarsh loss is caused by a variety of factors. Due to the many elements that could affect naturally occurring wetlands, decision makers are faced with having to mitigate losses by trying to minimize impacts on many different scales. While these efforts should continue to be pursued, it would be helpful for decision makers to have the list of factors narrowed so that mitigation efforts are better focused.

For this study the explanatory variables were divided into the following groups: human impacts and natural environmental impacts. The human impact theme will focus on explanatory variables where humans have impacted the natural environmental such as population growth, land area in 1990, altering of wetlands, etc. The natural environment theme consists of naturally occurring variables that are found in nature such as hurricanes, storm surge and the like. Explanatory variables within the groups will be used in a regression analysis where the change in saltmarsh area from 1990-2010 will be the dependent variable.

The following Figure 1 demonstrates the relationship that each of these factors have on saltmarsh area as well as list the variables that will be analyzed in the study.

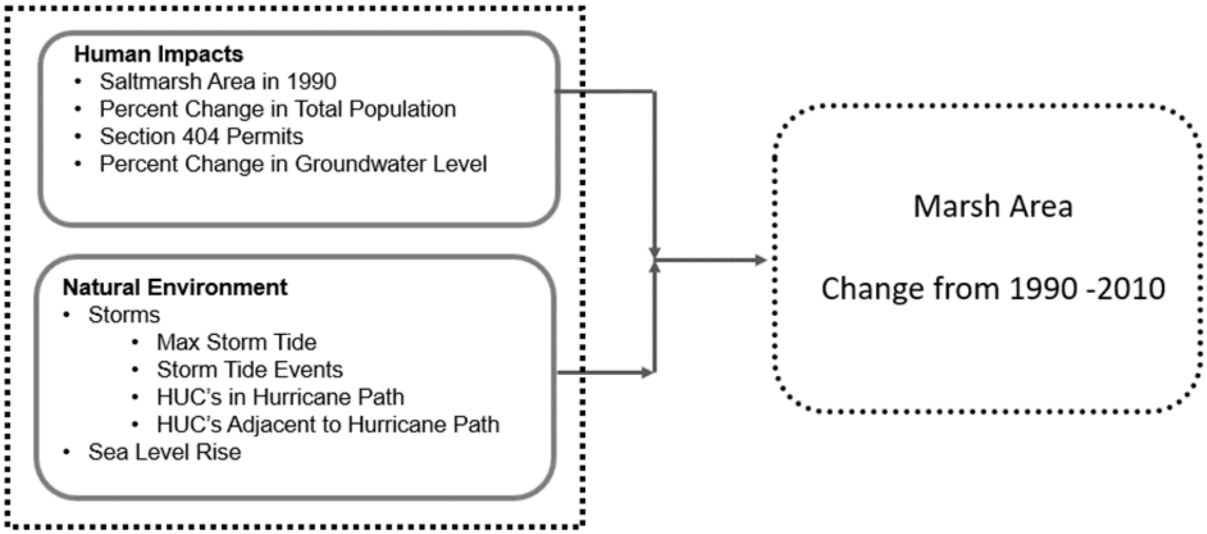

Figure 1. Conceptual framework for this study

Before discussing how each variable was processed and analyzed, the following subsections will further discuss the measurement of the dependent variable, as well as each independent variable and its importance relative to this study.

4.1 Dependent Variable Saltmarsh Area Change

The dependent variable in this analysis consists of saltmarsh area change that has either gained or lost area on the 373-mile expanse of Texas coastline from 1990-2010. The unit of analysis is 12-digit watersheds; saltmarsh area was calculated by how much the saltmarsh area changed from 1990-2010 in a watershed. For example, if there was originally 10 km^2 of saltmarsh area in a given watershed and in 2010 it rose to 100 km^2 in the same watershed, then an overall increase in saltmarsh area was experienced.

4.2 Independent Variables

4.2.1 Human Factors

4.2.1.1 Saltmarsh Area in 1990

Since this study is based on saltmarsh area change from 1990-2010, it was important to see if there was a correlation between the amount of saltmarsh area that was there originally versus the dependent variable which measured the change in time.

4.2.1.2 Section 404 Permits

As discussed in the literature review, human induced effects are a symptom of continued growth and development. From 1990-2010, the state of Texas saw a growth in business and commerce. Dredging projects, channelization and filling of wetlands was common and not unheard of. Persons' or entities interested in conducting these activities were by law required to apply for a permit with the United States Army Corps of Engineers (USACE). The USACE, is a federal agency who regulates any activities in waters of the United States, including wetlands under Section 404 of the Clean Water Act. When permits were distributed, the USACE required that unavoidable and necessary wetland losses be offset by replacing the natural wetlands with substitute wetlands either created, restored, or enhanced at the site of the loss or in some other location (Castelle et al., 1992). Prior to 2008, many studies had been conducted examining the effects of Section of 404 permits. Based on published studies, most concluded that the permits distributed by the USACE had done more harm than good. In fact, according to Kentula et al., (1992) one of the most underutilized methods of quantifying wetland loss was the record of permits issued by the USACE. Kentula et al., (1992) and Kelly (2001) were among the few researchers that used the permit record to estimate wetland losses (Highfield, 2006). Stein and Ambrose (1998) also relied on similar data to assess pre and post-permit conditions (Highfield, 2006). They concluded that the permit process had failed at minimizing overall cumulative impacts to wetlands associated with the riparian system (Highfield, 2006). In light of these comments, and other comments from the scientific community, non-governmental organizations, mitigation bankers, state and local agencies the USACE updated the regulations, including CFR 230 Compensatory Mitigation for Losses of Aquatic Resources. The update required monitoring of mitigation projects for a minimum of five years with longer monitoring periods required for aquatic resources with slow development rates as opposed to before where the regulations did not include this clause. Additional changes included using a watershed approach, requiring measurable, enforceable ecological performance standards and regular monitoring for all types of compensation and specifying the components of a complete compensatory mitigation plan, including assurances of long-term protection of compensation sites, financial assurances, and identification of the parties responsible for specific project tasks (Compensatory Mitigation for Losses of Aquatic Resources, 2008). However, since these changes were not adopted until June 2008, and the study was conducted primarily before any of the regulations had these clauses there is a high probability that the permits distributed by the USACE or Section 404 permits could have impacted saltmarshes from 1990-2010.

To test if permit distribution was increasing saltmarsh loss during the study time frame, permits issued under Section 404 of the Clean Water Act were obtained from the (USACE) from 1991-2010 through a Freedom of Information Act request. The permit record included the type of permit, the date issued, and the latitude/longitude of the permit. From 1991-2010, there was an overall increase in wetlands permits with the exception of a brief dip in 2007-2008 (see Figure 2). Of those 11,330 permits granted, 1,818 were general permits, 1,921 were individual permits, 1,272 were residential development, and 6,319 were nationwide permits.

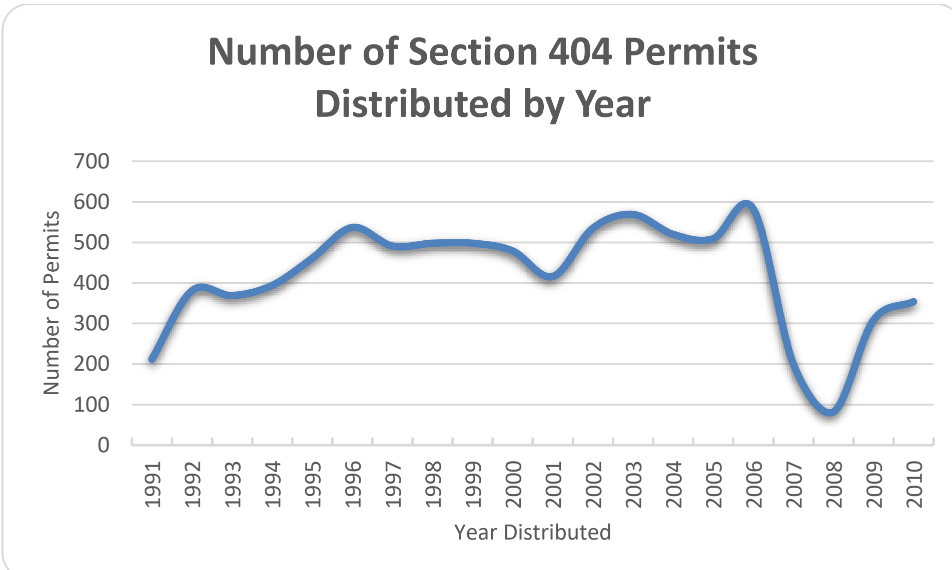

Figure 2. Section 404 permit distributions by year

The rise in permits throughout the years could be potentially demonstrating the growth and development into coastal areas.

4.2.1.3 Percent Change in Groundwater

In Texas, groundwater was originally unregulated and unmanaged, and due to excessive pumping some areas began to experience subsidence. In 1949, the State established Groundwater Conservation Districts (GCD) who was charged with the development and implementation of a plan for the effective management of groundwater resources in their jurisdictions. Most GCDs issue permits that regulate groundwater pumping and well-spacing in its district boundaries (Wythe, 2014). The districts, as well as counties that are part of a groundwater conservation district, are divided into 16 groundwater management areas (GMAs) that mostly reflect aquifer boundaries (Wythe, 2014). In many cases, GCDs were able to make large strides into regulating groundwater pumping through entities such as the Harris-Galveston Coastal Subsidence District. But in some areas progress was minimal, and it was not until 1997 that the GCDs were able to create Regional Water Planning Groups (RWPGs) which enhanced groundwater management in Texas by introducing a new era of regional planning (Joshi, 2005).

Subsurface fluid withdrawal, a process that has accelerated subsidence, is considered a primary cause of wetland submergence and loss of emergent vegetation (White, 1995). The general extraction of groundwater can generate land subsidence by causing the compaction of susceptible aquifer systems. In the Houston-Galveston area alone, there has been up to 3 meters of land-surface subsidence from large-scale groundwater withdrawal since 1906, even causing surface faulting (White, 1995). A study conducted by White et al. (1995) concluded that large rates of extraction and subsidence caused emergent vegetation to be converted to open water and shallow subaqueous flats on the downthrown side of faults where the rate of downward vertical movement and sea-level rise apparently exceeds marsh vertical accretion rates (White, 1995). Faced with subsidence issues and damage to the natural environment, the Texas Legislation created the Harris-Galveston Subsidence District (HGSD) in 1975. The District immediately began implementing regulatory procedures associated with their first groundwater regulatory plan. By 1999 the District mandated a groundwater reduction to only 30% by 2010, 70% by 2020 and 80% by 2030. In addition, a Disincentive Fee, $3.00/1000-gal of groundwater, was implemented in 2001, as a direct disincentive to sustained reliance on groundwater resources (Chaudhuri et al., 2014). As a result of regulatory limits on groundwater extraction, groundwater levels have risen, and reports of subsidence in the Houston-Galveston region have subsided.

Besides causing subsidence, excessive groundwater withdrawal can actually affect marsh soil condition and material exchange in coastal waters (Cao et al., 2012). Groundwater flow plays an important role in regulating nutrient transport and salinity in salt marshes, which in turn strongly affect ecological zonation and productivity (Wilson et al., 2011). Groundwater discharge from salt marshes also exports nutrients from salt marshes to tidal creeks, possibly impacting additional estuarine and coastal marine ecosystems (Wilson, 2010). If groundwater levels were to drop, it could possibly affect the natural processes needed for saltmarshes to thrive.

Since groundwater level can be an indicator for subsidence, and can be used as an indicator for saltmarsh health, I expect that as groundwater level rises, saltmarshes change is expected to rise.

4.2.1.4 Percent Change in Total Population

Throughout the study time frame from 1990-2010, there was a 48% increase in population growth in the State of Texas (Texas Department of Health and Human Services, 2014). Such a steep increase in population could potentially affect a variety of factors such as increased development and urban sprawl, which could ultimately affect saltmarshes. To measure the effect of change in the population, it will be used as an explanatory variable in the regression analysis.

4.2.2 Natural Environmental Factors

4.2.2.1 Sea Level Rise

Over the past century, tide gauges and satellite measurements have indicated that sea level is rising at an increasing rate (Paine, 2011). As sea level rises, the sustainability of saltmarsh is dependent upon the dominant macrophytes that maintain the elevation of their respective habitats within a relatively narrow portion of the intertidal zone by accumulating organic matter and trapping inorganic sediment (Morris, 2002). The long-term stability of these ecosystems is explained by interactions among sea level, land elevation, primary production, and sediment accretion that regulate the elevation of the sediment surface toward an equilibrium with mean sea level (Morris, 2002). However, if sea level rise is higher than sediment accretion levels then the expected outcome would be a loss in saltmarsh area. To test this hypothesis, relative sea level rise data will be used.

4.2.2.2 Storms

Saltmarshes are positioned at the interface between terrestrial and marine environment and are the first line of coastal defense against coastal storms (Bromberg, 2009). Coastal storms have long been recognized as agents of geomorphic change to coastal wetlands (Cahoon, 2006). A review of recent data on soil elevation dynamics before and after storms revealed that storms affected wetland elevations by storm surge (Cahoon, 2006). Hurricane storm surges can cause large-scale redistribution of sediments resulting in sediment deposition, erosion, compaction, disruption of vegetated substrates, or some combination of these processes (Cahoon, 2006). Although the amount of sediments delivered by storms are essential for marsh accretion, it varies greatly depending on the storm, especially when the health of the marsh is compromised by human impacts. During the twenty-year time frame, multiple storms were recorded to have hit the Texas coast. In this study, storms at or above Category 1 (Saffir Simpson Scale) will be used, resulting in a total of five storms to be examined during the twenty-year time frame. To measure storm damage on saltmarshes, shapefiles containing the path of a storm were acquired from NOAA. To measure storm impact, the storm variable was divided into multiple variables which include: watersheds that were in the direct path of a hurricane, watersheds that were adjacent to the hurricane path, a variable which indicates how many storm tide events a watershed experienced, a variable listing what the highest storm tide a watershed experienced. The following section will go into greater detail for how each variable was created.

4.3 Hypothesis

Based on the previous literature, it is gathered that saltmarsh loss can be attributed to a combination of human and natural factors. Based on the variables mentioned previously, I hypothesis that:

1. If there is an increase in saltmarsh area by 1km, I expect that the saltmarsh change that occurred from 1990-2010 would have decreased.
2. Dredging and filling activities as measured by Section 404 permits will have intensified the change in saltmarsh area.
3. If there was a positive percent change in groundwater meaning that if groundwater levels rose, I expect that saltmarsh area change would have decreased.

4. Percent Population Change will probably increase the change in saltmarsh area.
5. Rising sea levels are expected to intensify the change in saltmarsh area.
6. Maximum tide figures for storms are expected to increase the change in saltmarsh area.
7. The amount of storm tide events is expected to increase the change in saltmarsh area.
8. Watersheds in the direct path of a hurricane are expected to increase the change in saltmarsh area.
9. Watersheds in the adjacent to the path of a hurricane are expected to increase the change in saltmarsh area.

Table 3 summarizes the characteristics of each variable used in this study as well as the expected results of the analysis.

Table 3. Variable descriptions

	Variable	Description	Unit	Hypothesis
Dependent Variable	Change in Marsh Area km2	Marsh area in 2010 minus area in 1990	km^2	\
Human Factors	Saltmarsh area 1990	Area of saltmarsh in 1990	km^2	-
	Section 404 Permits	Total permits distributed throughout the study area from 1991-2010		+
	Groundwater Level Change	Percent change in groundwater levels from 2010 and 1990	ft, %	-
	Total Percent Population Change	Percent change of the 2010 and 1990 populations within a watershed	%	+
Natural Factors	Sea Level Rise	Rise in sea level over 20 years	mm	+
	Max Tide Experienced	Highest tide a watershed experienced during the 20 year time frame	ft	+
	Storm Tide Events	Number of tide events a watershed experienced		+
	HUCs in Hurricane Path	Watersheds that were in a direct hurricane path during the 20 year time frame		+
	HUCs adjacent to Hurricane Path	Watersheds that were in a adjacent to the direct hurricane path during the 20 year time frame		+

5. RESEARCH METHODS

The following section contains an overview of the selected study area, the methods used to process the dependent, independent variables, and the statistical analysis methods needed to process the results.

5.1 Study Area

The study area consists of the 373-mile stretch of Texas coastline, or the Texas Gulf Coast. The Gulf Coast region of Texas is located along the Gulf of Mexico in the southeastern part of the state. It includes the lower Rio Grande valley on the border with Mexico in the southwest, and the Sabine River basin on the Louisiana border in the northeast. The Gulf Coast aquifer is the largest aquifer in the region and the area’s main source of groundwater (Mace et al., 2006). The Gulf Coast is a nearly level, slowly-drained plain. It is dissected by streams and rivers flowing into the Gulf of Mexico (Gulf., 2018). The coast contains marshes, bays, jetties and open waters vital to many kinds of wildlife (Texas Coastal Habitats Overview, 2013). The following figure demonstrates the typical gulf coast profile starting from the gulf prairies and saltmarshes to the gulf waters. Because of its dynamic range of ecosystems, it fosters a wide range of habitat for many wildlife, including many humans.

Figure 3. Gulf Coast cross-section.
Figure 3 demonstrates saltmarshes furthest inland, then the coastal bays, the jetty, nearshore waters and the Gulf waters. Reprinted from Texas Coastal Habitats Overview by Texas Parks and Wildlife, Retrieved April 2017, from https://tpwd.texas.gov/fishing/sea-center-texas/flora-fauna-guide. Copyright 2013 by Texas Parks and Wildlife Department.

While the management and enhancement of natural resources is important to localities and upwards towards state entities, enhancement of coastal habitats is recommended to begin at the hydrologic system. A watershed provides a more comprehensive and rational setting to resolve water or natural resource problems than areas defined by political boundaries, whether national, state, tribal or local (Gelt,1998). For example, problems having to do with water quality or quantity or wildlife habitat are not likely to be confined to areas enclosed within political boundaries (Gelt,1998). Watersheds are also more likely to match the geographic scale of such problems. In addition, by using watersheds, they can be subdivided into various sized segments enhances their value as an appropriate and workable management unit (Gelt,1998).

For the previous reasons, this analysis will be conducted at watershed scale, and will be analyzed using 12th order watersheds (based on the USGS Hydrologic Unit Code (HUC)). Selection of the watersheds was based on the watersheds that only contained saltmarshes in either 1990-2010 or both. The following figure demonstrates the selected study area for the remainder of the analysis.

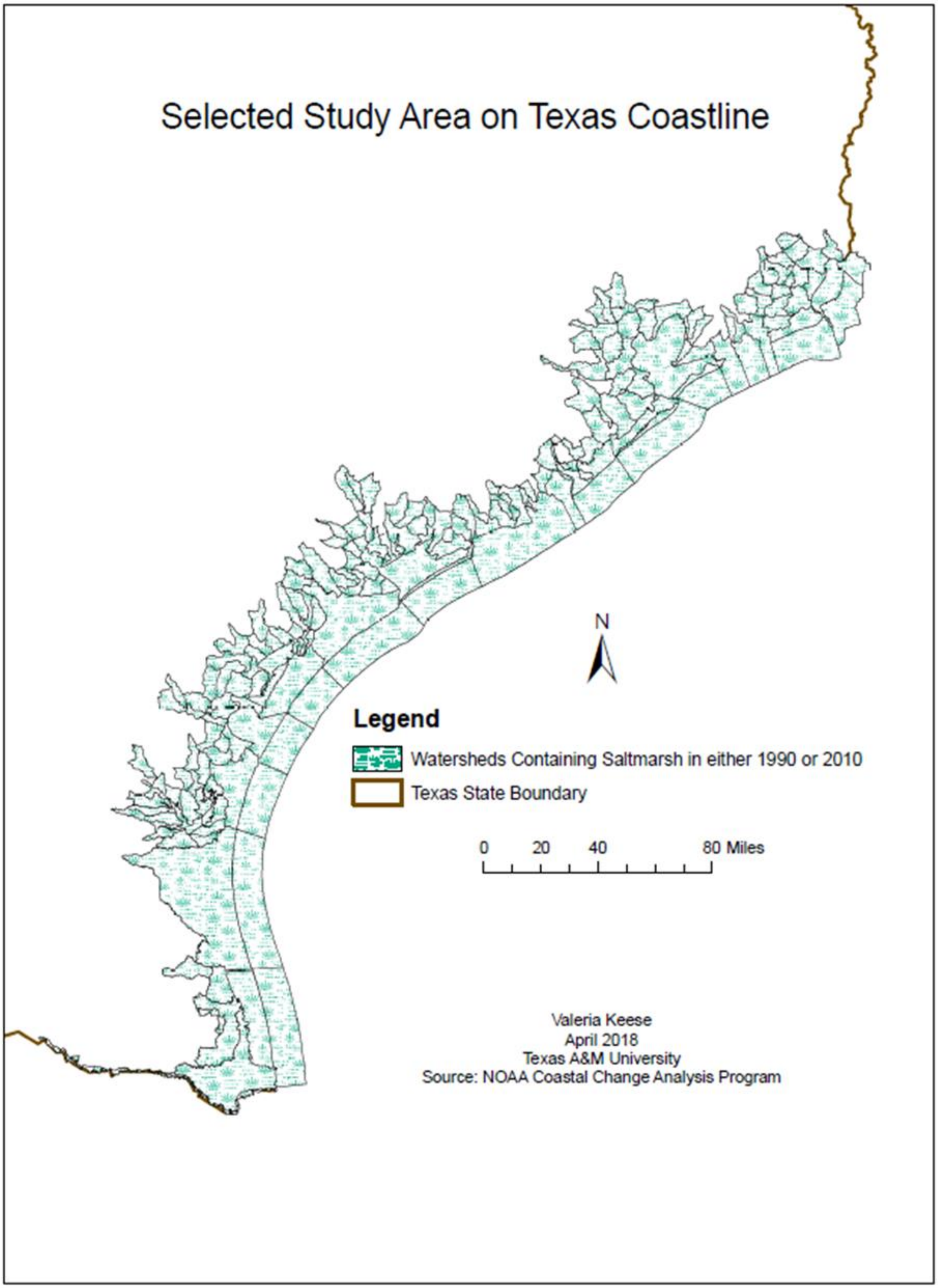

Figure 4. Selected study area on the Texas coastline

5.2 Variables

5.2.1 Dependent Variable Saltmarsh Area Change

To calculate the change in area of saltmarsh a given watershed, a 1990 and 2010 land use land cover (LULC) layer was retrieved from the NOAA Coastal Change Analysis Program (CCAP) dataset as well as a watershed layer from the National Hydrology Watershed Boundary Dataset. After removing all land classifications that were not labeled as “Palustrine Emergent Wetland”, saltmarsh area was calculated for both 1990 and 2010 using the tabulate area tool in the spatial analyst toolbox in ArcGIS; a Geographic Information System used for working in maps and geographic information. Once the table was created, the table was spatially joined to the watershed layer, and each watershed contained area of saltmarsh in 1990 and 2010. A simple subtraction of 2010-1990, revealed either a gain, loss, or no change in area. The following Figure 5 represents a distribution of the 176 watersheds that contained saltmarshes and either gained or lost saltmarshes for the 20-year timeframe.

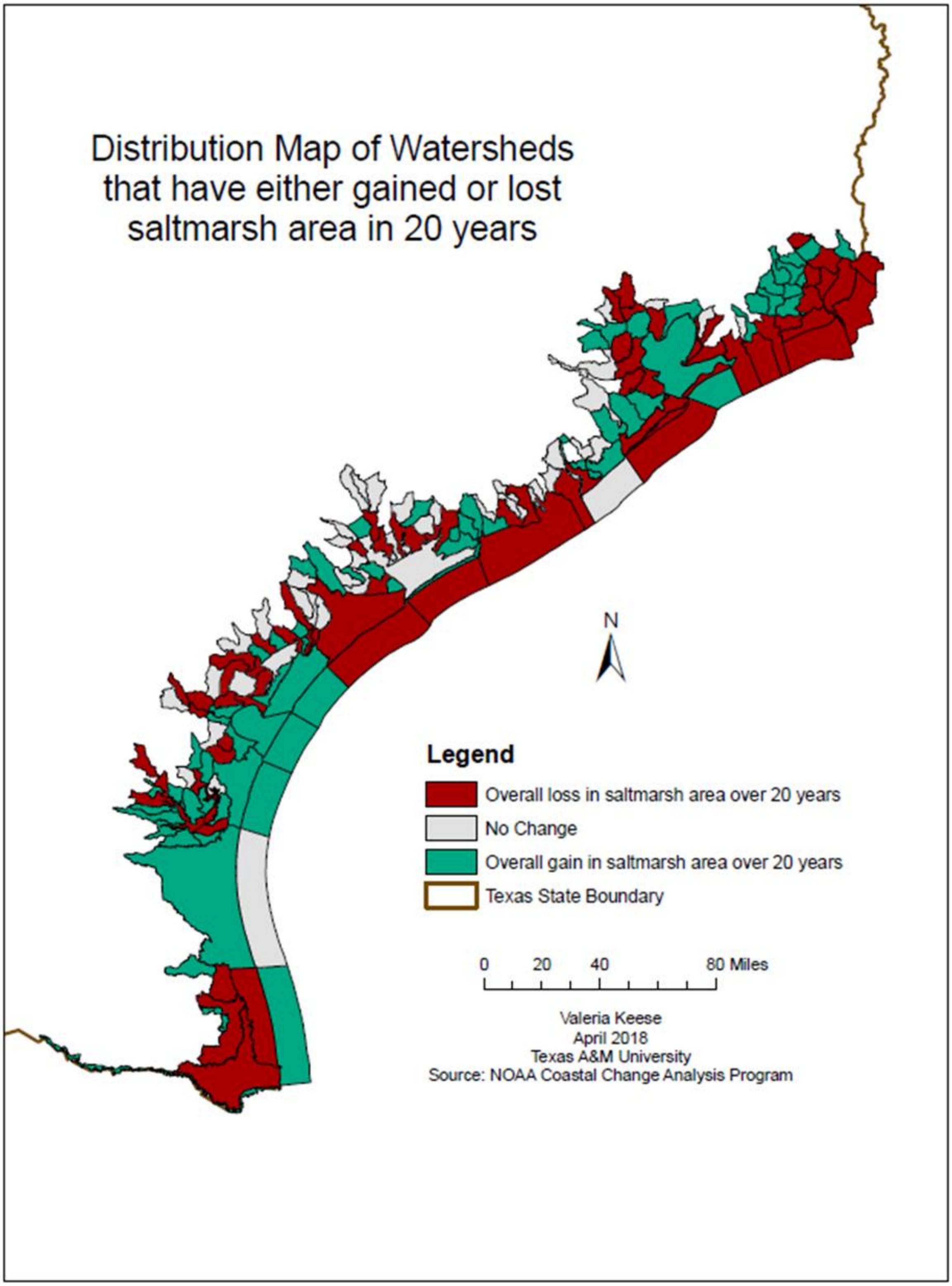

Figure 5. Distribution map of the watersheds that have either gained or lost saltmarsh area in 20 years

5.2.2 Saltmarsh Area 1990

Saltmarsh area for 1990, was acquired when the dependent variable was created.

5.2.3 404 Permits

As mentioned previously, Section 404 permits were retrieved from the USACE via records request. Once, the dataset was acquired it was plotted via coordinate locations, and spatially joined to the watersheds. By spatially joining the permit point layer to the watershed polygon layer it summed all the permits that were distributed for each watershed from 1991-2010[1]. From 1990-2010, a total of 11,330 permits were granted.

5.2.4 Sea Level Rise

To characterize rates of sea level at nine stations across the Texas Coast (Armitage et al., 2015) average sea level data was used from the National Oceanographic Atmospheric Association (NOAA) website. According to NOAA relative sea level rose at all nine stations see figure 6 and table 4 for further information; rates of increase ranged from 1.9 to 6.8 mm/year, with an average of 4.7 +/- 1.6 mm/year (Armitage et al., 2015). For the purposes of this study, average yearly increases for each station were multiplied by "20" to reflect average sea level increase for 20 years. The station information containing twenty-year sea level rise data was plotted into ArcGIS and interpolated using the spline tool since it intersected through all points and

[1] For a map distribution of permits in a watershed see A.1 in the Appendix

provided the best interpolation. Contours were then generated to reflect what areas in the water were rising based on the station information.

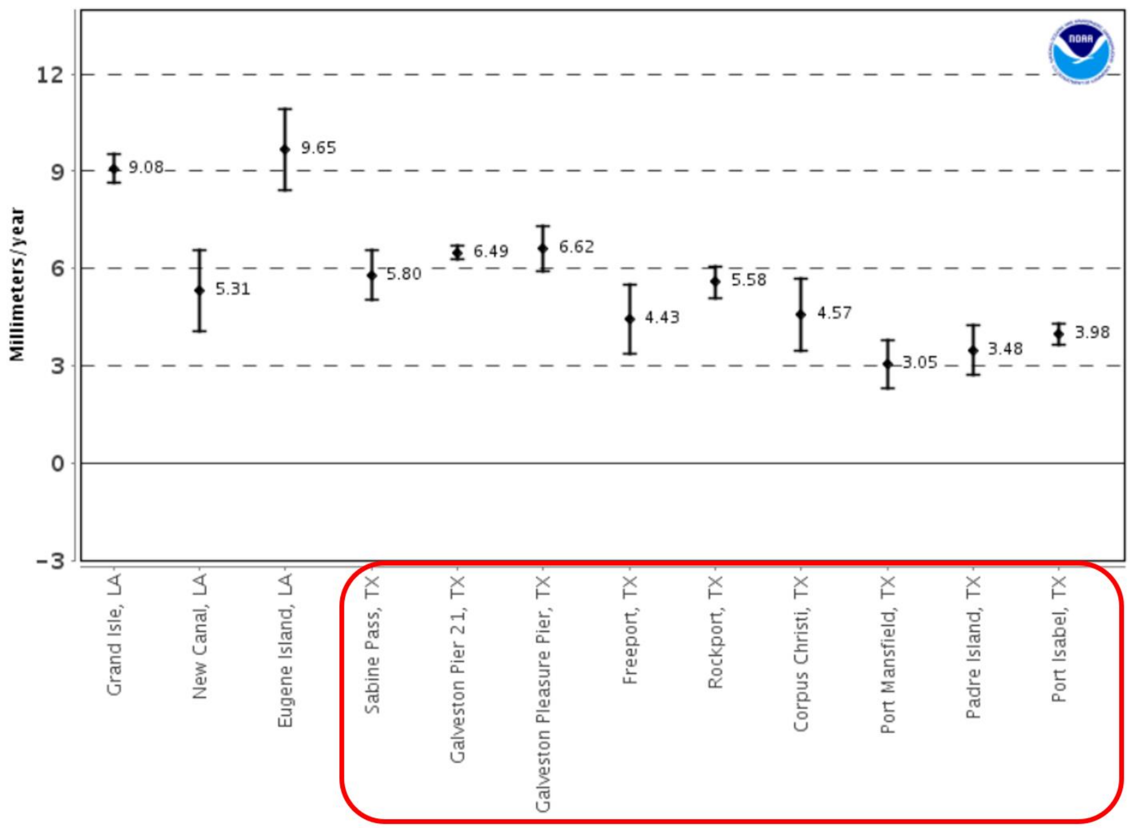

Figure 6. Sea level via tide gauges
Figure retrieved from NOAA website indicates average sea level rise per year over the course of recorded observations. Locations within the red box, indicate the areas used for this study. Reprinted from Mean Sea Level Trends for Tropical and Gulf of Mexico Stations. (n.d.). Retrieved April 26, 2017, from https://tidesandcurrents.noaa.gov/sltrends/tropicaltrends.html, 2013

Table 4. Tide gauge stations.
The table indicates all gauge stations across the state of Texas, and includes the year of when observations were first and lastly recorded as well as the average sea level trends with % confidence intervals.

Station ID	Station Name	First Year	Last Year	Year Range	Mean sea level Trends (mm/yr.)	+/- 95% Confidence Int.
8770570	Sabine Pass, TX	1958	2016	58	5.72	0.79
8771450	Galveston Pier 21, TX	1904	2016	112	6.47	0.23
8771510	Galveston Pleasure Pier, TX	1957	2011	54	6.62	0.69
8772440	Freeport, TX	1954	2008	36	4.43	1.05
8774770	Rockport, TX	1937	2016	79	5.53	0.49
8775870	Corpus Christi, TX	1983	2016	33	4.34	1.18
8778490	Port Mansfield, TX	1963	2006	43	1.93	0.97
8779750	Padre Island, TX	1958	2006	48	3.48	0.75
8779770	Port Isabel, TX	1944	2016	72	3.93	0.35

5.2.5 Groundwater Level

The groundwater level data for this study was obtained from the Texas Water Development board (TWDB). The groundwater level data, comes from decades of internal staff recording and inventorying wells used for irrigation, household needs, and stock watering, and even some for small commercial water suppliers or industrial purposes. Staff within TWDB primarily measure the wells for depth, well type, owner, driller, construction and completion data, aquifer, water-level and water quality data and are annually measured during the winter months when water levels are most indicative of static or ambient conditions (TWDB, 2018).

Prior to any statistical analysis, the data was processed to remove any wells not measured in 1990 and 2010 years respectively, average groundwater elevation and levels were averaged per year, and exported into ArcGIS to create groundwater level contour intervals via Inverse Distance Weighted Interpolation Methods. The contour lines were then intersected with each HUC and used to determine the average groundwater level per HUC.

To account for change from 1990-2010, the groundwater levels for 2010 and 1990 were subtracted. If it was positive, it meant there was an increase in groundwater level and a decrease if negative. To see the wells analyzed for this study see A.3 and A.4 in the Appendix.

5.2.6 Storms

To measure the impact of storms on saltmarsh, a few variables were generated to explain the relationship.

5.2.6.1 HUCs in Direct Path of Storm or Adjacent

During the 20year time frame, a series of storms hit the Texas gulf coast. For this thesis hurricanes that were either a Category 1 or higher on the Saffir Simpson scale were measured. Storms that fit this category include, hurricane Brett (1999), Claudette (2003), Rita (2005), Humberto (2007), and Ike (2008). Hurricane paths obtained from NOAA were then intersected with the watershed study layer. This generated a column indicating which watersheds had been in the direct path of a hurricane. From that selection I was able to select the watersheds that were directly adjacent to impacted watersheds.

5.2.6.2 Storm Tide and Storm Tide Events

While storm surge data would be a better proxy to measure an impact of a storm, it proved impossible to measure due to insufficient data. As an alternative for storm surge, storm tide data was used as it is a combination of storm surge and the astronomical tide, and is expressed in terms of height above a vertical or tidal datum (Defining Storm Surge., 2013). To calculate storm tide, tide information was acquired from Surgedat; a database of worldwide storm surge data. Tide data for each storm was downloaded into five separate excel documents. Each storm was geocoded, plotted, and converted into a line shapefile. To interpolate the tide gauge data, the spline tool via spatial analysis was used to generate a contour map for each storm. The end result was five different contour maps, which were intersected to the study area watershed layer, resulting in five columns in the attribute table. Within the attribute table I was able to calculate what the highest tide a watershed experienced, as well as how many tide events a watershed experienced. To see a map of hurricane paths, see A2 in the Appendix.

5.2.7 Percent Change in Population Growth

Block group datasets were acquired from the United States Census Bureau, American Community Survey 1990; 2010.to acquire the total population for each year. Once the shapefiles were acquired, they were each joined to a separate watershed layer. From these two shapefiles, I was able to calculate the percent of area a block group was in within a watershed. Once the percent area of a block group was calculated, it was multiplied by the census variable value. However, since most watersheds had multiple block groups, values had to be aggregated for each watershed. Once, a value was given for each watershed then percent change was calculated.

5.3 Statistical Analysis

To determine the key drivers of loss, a OLS regression model was estimated. For this study, the use of a panel data was necessary to study the dynamic changes in cross-sectional units over time. To address assumptions, a series of tests were conducted to test for multicollinearity and heteroscedasticity (See A.5 and A.6 in the Appendix for Pearson's Correlation Analysis, and VIF values). The results indicated that no variables were collinear however, there was heteroscedasticity. To account for this a robust regression analysis was conducted.

This approach was useful because it accounted for unobservable omitted variables, a key component for this study, as there are many unaccounted for variables that could be affecting wetlands. For this study, the robust regression model is as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \ldots + e$$

$$\begin{aligned} &Saltmarsh\ Area\ Change \\ &\quad = \beta_0 + \beta_1 Permits + \beta_2 GWLevelChange + \beta_3 Total\ Population\ Change \\ &\quad + \beta_4 Sea\ Level\ Rise + \beta_5 Max\ Tide\ Experienced + \beta_6 Storm\ Tide\ Events \\ &\quad + \beta_7 HUCs\ in\ Hurricane\ Path + \beta_8 HUCs\ Adjacent\ to\ Hurricane\ Path \\ &\quad + error(e) \end{aligned}$$

With the exception of the HUC’s in and adjacent to hurricane paths, all independent variables were continuous.

6. RESULTS

The following section is composed of two different subsections describing summary statistics and the regression results.

6.1 Descriptive Statistics

Table 5 reports summary statistics of all variables used in the regression analysis. As expressed in the prior sections explanatory variables were divided into two groups; human factors, and natural factors. There was a total of 176 watersheds that contained saltmarshes in either 1990 or 2010, resulting in a total sample size of 176 observations.

Table 5. Summary statistics

	Variable	Obs	Mean	Standard Deviation	Min	Max
Dependent Variable	Change in Marsh Area (km^2)	176	-0.03915	0.3906388	-3.35959	1.707246
Human Impacts	Land Area in 1990 (km^2)	176	11.54794	25.29292	0	178.6399
	Section 404 Permits 1990-2010	176	64.375	101.6185	0	763
	Percent Change in Groundwater Level1990-2010 (ft.)	176	0.5181687	34.81776	-100	66.66667
	Percent Change in Total Population 1990-2010	176	124.8935	551.3828	-86.9875	5614.002
Natural Factors	Sea Level Rise (mm)	176	109.7727	28.52477	40	160
	Max Tide Experienced (ft.)	176	5.543352	5.192017	0	19.4
	Storm Tide Events	176	1.460227	1.295534	0	4
	HUCs in Hurricane Path	176	0.176136	0.382023	0	1
	HUCs Adjacent to Hurricane Path	176	0.289773	0.4549511	0	1

As seen in Table 5, some of the independent variables are based on a change analysis from 1990-2010, while other explanatory variables are fixed numbers. The first independent variable is a fixed variable consisting of the area of saltmarsh in 1990, the minimum value represents the minimum about of area in a watershed, while the largest area of saltmarsh is represented by the maximum value. The second variable is also a fixed number composed of the total number of permits obtained over 20 years in a watershed. Groundwater level change is not a fixed value but is rather describing how groundwater changed over 20 years by percent, the same explanation also describes how percent change in total population was calculated. Percent change for both values was calculated using the following formula,

$$Percent\ Change = \left(\frac{2010\ Value - 1990\ Value}{1990\ Value}\right)100$$

Natural factors such as sea level rise, max tide, storm tide, watersheds adjacent or in hurricane paths were fixed values.

6.2 Regression Results

From 1990-2010, roughly 48 miles of saltmarsh area was lost. The following results seeks to answer what variables are driving marshes to have lost area during the 20-year study period. To answer that question, the dependent variable “Marsh Area Change” was analyzed by conducting a general OLS robust regression analysis.

Table 6. Regression results

Dependent: Saltmarsh Area Change (km)	Human Impacts	Natural Impacts
Saltmarsh Area 1990 (km)	-0.000214***	-0.000238***
	(0.000042)	(5.72)
1990-2010 Permits	0.000029***	0.000029***
	(0.000010)	(2.85)
Percent Change in Groundwater 90-10	-0.000034	0.000002
	(0.000030)	(0.06)
Percent Change in Population 90-10	-0.000009***	-0.000010***
	(0.000002)	(5.93)
Sea Level Rise 20 Years (mm)		-0.000108***
		(2.71)
Max Tide Experienced by HUC (Ft)		0.000238
		(0.67)
Total Tide Events Experienced by HUC		-0.001580
		(1.08)
HUC in path of Hurricane		-0.001898
		(0.66)
HUC Adjacent to Hurricane		0.002090
		(0.92)
_cons	0.0014	0.013686***
	(0.0013)	(3.24)
R^2	0.23	0.34
N	176	176

* p<0.1; ** p<0.05; *** p<0.01

As shown on Table 6, four of the nine independent variables proved to be statistically significant at the 1% value, the rest were not statistically significant as shown on the second column. Looking at just the human impacts, all explanatory variables were significant with the exception of groundwater change. Saltmarsh area in 1990 was significant at the 1% level, meaning that for every 1 square kilometer of saltmarsh area in 1990 saltmarsh area change would decrease by 0.0214 km^2. Section 404 permits were also significant at the 1% level indicating that for one-unit increase in permits the change in saltmarsh would increase further by 0.0029 km^2. Groundwater levels were not significant but the results indicate that as groundwater levels changed by 1% saltmarsh area change increased by 0.0034 km^2. The results for percent change in total population indicate that as population changed by 1%, it decreased the change in saltmarsh area by 0.0009 km^2.

Sea level rise results were significant at the 1% level, meaning that as sea level rose, it decreased the change in saltmarsh area by 0.0108 km^2 area. The remainder of the explanatory variables proved to not be significant, but their results were interesting nonetheless. If a watershed experienced a really high tide, the results indicate that the saltmarsh area changed faster by 0.0238 km^2, while if a watershed experienced re-occurring tide events, it decreased the change by 0.158 km^2. If a watershed was in a direct line of a hurricane, it proved to decrease the change in saltmarsh area, and on the opposite side, if a watershed was adjacent to a watershed that experienced a hurricane it would increase the change in saltmarsh area.

7. DISCUSSION AND RECOMMENDATIONS

Having one of the largest coastlines in the US, the state of Texas is faced with balancing the use of its natural resources while also protecting them. While this balancing act is altogether quite difficult to achieve, it can be accomplished. In this section, I discuss the values that were significant in the regression results in more detail, review the limitations of this study, and conclude the section with policy recommendations.

7.1 Discussion on Explanatory Variables

The results of the OLS robust regression model reflect the drivers that correlate with either a decrease or an increase in the change of saltmarsh area during the 20-year time frame. The paragraphs below highlight only the variables that were statistically significant.

7.1.1 Saltmarsh Area in 1990

Based on the results from the regression model, if 1 km^2 of saltmarsh area was added in 1990, it would have decreased the amount of change that occurred in 2010. Looking into the future, if saltmarshes are expected to decrease based on rising sea levels, climate change, urban sprawl or the various factors discussed in the literature review, then the only way to deter saltmarshes from decreasing even further is to conserve and plant additional saltmarshes; the more you have, the less you have to lose concept. For example, by acquiring untouched coastal lands and conserving the existing saltmarshes it would decrease the change seen in saltmarsh area. The results from the regression analysis, only reinforces the idea of conserving, or creation of new saltmarshes to deter loss in the future.

7.1.2 Section 404 Permits

In 20 years the state of Texas has seen an abundance of economic and development growth. While many safeguards and regulations have been put in place to protect wetlands, the results from the regression analysis indicate that despite the federal governments' caution to protect wetlands during dredging or filling activities, wetland area change positively correlates with added permits. Before a Section 404 permit is distributed, USACE requires that unavoidable and necessary wetland losses be offset by replacing these natural wetlands with substitute wetlands either created, restored, or enhanced at the site of the loss or in some other location (Castelle et al., 1992). In spite of current efforts to replace wetlands, investigations found that many replacement projects result in lost acreage, wetland types, and wetland functions (Castelle et al., 1992). The frequent failure of many mitigation projects occur for many reasons.

Research suggests that created wetlands do not look, or function, like the natural systems they are intended to replace. (Campbell, Cole & Brooks, 2002). In some cases, mitigation projects are often far from the location of the lost wetland. Consequently, wetland functions added by the constructed wetland have been moved from a place where they are needed to a place where they were superfluous (Highfield, 2008). Additional research also notes that mitigation may not always occur, even when required as a condition of the permit (Highfield, 2008). So when reviewing the results in the regression analysis, it was not surprising to see that if a permit was added the change in saltmarsh area further increased. Meaning, the change that occurred during the 20 years, had partly transpired because of the Section 404 permits. Figure 7 represents a density map of Section 404 permits distributed during the study time frame which reinforces the idea that permits affected saltmarsh area. Areas with intense blue in Figure 7 indicate a higher density in permits, and the areas outlined in green or red indicate if the watershed experienced a gain or decrease in area. Areas that experienced a high distribution of permits, like Galveston Bay, the Port Arthur-Beaumont and the Brownsville areas of Texas all saw an overall loss in saltmarsh area over the 20 years.

While these results reflect the regulations that were in place prior to 2008, it demonstrates the damages that development of natural areas has had on our marine resources. It can also be inferred that while the regulations were put in place to deter alternation of wetlands- without long term monitoring conditions in the regulations the saltmarshes may have seen the consequences. To ensure that the regulations from 2008, are indeed working or need to be updated I recommend a similar study such as this thesis to be conducted from 2008 onward. It is also recommended that an additional study be performed to analyze the effects of different types of permits distributed. For example, in areas like Corpus Christi, as shown in Figure 7, there was a high degree of permits being issued, but the watersheds seemed to experience a gain in saltmarsh. I can only speculate that even though there are a large number of permits in that area, those permits are not necessarily high impact permits and may not be damaging wetlands. Section 404 permits that represent large projects or significant impacts will likely have greater positive effects on watersheds' streamflow measurements (Highfield, 2008). To truly understand what could be occurring, a future study looking at the implications of different types of permits should be examined.

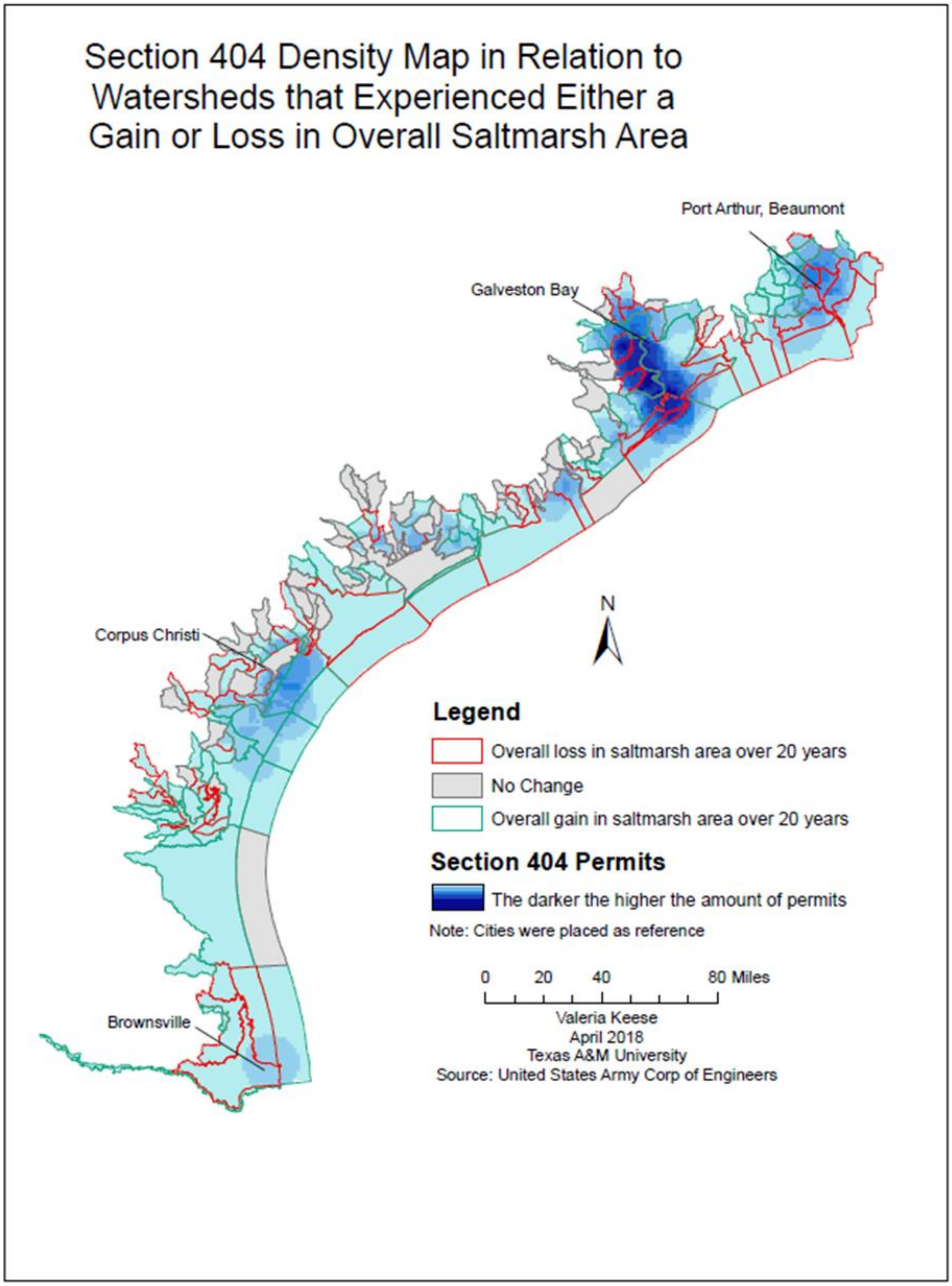

Figure 7: Section 404 permit density map in relation to watersheds that experienced either a gain or loss in overall saltmarsh area.

7.1.3 Percent Change in Population

From 1990-2010, the state of Texas experienced a 48% increase in population. According to the regression results, as population change occurred it decreased the amount of area change in saltmarshes. Previous literature findings explain that as population grows, natural resources including saltmarshes are usually lost due to urban sprawl, movement into coastal areas, etc. However, the results seem to contradict the literature. Part of the limitations conducted with this study was that when population was calculated per watershed, the assumption was that there was equal distribution of persons within the watershed. Realistically that is not the case. Some watersheds may experience higher and denser populations in a small area, and the rest be completely rural. By using this assumption, the results do not “see” where the growth in population actually occurred, and so the results are not truly representative of the impact of population growth on saltmarshes. To truly understand what is occurring, I recommend that a follow up study be conducted to measure “where” the growth occurred. Perhaps the growth occurred within urban centers, or the growth was not near coastal wetlands but rather in upmost northern areas of the Coastal Zone Boundary. The study should focus on areas that had low population density in 1990, and a high population density in 2010, and compare the saltmarsh area distribution between the 2 years. By conducting this study, it can measure if population density did in fact affect wetlands.

7.1.4 Sea Level Rise

When accounting for sea level rise, the results indicated that sea level rise was responsible for the change in 1990-2010 to decrease in momentum. Although the results contradict the findings of past literature, the results are not surprising for the study time frame of only 20 years. Prior to complete inundation of saltmarshes due to rising sea levels, coastal wetland plants are expected to respond to global sea level rise by migrating toward higher elevations. In a study conducted in Galveston, TX, models aimed at understanding the effects of sea level rise on saltmarshes determined that low lying coastal wetlands such as *Spartina alterniflora* are expected to respond to global sea level rise by migrating toward higher elevations (Feagin, 2010). In fact, upward zonal migration patterns of *Spartina alterniflora* has been seen to creep into upland areas highly dominated by *Spartina patens*, with some *Juncus roemerianus, Baccharis halimifolia* (Feagin, 2010). In a similar study conducted in the New England area, revealed that *Spartina alterniflora* (cordgrass) was rapidly moving landward at the expense of higher-marsh species. The study concluded that the timing of the initiation of cordgrass migration is coincident with an acceleration in the rate of sea-level rise recorded by the New York tide gauge (Donnelly, 2001). These results suggested that increased flooding associated with accelerating rates of sea-level rise has stressed high-marsh communities and promoted landward migration of cordgrass (Donnelly, 2001). However, despite the upward expansion of saltmarshes, human development is expected to limit the potential migration and has already been shown to be a limiting factor to coastal plant species' response patterns (Feagin et al., 2010). If this occurs, and climate warming causes sea-level rise rates to increase significantly over the next century, these cordgrass-dominated marshes will likely drown, resulting in extensive losses of coastal wetlands (Donnelly et al., 2001).

7.2 Limitations

Besides the limitations mentioned within the previous section regarding population, the other limitations to this study were primarily targeted towards lack of data. For example, while sea level rise data proved to be significant the data would be much more powerful if there were more tide gauge stations in the state of Texas. Of 373 miles, only nine stations are measuring sea levels. With very few data points, interpolations can range high and may not help future studies that are looking at smaller scales. Measurement of subsidence would have greatly benefitted the study as well, but due to lack of publicly available data by GCDs it was not possible to analyze the explanatory variable. Besides lack of available public data for explanatory variables, the study had a small sample size. In depth study, or recommendations were limited because not enough data was present.

7.3 Policy Recommendations

Based on the findings of this analysis there are a few takeaways that can be recommended to prevent future decline in saltmarsh.

1. Although the study was able to find correlation between population growth and saltmarsh change, it is recommended that an additional study be conducted at the local level to determine how change in population density impacted wetlands.
2. While the federal government has made great strides in protecting wetlands, based on numerous studies and this analysis, the results demonstrate that watersheds are experiencing a loss in saltmarsh area as permits are being issued. However, since the study did not discriminate against permit type and permits were viewed holistically, it was not possible to determine which type of

permits were responsible for saltmarsh decline. It is then recommended that the USACE conduct additional studies to identify which type of permits are having significant effects on saltmarshes as well as the type of marshes that are being lost.

3. In addition to recommendation #2, it is suggested that a subsequent study be conducted to measure the efficiency of the regulations being updated after 2008.
4. Although natural factors like sea level rise, and hurricanes are difficult to prevent from occurring, community involvement could prevent the loss of saltmarshes. Purchase of coastal lands and development rights acquisition can be useful tools though which U.S. salt marshes can be assisted in surviving sea level rise. In areas where zonal saltmarsh migration is expected to occur, areas anticipating creep could zone that area as a conservation zone to prevent future development.

8. CONCLUSIONS

This thesis employed the use of publically available data, and the use of spatial and statistical analysis to determine what were the leading drivers of saltmarsh along the Texas coast during a twenty-year time frame. Using salt marsh area change as the dependent variable, a general OLS robust regression model was used to evaluate the explanatory variables that strongly correlated with area change within a watershed. The study focused on two different groups of explanatory variables; human and natural factors. Both themes included variables that were statistically significant. Results indicate that if more saltmarsh area was present prior to 2010, then the change would decrease significantly. Additionally, Section 404 permits granted by the U.S. Army Corps of Engineers that permitted the alteration of wetlands indicated that as more permits were distributed, the change that occurred from 1990-2010 increased significantly. Change in population proved quite the opposite, as population change occurred it decreased the amount of area change in saltmarshes. As mentioned in the discussion this was the result of how the data was processed and the assumptions when calculating population change. Similarly, sea level rise also decreased the amount of change exhibited by saltmarshes. Based on literature findings the results are only showing what is occurring in the twenty-year timeframe and are not representative of long term rise.

Due to the very vulnerable position saltmarshes are in, protection of saltmarshes from both human and natural factors should be exercised.

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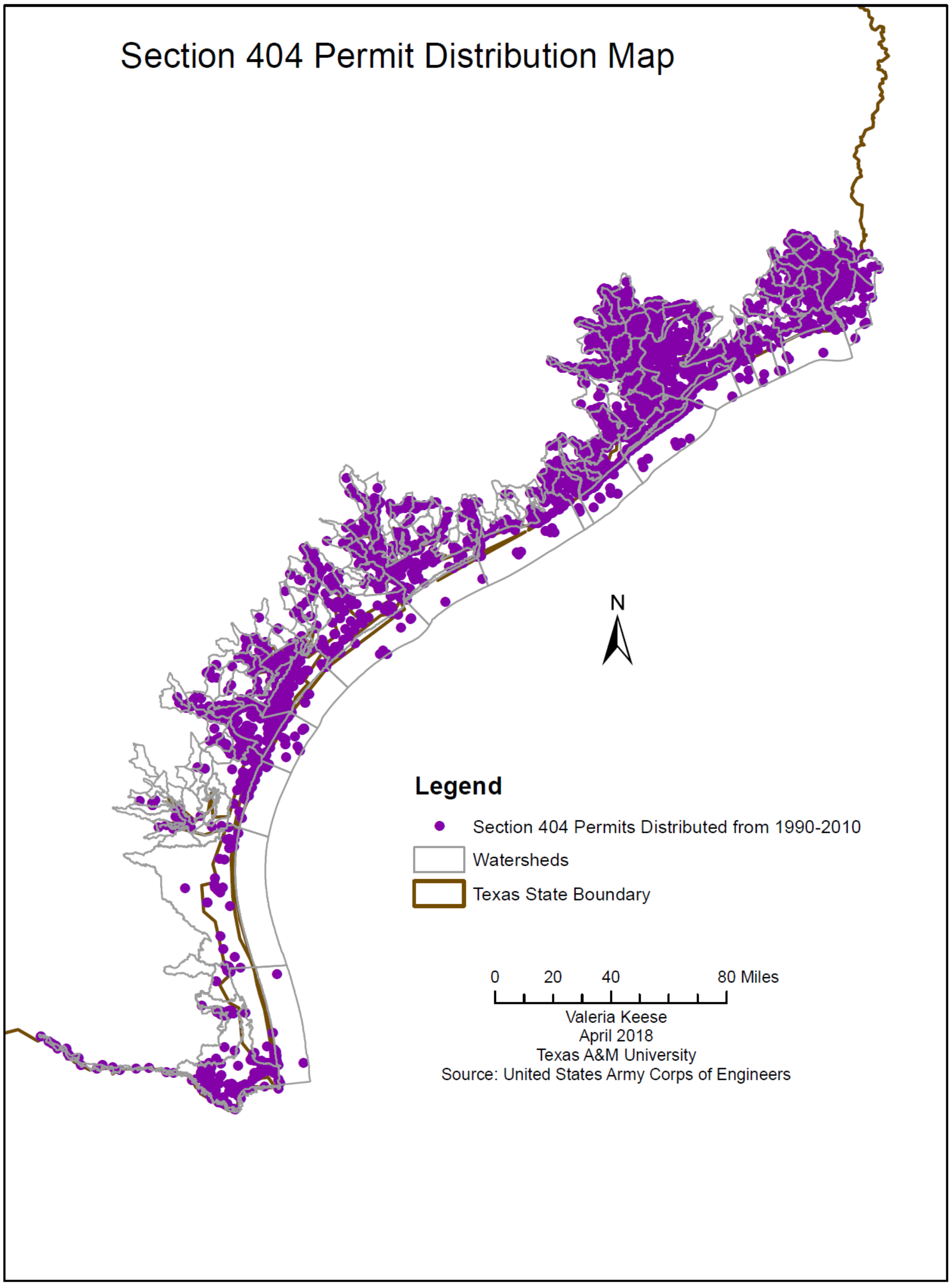
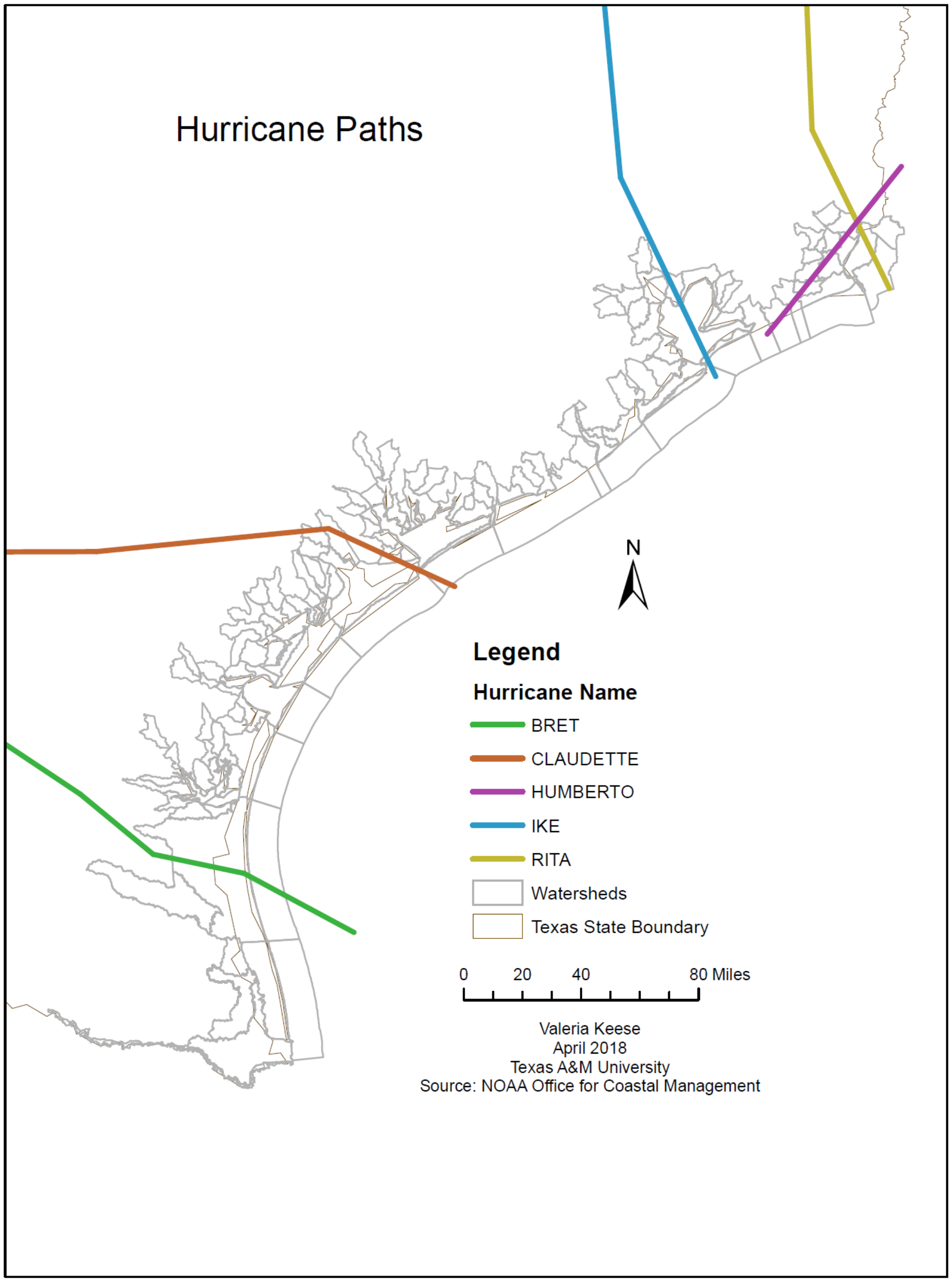
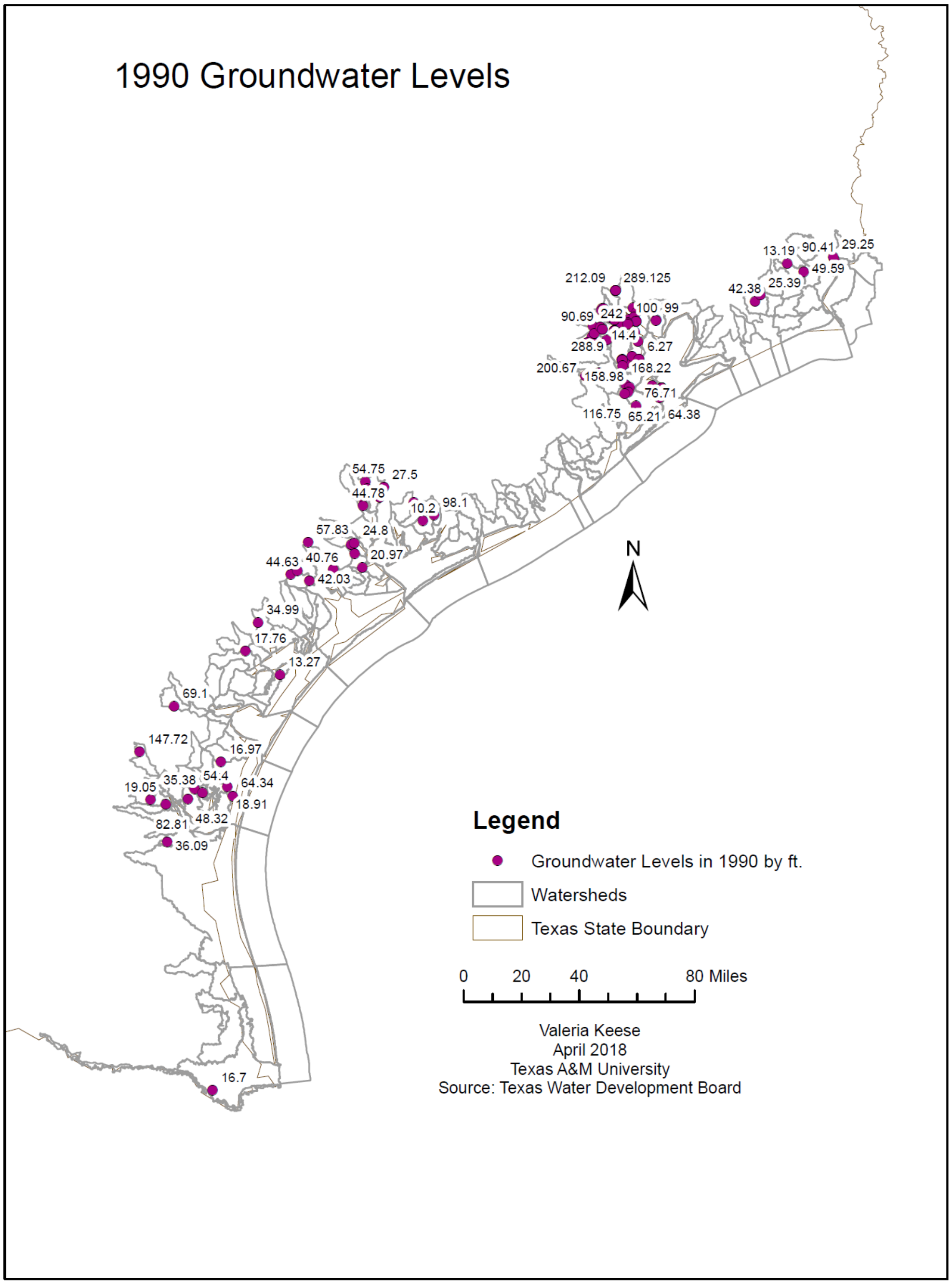


A.1 Section 404 Permit Distribution Map
Notes: This map displays the total amount of permits distributed by the USACE from 1990-2010. Data obtained via records request from USACE.

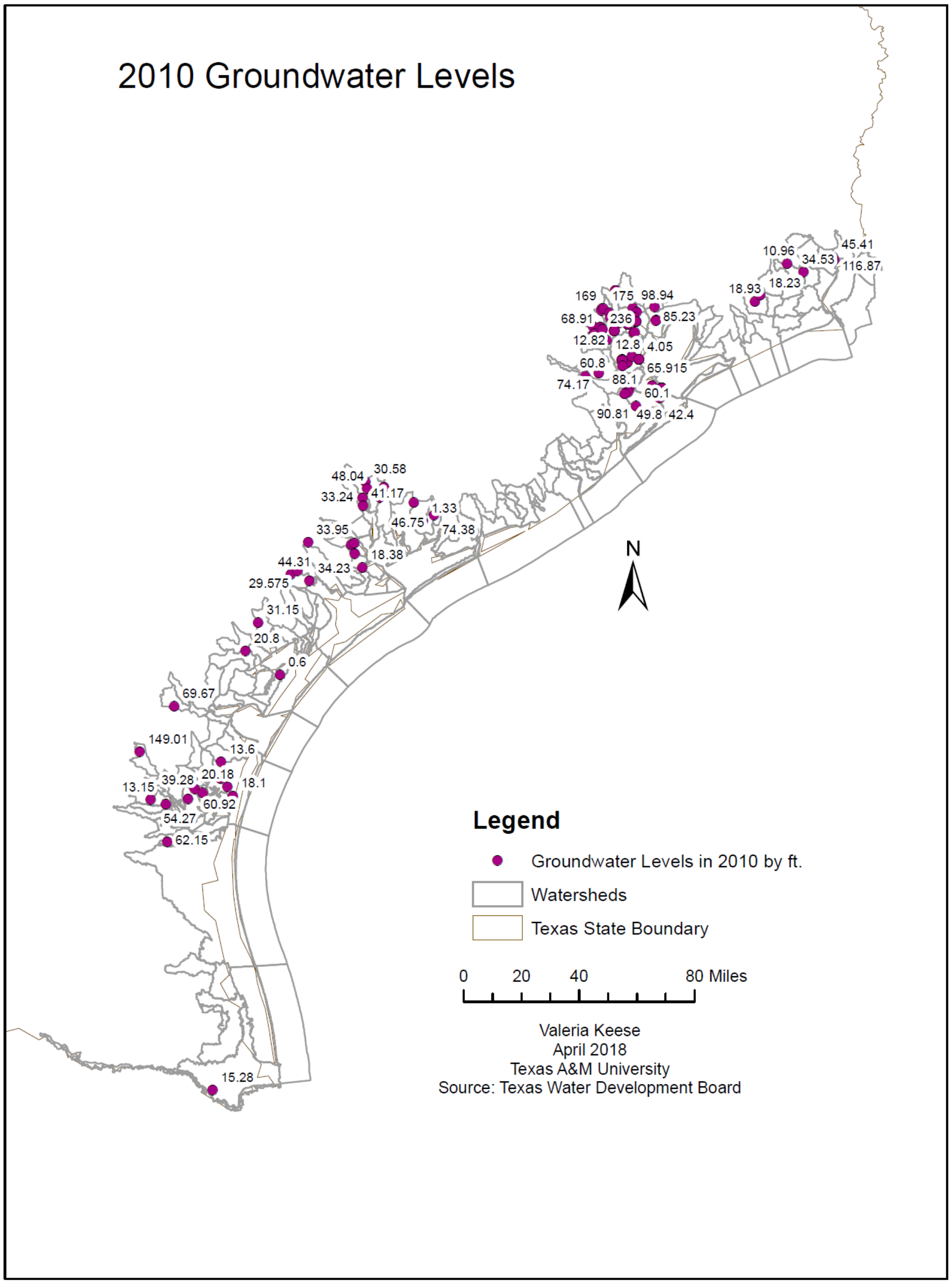


A.2 Hurricane Paths
Notes: This map displays the paths of hurricanes that crossed the study area from 1990-2010. Hurricane path data was obtained from NOAA Office for Coastal Management.



A.3 1990 Groundwater Wells

Notes: The map above demonstrates groundwater levels in ft. in 1990. Levels were obtained by the Texas Water Development Board.



A.4 2010 Groundwater Wells
Notes: The map above demonstrates groundwater levels in ft. in 1990. Levels were obtained by the Texas Water Development Board.

A.5 Pearson's Correlation Analysis

	Pearson's Correlation Analysis										
	Variable	1									
1	**Saltmarsh Area 1990 (km)**	-0.2082***	1								
2	**1990-2010 Permits**	0.0081	0.1693**	1							
3	**Percent Change in Groundwater 90-10**	0.1147	0.1511**	0.0675	1						
4	**Percent Change in Population 90-10**	0.0234	-0.089	-0.0723	-0.0337	1					
5	**Sea Level Rise 20 Years (mm)**	-0.0507	0.0022	0.2256***	0.3503***	-0.0595	1				
6	**Max Tide Experienced by HUC (ft)**	-0.1468**	0.3214***	0.3318***	0.1953***	-0.1326**	0.4047***	1			
7	**Total Tide Events Experienced by HUC**	-0.1502**	0.3516***	0.3317***	0.2423***	-0.1336**	0.4033***	0.8494***	1		
8	**HUC in path of Hurricane**	-0.1451**	0.1271**	0.0678	0.1109	-0.0261	0.1767**	0.3539***	0.3548***	1	
9	**HUC adjacent to Hurricane**	0.0321	0.0835	0.106	0.0038	0.0399	-0.0081	0.0735	0.1118	-0.2953***	1
	legend: * p<.1; ** p<.05; *** p<.01										

A.6. Variance Inflation Factor (VIF) for all variables

Variable	VIF	1/VIF
Saltmarsh Area 1990 (km)	1.21	0.826329
1990-2010 Permits	1.17	0.858275
Percent Change in Groundwater 90-10	1.18	0.844729
Percent Change in Population 90-10	1.03	0.972646
Sea Level Rise 20 Years (mm)	1.4	0.712403
Max Tide Experienced by HUC (ft)	3.76	0.266148
Total Tide Events Experienced by HUC	3.94	0.253793
HUC in path of Hurricane	1.33	0.749198
HUC adjacent to Hurricane	1.18	0.847971
Mean VIF	1.8	