

# Physical and Program Options for the Inland Migration of Louisiana's Coastal Wetlands in Response to Relative Sea Level Rise

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A Report for the Coastal Protection and Restoration Authority of Louisiana

By

Heidi Beck, Alicia Bihler, Melissa Kemm, Sam Pardo, and Douglas Perron

Dr. P. Lee Ferguson, Advisor

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## Executive Summary

Louisiana contains over a third of the coastal wetlands in the contiguous U.S., but has seen a drastic reduction in total wetland area in the last century. This loss is especially troubling for coastal Louisiana where wetlands play a vital role in protecting and supporting the state's economy and culture. Under natural conditions, coastal wetlands will move upland with rising sea level or sinking land. However, engineered structures and shore armoring, such as levees, seawalls, and bulkheads, impede this process. Advanced planning for wetland migration is needed to keep communities and infrastructure out of harm's way from encroaching open water and to mitigate future wetland loss. This project investigates the potential for wetland migration in Louisiana through 1) the mapping and analysis of coastal wetland migration and 2) an examination of policy alternatives relevant to wetland migration.

Wetland loss and migration were analyzed in Lafourche, St. Mary, and Vermilion parishes using the Sea Level Affecting Marshes Model. Moderate and less optimistic values of subsidence rates were modeled with constant global sea level rise projections to identify the impacts of dike and levee protection on wetland loss and the upland migration of coastal wetlands. The percent of wetland loss offset by wetland migration was calculated for each parish in an effort to aid in management decisions. It was found that wetland migration into dry land areas did not occur in any of the three parishes unless dike and levee protection of undeveloped dry lands was removed. The intensity of subsidence and the distribution of dry land greatly impact the overall benefits of allowing coastal wetlands to migrate into dry lands. This observation was exemplified in Lafourche Parish, which has a limited distribution of dry land and was modeled using higher subsidence rates than those found in both St. Mary and Vermilion parishes. Not only was the net loss of wetlands greater when dike and levee protection was removed in Lafourche Parish, but the total amount of wetland gain by means of wetland migration was incapable of offsetting a significant amount wetland loss.

The policy analysis was developed with consideration for the framework of Louisiana's Comprehensive Master Plan for a Sustainable Coast. An exploratory model was created to assist coastal managers and stakeholders in policy decisions regarding the migration of wetlands along Louisiana's coastline. The model was constructed using five main criteria and six different policy alternatives. Policy criteria included wetland migration, flood risk, equity, adaptability, and political feasibility, and the policy alternatives assessed were rolling easements, density restrictions, transferable development rights, conservation easements, defeasible estates and voluntary acquisition. Applying the policy model in scenarios where dike and levee protection is removed reveals that rolling easements would only be appropriate in Vermillion or St. Mary parishes where potential for wetland migration is high. In Lafourche parish, where potential for wetland migration is low, an emphasis on minimizing flood risk suggests that transferable development rights would be the best alternative to pursue. Applying the policy model in areas where dikes and levees are present also favors transferable development rights as the optimal policy alternative. Moreover, this final demonstration suggests that a wetland migration policy can serve to address the CPRA priority of minimizing "induced risk," while also adapting to changes in flood protection planning.

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## List of Acronyms

CPRA	Coastal Protection and Restoration Authority
CWPPRA	Coastal Wetlands Planning, Protection and Restoration Act
CWRP	Coastal Wetlands Restoration Plan
CZMA	Coastal Zone Management Act
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GSLR	Global Sea Level Rise
IPCC	Inter-Governmental Panel on Climate Change
LCA	Louisiana Coastal Area
LOOP	Louisiana Offshore Oil Platform
MHWS	Mean High Water Spring
MTL	Mean Tide Level
MRGO	Mississippi River Gulf Outlet
NOAA	National Oceanographic and Atmospheric Administration
NWI	National Wetlands Inventory
NWF	National Wildlife Federation
NAVD88	North American Vertical Datum 1988
RSLR	Relative Sea Level Rise
SLAMM	Sea Level Affecting Marshes Model
SLR	Sea Level Rise
TDR	Transferable Development Rights
TNC	The Nature Conservancy
USACE	US Army Corps of Engineers
USGS	US Geological Survey

# Introduction

## America's Wetland

The Mississippi River drains over 40 percent of the conterminous U.S. into an estimated 4,680 square miles of wetlands along the Louisiana coast (Couvillion et al. 2011, U.S. EPA 2012). This exceptional landscape is referred to as "America's Wetland" due to the immense ecological, economic, and cultural contribution it makes to the state of Louisiana and the nation as a whole. Louisiana's wetlands play an especially vital role in protecting vulnerable communities and highly valued infrastructure.

Louisiana's coastal wetlands provide habitat for thousands of plant and animal species and are considered to be a unique component of our nation's natural heritage. The North American Flyway, a major migratory path for birds, passes directly over coastal Louisiana where wetlands function as an essential temporary habitat for millions of migratory birds each year (LA Department of Wildlife and Fisheries 2011). Additionally, 17 endangered and threatened species inhabit south Louisiana including the bald eagle, Gulf sturgeon, Louisiana black bear, and several species of sea turtles (CPRA 2011a). This ecologically rich landscape holds great intrinsic value, but it also creates jobs and recreational opportunities associated with birding, hunting, and eco-tourism that contribute nearly 1.5 billion dollars a year to the state's economy (LA Department of Wildlife and Fisheries 2006).

By providing shellfish habitat and nursery habitat for juvenile fish, the wetlands of Louisiana support commercial and recreational fisheries that contribute over 4 billion dollars and more than 45,000 jobs to Louisiana's economy (LA Department of Wildlife and Fisheries 2006). This includes the nation's largest shrimp, oyster and blue crab fisheries that, along with finfish landings, represent more than 24 percent of the commercial fish landings by weight in the lower 48 states (U.S. Department of Commerce 2009). Louisiana marshes also provide habitat for alligators that produce an annual harvest of over 100 million dollars (LA Department of Wildlife and Fisheries 2006).

Louisiana's coastal wetlands provide storm surge protection for extremely valuable and nationally significant energy and shipping infrastructure. The network of energy facilities located along the coast produces or transports over 30 percent of the nation's oil and gas supply and plays a part in 50 percent of the nation's refining capacity (LA Department of Natural Resources 2010). This includes nearly 9,300 miles of pipelines that cut across coastal marshes in every direction (CPRA 2011a). Five of the fifteen busiest ports, ranked by total tons, are located in Louisiana representing 19 percent of annual U.S. waterborne commerce (USACE 2009).

Wetlands, which are omnipresent across the Louisiana coastal landscape, provide the setting for culturally unique communities. For over 12,000 years, the natural resources found along the coast have allowed many civilizations to prosper, including the Chitimacha Tribe who has inhabited the area for at least 2,500 years. New Orleans was founded 300 years ago and quickly became a center of international commerce, attracting people from around the world. Today, Louisiana has the highest percentage of native born residents of any state in the nation (Ardoin et al. 2007). Louisiana's wetlands also provide protection for residential communities. As of 2009, over 2 million residents, nearly 50 percent of the state's population, lived along the coast (U.S. Census Bureau 2009).<sup>1</sup> These proud, deeply rooted coastal communities depend on a healthy buffer of wetlands for their livelihood, protection, and cultural identity.

### **A History of Land Loss**

Nearly a century of coastal land loss has severely threatened the existence of this way of life.<sup>2</sup> Louisiana is home to 37 percent of the coastal wetlands in the coterminous U.S., yet it has seen a drastic reduction of 1,833 square miles since the 1930s. This reduction in wetland area accounts for 25 percent of Louisiana's total wetland loss during that time and an astounding 90 percent of the nation's total coastal wetland loss (Couvillion et al. 2011). Given the importance of wetlands to the vitality of locally and nationally significant assets, this trend is a state crisis and a national emergency (CPRA January 2012). While the rate of loss has slowed from nearly 40 square miles per year from 1956 to 1978 (Barras et al. 2008) to 16 square miles per year from 1985 to 2010 (Couvillion et al. 2011), a continued net loss is likely.

### **Sources of Wetland Loss**

There is no singular cause for the current state of wetland loss. Among the chief threats are invasive species, storm damage, saltwater intrusion, human disturbances, and land subsidence.

Invasive species, like the Nutria, contribute to wetland loss. Nutrias (*Myocastor coypus*) are herbivorous South American rodents that feed on wetland plants. These rodents degrade freshwater and brackish marshes during an "eat out" event, leaving a hole in the marsh. These events can lead to further deterioration and increased erosion of marshes (Carter et al. 1999).

Large storm events can be considerably destructive to coastal wetlands not only as a result of wind and wave erosion, but also due to sediment deposition. Over a four year period (2004-2008), hurricanes Katrina, Rita,

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<sup>1</sup> Coastal population calculated from the sum of the populations of the 19 coastal parishes: Assumption, Calcasieu, Cameron, Iberia, Jefferson, Lafourche, Livingston, Orleans, Plaquemines, St. Bernard, St. Charles, St. James, St. John the Baptist, St. Martin, St. Mary, St. Tammany, Tangipahoa, Terrebonne, and Vermilion.

<sup>2</sup> For coastal Louisiana, the term "land loss" is often used interchangeably with "wetland loss."

Gustav and Ike resulted in an approximate loss of 328 square miles of marsh, which exceeds the amount of total loss occurring over the previous 25 year period (1978-2004) (Barras et al. 2008, Barras 2009). Sediment accumulation on wetlands during large storms and hurricanes can be considerably destructive to coastal wetlands (Baumann et al. 1984, Cahoon et al. 1995, Barras 2006). In 2005, Hurricanes Katrina and Rita deposited over 5 centimeters of sediment across large areas of coastal wetlands (Turner et al. 2006). Though this sediment accumulation was 89 percent of the average accumulation in healthy marshes on the Deltaic plain (Turner et al 2006), the combined impacts of Hurricanes Katrina and Rita resulted in an approximate 217 square miles of land loss (Barras 2006).

Saltwater intrusion is the process by which saltwater from the ocean slowly encroaches on the surface soils and groundwater supplies of freshwater areas (USGS 2008). Storm events, tides, or a rise in sea level can move saltwater higher in the estuary covering coastal lands. As saltwater moves farther up the channel, plant species growing in brackish marshes are placed under increased stress (DeLaune and Peseshki 1994). Increased stress can ultimately kill marsh plants, thus increasing the risk of erosion and human efforts to ameliorate the problem.

In 1927, a devastating flood set in motion a series of events that would change the Louisiana coast. Rains exceeding 10 times the yearly average of the Mississippi River Valley caused one of the worst floods in history. The flood covered an area equal to the size of Massachusetts, Connecticut, New Hampshire, and Vermont combined. In certain places, the river was a record 70 miles wide (Ambrose 2001). In response to the flood, throughout the 1930s and 1940s the U.S. Army Corps of Engineers (USACE) built extensive levees and other flood prevention systems (Ambrose 2001, OCPR 2011). The development of levees offered far better protection for homes and agricultural land. However, a major tradeoff of this protection involves the disruption of sediment flow across the landscape. Dams built along the Mississippi River have also reduced sediment loads by up to 50 percent, thereby reducing sediment delivery to coastal wetlands in Louisiana (Blum and Roberts 2009). Additionally, alterations to the natural landscape in favor of navigation and natural resource production, such as channelization of the Mississippi River and canal dredging, exacerbate wetland loss as well. The increase in the number of canals within coastal Louisiana can be directly correlated with land loss, which ultimately leads to an increase in the amount of open water and additional wetland dieback along the marsh edges (Bass and Turner 1997).

Subsidence, or the sinking of land, is another source of wetland loss and a core topic of discussion within this report. Subsidence results in a change in flooding intensity and salinity thus potentially affecting coastal marsh plants and subsequent erosional processes (DeLaune and Peseshki 1994). Various causes of subsidence include tectonic activity, sediment compaction, and subsurface fluid extraction (Glick et al. 2011).

Sediment compaction is often cited as a large contributor to subsidence in coastal Louisiana (Meckel et al. 2006, Törnqvist et al. 2008). However, subsurface fluid withdrawal of natural resources has a significant influence on subsidence rates. Recent work has demonstrated a close link between subsidence rates and subsurface fluid withdrawal (specifically oil and gas hydrocarbons), and the decline in oil and gas production may be responsible for recent decreases in subsidence rates (Morton and Bernier 2010, Kolker et al. 2011). Additionally, the effects of processes such as glacial isostatic adjustment have recently been quantified at roughly an order of magnitude smaller than previously estimated (Yu et al. 2012). The extent to which these different processes contribute to total subsidence and the spatial heterogeneity of these processes leads to large variability in the subsidence rates across the coastal landscape (Table 1).

**TABLE 1. RANGE OF SUBSIDENCE RATES FOR SIX CATEGORIES OF SUBSIDENCE PROCESSES (YUILL ET AL. 2009).**

<b>Subsidence Process</b>	<b>Range of Identified Rates (mm yr<sup>-1</sup>)</b>	<b>Representative Area Affected</b>
Tectonic/Fault Slips	0.1-20.0	Coastal regions, continental margins, Holocene delta
Holocene Sediment Compaction	1.0-5.0	Holocene delta, lower Mississippi River valley
Sediment Loading	1.0-8.0	Holocene delta, lower Mississippi valley
Fluid Withdrawal	Up to 23	Coastal Regions
Glacial Isostatic Adjustment	0.6-2.0	Gulf region
Surface Water Management	0.1-10.0	Developed wetlands

## Climate Change

In 2005, atmospheric concentrations of the greenhouse gases carbon dioxide and methane exceeded the natural range of concentrations from the last 650,000 years (IPCC 2007a). Global increases in carbon dioxide are due primarily to the use of fossil fuels and changes in land-use. Anthropogenic sources are not the only cause of climate change, but they have produced inputs into the global system that have accelerated the natural process. Advances since the Intergovernmental Panel on Climate Change's (IPCC) 3<sup>rd</sup> Assessment Report show anthropogenic influences extend beyond average surface temperature to other aspects of the climate including sea level rise (SLR) and increased temperature extremes (IPCC 2007a).

Global warming contributes to rising sea level by thermal expansion of the ocean and export of water from melting terrestrial ice (Rahmstorf 2007, Church et al. 2008, Nicholls and Cazenave 2010). The IPCC predicts that global sea level will rise between 18 and 59 centimeters by the year 2100 (IPCC 2007a). More recent models suggest that, over the next century, global sea level will easily exceed one meter with some sources setting the upper bound as high as two meters (Rahmstorf 2007, Pfeffer et al. 2008, Grinsted et al. 2009).

However, the IPCC's assessment does not attempt to factor in the rate of ice sheet flows, or carbon cycle feedbacks, due to a lack of information. For this reason, the IPCC 2007 estimates can be considered conservative. Recent trends in high precision satellite data for the years of 1993 to 2009 suggest that the ice sheets are indeed melting at a faster rate and have surpassed thermal expansion as the primary driver of global SLR (Nicholls and Cazenave 2010, Rignot et al. 2011). Therefore, recent modeling that puts forth a range of one to two meters is feasible and should be used as an upper bound when planning for adaptation.

The set of forces driving regional SLR is different than what dictates SLR on a global scale and is made up of three mechanisms: meteo-oceanographic factors, which includes rates of thermal expansion, changes in long-term wind and atmospheric pressure, changes in ocean circulation (Han et al. 2010), changes in the regional gravity field of the Earth, and vertical land movements (Nicholls et al. 2011). Therefore, localized SLR models will be needed to accurately account for local SLR along the Gulf Coast and Mississippi Delta region.

Adding further complexity to SLR modeling is that non-climatic forces from both human and natural causes can overshadow any estimation of global SLR (GSLR). It is often difficult to separate the impact of GSLR, subsidence, and accretion on the overall change in land and water levels and many researchers have combined the two factors under the term relative sea level rise (RSLR) (Louisiana Wetland Protection Panel April 1987).

The impact of RSLR is greater than that of saltwater intrusion as it has a direct negative effect on wetlands. The amount of open water seaward of a wetland plays a large role in the erosion rates for that wetland. As the fetch increases, wave activity will increase. This increase in wave activity works to speed wetland erosion (Smith et al. 2010). A second cost of rising sea levels is the salinization of estuaries and freshwater systems (IPCC 2007b), further accelerating saltwater intrusion. Therefore, RSLR poses a threat to wetlands in coastal Louisiana not only because of its degenerative effect, but also due to its capacity for enabling other naturally degrading processes.

## **Migration of Coastal Wetlands in Response to RSLR**

A common conceptual model of wetland processes is that marsh surface elevation will change in response to RSLR (Cahoon et al. 2009). Specifically, a coastal marsh will survive if it builds vertically at a greater than or equal rate to RSLR. However, if it builds vertically at a slower rate then it will gradually become submerged and convert to either an intertidal mudflat or open water (Cahoon et al. 2009). If a marsh is successful in building vertically then it has the opportunity to "migrate" inland with rising sea level so long as the slope of the land is not too steep and there are no man-made barriers impeding its movement (Cahoon et al. 2009).

Coastline development and land use practices can limit the potential upland migration of coastal wetlands. Hardened structures, such as dikes, levees, or roads, can impede wetland migration into dry land areas. A 1989 EPA study on wetland vitality in the Mid-Atlantic region found that 65 percent of the wetlands would convert to open water with a 70 centimeters rise in sea level. If shoreline armoring were allowed, it would result in a complete loss of wetlands. On the other hand, the study found that only 27 percent of wetlands would be lost if migration was allowed onto undeveloped lands, and only 16 percent would be lost if migration was allowed onto developed lands (Park et al. 1989).

A more thorough treatment of both wetland migration and policy development are found in the geospatial analysis and policy analysis sections below. This section is simply meant to illustrate the basic process of wetland migration and the potential for wetland loss mitigation with an effective migration policy.

# GEOSPATIAL ANALYSIS

## Objectives

The geospatial component of the project is focused on modeling the current conditions of Louisiana's coast, the effects of future GSLR and subsidence, and identifying corridors for the migration of wetlands. Instead of modeling Louisiana's entire coastline, a case study approach was used allowing for the use of finer resolution data and model calibration. Three coastal parishes were chosen for the variety of physical characteristics they encompass and modeled using the Sea Level Affecting Marshes Model (SLAMM). Wetland landcover change was modeled under several different rates of GSLR and subsidence scenarios for each parish by the year 2100. Parish-specific estimates for coastal change by 2100 and migration corridors are presented in map and tabular form for the CPRA of Louisiana's consideration in future management plans of the Louisiana coast.

## Louisiana's Coastal Plains

Louisiana's coastal zone is comprised of two distinct geomorphic regions: the Chenier Plain in the southwestern part of the state and the Delta Plain in the central and southeastern part of the state (Figure 1). The Chenier and Delta plains have distinct geological histories that result in different observed rates of erosion, accretion, and subsidence in each region.

The Chenier Plain is formed by a series of prograding mudflats intermittently reworked into sand and shell ridges (Penland and Suter 1989). Historically, the Chenier Plain was supplied by longshore transport of sediment from the Mississippi River. This accretion, or accumulation, of sediment created the ridges and as the river shifted and abandoned a delta, sediment delivery would decrease and the shore would retreat. Today, the Atchafalaya diversion supplies sediment to the Chenier Plain via longshore sediment transport (Buster and Holmes 2001). Though a different system, and subject to different physical constraints, the Chenier Plain is intrinsically linked to the Delta Plain and the sediment load of the Atchafalaya and Mississippi Rivers.

In contrast to the Chenier Plain, the Delta Plain was formed by the deposition of sediments from shifting courses of the Mississippi River (Britsch and Dunbar 1993). The mouth of the Mississippi River has shifted paths several times over the past 6,000 years resulting in 14 distinct lobes, including the present day Bird's Foot lobe (Frazier 1967). The Mississippi River has been estimated to deliver 6.2 million kilograms of sediment to the Gulf of Mexico annually (Coleman et al. 1988). Historically, this sediment was distributed around the current lobe and spread across the plain resulting in the creation of the marshes and swamps that now make up the eastern coastline of Louisiana (OCPR 2011). However, with the construction of dams,

levees and dikes, sediment flow has been disrupted in the Delta Plain leaving this area of the coast highly vulnerable to subsidence. As a result, portions of the Delta Plain are considered “inactive” as those areas have reduced or no fluvial activity any longer (Mac et al. 1998).

This local variability produces a variable and large range of subsidence rates throughout the coast (Syvitski et al. 2009, DeMarco et al. 2011). The geology of each region plays a critical role in modeling SLR in coastal Louisiana. While SLR is largely driven by GSLR on the Chenier Plain, SLR in the Delta Plain is driven by RSLR due to the high subsidence rates found in this area of the coast (Gonzalez and Törnqvist 2006).

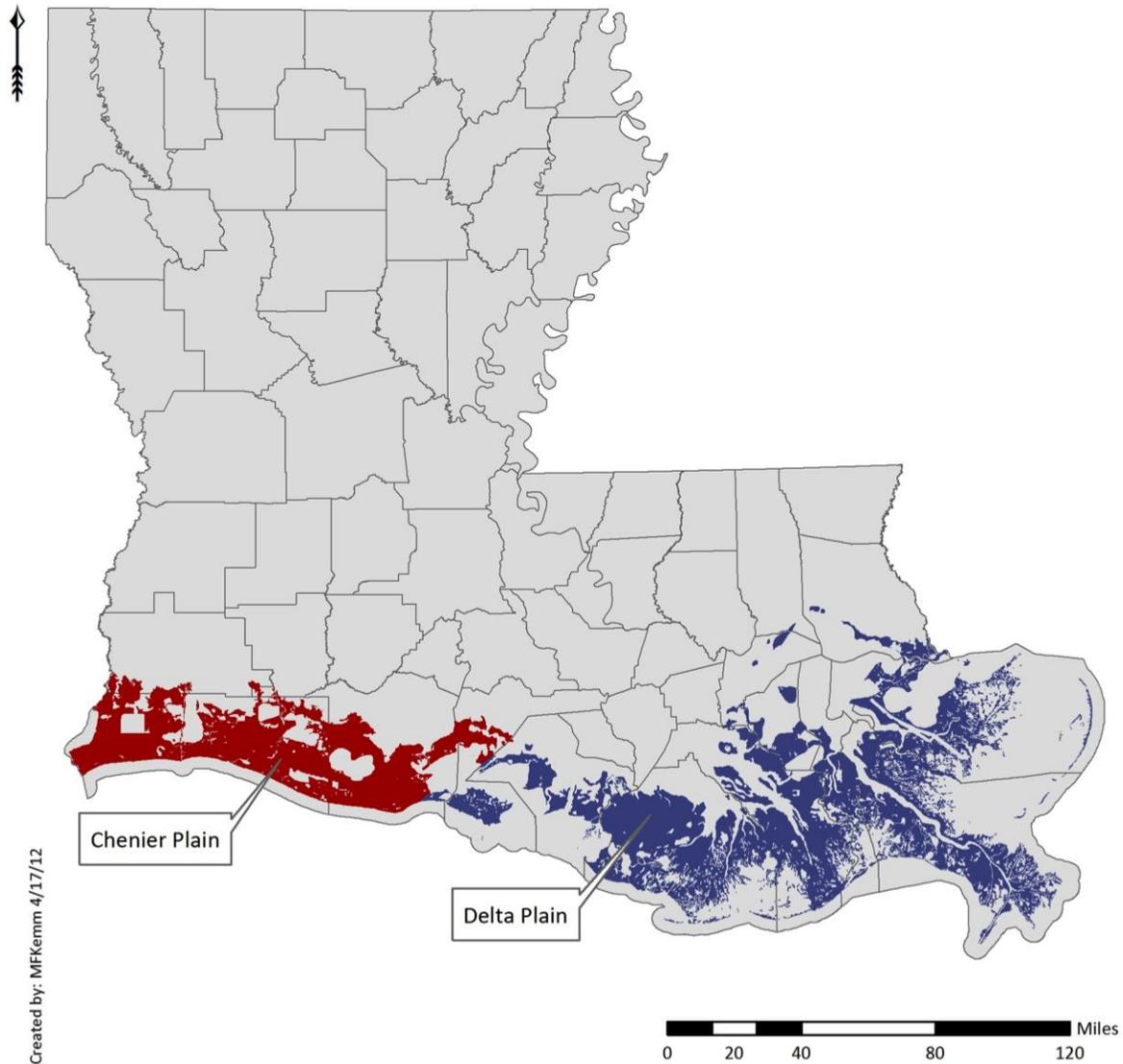


FIGURE 1. LOUISIANA'S COASTAL PLAINS.

## Site Selection

The three parishes used for the case study, Vermilion, St. Mary, and Lafourche, were selected based on their differences in geomorphology and landcover (Figure 2 and Table 2).

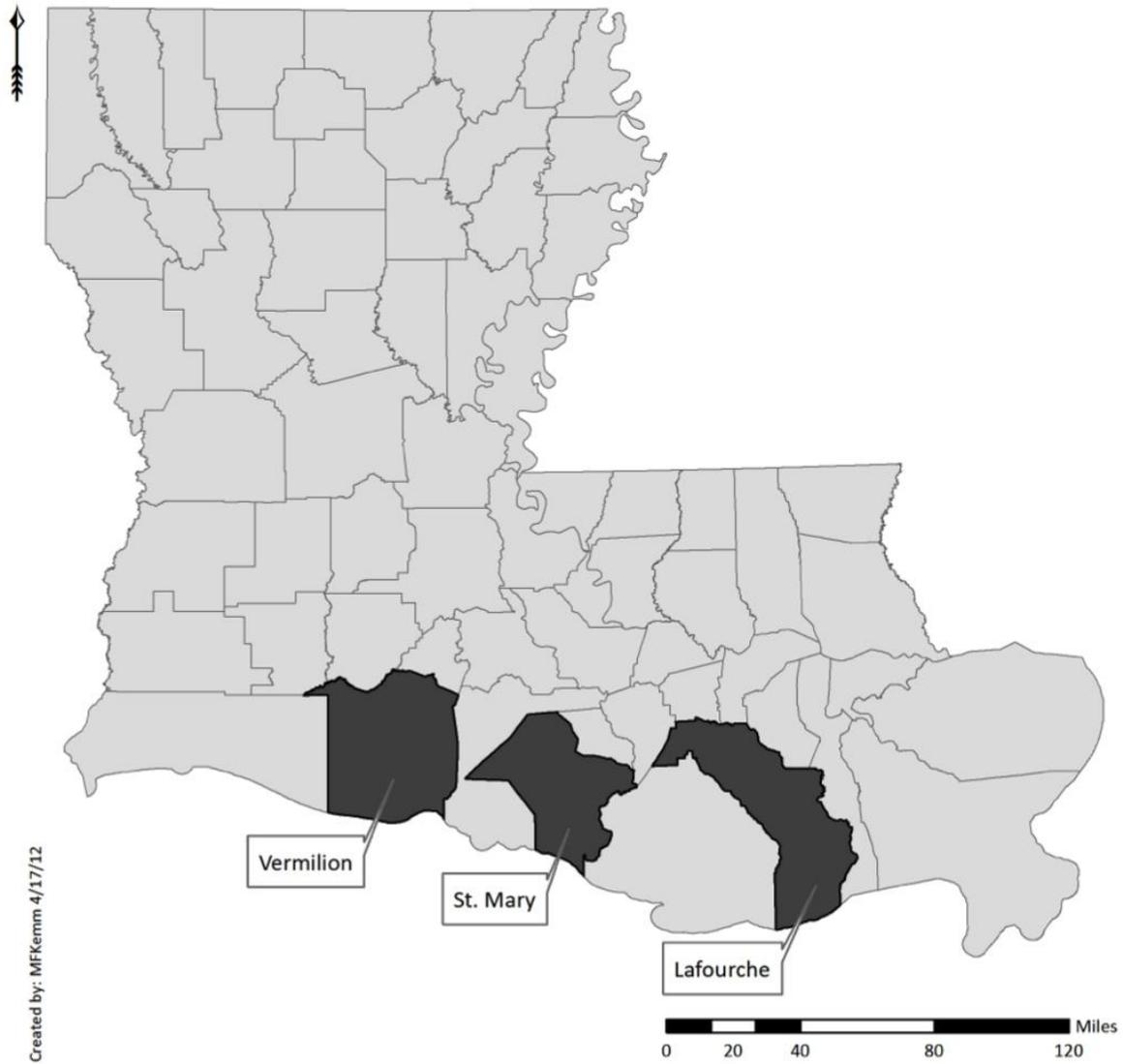


FIGURE 2. THREE PARISHES USED IN SPATIAL ANALYSIS.

TABLE 2. SUMMARY CHARACTERISTICS OF EACH PARISH.

	<b>Lafourche</b>	<b>St. Mary</b>	<b>Vermilion</b>
Coastal Plain Type	Inactive Delta	Active Delta	Chenier
2000 Population	89,974	53,500	53,807
2010 Population	96,318	54,650	57,999
Main Industries	Fishing, Oil and Gas, and Agriculture	Education and health care, manufacturing, entertainment and recreation	Education and health care, agriculture, and retail trade
Area (square miles)	1,468	1,118	1,538
% Wetland Cover	46%	39%	32%
Top 3 Landcover Types (decreasing order)	Irregularly flooded marsh, undeveloped dry land, and inland fresh marsh	Swamp, undeveloped dry land, and tidal fresh marsh	Irregularly flooded marsh, undeveloped dry land, and inland fresh marsh

### Lafourche Parish

Lafourche Parish is the most populated of the three parishes within this study and is home to 96,318 people according to the U.S. Census Bureau (2010). This is an increase of 7.1 percent from the 2000 U.S. Census.

Lafourche Parish’s population is concentrated along the Lafourche Bayou as it extends south, which is typical in southern Louisiana as the edges of land along the bayou often are the highest elevations. This is visible in the figure below where the dry land areas are centered in the middle of the parish and move south following the path of the bayou (Figure 3). In addition to this traditional distribution of the population, Lafourche Parish has a concentration around the city of Thibodaux in the northwestern part of the parish. The city of Thibodaux occupies roughly 2.5 percent of the parish, yet is home to over 20,000 residents (Lafourche Parish Government 2012). As Thibodaux is far inland, it is fairly dry and currently is surrounded by mostly dry undeveloped land.

Lafourche’s primary industries are fishing, oil and gas, and agriculture. Port Fourchon, located in the southern part of Lafourche parish, serves as the base of operations for over 250 companies, including Louisiana Offshore Oil Port (LOOP). LOOP handles 10 percent of domestic oil, 10 percent of the nation’s foreign oil, and is connected to 50 percent of the U.S. refining capacity. Port Fourchon is a vital player in the nation’s oil and gas production furnishing 15 to 18 percent of the country’s oil supply, and servicing 90 percent of the Gulf of Mexico’s deepwater oil production (The Greater Lafourche Port Commission 2012). Lafourche Parish lies just east of the Mississippi River and sits on the Inactive Delta Plain. Thus, this location leads to higher rates of subsidence than either St. Mary or Vermilion parishes. For this analysis, areas north of Larose were assigned higher rates of subsidence than areas south of Larose.

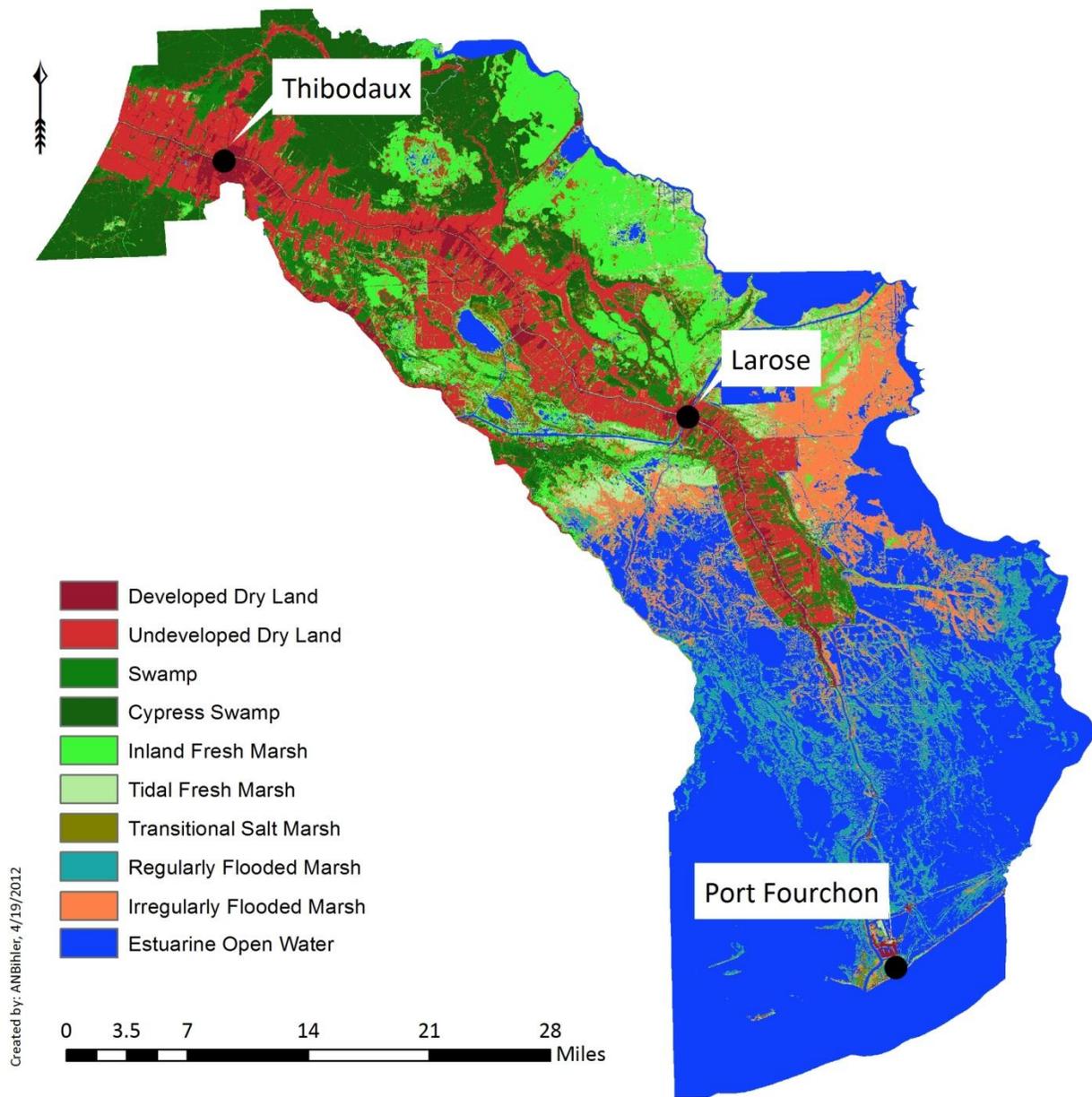


FIGURE 3. OVERVIEW MAP OF LAFOURCHE PARISH.

## St. Mary Parish

St. Mary Parish is located in the Active Delta Plain and is home to the Atchafalaya River Delta, which is considered one of the few places in the Delta Plain that is actively accreting sediment (Couvillion et al. 2011). The Atchafalaya River contains the 5th largest sediment discharge of any river in North America (Ford and Nyman 2011). Although the inflow from the Red River and Mississippi River is highly managed, the Atchafalaya River encompasses an extensive floodplain, which provides a variety of ecological services. Sediments carried by the Atchafalaya River drive the growth of the Atchafalaya River Delta and the Wax Lake Outlet Delta (Ford and Nyman 2011).

Regardless of the actively accreting sediment from the Atchafalaya River, the rate of subsidence throughout St. Mary Parish is estimated to be between 5 and 7 millimeters per year (DeMarco et al. 2011). However, there are some areas that are an exception to parish-wide subsidence rate estimates. For example, there is a small area of flotant, or floating, marsh located east of the Atchafalaya River Delta (Sasser et al. 1996). Flotant marshes are thought to be resilient with the onset of rising water levels, but are vulnerable to changing water parameters such as salinity (Sasser et al. 1996). Additionally, a small area in the western portion of the parish contains the Belle Isle Salt Dome (Figure 4), which has an estimated uplift of about 2 to 3 millimeters per year (DeMarco et al. 2011).

The largest city in St. Mary Parish is Morgan City (Figure 4), which lies alongside the Atchafalaya River and is protected by levees. According to the 2010 U.S. Census, the total population in St. Mary Parish was 54,650 and has increased by 2.1 percent since the 2000 U.S. Census. Dominant industries within St. Mary Parish include educational services, health care, manufacturing, entertainment and recreation. Occupations in agriculture, forestry, fishing, hunting and mining account for roughly 10 percent of the civilian employed population (US Census Bureau, 2010).

In terms of landcover, St. Mary Parish is mostly composed of swamp, undeveloped dry land, and tidal fresh marsh (Table 2). Undeveloped dry lands are primarily used for agriculture (Figure 4). Only 4 percent of St. Mary's total landcover is developed dry land. There is an extensive system of levees and dikes within the parish boundaries, which protect both dry lands and some freshwater wetland areas from flooding waters. St. Mary's landcover consists of about 41 percent wetlands; freshwater marshes and swamps constitute the dominant wetland types of this area of the coast.

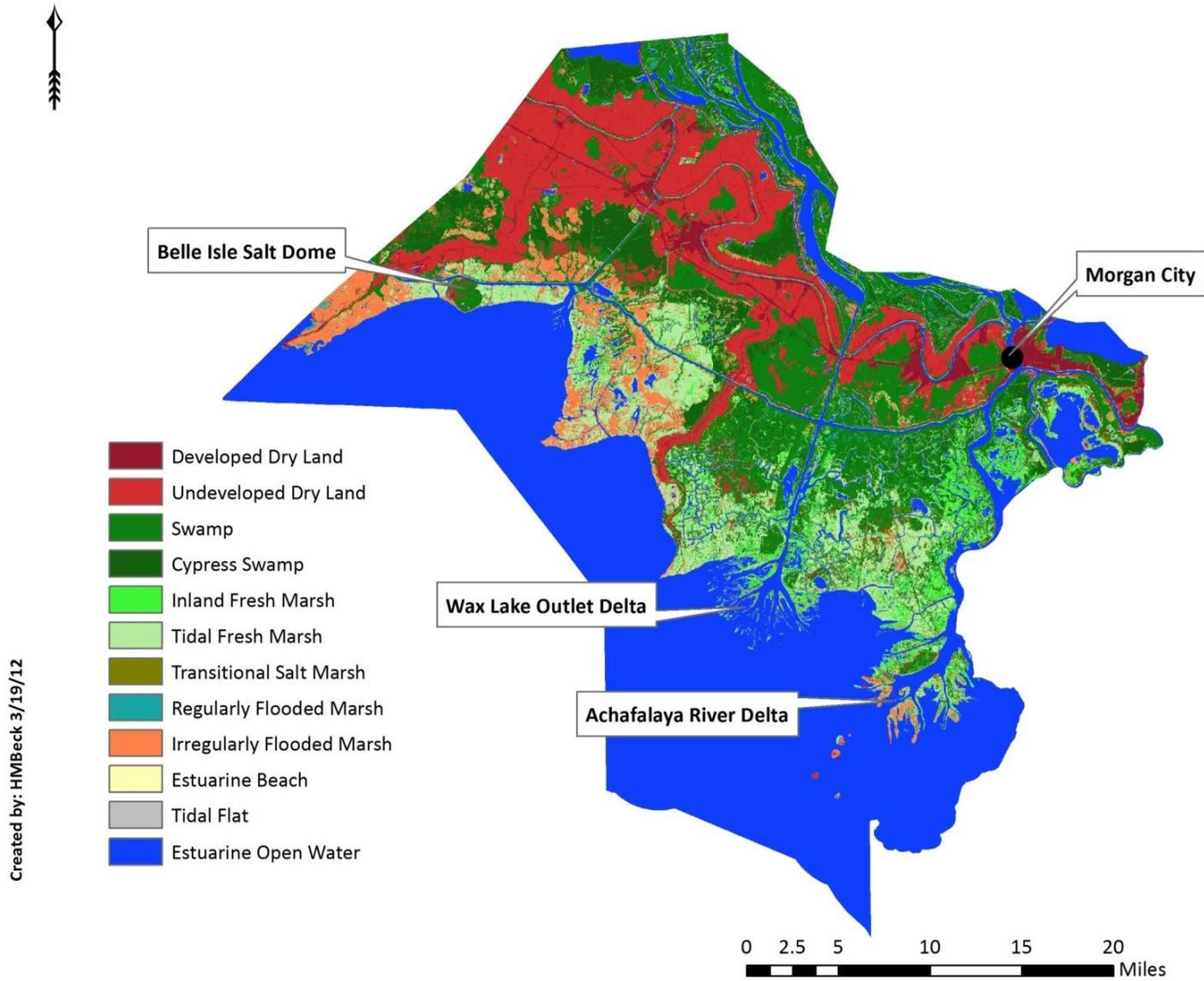


FIGURE 4. OVERVIEW MAP OF ST. MARY PARISH.

## Vermilion Parish

Vermilion Parish is home to 57,999 people as of the 2010 U.S. Census, which represents a 7.8 percent increase in population since the 2000 Census. Vermilion is the “Most Cajun Place on Earth” according to U.S. Census records with nearly 50 percent of Vermilion citizens claiming Cajun (Vermilion Parish Tourist Commission 2012). The major towns and cities in Vermilion Parish are concentrated near Louisiana Highway 14 in the northern part of the parish. The parish seat is located in Abbeville, which has a population of 12,257 residents (U.S. Census Bureau 2010).

The major cities in Vermilion parish are surrounded by undeveloped dry land that is mostly agricultural lands (Figure 5). As of 2011, Vermilion parish contained the third largest rice acreage area in the state of over 51,000 acres (LSU AgCenter 2011). Vermilion’s main industries are educational, healthcare, and social services; agriculture, forestry, and fishing; and retail trade.

Adjacent to White Lake is the White Lake Wetland Conservation Area that includes 71,000 acres of marsh and wetlands (LA Department of Wildlife and Fisheries 2010). Vermilion has two ports, which are each located along Vermilion Bay. Located just south of the city is the Abbeville Harbor and Terminal District, in which the coastal port’s main inbound and outbound cargos are oil rig supplies. Located on the Iberia and Vermilion parish line is the Twin Parish Port District that is home to the Delcambre District Seafood market where consumers are able to purchase seafood direct from shrimpers (CPRA 2011b).

Vermilion Parish is located in the Chenier Plain, and thus has the lowest subsidence rates of the three parishes in the case study.

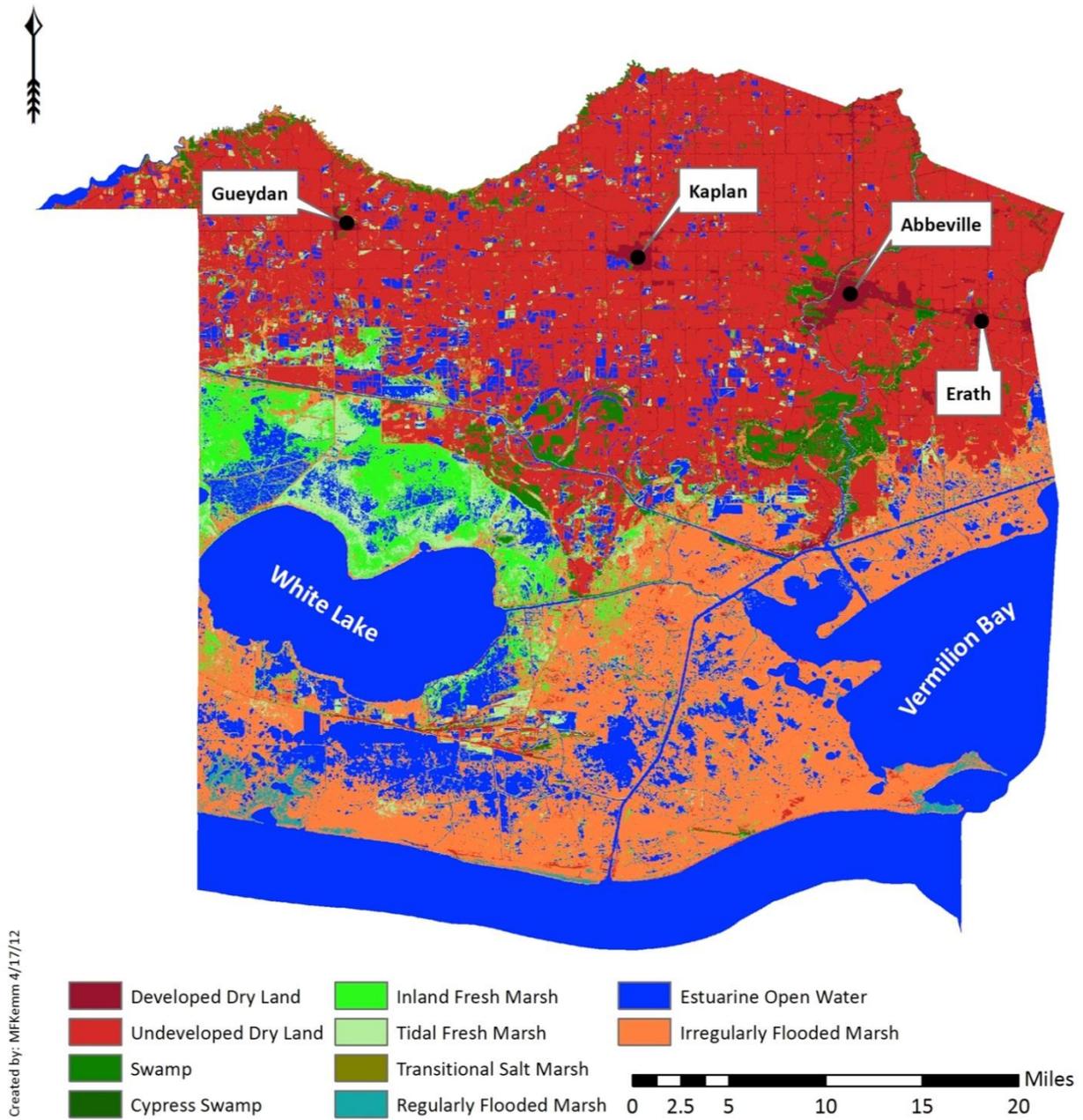


FIGURE 5. OVERVIEW MAP OF VERMILION PARISH.

## Geospatial Model Summary

### Overview of SLAMM

The Sea Level Affecting Marshes Model (SLAMM) is a tool that enables the user to assess the impact of RSLR on coastal habitats. RSLR is determined within SLAMM by the inclusion of site-specific data such as rates of subsidence or uplift, historic trends of GSLR, and the projected rate of future GSLR.

Required spatial inputs for the model include elevation, slope, and wetland data in ASCII raster format.

Optional inputs include dike coverage, percent impervious surface and local uplift or subsidence data.

Additionally, site-specific parameters such as tide range, salt elevation, marsh erosion and accretion rates, and historical GSLR trends can be specified within the model. GSLR scenarios may be based on IPCC projections or defined by the user. SLAMM outputs both tabular and GIS data, which display habitat and shoreline change for a desired year or series of years.

SLAMM has been in development since the mid-1980s and has been utilized in various studies within the U.S. and abroad (Park et al. 1989, Clough 2010, Akumu et al. 2011, Clough et al. 2011). The version currently available and used in this particular study is SLAMM 6.0. Within SLAMM 6.0, there are six primary processes that affect wetland fate in response to GSLR (Clough et al. 2010):

1. Inundation: As the salt elevation and water levels rise, minimum elevation and slope are used to calculate inundation of land on a cell-by-cell basis. Values for accretion and subsidence rates are used to calculate any additional change in elevation.
2. Erosion: The proximity of a cell to open water and the fetch, or the unobstructed distance in which wind can travel over open water, are used to determine an erosional threshold. Within SLAMM 6.0, once a fetch threshold of 9 kilometers is breached, constant erosion will occur based on user-defined erosional rates.
3. Overwash: Overwash is the unidirectional movement of water and sediment over a beach crest typically observed after storm events (USACE 2004). SLAMM assumes that barrier islands 500 meters or less in width will undergo overwash within a user-defined time frequency. Wetlands located on the leeward, or lower energy, side of barrier islands are thought to be vulnerable to conversion due to this flow of water and sediment. Sediment transport and beach migration are calculated within this model process. The frequency of overwash in years and an additional value of beach sedimentation rate ( $\text{mm yr}^{-1}$ ) may be adjusted site-specifically.

4. Saturation: The migration of coastal wetlands onto adjacent uplands can occur as a result of the water table rising with sea level. However, SLAMM is not a hydrodynamic model given that saline inundation within the model may only occur if a cell is connected to a saltwater source based on an eight-sided connectivity algorithm. There is an option within SLAMM 6.0 to utilize a soil saturation feature in which the water table will rise with rising sea levels. Unfortunately, this feature results in streaking within the final model output producing questionable results. Thus, this feature was not used within this study.
5. Accretion: Accretion involves the upward growth of marshes as a result of the accumulation of sediment and biomass. This process may be intensified by the type and amount of above and belowground vegetative biomass (Morris et al. 2002). Accretion within a specific site may vary significantly according to habitat type and biomass, elevation, tidal range, salinity, and proximity to rivers or tidal channels. SLAMM calculates the accretion of a site based on a function of cell elevation, proximity to river or tidal channels and a user-defined accretion rate according to marsh type. Marsh types that are assigned accretion rates within SLAMM include regularly flooded, irregularly flooded and tidal fresh marshes.
6. Salinity: A new addition to SLAMM 6.0 is the salinity model. The salinity model is an optional feature in which the user can define freshwater flows and the slope of an estuary's salt wedge within the study area. Salinity is thought to significantly affect wetland persistence and migration with rising sea levels. However, the use of the salinity model is not currently encouraged by the model creators without closer collaboration with SLAMM experts as it is still experimental and hypothetical (Clough 2012). Therefore, the salinity model was not utilized within this study although there are significant freshwater flows within the study area.

These six processes are the basis for an intricate decision tree, which determines the conversion of wetland classes. All landcover classes are assigned a range of elevations in which they fall under and those ranges may be edited within SLAMM 6.0. It may be necessary to edit minimum elevations for some freshwater marsh areas in which current areas may fall below the default setting (Clough 2012). Once inundated and the elevation of a cell falls below the assigned minimum elevation for its assigned landcover class, certain areas will undergo conversion to another landcover type. Exceeding the fetch threshold will result in a different type of conversion for some landcover types. For example, once cells assigned to the swamp category fall below the assigned minimum elevation and there is no constant erosion, those cells will convert to

transitional salt marsh (Table 3) (Clough et al. 2010). However, under constant erosion and inundation, cells assigned to the swamp category will convert to tidal flat (Clough et al. 2010).

**TABLE 3. ASSUMPTIONS OF WETLAND CONVERSION IN SLAMM.**

<b>Original Landcover</b>	<b>Conversion To (only inundation)</b>	<b>Conversion To (with erosion*)</b>
Dry Land	Transitional salt marsh, ocean beach, or estuarine beach, depending on context	Tidal Flat
Swamp	Transitional salt marsh	Tidal Flat
Cypress Swamp	Open water	Tidal Flat
Inland Fresh Marsh	Transitional salt marsh	Tidal Flat
Tidal Swamp	Tidal Fresh Marsh	Tidal Flat
Tidal Fresh Marsh	Irregularly Flooded Marsh	Tidal Flat
Transitional Salt Marsh	Regularly Flooded Marsh	Tidal Flat
Irregularly Flooded Marsh	Regularly Flooded Marsh	Tidal Flat
Regularly Flooded Marsh	Tidal Flat	Tidal Flat
Mangrove	Estuarine Water	Estuarine Water
Ocean Flat	Open Ocean	Open Ocean
Tidal Flat	Estuarine Water	Estuarine Water
Estuarine Beach, Ocean Beach	Open Water	Open Water

\*Erosion will occur if a cell is adjacent to open water and the fetch is > 9km.

### Limitations of SLAMM

As with any model, the results are limited by the availability of quality data and the inability of the model to account for a complexity of processes that may or may not be fully understood. Higher resolution, or finer scale, elevation data from a recent date is one of the most important inputs for this model as the vulnerability of coastal wetlands to SLR may be determined at a highly localized scale. Using finer resolution landcover data from an analogous date to that of the elevation data will improve the model results as there will be fewer discrepancies between the datasets. On the other hand, if lower resolution elevation and landcover data that varies in date is used it is possible for the user to implement a tool within SLAMM called the elevation preprocessor. The wetland preprocessor adjusts the landcover data so that landcover classes fall within the defined elevation ranges defined within the model parameters. This process simply aligns the data inputs and commonly results in the reassignment of landcover types in certain areas where elevation values do not match the expected landcover. The elevation preprocessor does not provide as realistic of an image as would be observed when using higher quality data.

As mentioned previously, SLAMM is not a hydrodynamic model nor does it account for other complex processes related to geomorphology or increasing intensity of hurricanes (Clough et al. 2010, Glick et al. 2011). A specific limitation in modeling the Louisiana coast involves effectively modeling the effect of RSLR on floatant marshes, which are thought to be resilient to rising water levels and storm activity yet vulnerable to changing water quality (Sasser et al. 1996, Sasser et al. 2007). Since SLAMM models wetland conversion based on cell elevation, the model is not entirely appropriate for use in these specific areas of the coast without the incorporation of a hydrodynamic analysis (Clough et al. 2011). As will be discussed later in the Methods and Data Sources section of this report, floatant marsh areas modeled within this study were assigned higher accretion rates to account for the assumed resilience of these areas to rising seas. However, the observed rates of conversion of these marsh areas as sea levels rise is limited by a lack of ability to accurately model changing water quality.

### Alternative SLR Models

There are several approaches to modeling and analyzing the vulnerability of coastal areas to SLR. McLeod et al. (2010) outline several SLR models that differ in application according to the objective and scale of the respective study. Models discussed include basic geospatial inundation analysis models, ecological landscape simulation models, and models that integrate both biophysical and socioeconomic components of analysis. The choice of model is dependent upon the overall objectives of the project as well as the available time and resources. For example, basic geospatial inundation models are inexpensive and quick to implement. Although useful to some extent, this type of modeling is limited by its simplicity and oversight of some principles or necessary final products that other models may offer. Some government agencies have the resources to fund more intensive modeling projects that can tackle a more integrated or specific approach.

SLAMM was the chosen model for this study due to its assessment of the vulnerability of coastal wetland habitats and its inexpensive implementation. Additionally, SLAMM offers the ability to adjust parameters according to site-specific data. This characteristic is beneficial when modeling the Louisiana coast as local conditions vary significantly across the landscape. SLAMM has also previously been used by the National Wildlife Federation (NWF) to model the effects of RSLR on coastal wetlands in Louisiana's Delta Plain (Clough et al. 2011). Not only does this provide a foundation for this study, but it also provides an avenue of comparison and reaffirmation of the utility of SLAMM for coastal management in Louisiana. This study, in particular, is similar to what was implemented within the Clough et al. (2011) NWF report in regards to the model parameters and data inputs used within SLAMM. However, the NWF study focuses solely on the Inactive Deltaic Plain while this study implements a case study of sites located across Louisiana's coastal plains.

## GSLR Scenario Options within SLAMM

SLAMM provides a selection of preset GSLR scenarios based on IPCC projections that vary in rate and maximum rise by the year 2100. Each of these scenarios illustrate different futures with respect to economic growth, global population growth and technological advances (IPCC 2001). Within SLAMM, while the rate of GSLR may remain constant, the extent of the rise by the year 2100 may vary depending on the user's preference. The default rate of GSLR used within SLAMM is modeled after the IPCC's A1B maximum scenario (Clough et al. 2010). The A1B scenario reflects a future in which there is high economic growth, significant technological advances, a global population that peaks mid-century and then declines, and less reliance on one source of energy (IPCC 2001).

For this study, GSLR rates of 0.5, 1.0, 1.5 and 2.0 meters by 2100 were implemented as requested by the CPRA. This range of GSLR rates is similar to values that have been used in previous studies, such as the previously discussed NWF 2011 report (Clough et al. 2011), thus offering the opportunity for future analysis and comparison.

## Methods and Data Sources

SLAMM was used to model Lafourche, St. Mary, and Vermilion parishes in 30-meter cell resolution data.

### Forecast Modeling of RSLR

#### ***Elevation Data***

Elevation data (DEM) was downloaded from the National Elevation Dataset for the most recent year in 1/3 Arc-second resolution, approximately 10-meter square cells. This dataset was used because it is dated after the 2005 hurricane season that drastically changed Louisiana's coast. Additionally, this data is available for the whole coast. To match the resolution of the landcover data, the DEM was aggregated into 30-meter square cells using a bilinear sampling technique. Slope was derived from the aggregated DEM in units of degrees.

#### ***Landcover Data***

Landcover data was provided by Brady Couvillion of the U.S. Geological Survey (USGS) at 30-meter resolution for Louisiana's coast based on 2007 landcover information (Couvillion 2010). The landcover classes used in this data set were reclassified into the appropriate SLAMM categories as shown in Table 4 using best judgment and following the classifications used within the 2011 NWF Report (Clough et al. 2011). Aggregation of the different classes of the 30-meter cells results in landcover types and areas shown in Table 5 as well as Figure 3, Figure 4, and Figure 5 for each of the three parishes.

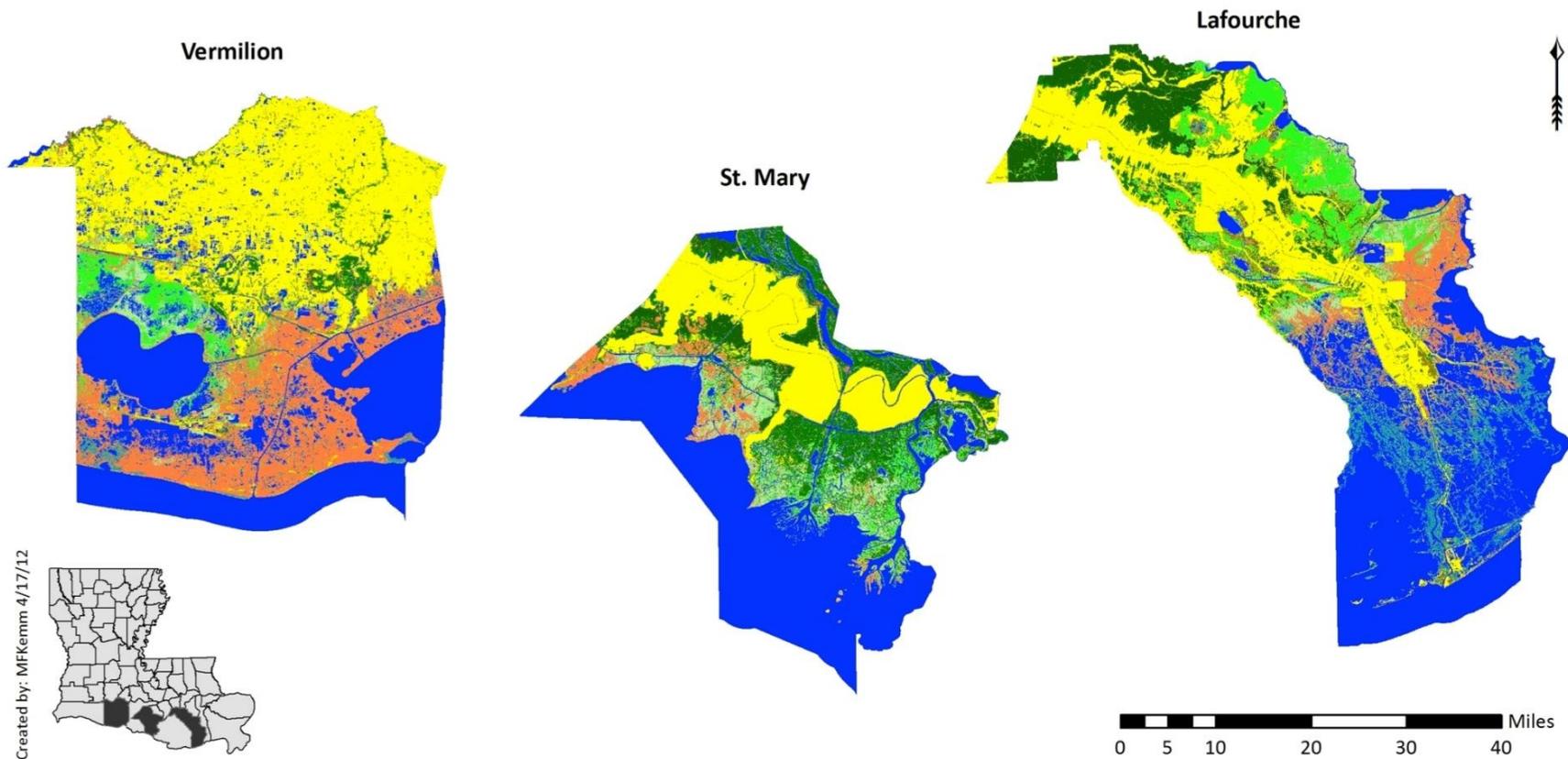
Dry land (SLAMM categories 1 and 2) is assumed to be protected from rising sea levels. Due to this, the dike file created for each parish encompasses all dry land areas. The dike file is supplemented with USACE levee data from 2009 and National Wetlands Inventory (NWI) data for the parishes from the late 1980s; we assume that any dikes included in the NWI dataset are still in use. Areas protected by dikes and levees for each parish are shown in yellow in (Figure 6).

TABLE 4. LANDCOVER TO SLAMM CLASSIFICATIONS.

USGS Wetland Classification (Couvillion 2010)	SLAMM Wetland Classification
High Intensity Developed Medium Intensity Developed Low Intensity Developed Developed Open Space	Dry Developed Land
Cultivated Pasture/Hay Grassland Bare Land Upland Evergreen Forest - Logleaf/Slash Pine Group Upland Evergreen Forest - Loblolly/Shortleaf Pine Group Upland Mixed Forest - Southern yellow pine/mixed hardwoods Upland Deciduous Forest - Mixed upland hardwoods Palustrine Forested Wetland (PFW) -Southern yellow pine/mixed hardwood group	Undeveloped Dry Land
PFW - Bottomland Ridges - Sweetgum/yellow poplar PFW - Bottomland - Sugarberry/elm/green ash PFW - Bottomland - Nutall oak/sweetgum/willow PFW - Bottomland Ridges - Cottonwood/willow/Sycamore PFW - Bottomland - Overcup oak/water hickory PFW - Swamp - Sweetbay/tupelo/red maple	Swamp
PFW - Swamp - Cypress/tupelo	Cypress Swamp
PFW - Swamp - Red maple lowland Palustrine Scrub/Shrub Wetland	Swamp
Scrub/Shrub Wetland - Wax Myrtle Estuarine Scrub/Shrub Wetland - Black Mangrove	Transitional Salt Marsh - Scrub/Shrub
Palustrine Herbaceous Wetlands (PHW) - delta splay PHW - cutgrass PHW - Maidencane PHW - thin mat PHW - cattail PHW - sawgrass	Inland Fresh Marsh
Intermediate Herbaceous Marsh (IHM) - bulltongue IHM - roseaucane IHM - bullwhip	Tidal Fresh Marsh
Brackish Herbaceous Marsh (BHM) - wiregrass BHM - paspalum BHM - wiregrass/saltgrass/oystergrass	Irregularly Flooded Marsh
Salt Herbaceous Marsh (SHM) - needle grass SHM - saltgrass SHM - oystergrass	Regularly Flooded Marsh
Water	Estuarine Water

TABLE 5. INITIAL LANDCOVER FOR PARISHES.

	Lafourche		St. Mary		Vermilion	
	Hectares	%	Hectares	%	Hectares	%
Dry Developed Land	36.9	3	29.5	3	33.3	2
Undeveloped Dry Land	186.3	13	139.1	12	504.6	33
Swamp	76.4	5	181.6	16	39	3
Cypress Swamp	161.6	11	70.8	6	7.8	1
Inland Fresh Marsh	167.8	11	44.3	4	77.6	5
Tidal Fresh Marsh	66.9	5	94.4	8	63.8	4
Transitional Salt Marsh	14.3	1	4.8	0	0.2	<1
Regularly Flooded Marsh	70.6	5	3.2	0	8.4	1
Irregularly Flooded Marsh	113	8	56.6	5	299	19
Estuarine Water	574.2	39	493.5	44	504.3	33
<i>Total</i>	1,468	-	1,118		1,538	-



Created by: MFKemm 4/17/12

FIGURE 6. LAND AREAS IN EACH PARISH PROTECTED BY DIKES AND LEVEES (SHOWN IN YELLOW).

### ***GSLR Scenarios***

Using the above data and methods, the SLAMM model was run for each parish for the years 2025, 2050, 2075, and 2100 modeling 0.5, 1.0, 1.5, and 2.0 meters of GSLR following the direction from the client. The four main SLAMM scenarios are a combination of dike and no dike protection for dry land and “moderate” and “less optimistic” subsidence scenarios. Additional runs were completed as part of the sensitivity analysis (see the Sensitivity Analysis section for more information).

### ***Historic Subsidence Rate***

Subsidence rates for each parish were provided by the CPRA for both “moderate” and “less optimistic” subsidence conditions. The “moderate” scenario corresponds to lower subsidence rate estimates for each parish and the “less optimistic” to the higher subsidence rate estimates. The use of different values for each parish follows methods used in the 2012 Draft Master Plan (CPRA January 2012) and accounts for the variable subsidence of each parish due to the geomorphic characteristics of Louisiana’s coastal zone. Subsidence rates for each parish and scenario are summarized in Table 6. Both the “moderate” and “less optimistic” subsidence rates were run with all GSLR scenarios implemented in this study. Not all land in coastal Louisiana is subsiding; there are small areas of uplift such as the salt domes located on the Delta Plain.

TABLE 6. SUBSIDENCE SCENARIOS USED FOR EACH PARISH.

<b>Scenario</b>	<b>Parish</b>	<b>Subsidence (mm yr<sup>-1</sup>)</b>
Moderate	Lafourche (N of Larose)	12
	Lafourche (S of Larose)	9
	St. Mary	5
	Vermilion	4
Less Optimistic	Lafourche (N of Larose)	21
	Lafourche (S of Larose)	13
	St. Mary	7
	Vermilion	6

### ***Salt Domes***

Southern Louisiana salt domes, referred to as the Five Islands, are all located near the western boundary of the Delta Plain. These salt domes experience an absolute uplift from several kilometers of depth due to the geological characteristics and activity of the surrounding and underlying strata (Autin 2002). These domes are circular in shape and range in elevations from roughly 20 to 50 meters above sea level. The Five Islands have had a long-standing importance to the mineral resources of southern Louisiana and have been exploited for the production of rock salt, salt brine, sulphur, oil and gas, and the geostorage of energy reserves (Autin 2002).

The Belle Isle Salt Dome is located in western St. Mary Parish (Figure 4) and has an estimated uplift of about 2 to 3 millimeters per year (DeMarco et al. 2011).

### ***Erosion***

The erosion rates used were the SLAMM defaults following the 2011 NWF report (Clough et al. 2011).

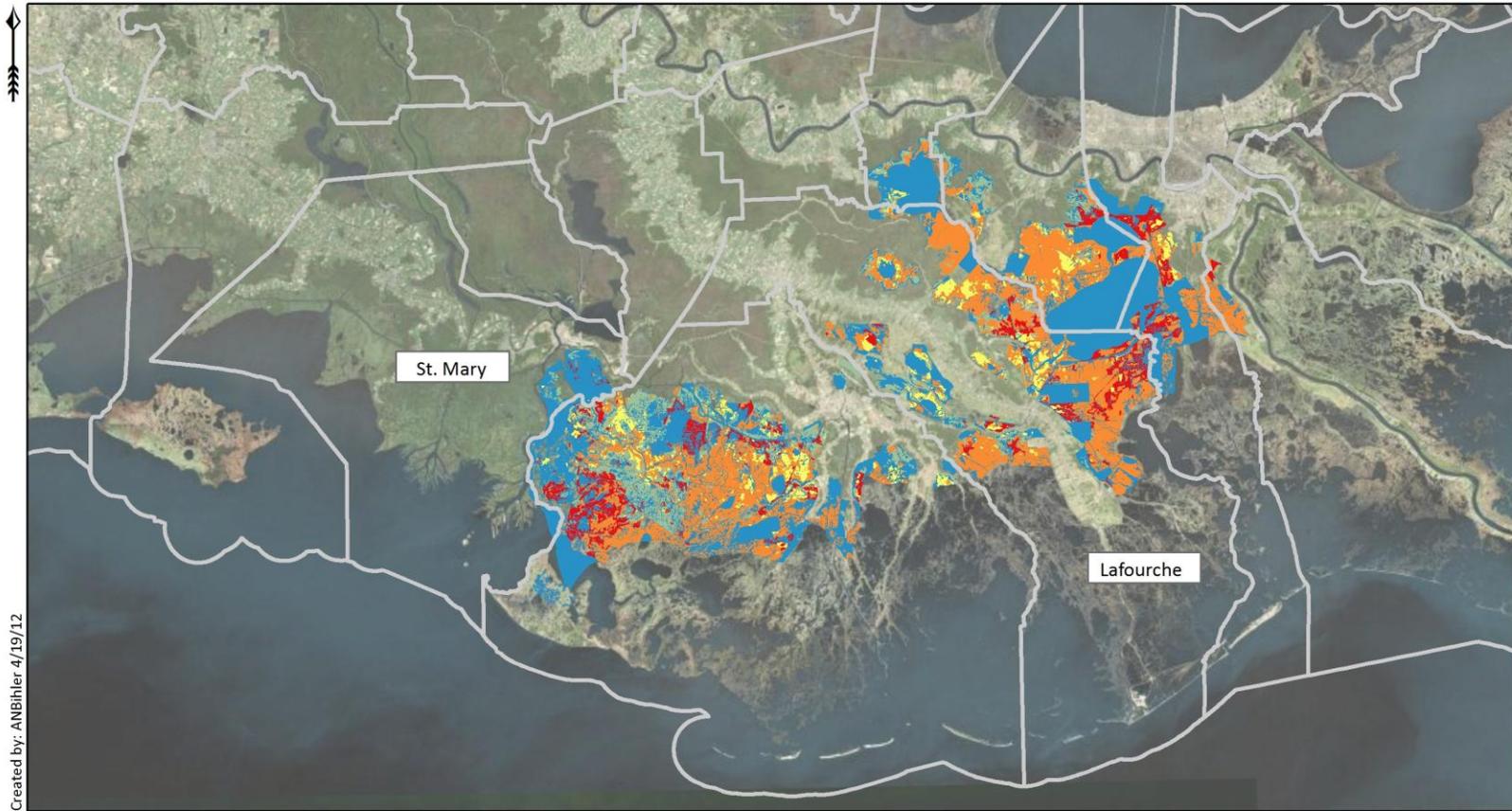
Previous research suggests that subsidence has a greater contribution to marsh loss than erosion in coastal Louisiana (Morton and Bernier 2010). For consistency, the same default SLAMM values were used for all three parishes. Values used are shown in the “Parameters” section below.

### ***Accretion***

Accretion rates used were taken from the 2011 NWF report, which were calculated from an average accretion value for marsh types based on a review of peer-reviewed literature (Clough et al. 2011). Values used are shown in the “Parameters” section below. The one exception is flotant marsh, which was assigned higher accretion values to account for the resilience of these areas to rising water levels.

### ***Flotant Marsh***

Landcover data from the 1990s in the Barataria and Terrebonne basins show flotant marsh covering over 547 square miles of freshwater and low salinity marsh areas (Sasser et al. 2007). Flotant marsh is comprised of a thick buoyant mat in a continuously floating organic matrix that allows the marsh to stay continually wet. Flotant marsh data is only available for Lafourche and St. Mary parishes as the study that yielded the data was focused on the Barataria-Terrebonne Estuary (Figure 7). Areas of flotant marsh in Lafourche and St. Mary parishes were modeled using subsites and assigning those sites higher accretion values of 15 to 20 millimeters per year (Clough et al. 2011).



**Flotant Marsh Type**

- Thick mat marshes of undetermined buoyancy
- Thick mat, herbaceous floating marshes
- Thick mat, woody floating marshes
- Thin mat, herbaceous floating marsh
- Other
- Louisiana Parishes

Basemap material from Bing Maps Aerial

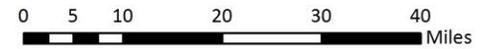


FIGURE 7. FLOTANT MARSH EXTENT.

**MTL to NAVD88 Correction**

In order to estimate the frequency of inundation for each cell within SLAMM, a correction factor is needed to convert the DEM from a North American Vertical Datum 1988 (NAVD88) to Mean Tidal Level (MTL). The National Oceanographic and Atmospheric Administration’s (NOAA) VDATUM software was used to correct the elevation data for the MTL. An average correction value was estimated for each parish or subsite. Random point files were created for each parish with location and elevation information extracted to each point. The point information was loaded into the VDATUM program and corrected using the appropriate coastal Louisiana correction file. The final MTL correction value is an average of the VDAUTM corrected values minus the DEM elevation.

Subsites are used within the SLAMM model to allow for modeling of areas with different model parameters or correction values. Lafourche Parish is modeled with subsites, but all subsites have the same MTL-NAVD88 correction. Areas in St. Mary Parish are modeled with subsites using unique MTL corrections to increase the accuracy of the model predictions (Table 7). (See Summary of SLAMM Parameters by Parish for more information and maps of the subsites.)

TABLE 7. MTL-NAVD88 CORRECTION VALUES FOR EACH PARISH.

Parish/Subsite	MTL-NAVD88 (m)
Lafourche*	-0.08
St. Mary-Subsite 1	-0.123
St. Mary-Subsite 2	-0.135
St. Mary-Subsite 3	-0.151
St. Mary-Subsite 4	-0.427
St. Mary-Subsite 5	-0.496
Vermilion	-0.145

\*Subsites are used in Lafourche Parish, but have the same MTL-NAVD88 correction.

### **Diurnal Tide Range**

Tide data was obtained from NOAA’s Tides and Currents website for tidal gauges within each parish (Table 8).

The diurnal tide range published for each site is based on a 19-year average. In regions of anomalous sea level changes, like the Gulf of Mexico, a shorter 5-year average is used (NOAA Tides & Currents 2012).

Lafourche and St. Mary parishes have multiple tidal gauges within their boundaries, so a surface was interpolated for the two parishes based on the tidal range. In Lafourche Parish, one average value was used for all subsites whereas in St. Mary Parish each subsite has a unique diurnal tide range value.

**TABLE 8. NOAA TIDE STATIONS WITHIN EACH PARISH THAT HAD USEABLE DATA.**

<b>Parish</b>	<b>NOAA Tidal Gage Site Name</b>	<b>Station Number</b>	<b>Diurnal Tide Range (m)</b>
Lafourche	East Timbalier Island, Timbalier Bay	8762223	0.402336
	Port Fourchon	8762075	0.374904
	Leeville, Bayou Lafourche	8762084	0.268224
	Texaco Gas Exploration Dock, Bay Rambo	8761962	0.222504
	Golden Meadow, Plaisance Canal	8762184	0.170688
	Texaco Dock, Hackberry Bay	8761819	0.27432
St. Mary	LAWMA, Amerada Pass, LA	8764227	0.475488
	Freshwater Canal Locks, LA	8766072	0.658368
	Berwick, LA	8764044	0.149352
	Cyremont Point, LA	8765251	0.51816
Vermilion	Freshwater Canal Lock	8766072	0.658

### **Salt Elevation**

The salt elevation, also known as the Mean High Water Spring (MHWS), is the elevation that is inundated approximately once every 30 days. Within SLAMM, the MHWS designates the vertical boundary between wetlands and dry lands or saline and fresh water wetlands (Clough et al. 2010). The MHWS is calculated by multiplying half of the great diurnal tide by 1.7 for each parish and subsite (Table 9). This method was used for its uniformity among parishes and use in previously published SLAMM applications (Clough et al. 2011).

TABLE 9. SALT ELEVATION FOR EACH PARISH.

<b>Parish/Subsite</b>	<b>Direction Offshore</b>	<b>MTL-NAVD88 (m)</b>	<b>Diurnal Tide Range (m)</b>	<b>Salt Elevation (m above MTL)</b>
Lafourche*	South	-0.08	0.29	0.24
St. Mary-Subsite 1	South	-0.123	0.74	0.629
St. Mary-Subsite 2	South	-0.135	0.568	0.483
St. Mary-Subsite 3	South	-0.151	0.426	0.362
St. Mary-Subsite 4	South	-0.427	0.274	0.233
St. Mary-Subsite 5	South	-0.496	0.129	0.11
Vermilion	South	-0.145	0.658	0.559

\* Subsites are used in Lafourche Parish, but have the same salt elevation.

## Summary of SLAMM Parameters by Parish

### ***Lafourche Parish Subsites and Model Parameters***

TABLE 10. LAFOURCHE PARISH SUBSITE PARAMETERS.

<b>Parameter</b>	<b>Global</b>	<b>Subsite 1</b>	<b>Subsite 2</b>	<b>Subsites 3-5</b>	<b>Subsites 6-11</b>
Description	Lafourche	South Parish	North Parish	South Floating Marsh	North Floating Marsh
NWI Photo Date - Hindcast	1956	1956	1956	1956	1956
NWI Photo Date - Forecast	2007	2007	2007	2007	2007
DEM Date (YYYY)	2009	2009	2009	2009	2009
Direction Offshore	South	South	South	South	South
MTL-NAVD88 (m)	-0.08	-0.08	-0.08	-0.08	-0.08
Great Diurnal Tide Range (m)	0.29	0.29	0.29	0.29	0.29
Salt Elev. (m above MTL)	0.24	0.24	0.24	0.24	0.24
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	2	2	2	2	2
Reg. Flood Marsh Accr (mm/yr)	8.5	8.5	8.5	15	15
Irreg. Flood Marsh Accr (mm/yr)	8.5	8.5	8.5	15	15
Tidal Fresh Marsh Accr (mm/yr)	9.8	9.8	9.8	15	15
Beach Sed. Rate (mm/yr)	1	1	1	1	1
Freq. Overwash (years)	30	30	30	20	20
Use Elev Pre-processor [True,False] - Hindcast	TRUE	TRUE	TRUE	TRUE	TRUE
Use Elev Pre-processor [True,False]- Forecast	FALSE	FALSE	FALSE	FALSE	FALSE

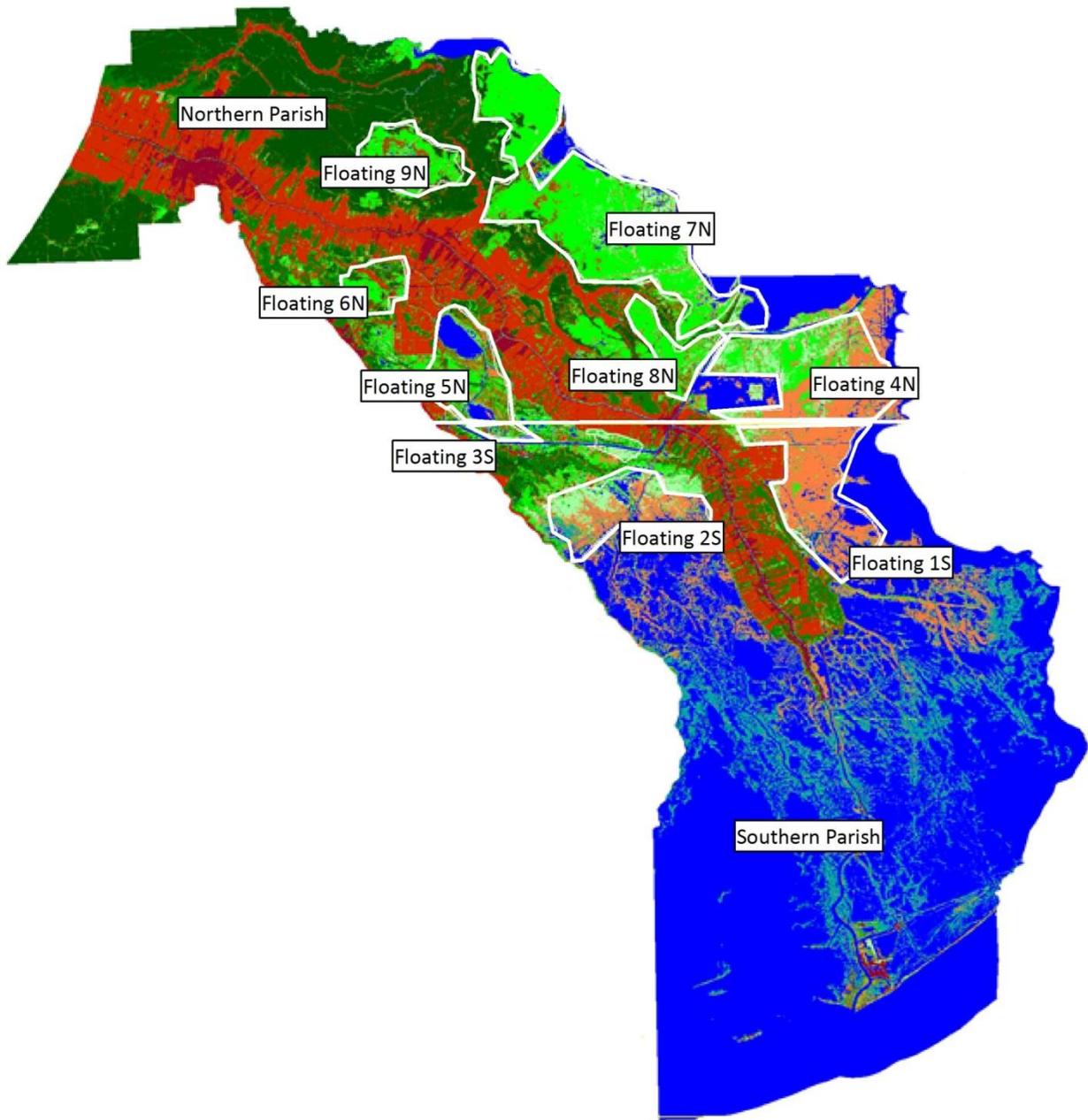


FIGURE 8. SUBSITES USED IN LAFOURCHE PARISH.

**St. Mary Parish Subsites and Model Parameters**

TABLE 11. ST. MARY PARISH SUBSITE PARAMETERS.

Parameter	Flotant Marsh	Subsite 2	Subsite 3	Subsite 4	Subsite 5	Subsite 6
NWI Photo Date - Hindcast	1956	1956	1956	1956	1956	1956
NWI Photo Date - Forecast	2007	2007	2007	2007	2007	2007
DEM Date (YYYY)	2009	2009	2009	2009	2009	2009
Direction Offshore	South	South	South	South	South	South
MTL-NAVD88 (m)	-0.427	-0.123	-0.135	-0.151	-0.427	-0.496
Great Diurnal Tide Range (m)	0.274	0.74	0.568	0.426	0.274	0.129
Salt Elev. (m above MTL)	0.233	0.629	0.483	0.362	0.233	0.11
Marsh Erosion (horz. m /yr)	1.8	1.8	1.8	1.8	1.8	1.8
Swamp Erosion (horz. m /yr)	1	1	1	1	1	1
T.Flat Erosion (horz. m /yr)	2	2	2	2	2	2
Reg. Flood Marsh Accr (mm/yr)	20	8.5	8.5	8.5	8.5	8.5
Irreg. Flood Marsh Accr (mm/yr)	20	8.5	8.5	8.5	8.5	8.5
Tidal Fresh Marsh Accr (mm/yr)	20	9.8	9.8	9.8	9.8	9.8
Beach Sed. Rate (mm/yr)	1	1	1	1	1	1
Freq. Overwash (years)	20	20	20	20	20	20
Use Elev Pre-processor [True,False] - Hindcast	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE
Use Elev Pre-processor [True,False] - Forecast	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

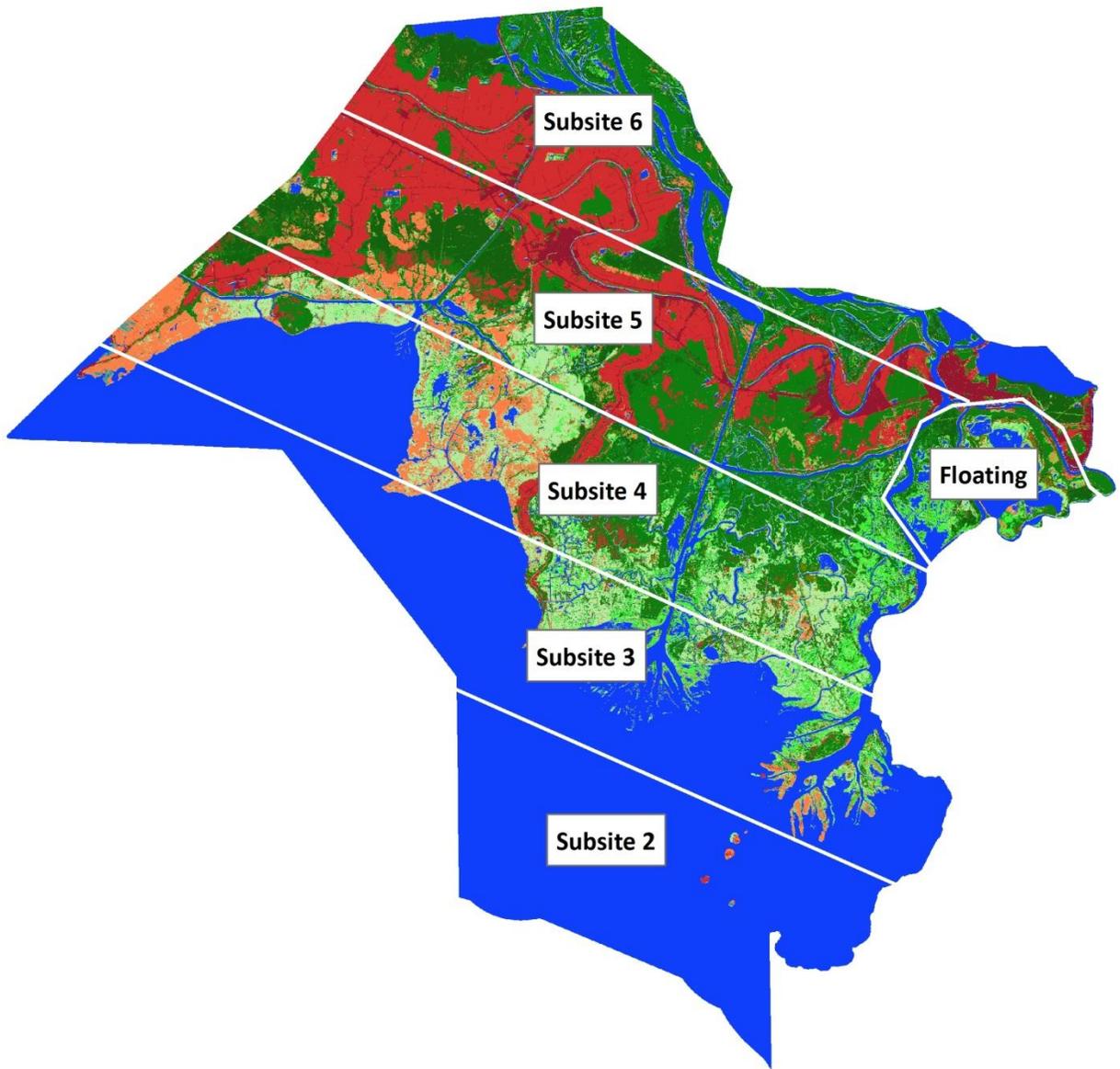


FIGURE 9. SUBSITES USED IN ST. MARY PARISH.

### **Vermilion Model Parameters**

Vermilion Parish was not modeled using subsites in the SLAMM model. The parameters below were used for the entire parish area.

TABLE 12. VERMILION PARISH PARAMETERS.

<b>Parameter</b>	<b>Vermilion</b>
NWI Photo Date - Hindcast	1956
NWI Photo Date - Forecast	2007
DEM Date (YYYY)	2009
Direction Offshore	South
MTL-NAVD88 (m)	-0.145
Great Diurnal Tide Range (m)	0.658
Salt Elev. (m above MTL)	0.559
Marsh Erosion (horz. m /yr)	1.8
Swamp Erosion (horz. m /yr)	1
T.Flat Erosion (horz. m /yr)	2
Reg. Flood Marsh Accr (mm/yr)	8.5
Irreg. Flood Marsh Accr (mm/yr)	8.5
Tidal Fresh Marsh Accr (mm/yr)	9.8
Beach Sed. Rate (mm/yr)	1
Freq. Overwash (years)	20
Use Elev Pre-processor [True,False] - Hindcast	TRUE
Use Elev Pre-processor [True,False] - Forecast	FALSE

## Model Calibration

Two methods of calibration were used to test the accuracy of the SLAMM modeling and site parameters in each parish: time zero landcover changes and a sensitivity analysis of model parameters. Additionally, a hindcast using 1956 data was run to test the model’s ability to predict current landcover conditions.

### **Time Zero Runs**

One of the first steps in the SLAMM modeling process is to convert the DEM to the same date (2009) as the wetland data (2007) known as the time zero for the model (Clough et al. 2010). Changes to the landcover in the time zero run are due to model parameters, accounting for uplift or subsidence, and the default landcover elevations set in SLAMM. SLAMM assumes that wetlands inhabit a range of vertical elevations as a function of the tide range (Clough et al. 2010).

The preset elevations were changed from the default values in SLAMM to values specific for the eastern and western Louisiana coastal area (Table 13) following methods outlined in Clough et al. (2011). The minimum elevation of the swamp and undeveloped dry land category for St. Mary Parish were decreased to reflect the unique freshwater flows in this area of the coast (Clough et al. 2010, Clough 2012). For Vermilion Parish, the undeveloped dry land minimum elevation was also decreased after analyzing the range of elevations and considering that much of the land use in this category is protected by dikes and used for agriculture.

TABLE 13. ELEVATION ANALYSIS VALUES.

	Lafourche		St. Mary		Vermilion	
	Min (m)	Max (m)	Min (m)	Max (m)	Min (m)	Max (m)
Dry Developed Land	0.22	0.50	0.27	0.50	0.27	0.50
Undeveloped Dry Land	0.22	0.50	-0.37	0.50	0.0	0.50
Swamp	0.22	0.50	-0.30	0.50	0.27	0.50
Cypress Swamp	-0.50	0.50	-0.50	0.50	-0.50	0.50
Inland Fresh Marsh	0.22	0.50	-0.05	0.27	-0.05	0.27
Tidal Fresh Marsh	0.13	0.22	0.11	0.27	0.11	0.27
Transitional Salt Marsh	0.13	0.22	0.16	0.27	0.16	0.27
Regularly Flooded Marsh	-0.10	0.31	-0.10	0.38	-0.10	0.38
Irregularly Flooded Marsh	0.07	0.31	0.08	0.38	0.08	0.38
Estuarine Beach	-0.13	0.50	-0.16	0.27	-0.16	0.27

The threshold for time zero changes was set at 5 percent change from the initial landcover data for dominant cover categories (Table 14). Any changes to the dominant landcover of less than  $\pm 5$  percent are considered acceptable within the model; all three parishes met this threshold. The transitional salt marsh category has the greatest amount of change for all three parishes and is also one of the least dominant categories for landcover, one percent or less of the total landcover in each parish, so any change in the area of the marsh will be a relatively large percent change. Any areas in the parish that are protected by dikes are protected from change in the time zero run.

**TABLE 14. TIME ZERO PERCENT CHANGE IN LANDCOVER CLASSES.**

	<b>Lafourche</b>	<b>St. Mary</b>	<b>Vermilion</b>
Dry Developed Land	0.00%	0.00%	0.00%
Undeveloped Dry Land	-0.53%	0.00%	-0.01%
Swamp	-3.75%	-0.05%	-0.95%
Cypress Swamp	-0.02%	-0.87%	-0.08%
Inland Fresh Marsh	-3.57%	-2.90%	-0.97%
Tidal Fresh Marsh	-1.57%	-5.99%	-6.68%
Transitional Salt Marsh	58.95%	27.35%	668%
Regularly Flooded Marsh	1.84%	66.56%	75.00%
Irregularly Flooded Marsh	-0.11%	6.31%	-0.70%

\* All categories with change greater than 5% are non-dominant landcover classes. In all runs, tidal flat was also created.

Initial Landcover

Time Zero Landcover

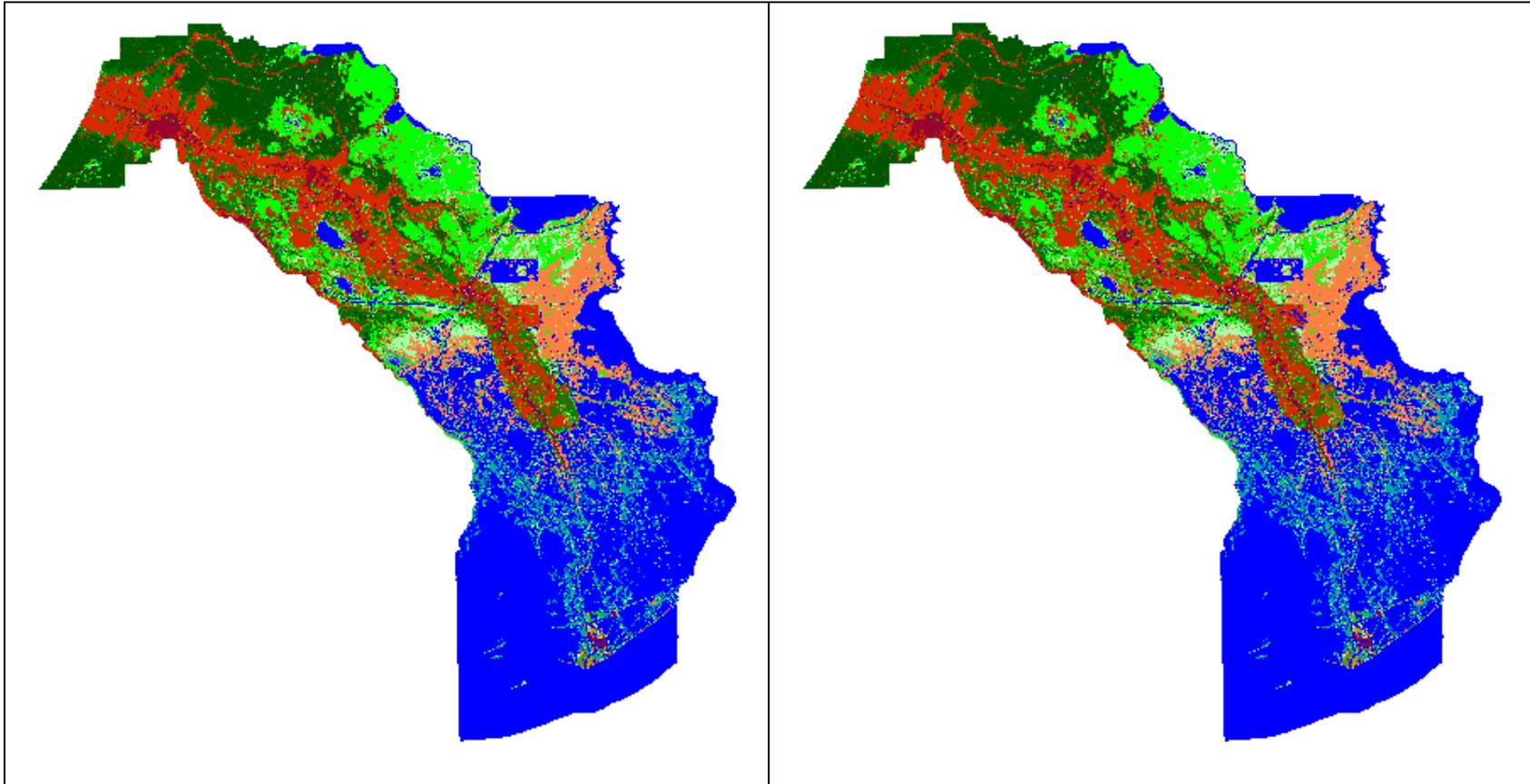


FIGURE 10. LAFOURCHE PARISH TIME ZERO ANALYSIS.

Initial Landcover

Time Zero Landcover

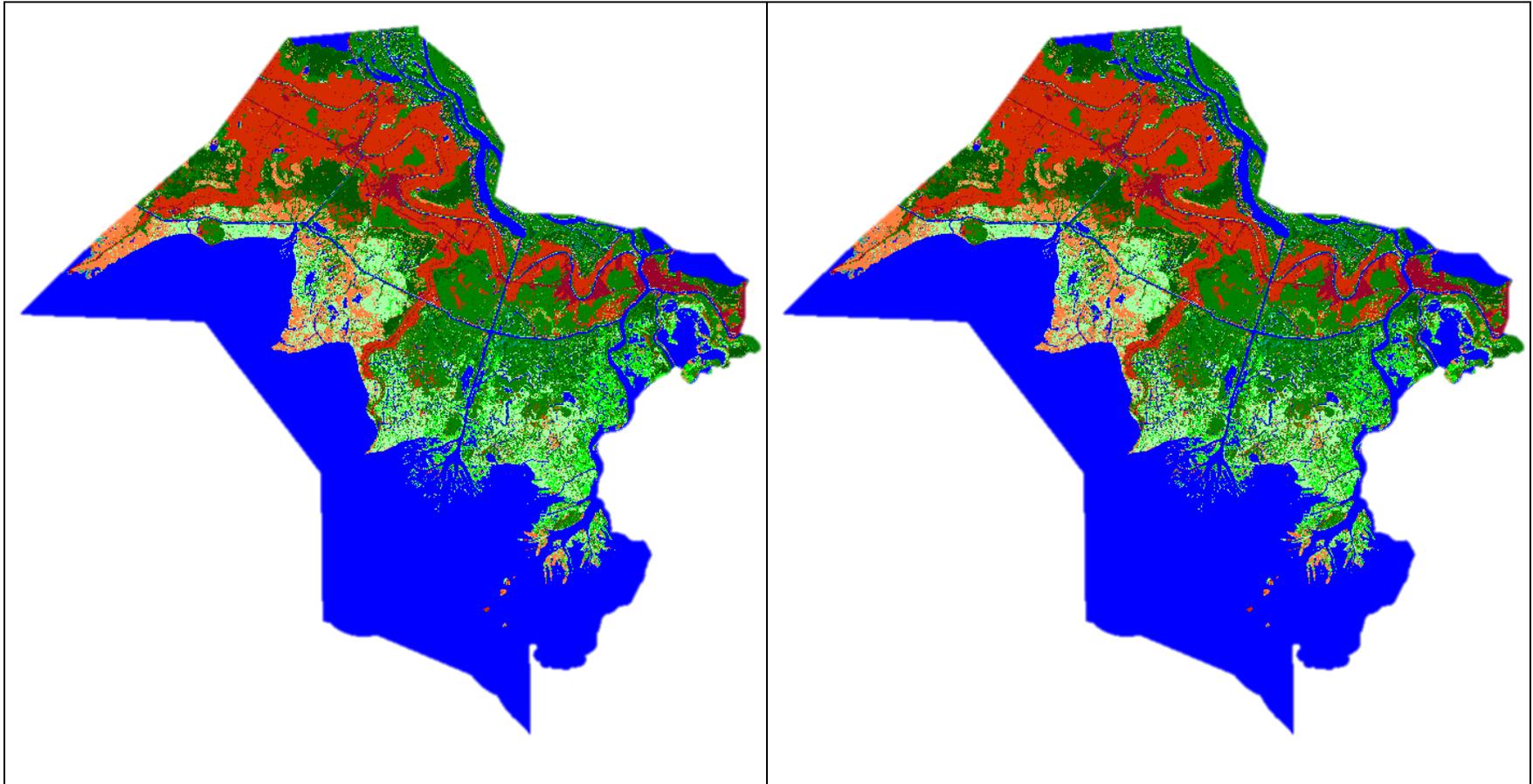


FIGURE 11. ST. MARY PARISH TIME ZERO ANALYSIS.

Initial Landcover

Time Zero Landcover

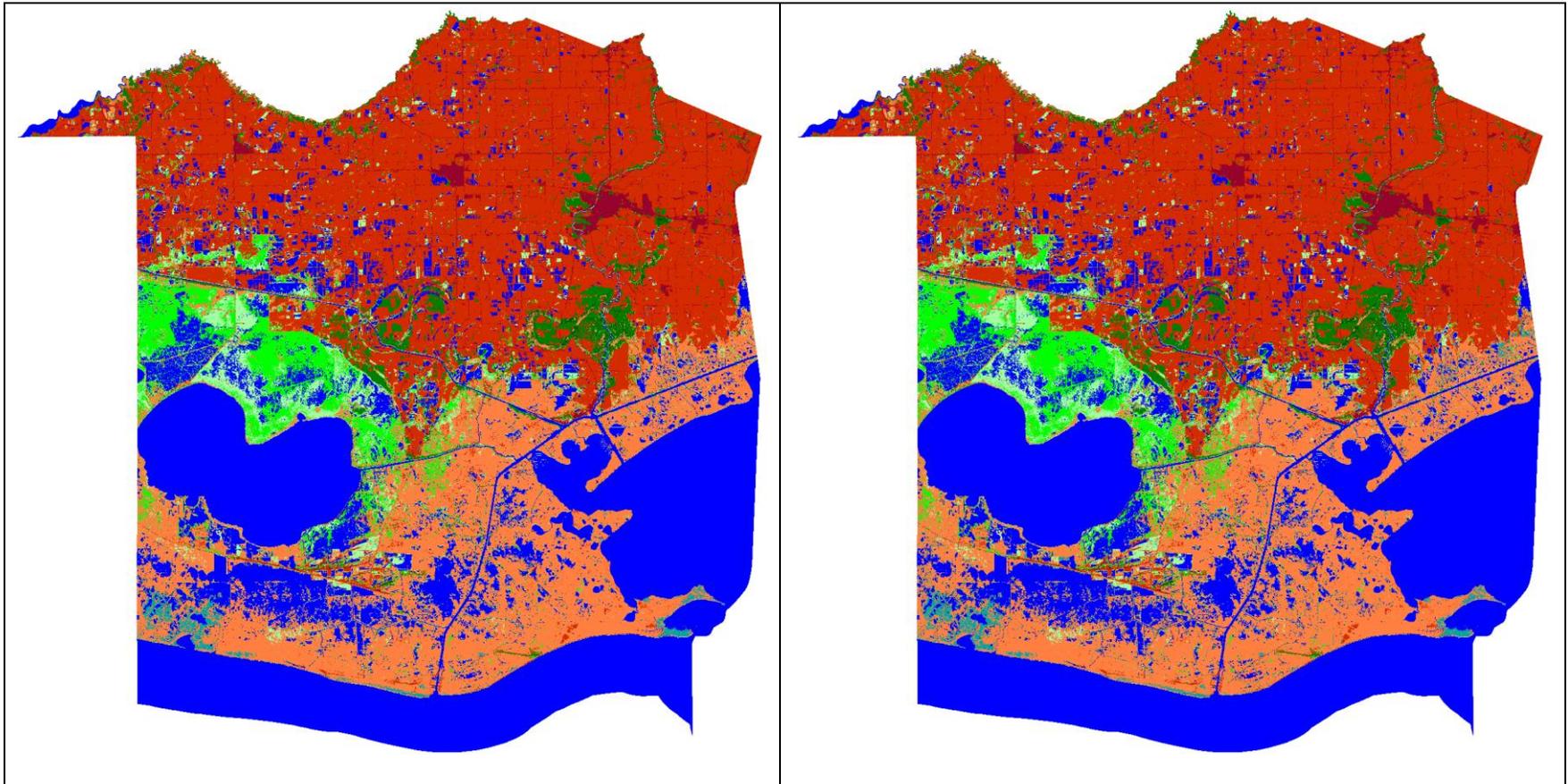


FIGURE 12. VERMILION PARISH TIME ZERO ANALYSIS.

### ***Sensitivity Analysis***

The goal of a sensitivity analysis is to identify the model parameters that have the greatest influence on the model output. Knowing this, model users can target parameters in which they wish to reduce the level of uncertainty (Saltelli and Saisana 2007). To estimate the sensitivity of SLAMM to various input parameters a one-way sensitivity analysis was performed.

A one-way sensitivity analysis allows us to independently evaluate each input parameter, and determine its effect on the model output (Clemen and Reilly 2001). For this analysis, several parameters were considered in the sensitivity analysis: the absence or presence of dikes, low or high subsidence rates, MTL correction, accretion rate for irregularly flooded marsh (referred to as “accretion” in this section), great diurnal tide range, and salt elevation. The baseline scenario for the analysis was set as a GSLR of 1.5 meters by 2100, developed dry land protected by dikes, and low subsidence, with all other parameters set to those used in the time zero runs. Each parameter in the sensitivity analysis was adjusted to 85 percent and 115 percent of the value used in the time zero run. For subsidence and dike protection, the analysis only required the value be changed to high or low (subsidence) or protection or no protection (dikes). This sensitivity analysis only considers the model output for the year 2100. Therefore, the conclusions drawn from this analysis can only be applied to the final model output. As will be discussed later, the parameters that are modeled as the most influential drivers in landcover change in the year 2100 may not be the most influential drivers at 2025 or 2050.

For the sensitivity analysis three landcover types representative of dry land, marsh, and forested wetland were selected: undeveloped dry land, irregularly flooded marsh, and swamp. The extent of dry developed land is relevant to our identification of wetland migration corridors. The significance of irregularly flooded marsh is that it is often the last wetland type before being converted to open water. Inland wetlands represent a small fraction of total landcover today in all three parishes and are at risk of near local extinction under higher SLR scenarios modeled.

The following tornado diagrams are designed so that the square miles for each landcover under the baseline condition are set as the vertical axis. The diagrams are designed, so those parameters with the greatest influence are on top, and those with the least are positioned at the bottom. In all cases, the subsidence and dike parameters dominate the first and second position as most influential.

The results of this analysis highlight the important role that subsidence plays in this modeling effort. Subsidence values were established by the state of Louisiana as a moderate rate, and a less optimistic rate.

The difference in this variable is driving a large amount of the change seen in different scenarios by the year 2100.

### Undeveloped Dry Land

The model predicts undeveloped dry land to be most sensitive to the presence of dikes and subsidence values. In all three parishes, removing dikes resulted in model outputs with large losses of undeveloped dry land. Lafourche is modeled to be most affected by dike removal with undeveloped dry land loss of 88 percent, compared to only 35 percent and 39 percent in St. Mary and Vermilion Parishes, respectively. This is not an unexpected trend for Lafourche as the subsidence rate (9 – 12 mm yr<sup>-1</sup>) is more than double the rates observed in St. Mary (5 mm yr<sup>-1</sup>) and Vermilion (4 mm yr<sup>-1</sup>) parishes. As the land subsides faster, inundation will happen quicker and more of the dry land will be lost to either wetland or open water conversion. Adjustments to the other input parameters by  $\pm 15$  percent have little effect on the overall results (Figure 13).

### Swamp

Similar to results for undeveloped dry land, swamp is modeled most sensitive to the absence or presence of dikes, followed by subsidence, and then the MTL correction. Adjusting the MTL correction by  $\pm 15$  percent changed the total swamp area by as much as 4 percent in St. Mary Parish, and less than 1 percent in Vermilion and Lafourche parishes (Figure 14).

### Irregularly Flooded Marsh

Both Lafourche and St. Mary Parish are modeled as most sensitive to subsidence of irregularly flooded marsh. In each case, the presence or absence of dikes is secondary. However, the situation is reversed in Vermilion. This is likely due to the location of dikes relative to the irregularly flooded marsh; dikes provide less protection to irregularly flooded marshes in Lafourche and St. Mary Parishes. For undeveloped dry land and swamps, MTL correction was the third most influential factor and this trend remains constant for irregularly flooded marsh as well. However, the extent to which MTL correction plays a role in the persistence of irregularly flooded marsh is comparatively much greater than for the other two land cover categories. A  $\pm 15$  percent change in the MTL correction parameter resulted in a high of  $\pm 6.5$  percent change in Lafourche Parish, and a low of  $\pm 2.3$  percent change in St. Mary Parish (Figure 15).

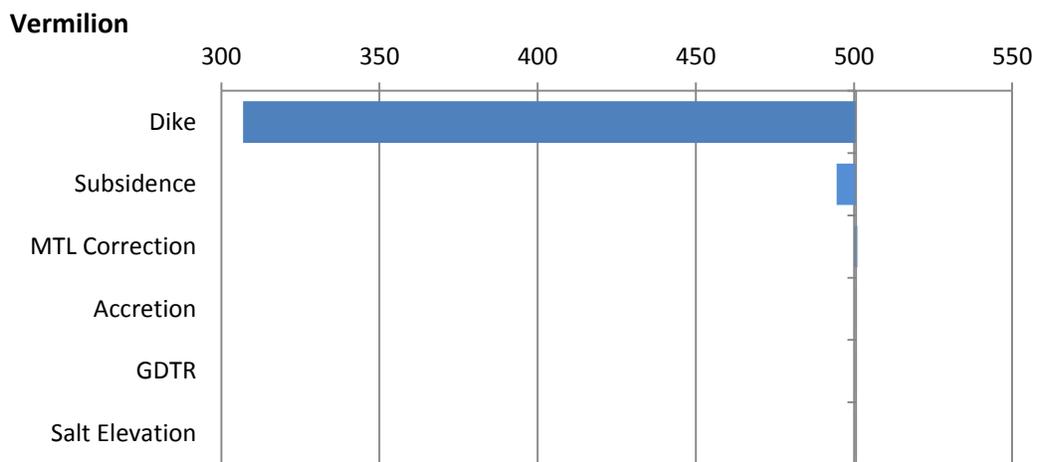
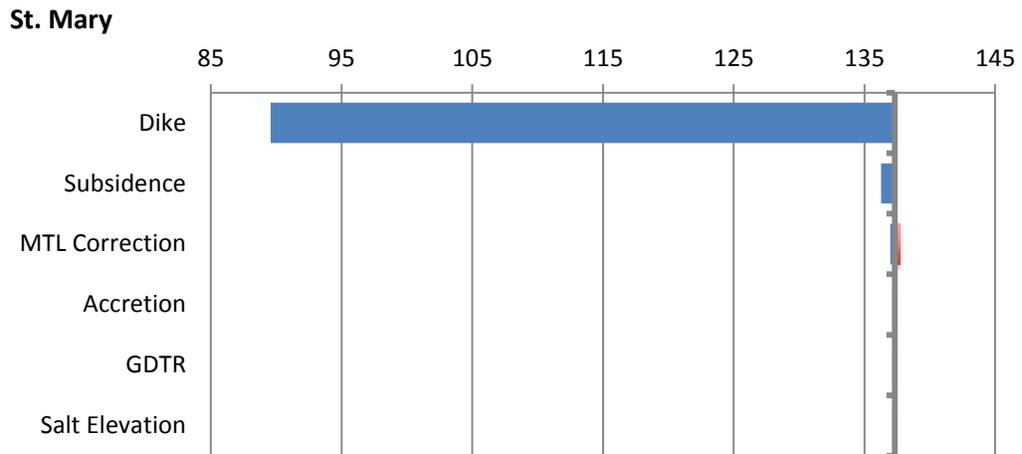
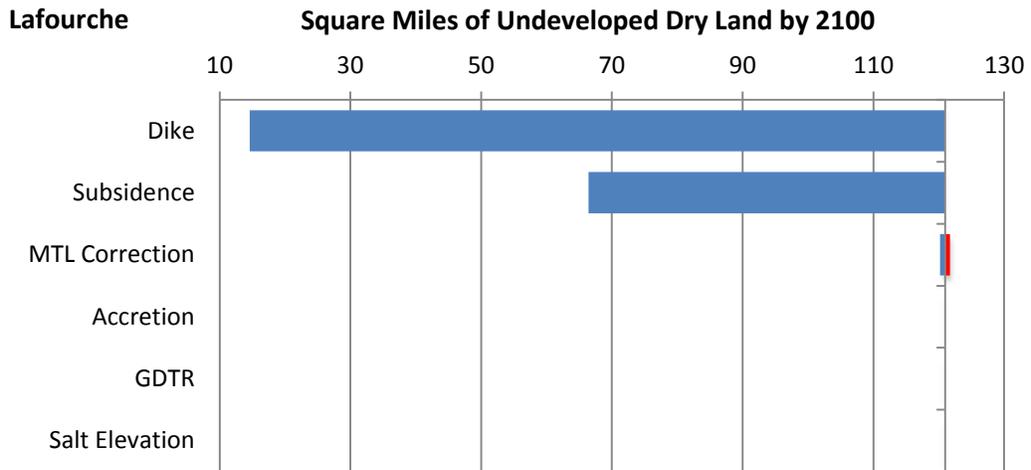


FIGURE 13. UNDEVELOPED DRY LAND SENSITIVITY ANALYSIS.

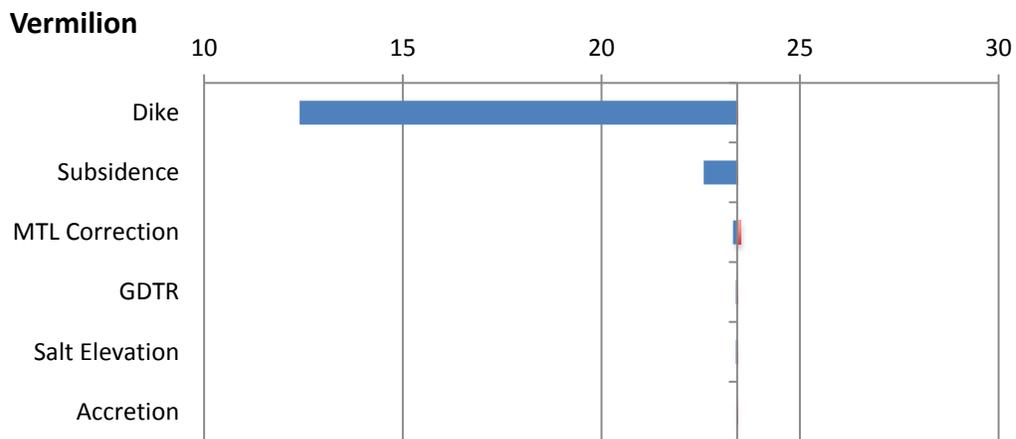
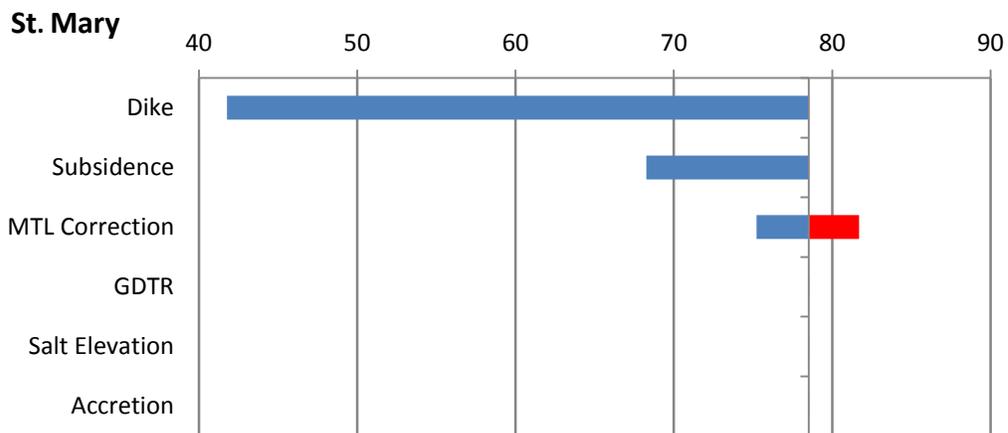
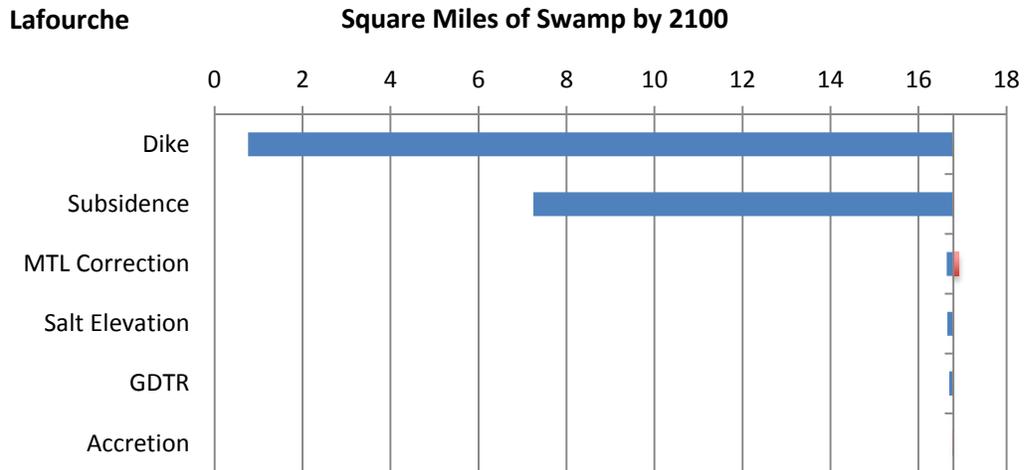


FIGURE 14. SWAMP SENSITIVITY ANALYSIS.

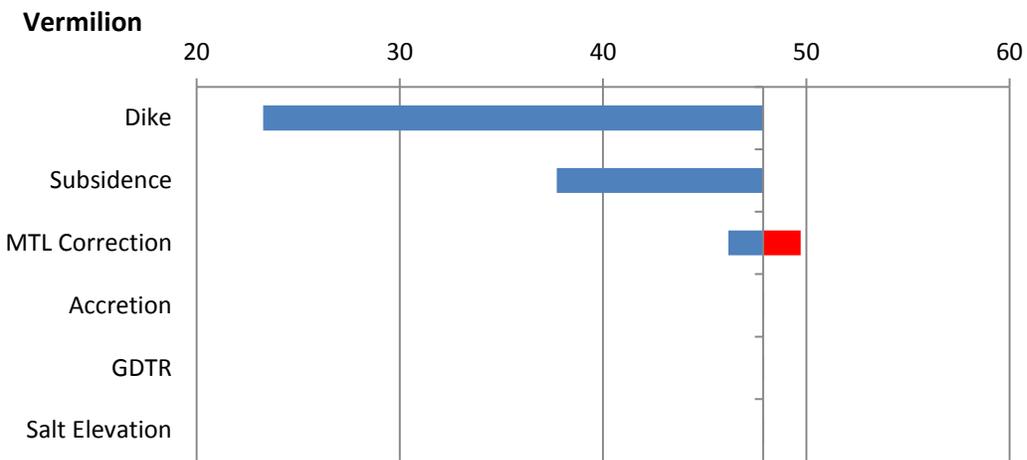
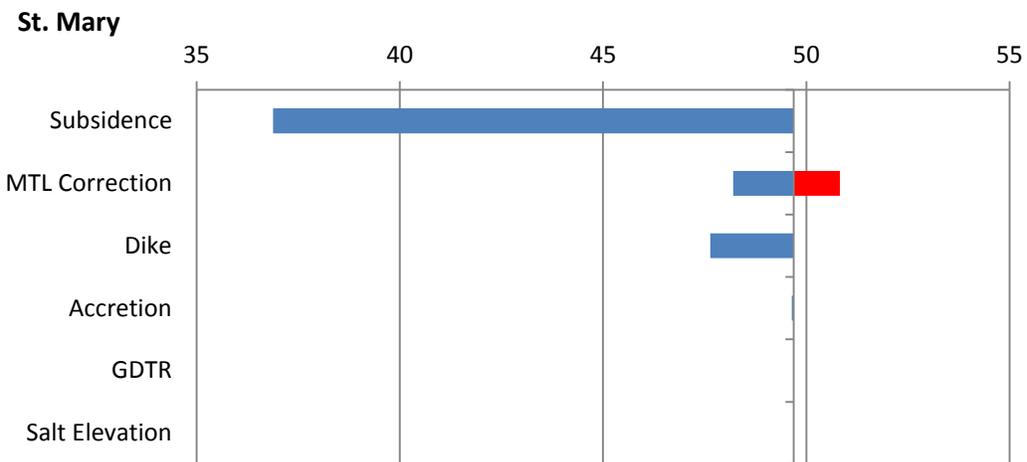
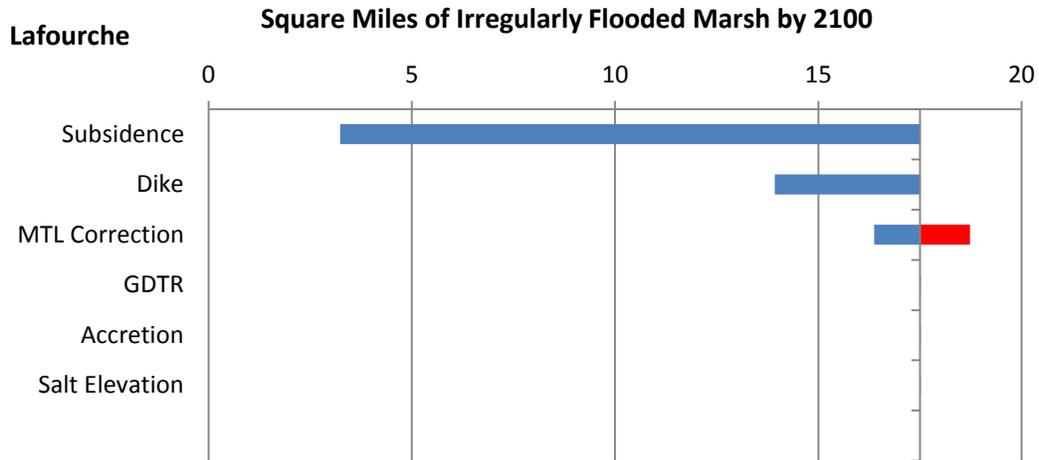


FIGURE 15. IRREGULARLY FLOODED MARSH SENSITIVITY ANALYSIS.

### **Hindcast**

In predicting landcover changes, a hindcast is a necessary step in understanding the predictive capacity of the model. Using the historic landcover data and estimating wetland coverage in response to RSLR, the hindcast indicates the accuracy of the model in predicting the effect of RSLR on wetlands within our study area.

The 1956 NWI data was obtained from William Jones of the USGS. The 1956 data is not as complete as current landcover data as on average it only covers half of the area of each parish. The attribute code for each of the NWI polygons was reclassified into SLAMM codes using the reclassification spreadsheet included with the SLAMM documentation (Clough et al. 2010). Landcover categories were combined (Table 15) to account for limitations in the historical data and to follow methods used in a 2011 NWF report (Clough et al. 2011).

TABLE 15. COMBINED SLAMM CATEGORIES WITHIN HINDCAST ANALYSIS.

<b>SLAMM Classification</b>	<b>Combined Classification</b>
Developed Dry Land	Developed Dry Land
Undeveloped Dry Land	Undeveloped Dry Land
Swamp	Swamp
Cypress Swamp	
Tidal Swamp	
Inland Fresh Marsh	Tidal Fresh Marsh
Tidal Fresh Marsh	
Trans. Salt Marsh	Regularly Flooded Marsh
Regularly Flooded Marsh	
Irregularly Flooded Marsh	
Estuarine Beach	Tidal Flat
Tidal Flat	
Rocky Intertidal	
Inland Open Water	Estuarine Open Water
Riverine Tidal Open Water	
Estuarine Open Water	

The hindcast model was run with the same DEM as the forecasting model because elevation data dating back to the 1950's is poor quality. The DEM and slope files were clipped to the same extent as the 1956 NWI data. Due to the large difference in the wetland data and DEM dates (1956 and 2009), the elevation preprocessor was used. The hindcast model was run under the condition to protect all dry land, but without a dike file loaded. The model was completed in one time step from 1956 to 2007 (the date of the landcover data from Couvillion 2010).

Older elevation data sets are often derived from topographic maps, and have very coarse resolution. This is especially the case in Louisiana where there is not very much topographic relief. SLAMM developers included the elevation preprocessor in the model for situations such as this when inadequate elevation data is available. The elevation preprocessor estimates elevation ranges as a function of the tide ranges and their known relationships between wetland types (Clough et al 2010). The use of the elevation preprocessor will likely limit the model's predictive capabilities and is important to remember this when analyzing the hindcast results.

Additionally, much of the model's predictive capability relies on the spatial accuracy of the 1956 landcover data. This 1956 landcover data did not distinguish between some narrower defined wetland categories. Thus, relevant categories were clumped together in broader categories for this analysis (Table 15) (Clough et al. 2011). Due to the highly variable rates of subsidence both spatially and temporally along the coast, the observed GSLR rate of 10.9 centimeters from 1956 to 2007 was extrapolated to a historic trend of -2.14 millimeters per year (IPCC 2007b, Clough et al. 2011) instead of developing separate subsidence grids for each parish.

The model was interpreted by comparing the predicted percent landcover to the observed percent landcover rather than estimating accuracy on a cell-by-cell basis, which has been shown to be influenced by the cell size due to the majority-takes-all rule of decreasing resolution (Chen and Pontius 2011). However, a simple percent cover assessment does not take into account spatial variability of results. To account for this, a visual inspection of results was performed for each parish.

The model yielded more accurate results when broad categories were considered (Table 16). For example, the model was not very accurate in predicting extent of salt and fresh marsh individually. However, when these two categories were considered together the model was much more successful—predicting 24 percent for Lafourche (actual 30 percent) and 19 percent for St. Mary (actual 18 percent). The discrepancy is likely due to the estimated salt elevation and, therefore, extent of the salt and fresh marsh. However, total area is very similar. In Vermilion, the model under-predicts the extent of total marsh in the parish; however a large portion of this underestimation is likely a product of inaccurate 1956 landcover data.

TABLE 16. OBSERVED AND PREDICTED PERCENT LANDCOVER FOR CASE STUDY PARISHES BY 2007.

Landcover Type	Lafourche		St Mary		Vermilion	
	<i>Observed</i>	<i>Predicted</i>	<i>Observed</i>	<i>Predicted</i>	<i>Observed</i>	<i>Predicted</i>
Salt Marsh	20	24	6	19	46	24
Fresh Marsh	10	0	12	0	21	3
Total Marsh	30	24	18	19	67	26
Swamp	3	3	23	18	3	1
Beach	0	0	0	0	0	0

Since the accuracy of the hindcast model must be considered with the quality of the data inputs, it is useful to look at the spatial extent of landcover for each parish (Figure 16, Figure 17 and Figure 18). Much of the variation observed in both the Vermilion and Lafourche Parish predictions can be attributed to the poor quality 1956 landcover data. For example, the 1956 data classified inland Lafourche Parish as estuarine open water. This classification is very unlikely as the area is extensively populated with salt and fresh marsh in the year 2007. Likewise, flotant marsh data collected for Lafourche Parish in the 1990s indicates flotant marsh occupied the northern inland areas (Sasser et al. 2007). In western Vermilion Parish a similar discrepancy is noted; the 1956 data classifies the bay as almost exclusively open water with very little fresh marsh. However, the 2007 landcover data shows extensive fresh marsh in the area, so it is unlikely that there was no fresh marsh in this area in 1956.

In all three parishes, the model predicts square miles of wetland loss that closely matches what was observed in 2007. However, upon spatial inspection the model fails to predict the spatial accuracy of wetland loss and conversion. SLAMM is very sensitive to the DEM vertical error, historic trend of RSLR, accretion, and sedimentation rates (Chu-Agor et al. 2011). With the exception of historic RSLR, we had little information in these four categories and the elevation pre-processor was used in an attempt to alleviate elevation data quality concerns. In addition, the hindcast was operated under the assumption that observed trends in accretion, tide range, and salt elevation were constant and equal to the observed values of today, which could introduce another source of error (Chen and Pontius 2011). Lastly, as indicated by the sensitivity analysis, the model for coastal Louisiana is very sensitive to subsidence. The hindcast did not use the subsidence values used in the forecast analysis. Instead, the observed historic trend of a 10.9 centimeter GSLR from 1956 to 2007 was extrapolated to a change in elevation of -2.14 millimeters per year.

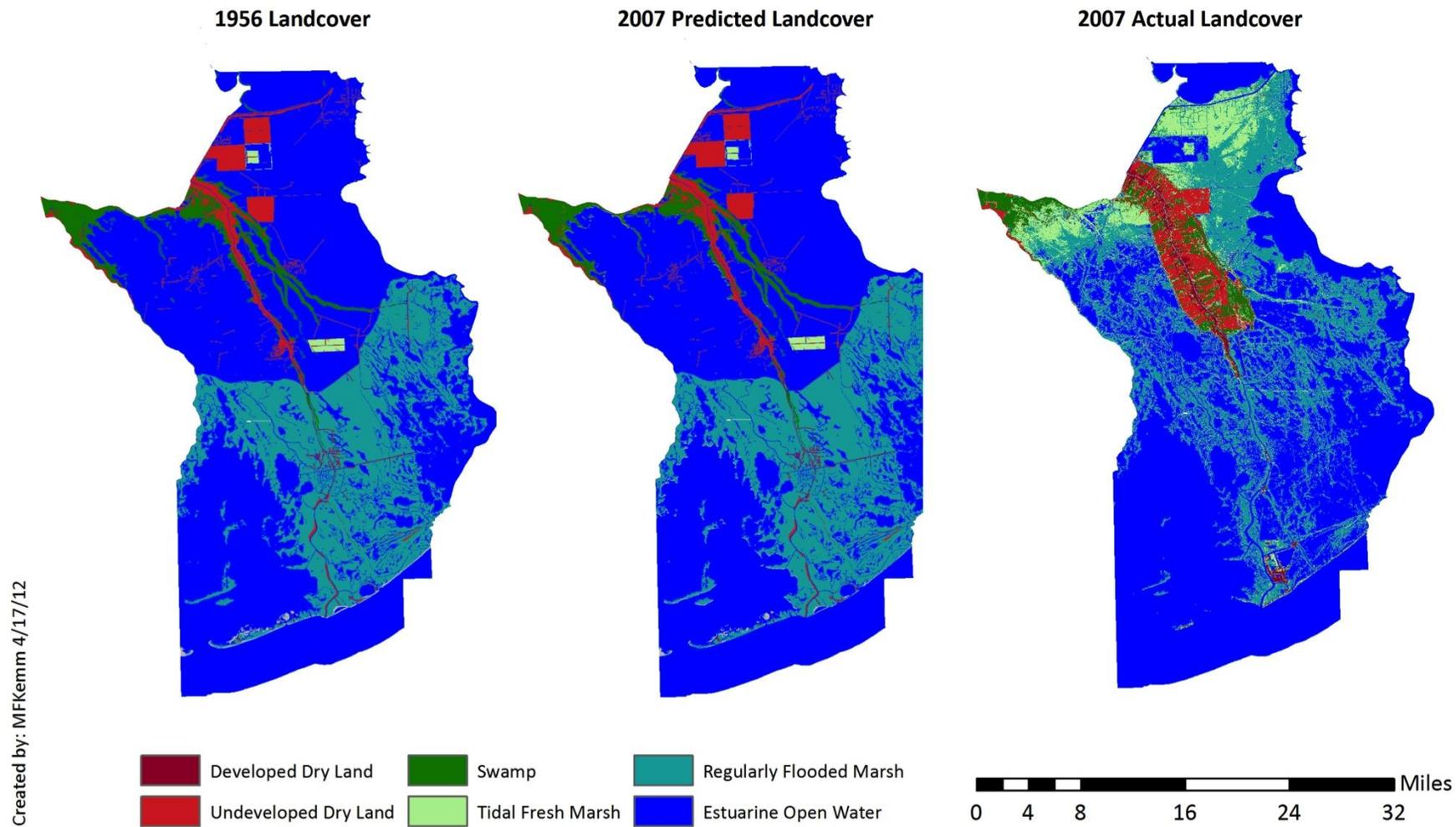


FIGURE 16. HINDCAST ANALYSIS RESULTS FOR LAFOURCHE PARISH. (LEFT) 1956 LANDCOVER DATA, (MIDDLE) 2007 MODEL PREDICTED LANDCOVER, AND (RIGHT) ACTUAL 2007 LANDCOVER FROM COUVILLION 2010.

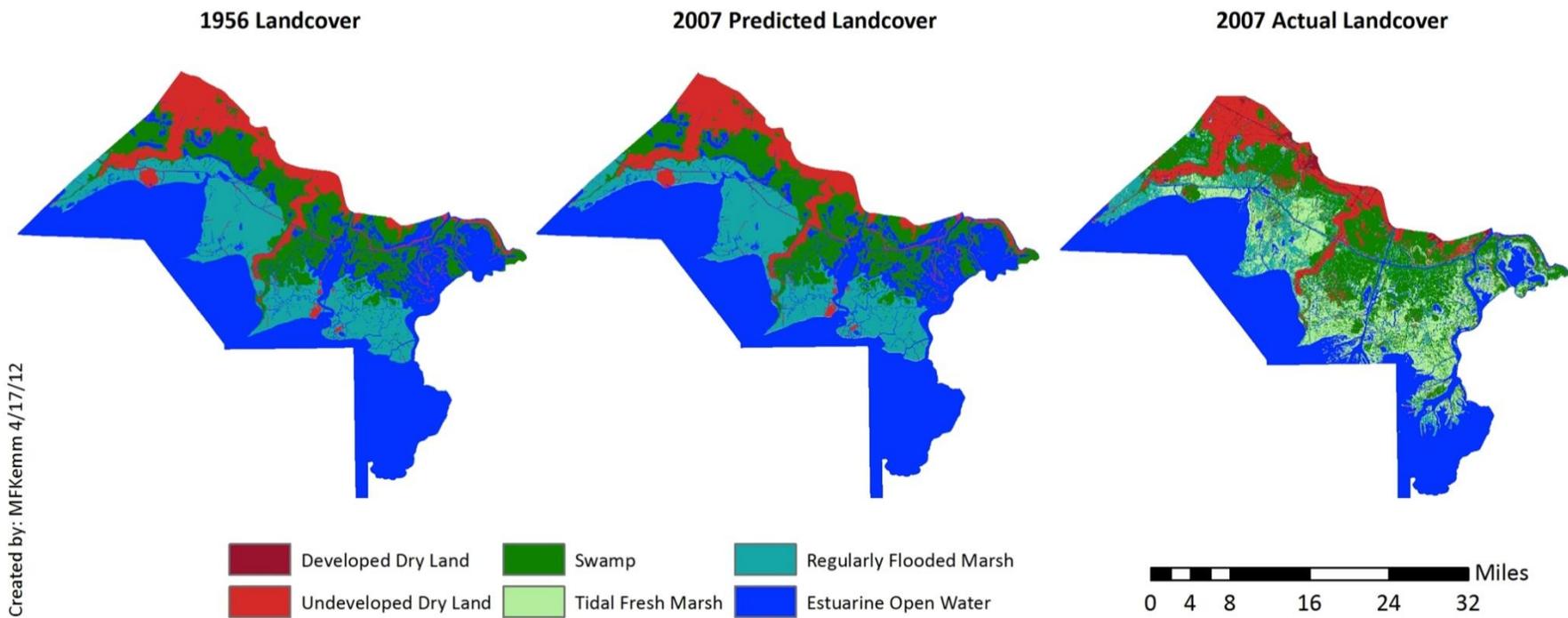


FIGURE 17. HINDCAST ANALYSIS RESULTS FOR ST. MARY PARISH. (LEFT) 1956 LANDCOVER DATA, (MIDDLE) 2007 MODEL PREDICTED LANDCOVER, AND (RIGHT) ACTUAL 2007 LANDCOVER FROM COUVILLION 2010.

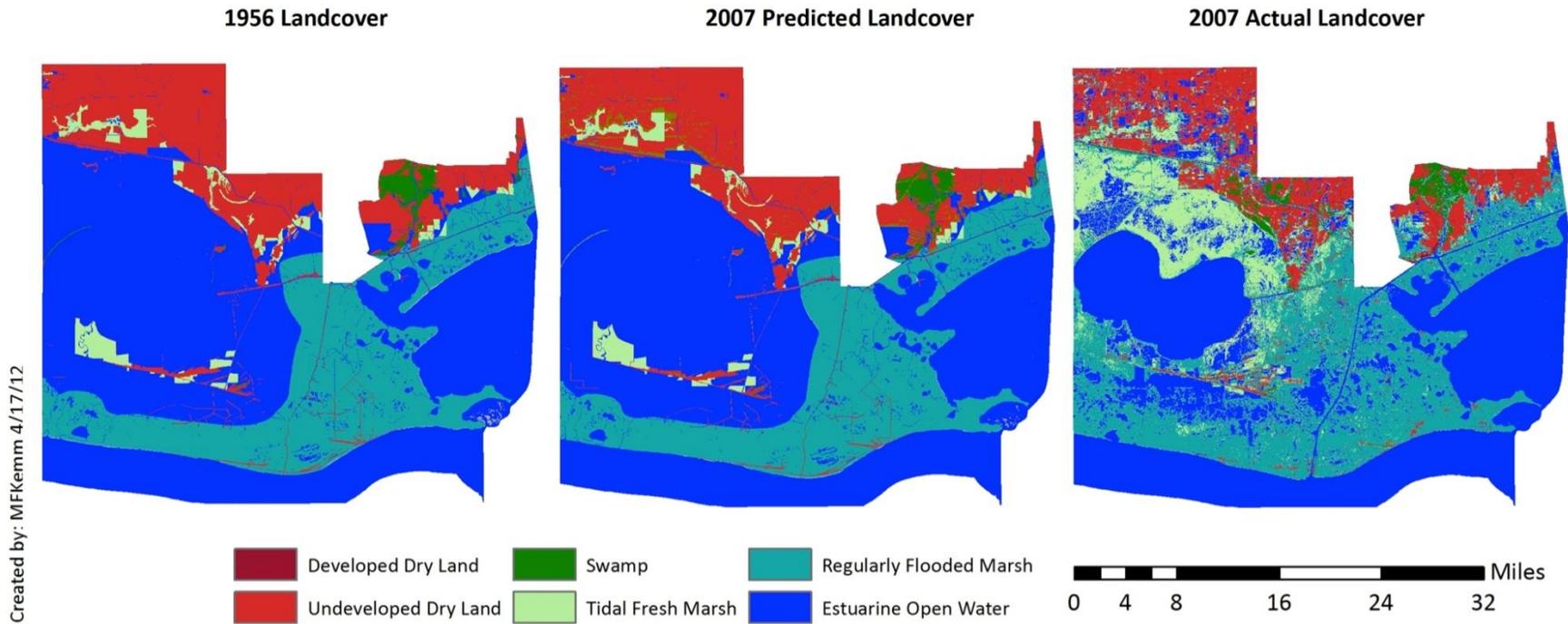


FIGURE 18. HINDCAST ANALYSIS RESULTS FOR VERMILION PARISH. (LEFT) 1956 LANDCOVER DATA, (MIDDLE) 2007 MODEL PREDICTED LANDCOVER, AND (RIGHT) ACTUAL 2007 LANDCOVER FROM COUVILLION 2010.

## Modeling Results and Discussion

RSLR modeling results within this study are twofold: observations regarding net change in the area of wetlands and the upland migration of wetlands.

*See Appendix for full documentation of SLAMM runs, tabular results, and map documentation.*

### Net Change in the Area of Wetlands

General trends in the overall net loss of wetlands were observed within modeling results in all three of the case study parishes. As expected, as GSLR increases within SLAMM, the net amount of wetland area lost increases. Likewise, a greater net loss of wetlands was modeled under higher subsidence conditions.

However, the effect of dike protection on the net loss of wetlands within the model varied between Lafourche Parish and the other two parishes. Lafourche Parish modeling exemplified a greater amount of net wetland loss occurring under no protection scenarios; Vermilion and St. Mary parish modeling showed the most net wetland loss occurring under protection scenarios (depending on GLSR in St. Mary Parish) (Figure 19). This observation may be explained by the variability in subsidence rates used in the modeling and the distribution of dry land across the three parishes (further discussed in “Upland Migration of Wetlands” section).

In all three parishes, swamp and fresh marsh areas are commonly observed to convert to salt marsh as RSLR increases. However, the less optimistic scenarios (higher GSLR and subsidence rates) that were modeled show these areas converting directly to tidal flat or open water in many cases. There was no change observed for developed dry land as every scenario modeled within this study assumes that this land will always be protected. Likewise, as dikes are assumed to protect both developed and undeveloped dry land, no change in undeveloped dry land cover was expected under protection conditions. Unexpectedly, a small amount of change was observed for undeveloped dry land in some model runs that incorporated dike protection. When a dike file is loaded within SLAMM, dry land is considered protected unless the RSLR exceeds 2.0 meters; RSLR did not exceed this value within this study. This change may be observed in dry land as a result of incomplete dike coverage or errors within the elevation dataset (Clough 2012). Within this study, it is likely that the quality of data inputs is the cause of this discrepancy.

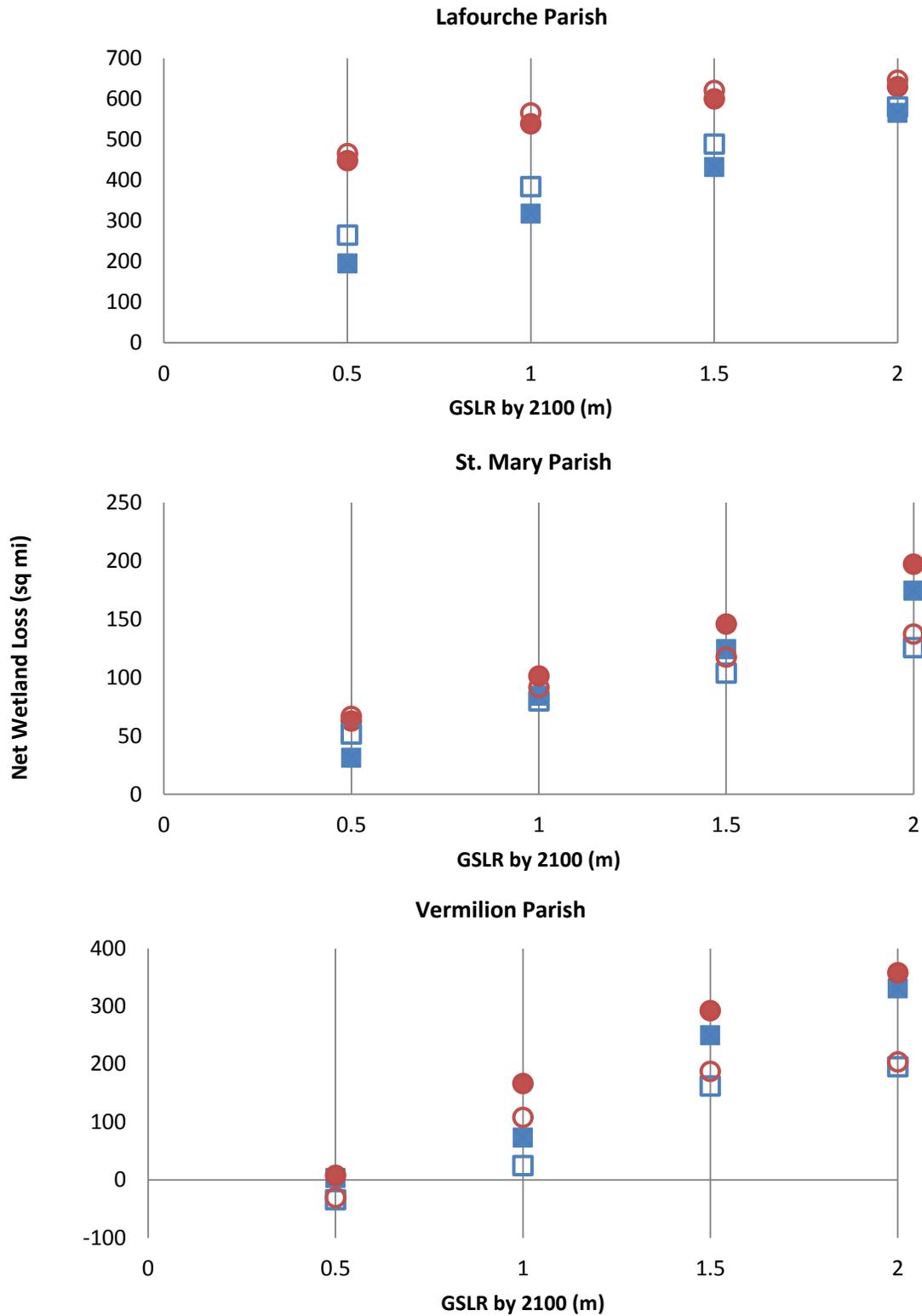


FIGURE 19. SLAMM RESULTS OF NET WETLAND LOSS IN EACH PARISH ACCORDING TO GSLR AND HIGH SUBSIDENCE (RED), LOW SUBSIDENCE (BLUE), NO DIKE PROTECTION (HOLLOW SYMBOLS), AND DIKE PROTECTION (SOLID SYMBOLS) CONDITIONS.

**Lafourche Parish**

By 2100, Lafourche Parish loses net wetland cover in all modeled scenarios (Table 17). However, some gain of wetlands is modeled under no dike protection conditions in the year 2025. Lafourche Parish experiences the most extensive loss of wetlands of all the parishes within this study. The highest net loss of wetlands modeled within Lafourche Parish (656.6 square miles accounting for 45 percent of the total parish area) occurs under the least optimistic conditions of a 2.0 meter GSLR by 2100 and high subsidence with no dike protection.

Open water originally constitutes 574 square miles (148,737 Ha) of landcover within Lafourche Parish. This coverage increases to 1,205 square miles (312,118 Ha) under 2.0 meters of GSLR with high subsidence and no dike protection conditions. Of the roughly 630 square miles (164,000 Ha) of land converted to open water within this extreme GSLR scenario, the majority of it represents a loss of freshwater swamp and marsh areas.

TABLE 17. NET WETLAND LOSS OVER TIME PERIOD IN LAFOURCHE PARISH IN SQUARE MILES. NOT PROTECTED/PROTECTED REFERS TO DIKE PROTECTION. HIGH/LOW REFERS TO RATE OF SUBSIDENCE. (VALUES IN PARENTHESIS INDICATE GAIN IN WETLAND AREA.)

		GSLR	2025	2050	2075	2100
Protected	Low	0.5	1.3	10.0	97.7	198.4
		1.0	1.6	22.8	203.9	322.6
		1.5	2.1	87.2	261.4	439.5
		2.0	2.6	144.3	303.6	575.0
	High	0.5	3.5	90.7	250.7	455.4
		1.0	2.6	128.7	290.3	547.6
		1.5	3.4	177.2	338.0	609.9
		2.0	4.8	206.2	411.1	640.6
Not Protected	Low	0.5	(6.8)	39.6	130.2	269.4
		1.0	(9.2)	42.8	242.4	390.4
		1.5	(12.0)	102.7	291.1	497.0
		2.0	(18.0)	170.0	330.9	589.5
	High	0.5	(17.7)	100.8	259.1	473.4
		1.0	(21.8)	158.0	324.3	574.8
		1.5	(25.1)	202.5	366.0	631.0
		2.0	(27.7)	223.5	401.8	656.6

### 0.5 meter GSLR by 2100

Under a 0.5 meter rise by 2100, a general trend of wetland loss is predicted for Lafourche Parish. In 2025, there is some gain in wetland area in scenarios where there was no dike protection. However, as time progresses and sea levels rise, the greatest loss of wetlands is observed under high subsidence with no dike protection. Within this scenario, the greatest net wetland loss modeled equals an area of 473 square miles (122,611 Ha) by the year 2100 (Table 17).

There is a decrease in fresh marsh and swamp categories that convert to salt marsh and open water by 2100. A positive percent change, indicating gain of area, is observed for transitional salt marsh, regularly flooded marsh, and open water. However, an increase is observed in transitional salt marsh only under low subsidence and dike protected conditions. Alternatively, negative percent change, indicating loss of area, is observed for cypress swamp, swamp, irregularly flooded marsh, inland fresh marsh, and tidal fresh marsh. There is also a general trend of loss of transitional salt marsh and regularly flooded marsh as RSLR continues to increase. Cypress swamp undergoes the greatest negative percent change ranging between 70 and 100 percent with the exception of high subsidence and protected conditions, which result in more loss of inland fresh marsh.

The swamp north of Thibodaux is lost by 2050 in the no protection scenarios and by 2075 in the protected scenarios. Most fresh marsh cover is lost by 2050 in high subsidence conditions. However, fresh marsh is prevalent until 2100 under low subsidence conditions (Figure 20).

### 1.0 meter GSLR by 2100

Under a 1.0 meter GSLR by 2100, a general trend of wetland loss is observed under higher subsidence conditions. In 2025, there is some gain in wetland area in scenarios which there was no dike protection. Again, subsidence is modeled as the driving factor of wetland loss. Under high subsidence and no protection, an area of 575 square miles (148,861 Ha) accounts for the greatest estimate of wetland loss under a 1.0 meter rise by 2100 (Table 17).

A positive percent change, indicating gain of area, is observed for transitional salt marsh, regularly flooded marsh, and open water. However, there is an increase in transitional salt marsh only under low subsidence and dike protected conditions. Alternatively, negative percent change, indicating loss of area, is observed for undeveloped dry land, cypress swamp, swamp, irregularly flooded marsh, inland fresh marsh, and tidal fresh marsh. Cypress swamp undergoes the greatest negative percent change ranging at about 100 percent with the exception of high subsidence and protected conditions, which result in more loss of inland fresh marsh.

In this modeled scenario, subsidence plays a significant role in wetland extent in 2100 under both protection and no protection conditions. In the low subsidence runs, there is a greater variety of marsh type; whereas in the high subsidence runs most marsh has converted to tidal flat. The low subsidence with dike protection run is the only condition with cypress swamp remaining in 2100 (Figure 21).

### 1.5 meter GSLR by 2100

Under a 1.5 meter rise by 2100, a general trend of wetland loss is observed for higher subsidence conditions. In 2025, there is some gain in wetland area in scenarios which there was no dike protection. Under high subsidence and no protection, an area of 631 square miles (163,428 Ha) accounts for the greatest estimate of wetland loss under a 1.5 meter rise by 2100 (Table 17).

A positive percent change, indicating gain of area, is observed for regularly flooded marsh (under low subsidence conditions) and open water. Alternatively, negative percent change, indicating loss of area, is observed for undeveloped dry land, all fresh marsh types and all salt marsh types. Cypress swamp undergoes the greatest negative percent change ranging at about 100 percent change with the exception of the low subsidence and protected scenario, which results in a greater loss of tidal fresh marsh instead of cypress swamp.

In the dike protected scenarios there is a loss of undeveloped dry land starting midway between Thibodaux and Larose and continuing south. The loss of undeveloped dry land is greater when there is no dike protection (average of 93 percent) than when protection is maintained (50 percent loss). The low subsidence with protection run is the only condition with cypress swamp remaining in 2100 (Figure 22).

### 2.0 meter GSLR by 2100

Under a 2.0 meter rise by 2100, a general trend of wetland loss is observed under higher subsidence conditions. In 2025, there is some gain in wetland area in scenarios without dike protection. Under high subsidence and no protection, an area of 657 square miles (170,048 Ha) of wetlands accounts for the greatest estimate of loss under a 2.0 meter rise by 2100 (Table 17).

A positive percent change, indicating gain of area, is observed for regularly flooded marsh under low subsidence and no protection conditions and open water. Alternatively, negative percent change, indicating loss of area, is observed for undeveloped dry land, all fresh marsh types and all salt marsh types. All fresh marsh types undergo the greatest negative percent change ranging at about 100 percent.

By 2100, most of the parish is under water (Figure 23). Model results indicate that low subsidence and dike protection can preserve most of the undeveloped dry land and marsh. All of the land south of Larose converts to open water except for the road to Port Fourchon.

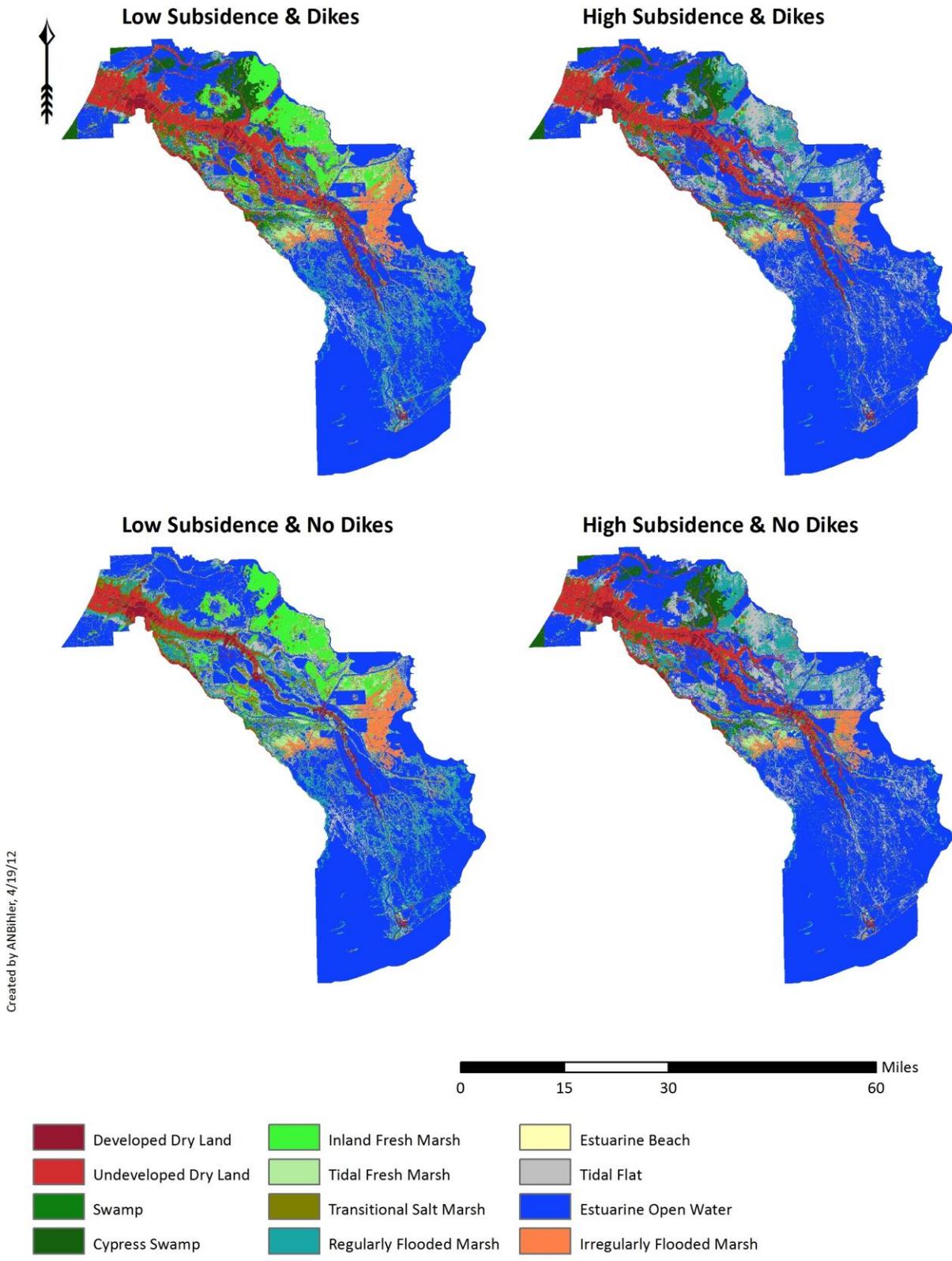


FIGURE 20. LAFOURCHE PARISH IN 2100 UNDER A 0.5 METER GSLR.

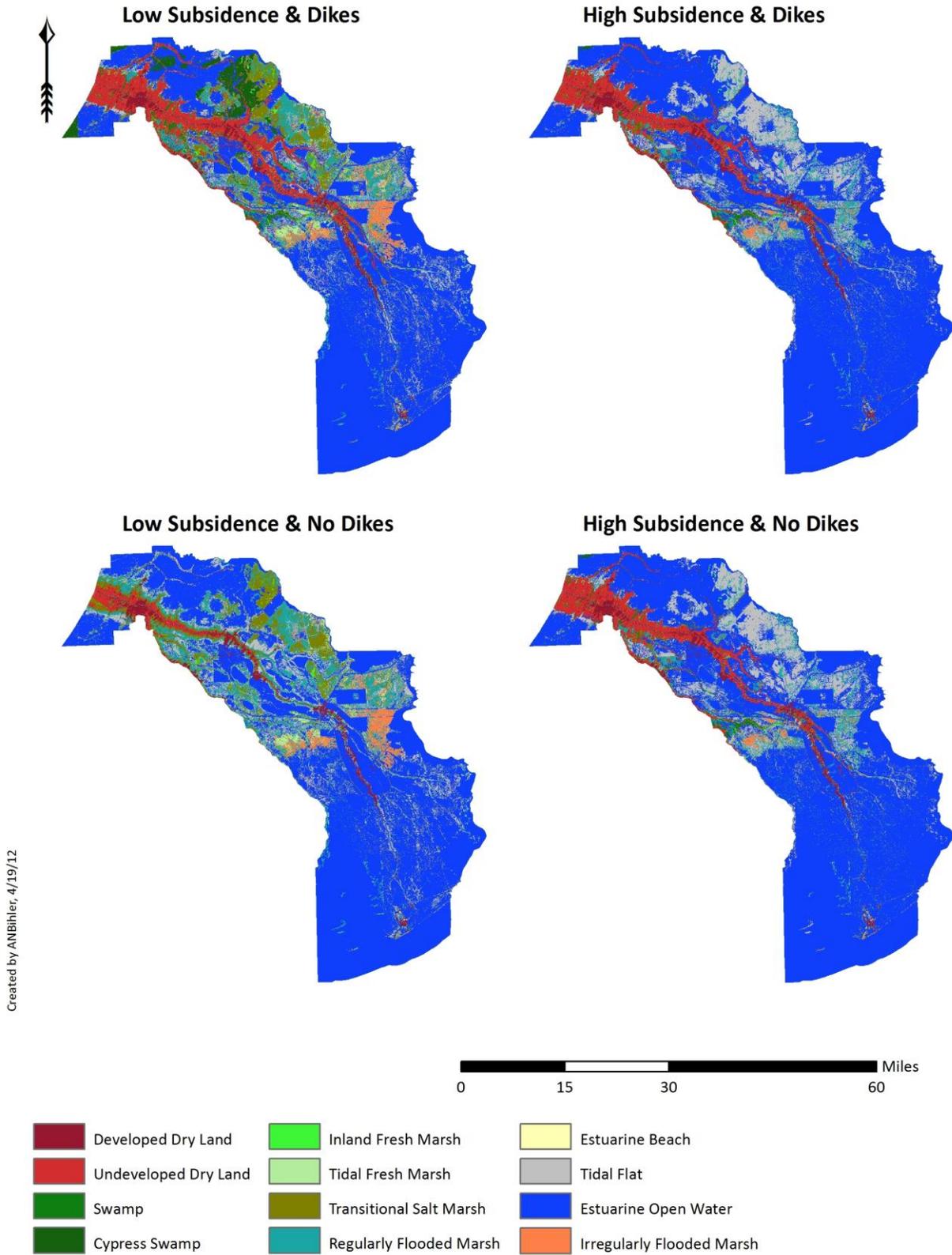


FIGURE 21. LAFOURCHE PARISH IN 2100 UNDER A 1.0 METER GSLR.

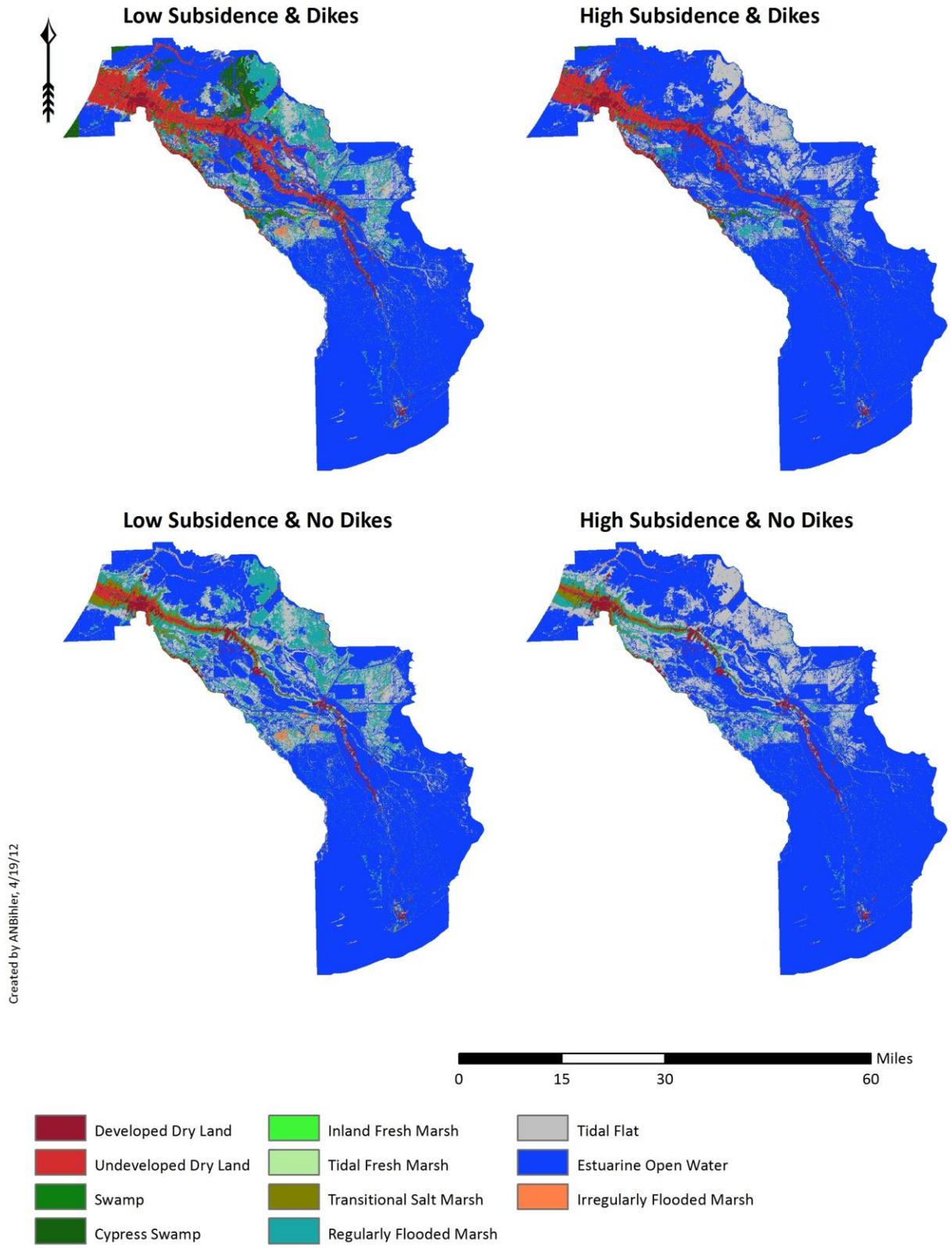


FIGURE 22. LAFOURCHE PARISH IN 2100 UNDER A 1.5 METER GSLR.

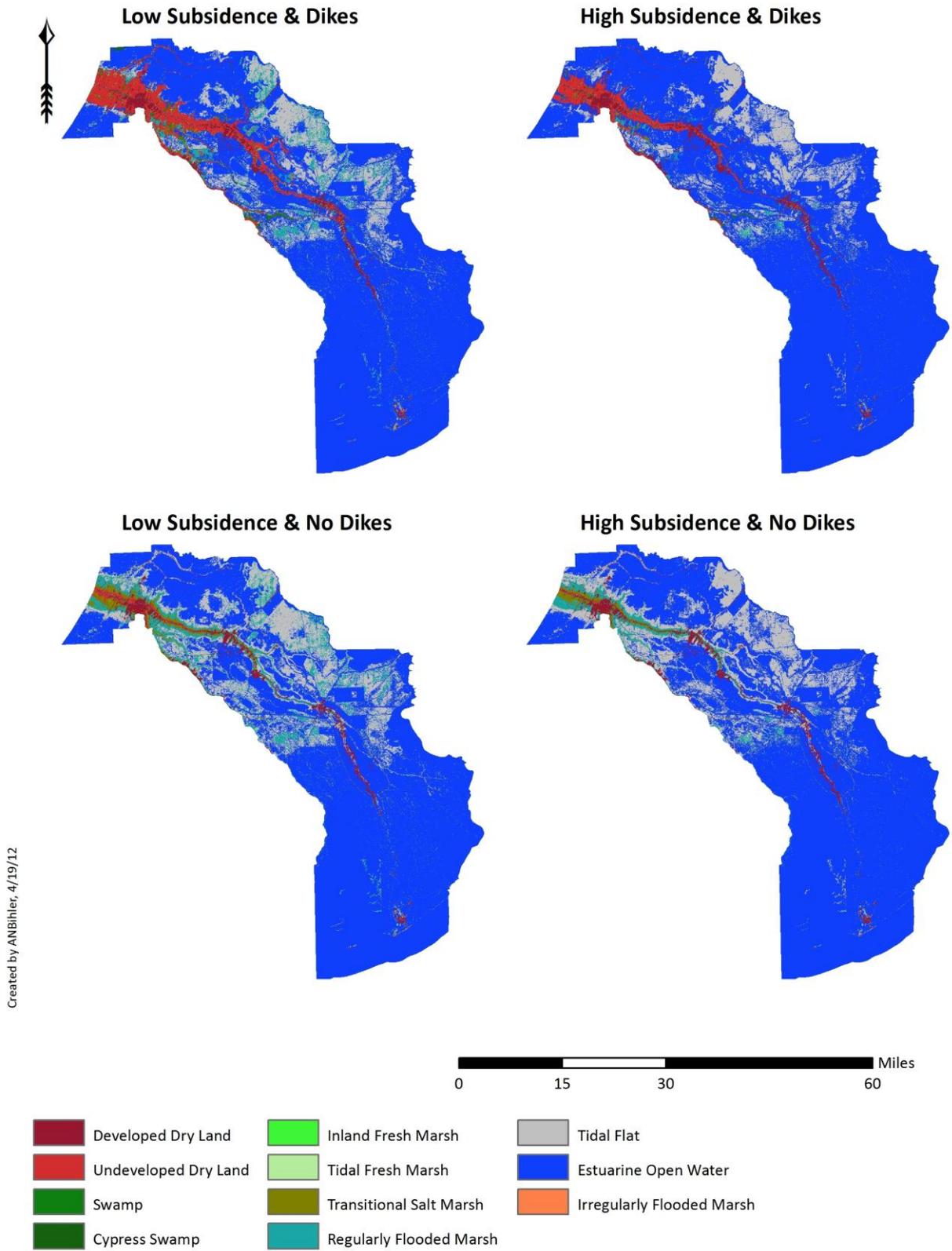


FIGURE 23. LAFOURCHE PARISH IN 2100 UNDER A 2.0 METER GSLR.

**St. Mary Parish**

As modeled within SLAMM, St. Mary Parish experiences a net loss of wetlands from 2007 to 2100 regardless of the GSLR, protection, or subsidence conditions specified within the model. The highest net loss of wetlands modeled (200.3 square miles accounting for 18 percent of the total parish area) within St. Mary Parish occurs under the least optimistic conditions of a 2.0 meter GSLR by 2100 and high subsidence with dike levee protection (Table 18).

Open water originally constitutes 494 square miles (127,841 Ha) of landcover within St. Mary Parish. This coverage increases to 624 square miles (161,599 Ha) under 2.0 meters of GSLR with high subsidence and with dike protection conditions. Of the roughly 131 square miles (34,000 Ha) of land converted to open water within this extreme RSLR scenario, the majority of it represents a loss of freshwater swamp and marsh areas. Cypress swamp appears to be the most vulnerable landcover type and the first dominant landcover type in the parish to convert to open water.

**TABLE 18. NET WETLAND LOSS OVER TIME IN ST. MARY PARISH IN SQUARE MILES. NO PROTECTION/PROTECTION REFERS TO DIKE PROTECTION. HIGH/LOW REFERS TO SUBSIDENCE RATES.**

		<b>GSLR</b>	<b>2025</b>	<b>2050</b>	<b>2075</b>	<b>2100</b>
<b>Protection</b>	<b>Low</b>	<b>0.5</b>	1.4	7.3	16.0	31.7
		<b>1.0</b>	2.2	15.1	59.0	85.8
		<b>1.5</b>	3.5	27.1	79.3	126.3
		<b>2.0</b>	4.6	51.4	93.2	177.2
	<b>High</b>	<b>0.5</b>	2.0	11.7	34.8	63.8
		<b>1.0</b>	3.1	20.1	71.4	102.9
		<b>1.5</b>	4.2	41.5	85.7	148.3
		<b>2.0</b>	5.4	58.2	102.3	200.3
<b>No Protection</b>	<b>Low</b>	<b>0.5</b>	2.0	8.5	17.6	52.3
		<b>1.0</b>	2.5	15.3	56.7	81.2
		<b>1.5</b>	3.9	26.4	66.8	105.6
		<b>2.0</b>	4.8	47.9	66.2	127.8
	<b>High</b>	<b>0.5</b>	2.4	12.7	35.7	67.7
		<b>1.0</b>	3.5	20.0	66.1	93.0
		<b>1.5</b>	4.4	39.5	67.2	119.5
		<b>2.0</b>	5.5	53.1	69.9	139.5

### 0.5 meter GSLR by 2100

Under a 0.5 meter rise by 2100, a general trend of more wetland loss is predicted within the higher subsidence scenarios (Figure 24). Additionally, scenarios with no dike protection resulted in more wetland loss than those with dike protection. Under high subsidence and no dike protection, an area of 68 square miles (17,537 Ha) accounts for the greatest estimate of wetland loss under a 0.5 meter rise by 2100 (Table 18).

Under this lower GSLR scenario, subsidence is modeled as the driving factor of inundation and conversion of landcover types. A positive percent change in area, indicating gain, is observed for open water, transitional salt marsh, regularly flooded marsh, and tidal flat. Alternatively, a negative percent change in area, indicating loss, is observed for cypress swamp, swamp, irregularly flooded marsh, inland fresh marsh, and tidal fresh marsh. Cypress swamp undergoes the greatest negative percent change ranging between 60 and 80 percent.

### 1.0 meter GSLR by 2100

Under a 1.0 meter rise by 2100, a general trend of more wetland loss is observed within the higher subsidence scenarios (Figure 25). However, unlike the 0.5 meter runs, as sea levels rise dike protection appears to have a greater effect on wetland loss. Under high subsidence and dike protection, an area of 103 square miles (26,662 Ha) of wetlands accounts for the greatest estimate of loss under a 1.0 meter rise by 2100 (Table 18).

Much like the 0.5 meter GSLR scenario in St. Mary, a positive percent change in area, indicating gain, is observed for open water, transitional salt marsh, regularly flooded marsh, and tidal flat. Alternatively, a negative percent change in area, indicating loss, is observed for cypress swamp, swamp, irregularly flooded marsh, inland fresh marsh, and tidal fresh marsh. Cypress swamp undergoes the greatest negative percent change ranging between 80 and 90 percent.

### 1.5 meter GSLR by 2100

Under a 1.5 meter rise by 2100, a general trend of more wetland loss is observed within the higher subsidence scenarios (Figure 26). As sea levels rise from 2050 to 2100 dike protection appears to have a more dominant effect on wetland loss. Under high subsidence and dike protection, an area of 148 square miles (38,404 Ha) accounts for the greatest estimate of wetland loss under a 1.5 meter rise by 2100 (Table 18).

As previously discussed, a positive percent change in area, indicating gain, is observed for open water, transitional salt marsh, regularly flooded marsh, and tidal flat. Alternatively, a negative percent change in area, indicating loss, is observed for cypress swamp, swamp, irregularly flooded marsh, inland fresh marsh,

and tidal fresh marsh. Cypress swamp undergoes the greatest negative percent change ranging between 90 and 95 percent.

### 2.0 meter GSLR by 2100

Under a 2.0 meter rise by 2100, a general trend of more wetland loss is observed within the higher subsidence scenarios (Figure 27). However, as mentioned previously, greater loss of wetlands is observed under dike protected conditions as sea levels rise. Under high subsidence and dike protection, an area of 200 square miles (51,875 Ha) accounts for the greatest estimate of wetland loss under a 2.0 meter rise by 2100 (Table 18).

Again, a positive percent change in area, indicating gain, is observed for open water, transitional salt marsh, regularly flooded marsh, and tidal flat. Alternatively, a negative percent change in area, indicating loss, is observed for cypress swamp, swamp, irregularly flooded marsh, inland fresh marsh, and tidal fresh marsh. Cypress swamp undergoes the greatest negative percent change ranging between 95 and 100 percent.

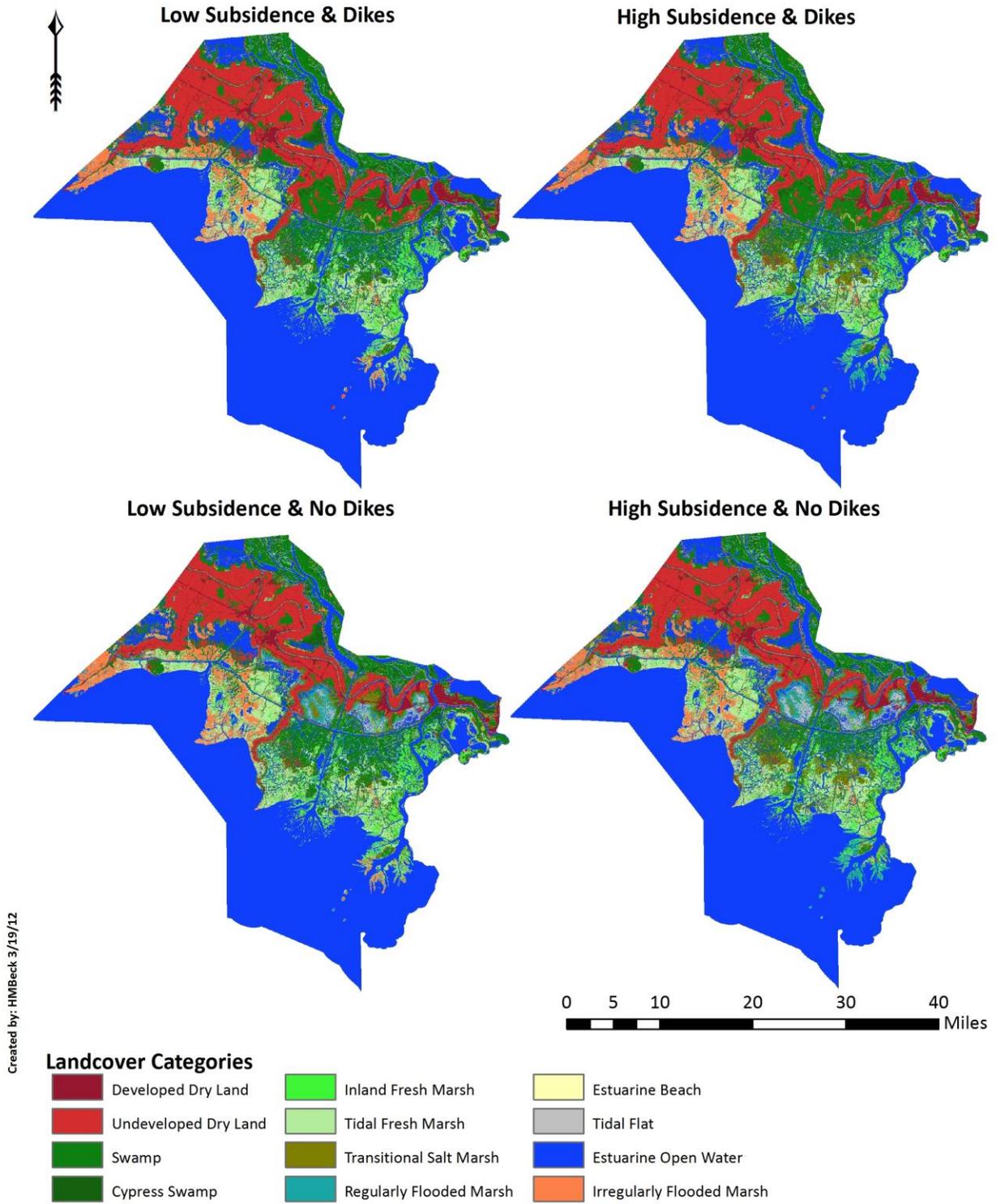


FIGURE 24. ST. MARY PARISH IN 2100 UNDER A 0.5 METER GSLR.

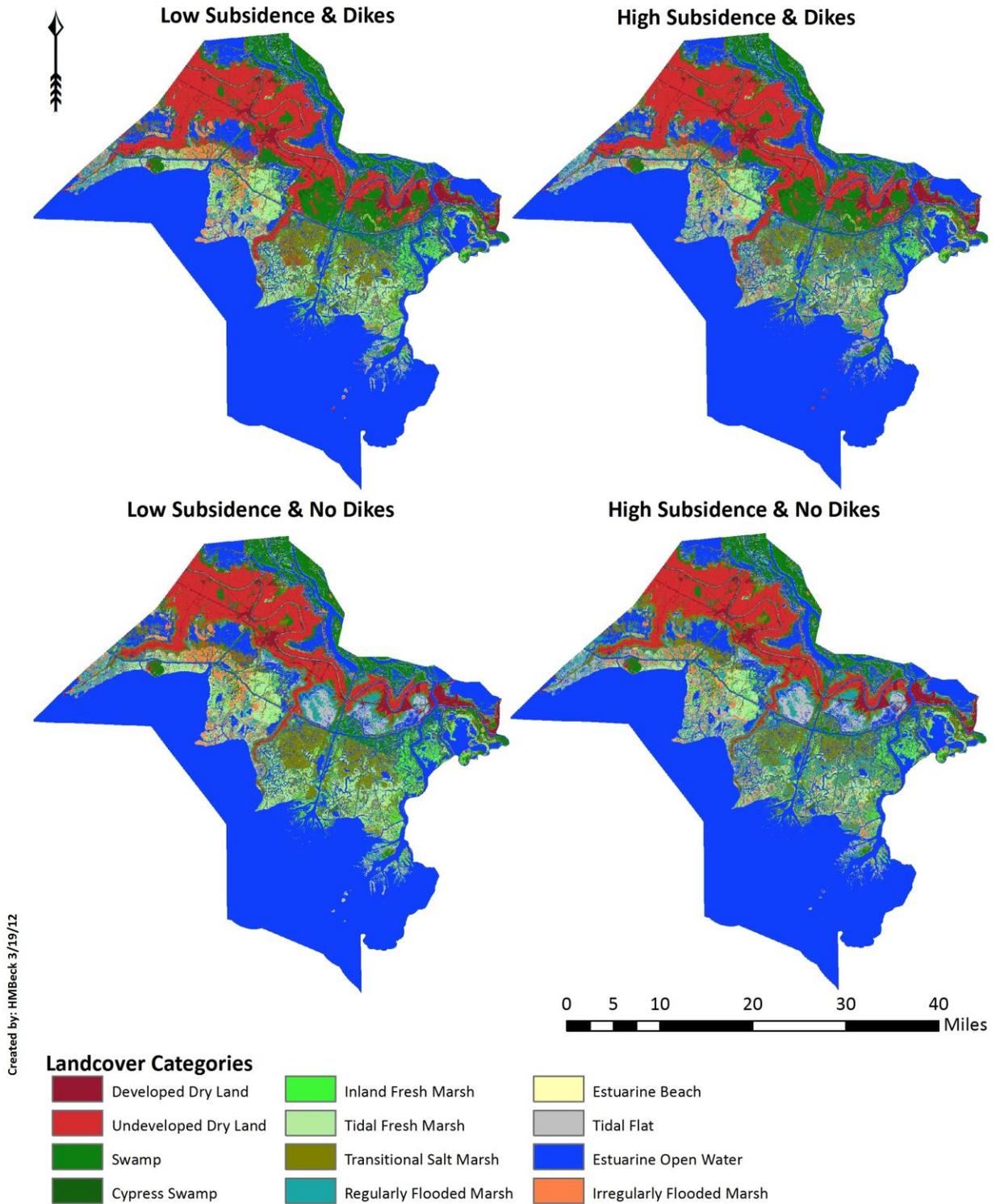


FIGURE 25. ST. MARY PARISH IN 2100 UNDER A 1.0 METER GSLR.

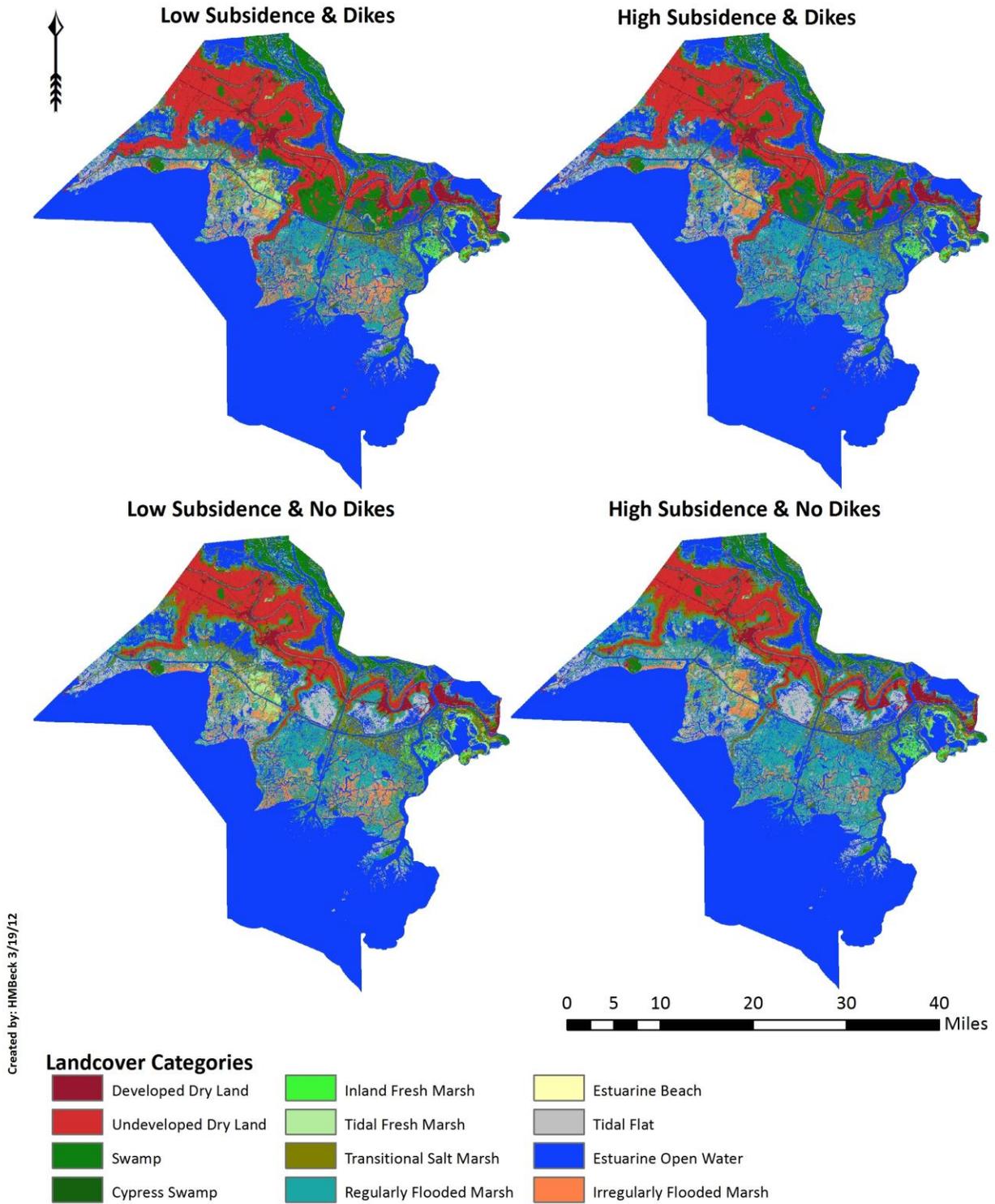


FIGURE 26. ST. MARY PARISH IN 2100 UNDER A 1.5 METER GSLR.

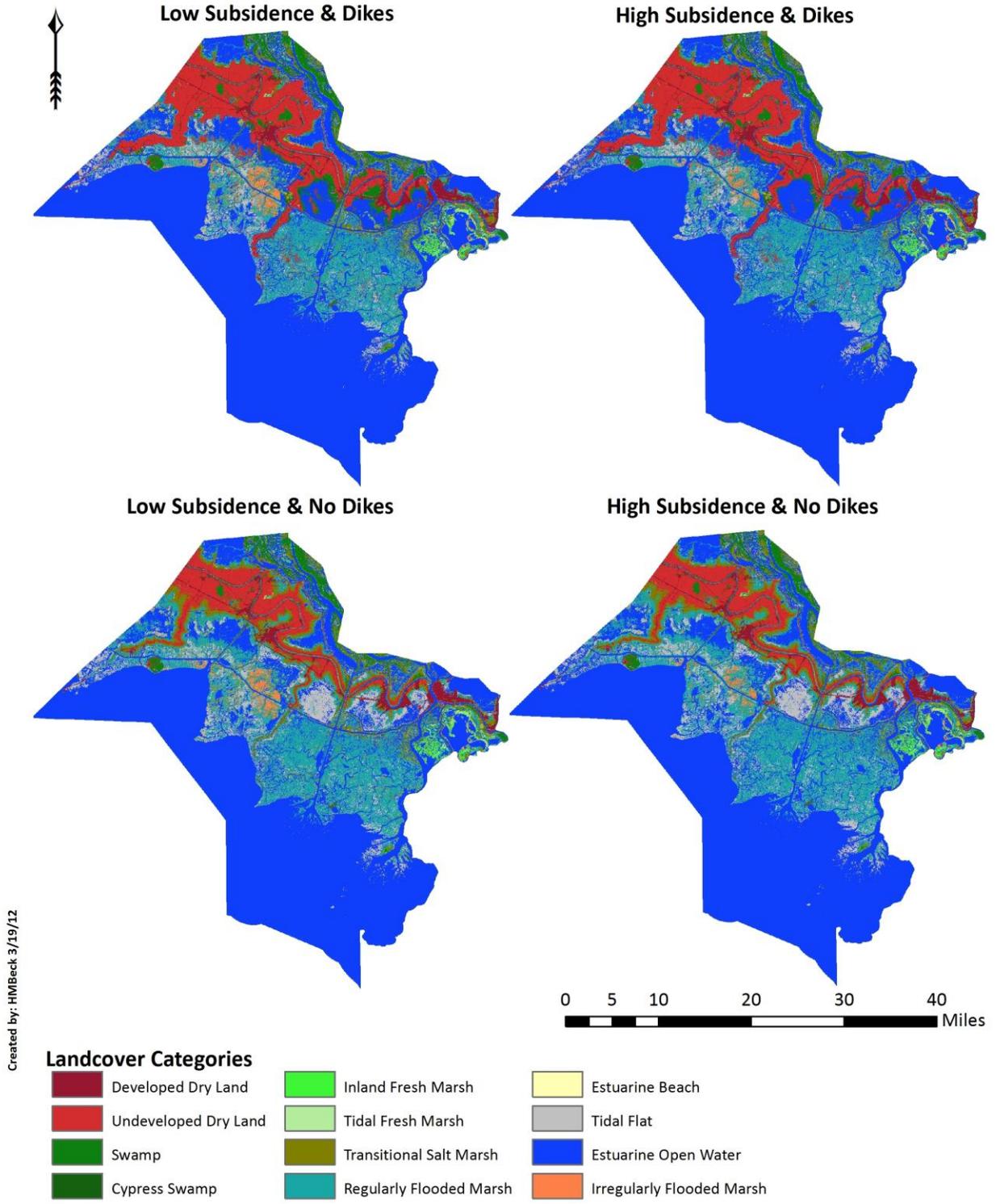


FIGURE 27. ST. MARY PARISH IN 2100 UNDER A 2.0 METER GSLR.

**Vermilion Parish**

By 2100, Vermilion Parish was modeled to lose wetland cover in all scenarios except for the 0.5 meter GSLR with no dike protection scenario. The highest net loss of wetlands modeled (363.5 square miles accounting for 24 percent of the total parish area) within Vermilion Parish occurs under the least optimistic conditions of a 2.0 meter GSLR by 2100 and high subsidence with dike protection (Table 19).

Open water originally constitutes 504 square miles (130,637 Ha) of landcover within Vermilion Parish. This coverage increases to 789 square miles (204,395 Ha) under 2.0 meters of GSLR with high subsidence and with dike protection conditions. As RSLR increases, there is a decrease in fresh marsh and swamps and an increase in salt marshes in the parish. With the increase in the magnitude of RSLR by 2100, there is an increase in open water and tidal flats in the southern half of the parish.

TABLE 19. NET WETLAND LOSS OVER TIME IN VERMILION PARISH IN SQUARE MILES. NO PROTECTION/PROTECTION REFERS TO DIKE PROTECTION. HIGH/LOW REFERS TO SUBSIDENCE RATES. (VALUES IN PARENTHESIS INDICATE GAIN IN WETLAND AREA.)

		GSLR	2025	2050	2075	2100
Protection	Low	0.5	1.6	2.5	2.9	3.3
		1.0	2.1	5.3	13.7	74.1
		1.5	2.8	12.9	70.9	253.9
		2.0	3.8	17.3	159.6	336.0
	High	0.5	1.9	3.4	4.3	7.8
		1.0	2.5	9.1	30.8	169.0
		1.5	3.5	15.3	118.7	297.0
		2.0	4.9	21.4	197.8	363.5
No Protection	Low	0.5	(2.5)	(7.1)	(24.6)	(34.8)
		1.0	(4.5)	(8.7)	(23.1)	24.8
		1.5	(6.3)	(10.7)	10.6	164.7
		2.0	(7.8)	(20.8)	66.7	198.5
	High	0.5	(4.0)	(8.8)	(24.1)	(31.0)
		1.0	(6.0)	(9.4)	(13.7)	109.4
		1.5	(7.5)	(15.8)	46.9	190.6
		2.0	(8.5)	(24.7)	88.1	207.3

### 0.5 meter GSLR by 2100

Under high subsidence and dike protection, an area of 7.8 square miles (2020 Ha) accounts for the greatest estimate of wetland loss under a 0.5-meter rise by 2100 (Table 19). There is a decrease in fresh marshes and swamps under all conditions and an increase in salt marsh coverage; in the scenarios where dry land is protected, the category with largest area lost by 2100 is swamp. In all scenarios open water, undeveloped dry land, and irregularly flooded marsh are the dominant landcover types (Figure 28).

### 1.0 meter GSLR by 2100

Under high subsidence and dike protection, an area of 169 square miles (43,771 Ha) of wetlands accounts for the greatest estimate of loss under a 1.0 meter rise by 2100 (Table 19). In all four runs irregularly flooded marsh is the category with greatest loss of total area followed by tidal fresh in the protected runs and undeveloped dry land in the no dike protection runs. Regularly flooded marsh has the greatest gain in total area in the low subsidence runs and tidal flat. This is followed by regularly flooded marsh, which has the greatest gain in total area in the high subsidence runs. The loss of irregularly flooded marsh makes sense as over time the frequency of inundation will increase and rising sea levels will move the saltwater inland causing loss of cypress swamp and fresh water marshes.

Following from the previous GSLR scenario, the high subsidence scenarios experience greater wetland loss than low subsidence scenarios (Figure 29).

### 1.5 meter GSLR by 2100

Under high subsidence and dike protection, an area of 297 square miles (76,923 Ha) accounts for the greatest estimate of wetland loss under a 1.5 meter rise by 2100 (Table 19). The average of all four runs is 146 square miles (37,835 Ha). In all scenarios, wetland loss in 2075 is more than doubled in 2100 and the scenarios with dikes have greater loss than those runs without dikes. Over 65 percent of each tidal fresh marsh, inland fresh marsh, and cypress swamp cover is lost by 2100 in all scenarios within this scenario.

However, continuing the trend from the previous two scenarios, irregularly flooded marsh has the greatest decline, which is represented between 80 and 95 percent loss depending on the scenario. In the scenarios without dike protection, regularly flooded marsh has greater gains in landcover. In this scenario, we see the dominant gain of tidal flat of over 151 square miles (39,000 Ha). All swamps erode to tidal flat before converting to open water (Figure 30).

### 2.0 meter GSLR by 2100

Under high subsidence and dike protection, an area of 364 square miles (94,276 Ha) accounts for the greatest estimate of wetland loss under a 2.0 meter rise by 2100 (Table 19). Open water is approximately half of the parish area in 2100 in all scenarios. Dominant landcover classes in all scenarios include open water,

undeveloped dry land, tidal flat, and regularly flooded marsh. All fresh marsh and swamp categories are less than 1 percent of total landcover. In the no dike protection scenarios, almost 50 percent of the undeveloped dry landcover is lost by 2100. Wetland loss averages 90,000 hectares with dikes and averages 193 square miles (50,000 Ha) without dikes. The irregularly flooded marsh that was prevalent in the south of Vermilion is converted to open water and fragmented tidal flat by 2100 (Figure 31).

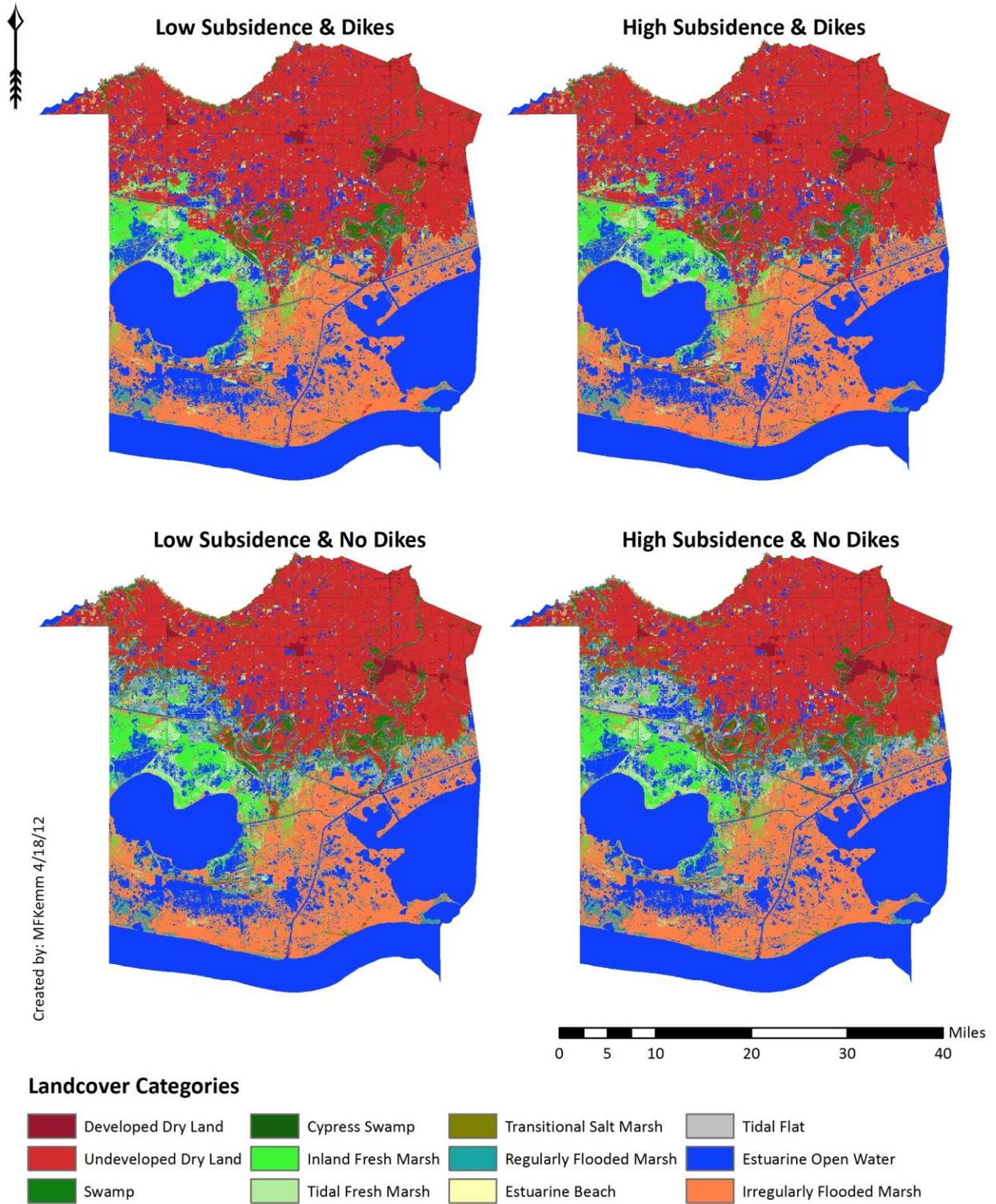


FIGURE 28. VERMILION PARISH IN 2100 UNDER A 0.5 METER GSLR.

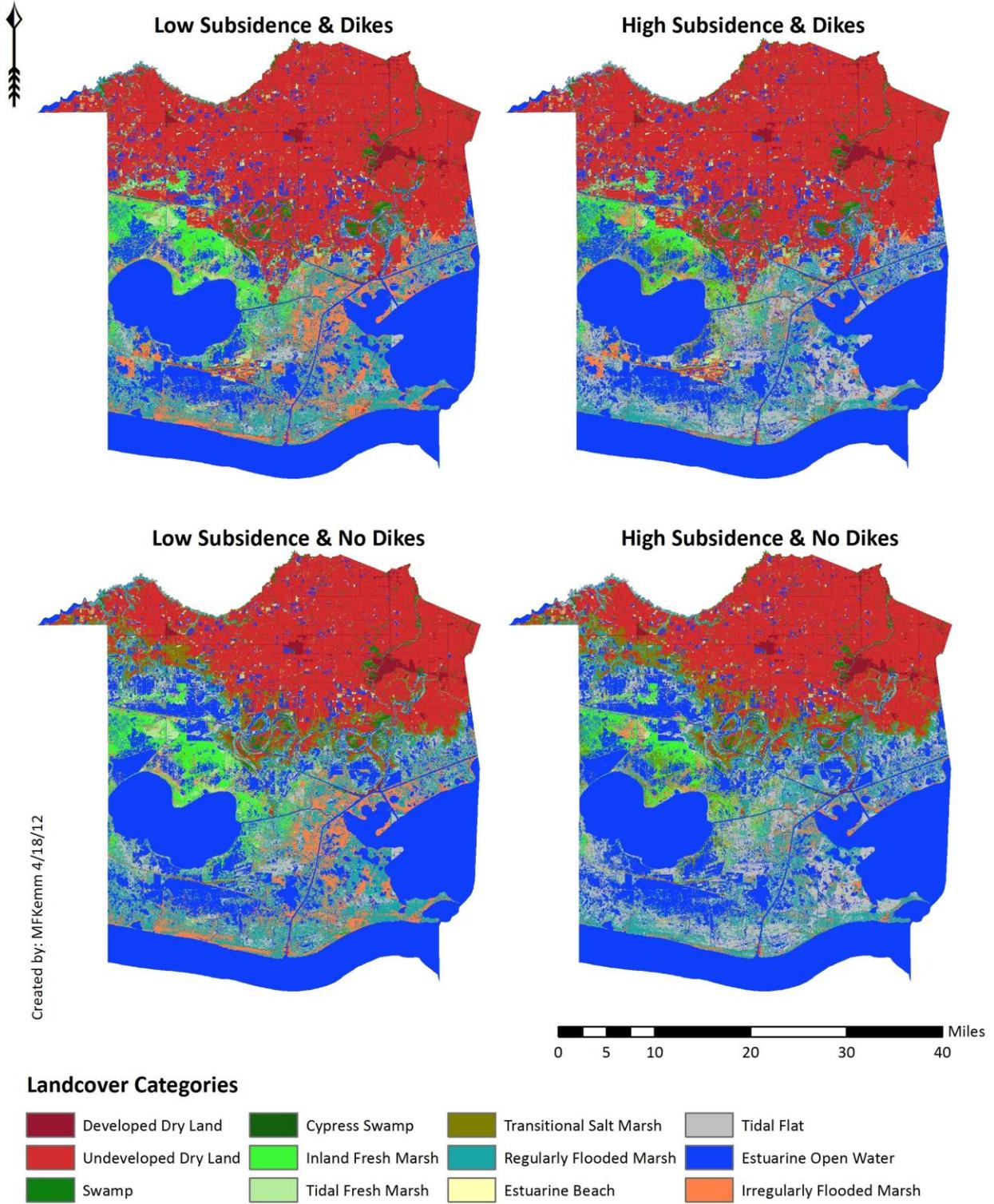


FIGURE 29. VERMILION PARISH IN 2100 UNDER A 1.0 METER GSLR.

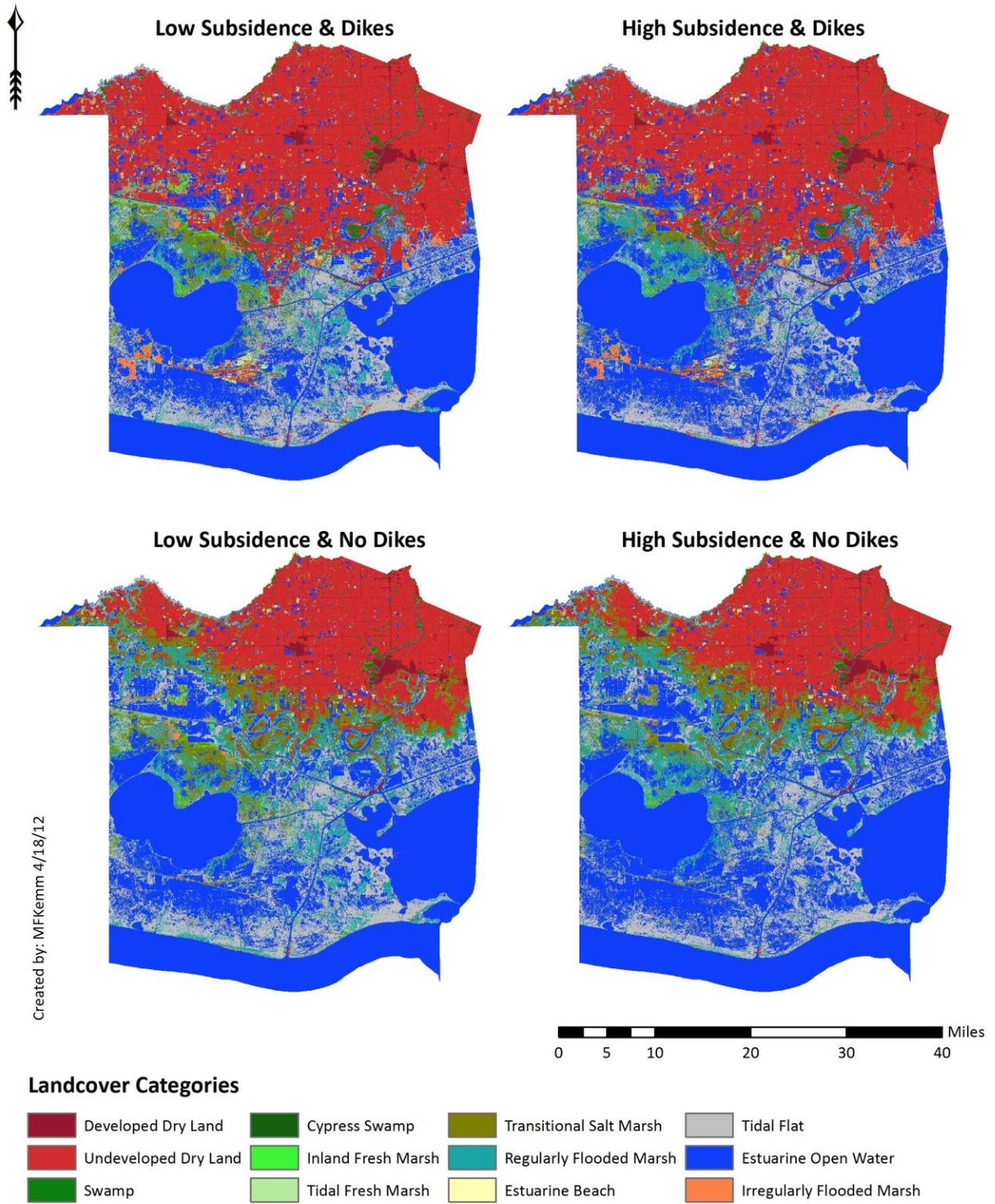


FIGURE 30. VERMILION PARISH IN 2100 UNDER A 1.5 METER GSLR.

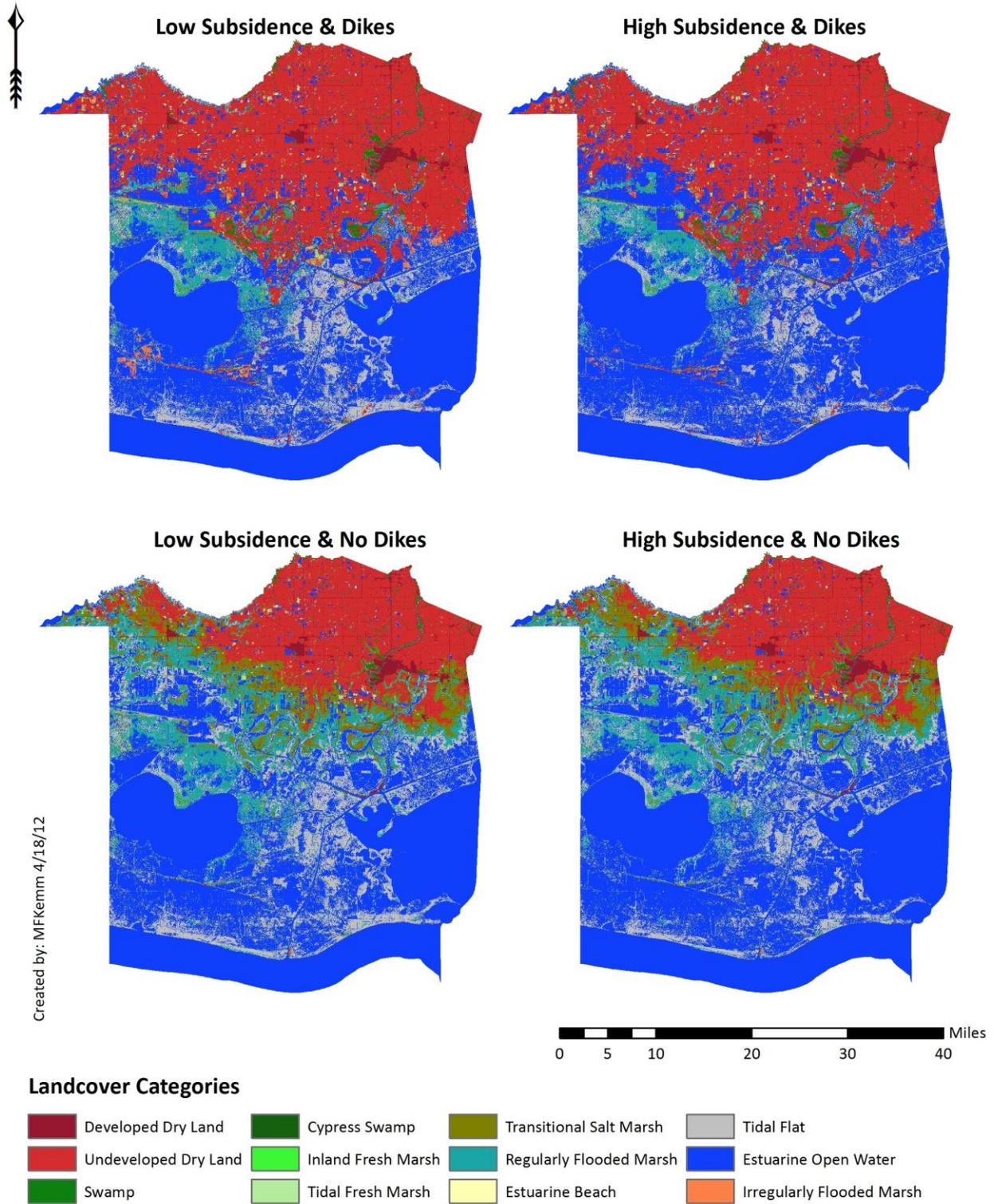


FIGURE 31. VERMILION PARISH IN 2100 UNDER A 2.0 METER GSLR.

## Upland Migration of Wetlands

Within this modeling effort, migration of wetland habitats into undeveloped dry land areas only occurs when those areas are not protected by dikes or levees. The primary use of these undeveloped dry upland areas in all three case study parishes is for agriculture (roughly 60 to 90 percent cultivated agriculture and 10 to 15 percent pastureland). Although these primary land uses and their potential effect on the process of wetland migration (i.e. soil properties, nutrient loading, etc.) into these areas must be taken into consideration, it is outside of the realms of this particular study.

Under the less optimistic scenarios of RSLR, modeling shows more wetland migration into undeveloped dry lands as sea levels rise (Figure 32). Alternatively, under these less optimistic scenarios there is a higher conversion of wetlands into open water. The benefits of removing protective barriers and allowing wetland migration into undeveloped dry lands are not equal across the case study parishes. The variability of subsidence rates and the distribution of dry land greatly impact the potential offset of wetland loss provided by the creation of new wetlands in dry upland areas.

For comparison purposes, the most (GSLR of 0.5 meters by 2100 and low subsidence) and least (GSLR of 2.0 meters by 2100 and high subsidence) optimistic scenarios are explored in more detail in the following sections.

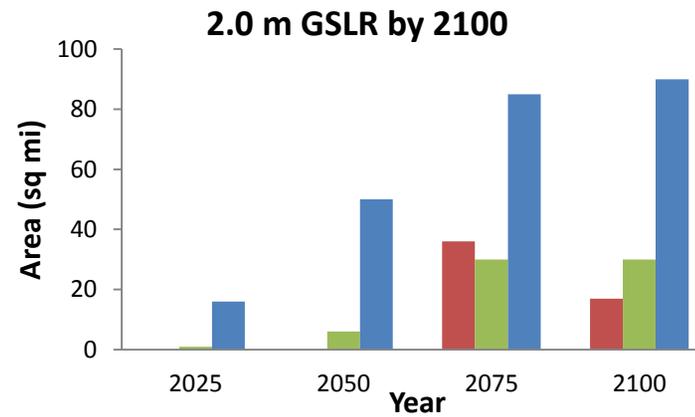
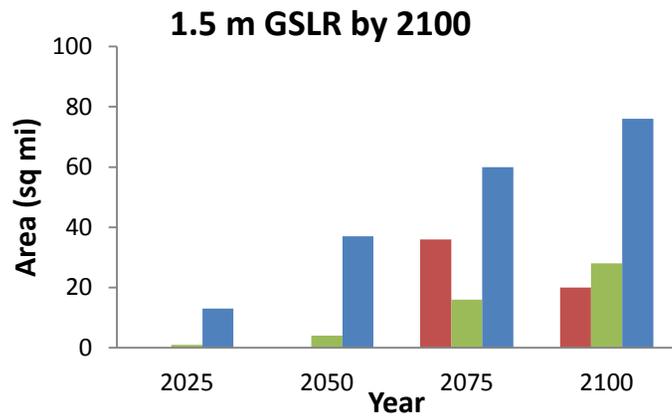
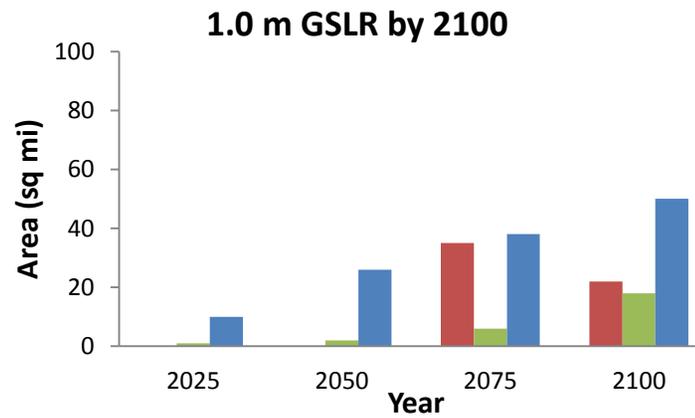
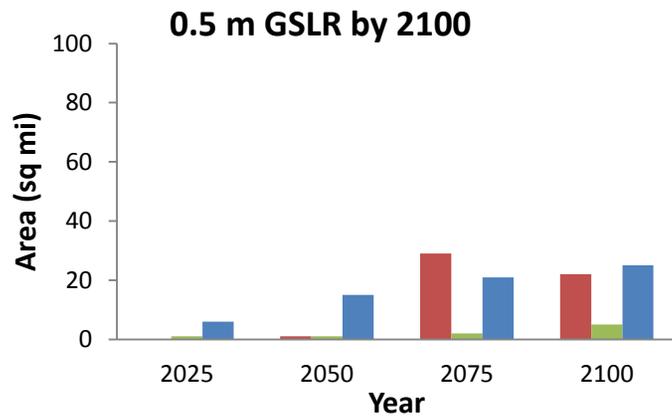


FIGURE 32. THE AMOUNT OF DRY LAND CONVERTING TO WETLANDS ACCORDING TO GLSR SCENARIO IN LAFOURCHE PARISH (RED), ST. MARY PARISH (GREEN) AND VERMILION PARISH (BLUE). THIS REPRESENTS LOW SUBSIDENCE AND NO DIKE PROTECTION CONDITIONS.

### **Lafourche Parish**

As in all the case study parishes, the presence of dikes in Lafourche Parish prohibits the migration of wetlands. Only by removing dikes is undeveloped dry land able to convert to wetlands in all scenarios modeled. However, the model predicts a greater net loss of wetlands in Lafourche with dike removal. Lafourche is unique in this situation as both St. Mary and Vermilion parishes exhibit less net loss under scenarios without dike protection. For both high and low rates of subsidence, the model predicts wetland migration occurring after 2050 in all GSLR scenarios (Figure 32). This is denoted by the absence of darker green colors in Figure 33 and Figure 34. All areas that are predicted to serve as migration corridors run parallel to Bayou Lafourche. This is not an unexpected trend as this reflects the distribution of dry land in Lafourche Parish. More total land is modeled to serve as a migration corridor under scenarios with higher rates of subsidence. This is due to the increased inundation of dry lands and their subsequent conversion under higher rates of subsidence.

Under the most optimistic scenario Lafourche is expected to gain 22 square miles (5,698 Ha) of wetlands by dry land conversion in the year 2100. Although, the removal of dike protection from Lafourche Parish allows for inland migration of wetlands, this conversion only offsets 8 percent of the expected wetland loss of 269 square miles (69,133 Ha) (Table 20). Under the least optimistic scenario, less land is able to keep up with the RSLR and only 10 square miles (2,590 Ha) of dry land convert to wetlands by the year 2100. This represents an offset of only 2 percent of the expected wetland loss of 657 square miles (170,162 Ha).

**TABLE 20. CHANGE IN WETLAND COVER FOR LAFOURCHE PARISH UNDER MOST OPTIMISTIC SCENARIO (0.5 METERS GSLR BY 2100 AND LOW SUBSIDENCE) AND LEAST OPTIMISTIC SCENARIO (2.0M GSLR BY 2100 AND HIGH SUBSIDENCE)**

<b>Scenario</b>	<b>Wetland Gain (sq mi)</b>	<b>Wetland Loss (sq mi)</b>	<b>% Loss Offset By Gain</b>
Most optimistic	22	269	8
Least optimistic	10	657	2

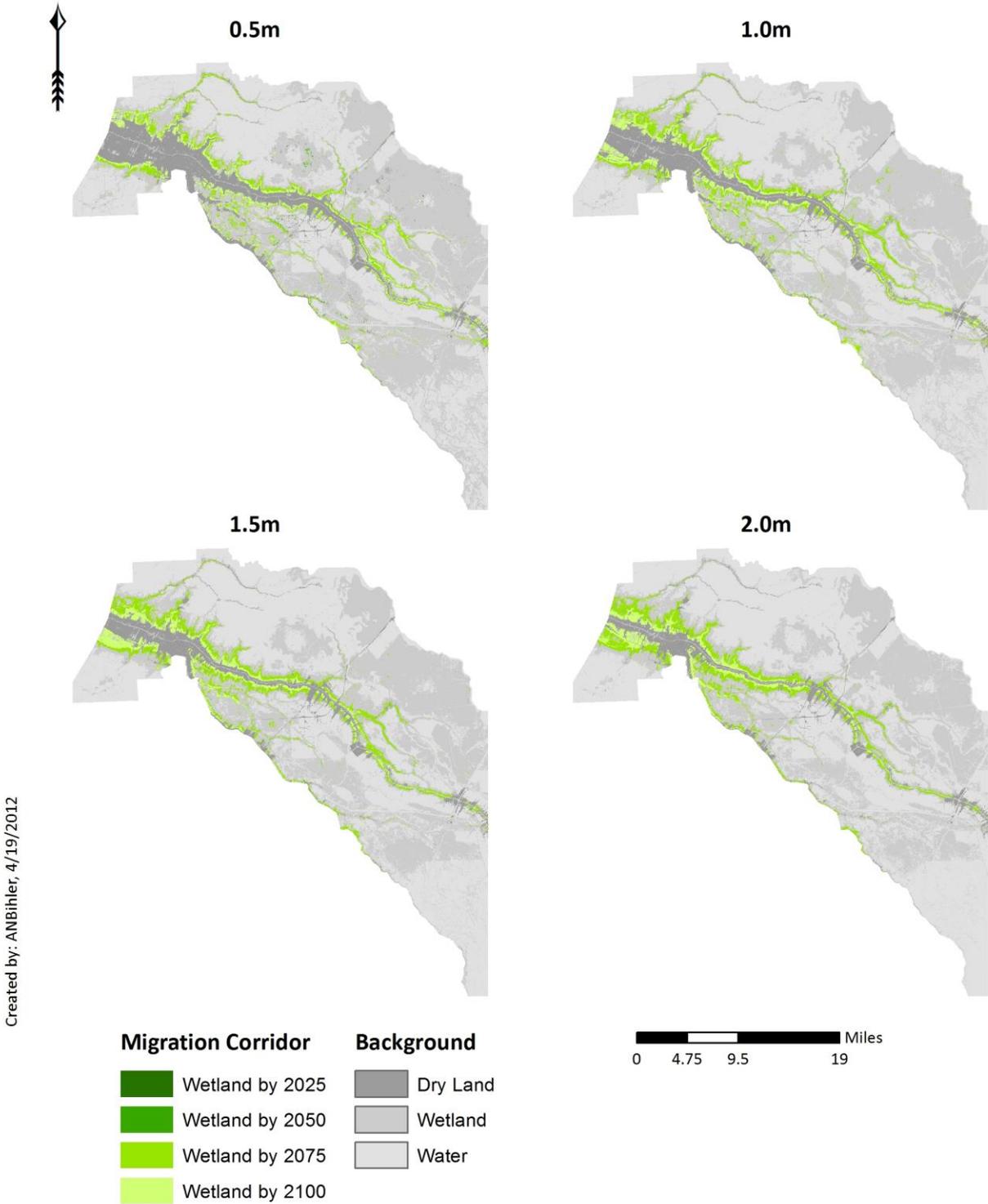


FIGURE 33. MIGRATION CORRIDORS FOR LAFOURCHE PARISH UNDER LOW RATES OF SUBSIDENCE.

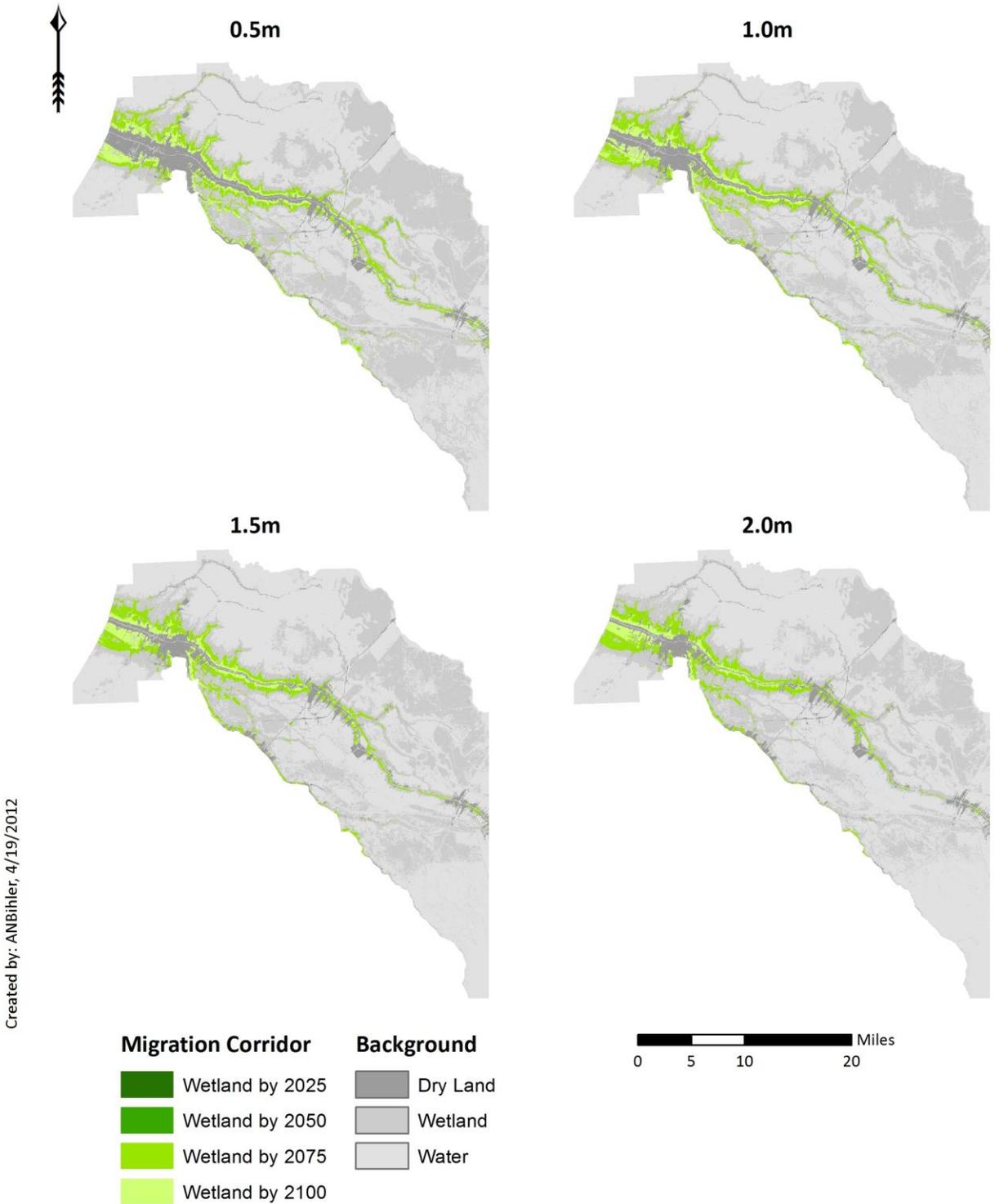


FIGURE 34. MIGRATION CORRIDORS FOR LAFOURCHE PARISH UNDER HIGH RATES OF SUBSIDENCE.

**St. Mary Parish**

As in all the case study parishes, the presence of dikes in St. Mary Parish prohibits the migration of wetlands. The removal of dikes in the parish will allow for wetland migration onto undeveloped dry land that runs along the Atchafalaya River and its adjacent diversions. For both high and low rates of subsidence, the model predicts wetland migration occurring as soon as 2025 in all scenarios (indicated in the darker green colors in Figure 35 and Figure 36). However, most of the wetlands that migrate onto dry land in the year 2025 later convert to tidal flat or open water in subsequent years.

The highest percentage of wetland migration onto undeveloped dry land observed within the model is occurring between the years 2075 and 2100 for all modeled scenarios with the exception of a 2.0 meter GSLR rise under a high subsidence condition in which the greatest amount of migration occurs between the years 2050 and 2075 (Figure 32). More total land is modeled to serve as a migration corridor under scenarios with higher rates of subsidence. This is due to the increased inundation of dry lands and their subsequent conversion under higher rates of subsidence.

Under the most optimistic scenario, St. Mary is expected to gain 5 square miles (1,295 Ha) of wetlands by dry land conversion in the year 2100. Although, the removal of dike protection from St. Mary Parish allows for inland migration of wetlands, this conversion only offsets 10 percent of the expected wetland loss of 52 square miles (13,468 Ha) (Table 21). Under the least optimistic scenario, 31 square miles (8,029 Ha) of dry land convert to wetlands by the year 2100. This represents an offset of 22 percent of the expected wetland loss of 140 square miles (36,260 Ha).

TABLE 21. CHANGE IN WETLAND COVER FOR ST. MARY PARISH UNDER MOST OPTIMISTIC SCENARIO (0.5 METERS GSLR BY 2100 AND LOW SUBSIDENCE) AND LEAST OPTIMISTIC SCENARIO (2.0M GSLR BY 2100 AND HIGH SUBSIDENCE)

Scenario	Wetland Gain (sq mi)	Wetland Loss (sq mi)	% Loss Offset By Gain
Most optimistic	5	52	10
Least optimistic	31	140	22

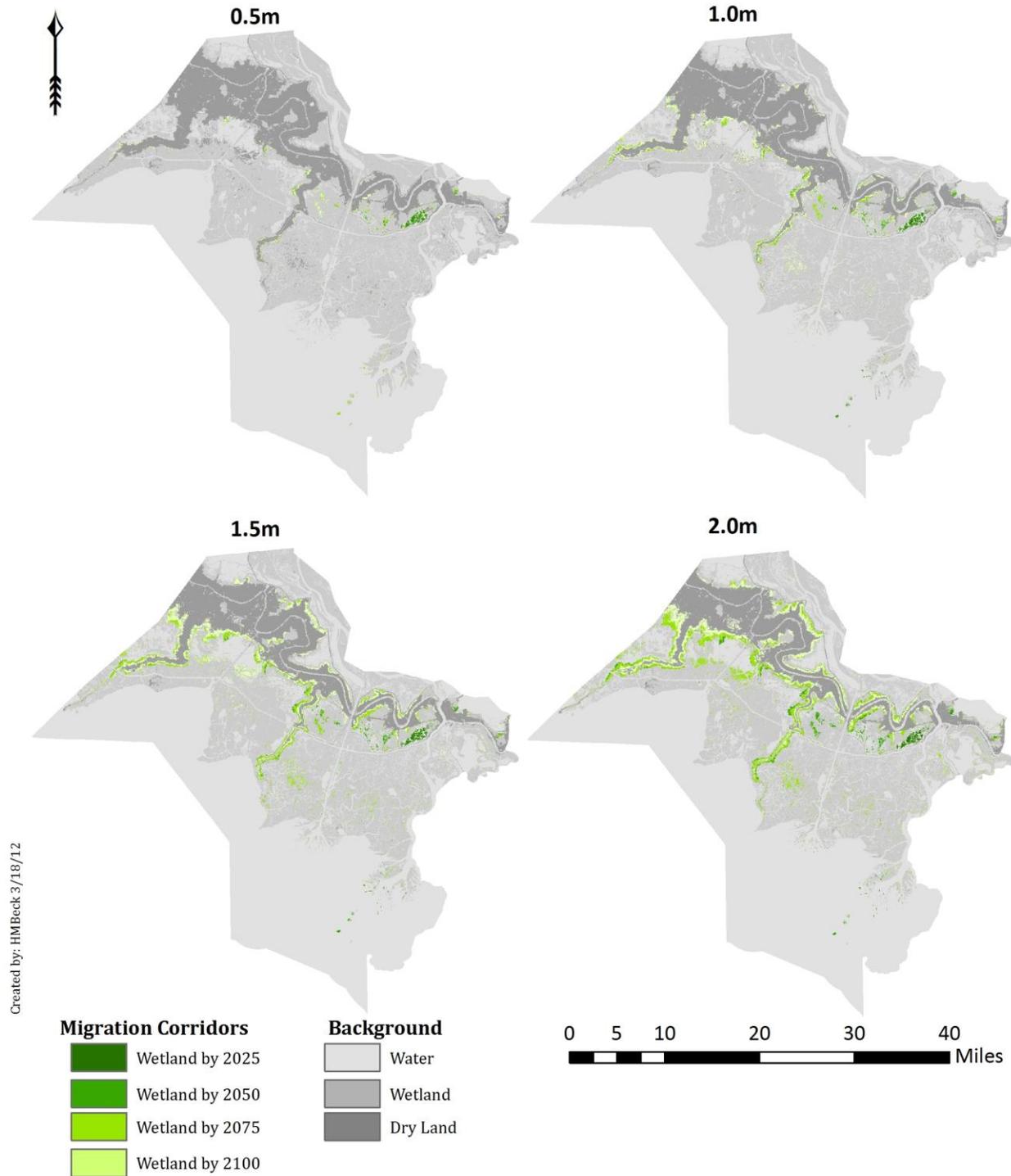


FIGURE 35. MIGRATION CORRIDORS FOR ST. MARY PARISH UNDER LOW RATES OF SUBSIDENCE.

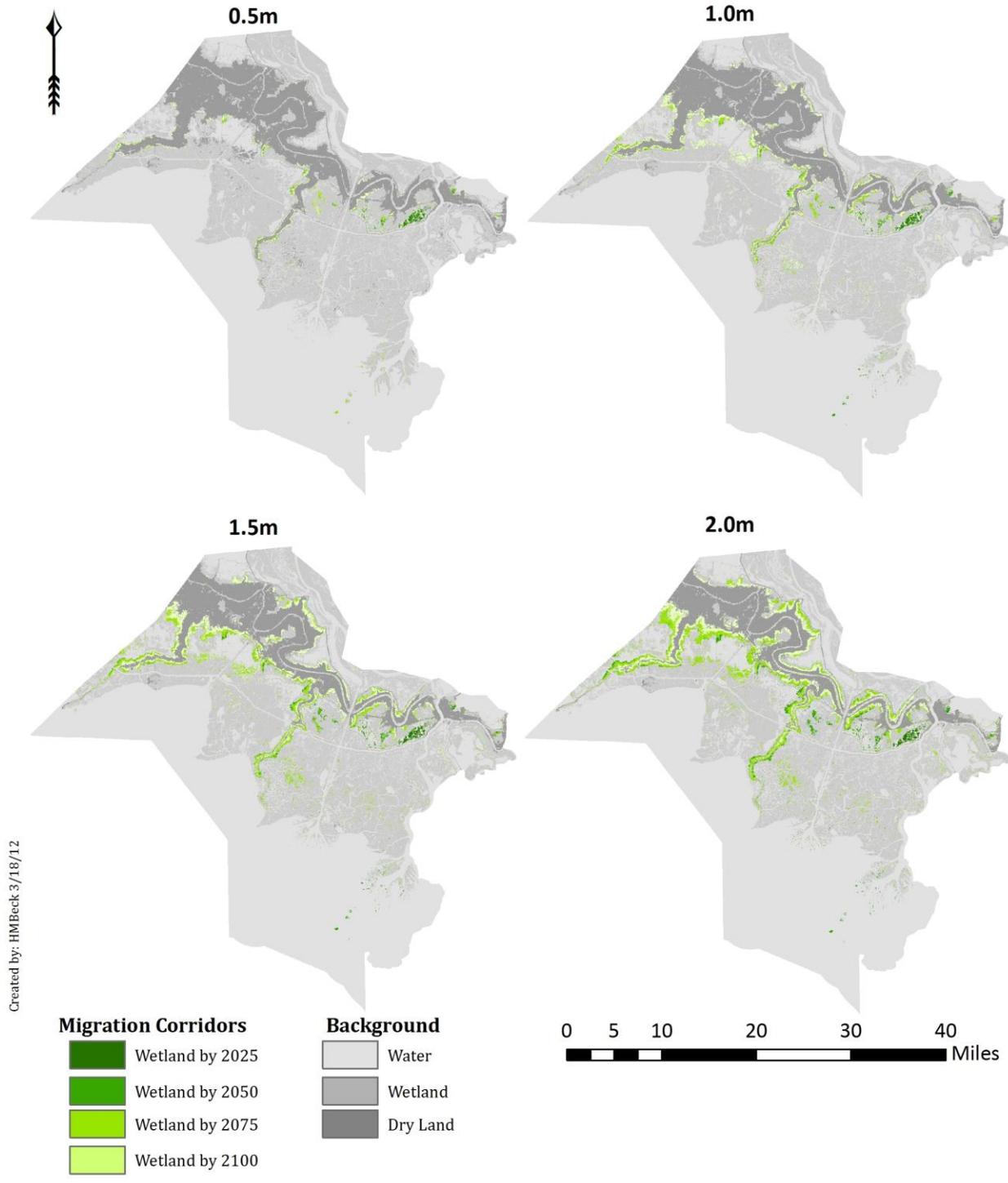


FIGURE 36. MIGRATION CORRIDORS FOR ST. MARY PARISH UNDER HIGH RATES OF SUBSIDENCE.

### **Vermilion Parish**

Of the three parishes, Vermilion has the greatest potential for wetland migration with the removal of barriers protecting undeveloped dry land. The removal of dikes in the parish will allow for wetland migration onto undeveloped dry land that covers most of the parish north of White Lake and Vermilion Bay. Wetland migration onto dry land begins in 2025, however most of those wetlands are lost to open water by 2100; wetland migration at and after 2050 is more likely to persist until 2100 (Figure 37 and Figure 38). Following a similar trend to the other parishes, more dry land is converted to wetlands by 2100 in the high subsidence scenarios. Additionally, as the predicted RSLR increases so does the potential for wetland migration.

There is no clear relationship between the area of persistent wetlands and area of wetland migration by 2100 in relation to the subsidence rate or GSLR scenario. However, for the lowest and highest GSLR scenarios, the area of wetland migration into undeveloped dry lands is greater than the area of persistent wetlands. Under a 1.5 meter GSLR, the area of persistent wetlands is larger. Under a 1.0 meter GSLR, low subsidence conditions result in a greater amount of persistent wetland area while under high subsidence conditions there is a greater area of wetland migration than persistent wetlands.

Under the most optimistic scenario, 25 square miles (6,475 Ha) of wetlands are expected to migrate into undeveloped dry lands in the year 2100. Under this more optimistic scenario, there is actually no modeled net wetland loss for Vermilion Parish (Table 22). Under the least optimistic scenario, 91 square miles (8,029 Ha) of dry land convert to wetlands by the year 2100. This represents an offset of 44 percent of the expected wetland loss of 207 square miles (53,613 Ha).

TABLE 22. CHANGE IN WETLAND COVER FOR VERMILION PARISH UNDER MOST OPTIMISTIC SCENARIO (0.5 METERS GSLR BY 2100 AND LOW SUBSIDENCE) AND LEAST OPTIMISTIC SCENARIO (2.0M GSLR BY 2100 AND HIGH SUBSIDENCE)

<b>Scenario</b>	<b>Wetland Gain (sq mi)</b>	<b>Wetland Loss (sq mi)</b>	<b>% Loss Offset By Gain</b>
Most optimistic	25	No loss	N/A
Least optimistic	91	207	44

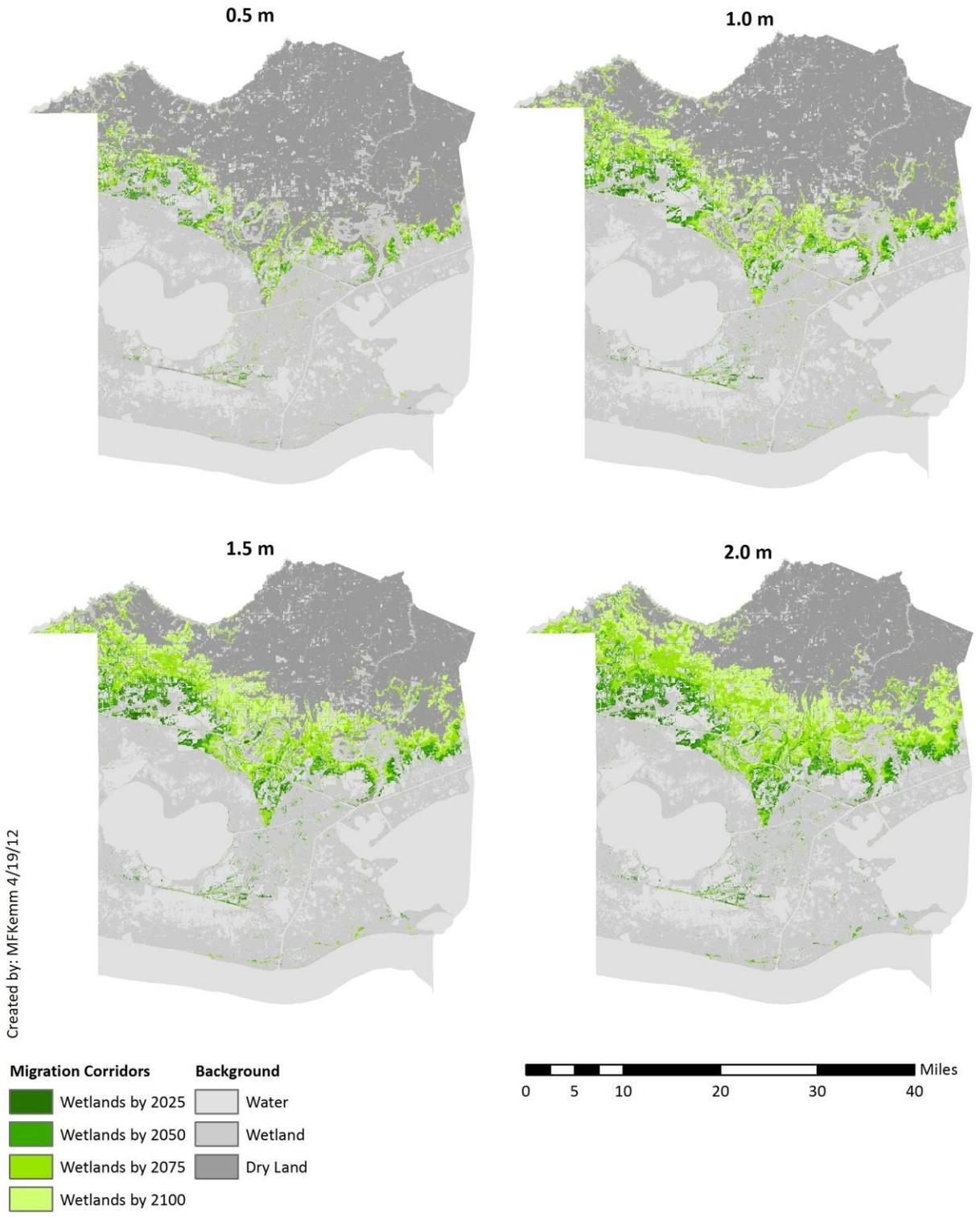


FIGURE 37. MIGRATION CORRIDORS FOR VERMILION PARISH UNDER LOW RATES OF SUBSIDENCE.

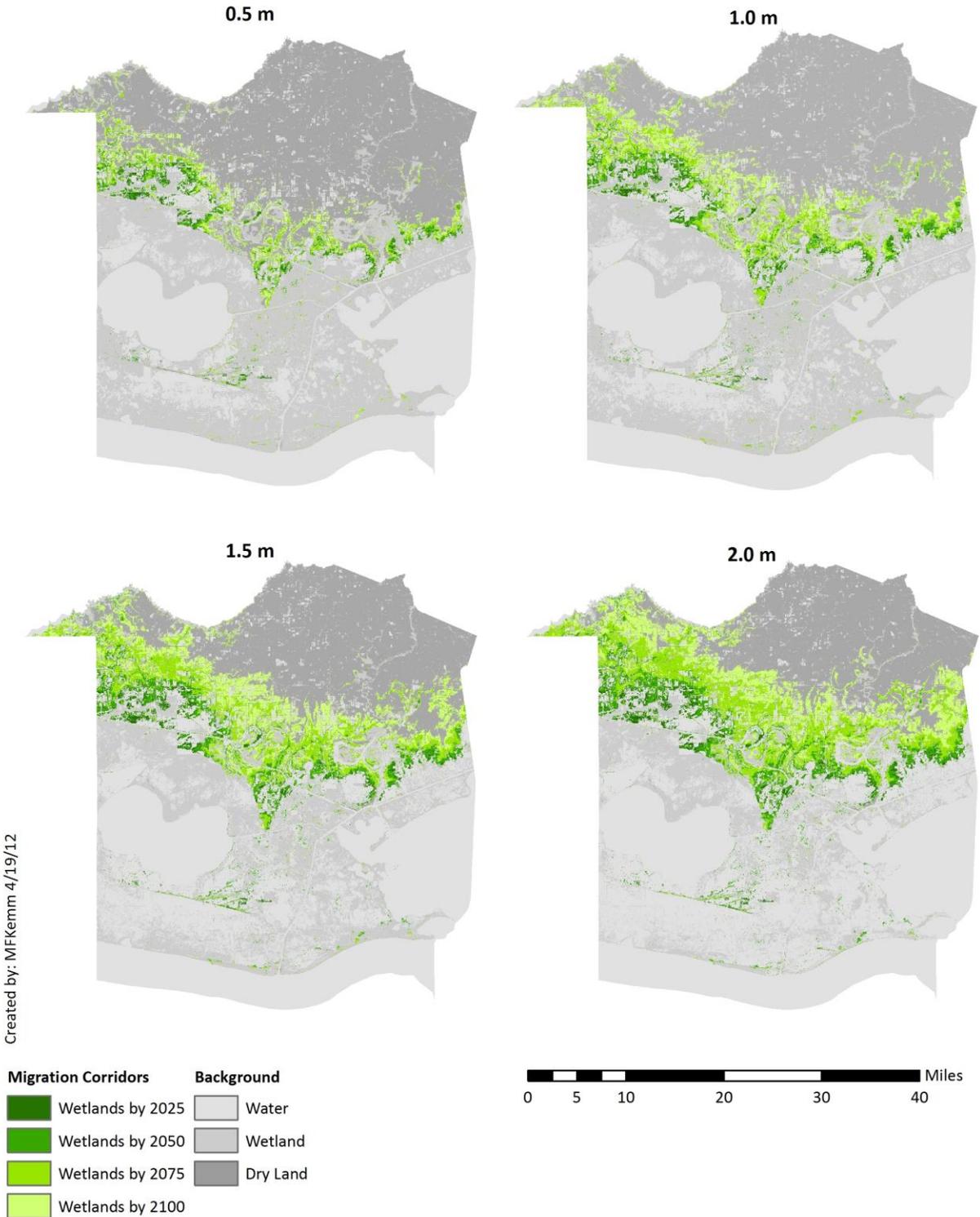


FIGURE 38. MIGRATION CORRIDORS FOR VERMILION PARISH UNDER HIGH RATES OF SUBSIDENCE.

## Geospatial Analysis Conclusion

Logically, barriers protecting undeveloped dry land along the Louisiana coast will impede the upland migration of coastal wetlands. Due to the variation in geophysical characteristics along Louisiana's coast, strategies to allow wetland migration by the removal of dikes, levees or other protective barriers may not result in equal benefits. This observation is evidenced within this study by the noted difference between Lafourche Parish and the other two parishes.

Lafourche Parish has been documented, and was modeled within this study, to have almost double the subsidence rates as that which is found in both Vermilion and St. Mary parishes. Additionally, dry land is distributed primarily along a thin area of land along Bayou Lafourche; the amount of dry land for wetlands to migrate onto is limited. As observed within our modeling, the amount of wetland migration, or wetland gain, into undeveloped dry lands in Lafourche Parish is not occurring at a rate swift enough to offset wetland loss. Additionally, unlike St. Mary and Vermilion parishes, more wetlands are lost in Lafourche Parish when there are no dikes or levees protecting dry lands. In St. Mary Parish and, primarily in Vermilion Parish, less wetlands are lost when there is no dike or levee protection of dry lands as there is a substantial amount of wetland migration occurring which is offsetting wetland loss.

The variability along Louisiana's coast must be taken into consideration as further coastal plans are developed which may strive to mitigate wetland loss by advocating wetland migration.

# Policy Analysis

## Objectives

The policy component of this project is focused on analyzing policy alternatives for wetland migration with consideration for the framework of Louisiana’s Comprehensive Master Plan for a Sustainable Coast. An exploratory approach was chosen to provide policy makers and stakeholders with a model to organize information and encourage inclusive and efficient decision-making process. The model includes the results of an analysis of six different policy alternatives with five main criteria. Applications of the policy model to wetland migration findings are included to demonstrate the exploratory decision making process.

## A History of Management Efforts

Since the 1970s, several management efforts at both the state and federal level have focused on wetland restoration in an effort to reign in the troubling reductions with little success. The path has been unnecessarily long and winding given that the two imperatives—state leadership and integrated planning—were already established before the first dedicated management framework was put in place in 1990. First, Congress enacted the Coastal Zone Management Act (CZMA) in 1972, which encouraged state’s to implement comprehensive coastal management plans. Most importantly, it recognized the superior knowledge and capability of the states, as opposed to the federal government, in managing their respective coastal zones (Jessen 2006). Second, a 1987 report by the Environmental Protection Agency (EPA) and the Louisiana Geological Survey concluded that sustainable management of coastal resources required long-term planning and the integration of several activities, including wetland restoration, flood protection, and commercial navigation (Louisiana Wetland Protection Panel April 1987). Despite this early guidance, it would take nearly three decades to develop the regulatory framework needed for sustainable management of coastal resources in Louisiana.

The CZMA lays the legal groundwork for comprehensive coastal management by states but the first dedicated regulatory program aimed at wetland conservation and restoration was largely a federal endeavor (Hebert 1997).<sup>3</sup> In 1990, the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) created the Louisiana Wetlands Conservation and Restoration Task Force (the “Task Force”), which combined state and federal decision-making and funding efforts. For every fiscal year, the Task Force submits a list of

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<sup>3</sup> The CWPPRA task force is comprised of five federal agencies and only one representative chosen by the Governor of Louisiana. The Task Force is chaired by the Secretary of the Army and includes representatives from the following federal agencies: Environmental Protection Agency (EPA), Department of the Interior, Department of Agriculture, Department of Commerce. See CWPPRA § 302(9).

projects to Congress for funding as part of an annual Coastal Wetlands Restoration Plan (CWRP). At first, the CWRP prioritized cost-effectiveness and near-term results in areas of immediate need (Hebert 1997, Schilmoeller 2006). The small scale of these projects, referred to as the “band-aid” approach to coastal restoration, made them easier to complete given the relatively small amount of funds that were available (Hebert 1997).<sup>4</sup> While many small projects were successful, they only addressed localized problems and the fragmented restoration strategy did little to slow the overall rate of wetland loss (Hebert 1997, Schilmoeller 2006).

The Task Force concluded that comprehensive basin scale restoration was needed and the Restoration Plan submitted in late 1993 reallocated a two-thirds majority of funding to large-scale projects with “systematic, process-level benefits” (Hebert 1997). Congress was evidently not convinced of the promise of this new strategy as the majority of projects chosen for funding during the mid-1990s were of the small scale variety (Coleman et al. 1998). Given the greater costs and uncertainty associated with large-scale projects, they wanted to see detailed feasibility studies first (Coleman et al. 1998). At about the same time, the Louisiana Governor’s Office identified the need to include even more stakeholder viewpoints and engaged scientists, local governments, and private citizens (USACE New Orleans District 2004, Schilmoeller 2006). The outcome of the renewed effort at both the state and federal level culminated in the Coast 2050 Plan, which became the official coastal restoration plan for the Task Force in December 1998. The projects in the new plan emphasized restoration and protection of natural processes including river diversions, marsh creation, and barrier island restoration and protection (USACE New Orleans District 2004). The most important and novel part was that the projects were organized and implemented as a coastwide strategy (USACE New Orleans District 2004).

Despite an improved scope and vision, the plans that proceeded from the Coast 2050 framework were much of the same—near-term action and long-term feasibility studies. In March of 2002, USACE partnered with the State of Louisiana to form the Louisiana Coastal Area (LCA) Comprehensive Coastwide Ecosystem Restoration Study Team. The LCA team performed in-depth, comprehensive analysis and developed seven sustainable restoration alternatives for funding consideration in fiscal year 2005. Dismayingly, the President’s budget guidance for the USACE in fiscal year 2005 steered efforts away from large-scale projects once again (USACE New Orleans District 2004, Day et al. 2007). In effect, this further cemented the band-aid

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<sup>4</sup> The relative level of funding is being compared to the cost of projects after 1994 and especially the amount dollars expected for the CPRA budgets over the next 50 years, which will be close to two orders of magnitude greater (up to \$40 million compared to as much as a \$1 billion). See Hebert (1997) at p. 1177 for CWPPRA funding and (CPRA January 2012) at p. 87 for funding going forward.

approach of small-scale, cost-effective priorities and reluctant long-term scoping. The timing of this hindrance was tragic as the storms of 2005 would prove that what Louisiana needed at that moment was an urgent effort to prepare for an inevitable disaster that 25 years of dedicated management was unable to alleviate.

### The 2005 Hurricane Season and the CPRA

The hurricane season of 2005 was disastrous in many ways: more than 1,400 lives were lost, over 200,000 homes sustained major damage, over a million residents were displaced, 20 percent of U.S. oil refining capacity was disrupted, the Port of New Orleans temporarily closed, and approximately 217 square miles of coastal marsh were converted to open water (Barras 2006, CPRA 2011b). After Hurricane Katrina, the levees that had been breached were found to lack the protection of wetlands whereas those that were left intact had benefited from wetland buffers (Jessen 2006). The catastrophic losses suffered during the 2005 hurricane season provided a costly and painful example of the need to follow through with the EPA's 1987 recommendation to integrate all coastal activities, which included wetland restoration, flood protection, and commercial navigation.

The case of the Mississippi River Gulf Outlet (MRGO) is a clear example of the potential for negative feedbacks when flood protection and navigation interests are not coordinated alongside restoration efforts. The MRGO is a canal that was dredged through the Breton Sound Basin in 1963 to provide a more direct route from the Port of New Orleans to the Gulf of Mexico. It is a deep, straight canal, which functions as a conduit for saltwater intrusion and hurricane storm surge (Day et al. 2007). While it has no doubt increased the economic activity of the Port of New Orleans, the MRGO has enabled the destruction of thousands of hectares of freshwater wetland forests and contributed to the storm surge that flooded New Orleans during Hurricane Katrina (Day et al. 2007). Furthermore, if degradation continues and all the wetlands to the east of the MRGO and Lake Borgne disappear, a similar surge would be three to six feet higher for St. Bernard Parish and New Orleans (CPRA 2007). This is just one example of how navigational needs have taken precedence over ecosystem needs in the past.

In response, Act 8 was passed by the Louisiana Legislature and signed into law by Governor Blanco in November of 2005. The act created the Coastal Restoration and Protection Authority (CPRA) and charged it with coordinating the efforts of local, state, and federal agencies to achieve long-term and comprehensive coastal area management (CPRA 2007). The agency does this by integrating coastal hazard protection and wetland restoration under one office, positioned directly under the governor. As a result, the CPRA is now the main overarching agency that deals with wetlands in the state. Act 8 also required the CPRA to establish a clear set of priorities for achieving coastal management (CPRA 2007). The CPRA accomplishes this by

creating a “Master Plan” which formulates all of the state’s coastal protection and restoration efforts. Once the plan is created by the CPRA, it is sent to the state legislature to be signed into law and then signed by the governor. The Master Plan moves through this rigorous process because once it becomes law all state agencies are mandated by executive order to be consistent with it (LDNR 2011). Master Plans are planned out to 50 years and updated every five years so that they can adapt to changes and review upcoming projects in greater detail (CPRA 2007). This point means that the Master Plan uses adaptive management, a structure that allows for strategy updates as environmental, political, and economic factors change. Adaptive management encourages reflection and assessment on a consistent basis, as opposed to when it becomes obvious that goals are not being met and costs for restoring damage and revising strategy increase greatly.

Most of the funding for the Master Plan will come from federal grants. The CPRA expects to receive a total of 50 billion dollars over the next 50 years (CPRA January 2012). Of the 50 billion dollars, 12.9 billion dollars will go to nonstructural protections, the program where wetland migration policies would fit. The 2012 Draft Master Plan does not currently include projects for wetland migration.

The first Master Plan was released in 2007 but was more of a scoping document on how future projects would be detailed. The upcoming 2012 Master Plan will be a more thorough document with projects explicitly planned out for the near future. According to the 2012 Master Plan (CPRA January 2012)<sup>5</sup>, the two primary factors driving the development of a project plan are:

1. Flood risk reduction
2. Land building or restoration

The Master Plan also established a set of decision criteria to reflect the diversity of interests amongst coastal residents and business owners. They included:

- Support of cultural heritage
- Distribution of flood risk reduction across socio-economic groups
- Flood protection of historic properties
- Flood protection of strategic assets
- Support of navigation
- Support of oil and gas
- Sustainability
- Use of natural processes
- Operations and maintenance

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<sup>5</sup> See CPRA (2012) at p. 48 for decision drivers and at p. 50 decision criteria.

When evaluating potential projects, these criteria are considered equally as important as the primary drivers. This allows the CPRA to consider how flood risk reduction and restoration will impact the array of interests along the coast (CPRA January 2012). The use of these criteria by the CPRA influenced this project as some of these were included in the analysis later.

## **The Way Forward: a Wetland Migration Policy**

Louisiana has made great strides towards sustainable coastal management with the integrated and adaptive approach of the Master Plan. A troubling fact, though, is that by not addressing the issue of “wetland migration” the policy accepts further untenable declines in wetland area and provides no plan of action for the diversity of stakeholders that rely on wetland services for their livelihoods.

Despite an aggressive restoration strategy fueled by an increased amount of funding, the CPRA does not expect to see a net increase in land until the 2040s under the moderate scenario (CPRA January 2012). This means that there is likely to be at least three more decades of net wetland loss in coastal Louisiana. Furthermore, the spatial variability of land loss in coastal Louisiana suggests that it is also likely that a smaller but gradual loss of wetlands will persist throughout the next 50 years. This is especially the case because overall net increases in land are predicted to be about the same as those that have been recorded in the Atchafalaya basin over the past decade (Couvillion et al. 2011).

The outlook for the less optimistic scenario is even bleaker with no net gain in wetlands projected over the next 50 years (CPRA January 2012). Regardless of how the remaining uncertainties unfold, a robust wetland migration policy is needed to mitigate land loss, reduce the risk to vulnerable communities, and increase the overall resiliency of Louisiana’s working coast. This case study illustrates the potential for mitigation with an effective wetland migration policy. It also suggests that policy design will have a measurable impact on migration success.

## Policy Analysis Framework: Exploratory Approach

We considered two basic frameworks for which to conduct our policy analysis: an exploratory model and a more traditional prescriptive model. The exploratory model provides a framework for heuristic, or experience-based, learning. The model is, therefore, built to guide search and selection, enable critical thinking and learning, and aid in the invention of options (Hendrick 1994). In general, exploratory models treat decision making as a creative and collaborative process (Figure 39).

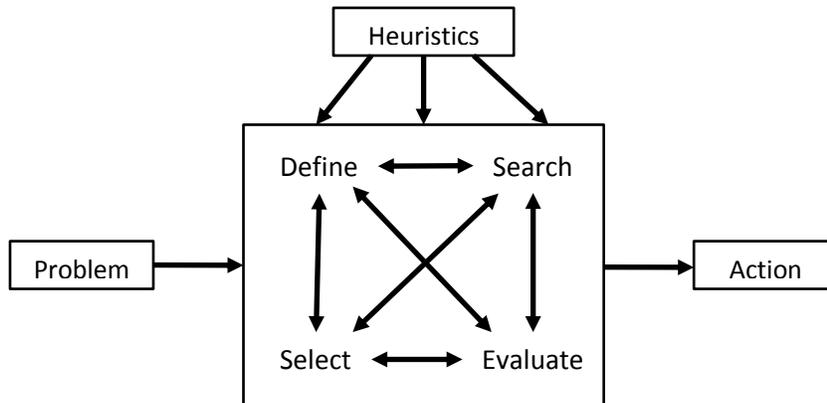


FIGURE 39. AN EXPLORATORY MODEL FOR POLICY MAKING (HENDRICK 1994).

The opposite approach would be to use a prescriptive model (Figure 40), which uses a deterministic process and rational thinking to rank or select alternatives (Hendrick 1994). In general, prescriptive models are built to provide a definitive answer with regards to specific parameters.

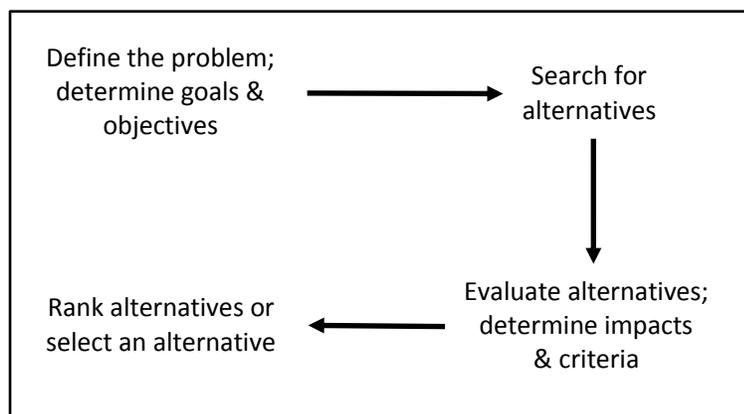


FIGURE 40. A PRESCRIPTIVE MODEL FOR POLICY MAKING (HENDRICK 1994).

The prescriptive approach is the traditional decision-making model and widely used, but it does have drawbacks. Criticisms of the traditional prescriptive approach include: the analysis of problems that are more amenable to a formal deterministic process, a tendency for researchers to only consider concepts that can be quantified, and invalid quantitative measurement of qualitative or abstract concepts (Hendrick 1994). Lastly, and perhaps most importantly for the State of Louisiana and the CPRA, politics and policy making are often complex and conflicting processes that require compromise and consensus building (Hendrick 1994). The deterministic nature of prescriptive models does not accommodate these vital policy making processes.

In contrast, the chief advantage of the exploratory approach is that it gives decision makers and stakeholders a framework to do their own analysis or gain a better understanding of the relevant tradeoffs that underpin and influence the problem solving process (Hendrick 1994, Bardach 2012). Hendrick (1994) notes, "Through exploration, analysis may reveal new aspects of the problem, change goals, identify new areas for research or reveal unexpected alternatives." In addition, Bardach (2012) agrees that "policy analysis is not just an exercise in truth-telling" and that it is instead "a pragmatic and responsible effort to facilitate reasonable discourse about a policy future that is inherently certain."

Using an exploratory approach is also keeping within the broader framework of that has been laid out by the CPRA in the 2012 Master Plan:

The Planning Tool was designed to translate the models' scientific output and show the practical implications of different options. However, the tool did not make decisions. It did not generate simple answers or a sole ranking of projects. Instead, the tool provided information about how groups of project met one or more of our objectives. (p.91)

Given the dynamic biophysical processes found along the Louisiana coast and the layered complexity with economic, social and political interests, we felt that no one alternative would be adequate to facilitate wetland migration, nor would such a prescriptive approach be appropriate to apply coast wide. Consequently, we chose to construct an exploratory model to provide policy makers and stakeholders with a framework to process the pertinent information in an effort to encourage an inclusive, enlightening, and efficient decision-making process.

## Policy Criteria

There is a large body of academic literature dedicated to wetlands, SLR, and policy, but very little focused on wetland migration policy by comparison. For example, a basic Google Scholar search for “wetlands” and “sea-level rise” returns over 52,000 articles and a narrower search for “wetlands” and “sea-level rise” and “policy” returns over 33,000 entries. In contrast, solely searching the term “wetland migration” only results in 236 total articles and searching for “wetland migration” and “policy” narrows the results slightly to 202 entries. Moreover, three-quarters of the latter have been published since the year 2000. It is not surprising that we were unable to locate even one dedicated wetland migration policy to evaluate as part of our analysis. Up to this point, much of the wetland migration research has been focused on modeling the potential for wetland migration on coarse scales and measuring the associated offset to socioeconomic losses from SLR.<sup>6</sup> Therefore, our analysis will investigate policy alternatives that are related to the process of wetland migration, but not specifically tailored to that objective. With this being the case, we have carefully outlined five main criteria with which to assess potential wetland migration policy alternatives. These criteria include: wetland migration, flood risk, equity, adaptability, and political feasibility.

## Wetland Migration

First and foremost, policy options will be assessed on their ability to allow wetland migration. Wetland migration creates new wetlands as water moves inland and therefore mitigates coastal wetland loss. The largest impediment to the movement of water, and therefore wetlands, is coastal armoring. The degree that alternatives prevent property armoring is one factor that will determine the success of the policy to facilitate wetland migration.

Another factor that will determine if wetlands can migrate is the amount of development that occurs in an area. The CPRA had acknowledged that while not all areas will be completely protected, those with high development will be given first priority (CPRA January 2012). These protections will be armoring on a large scale which will prevent water movement inland and the resulting wetland migration that will follow. By minimizing development in an area, protections will be discouraged which will stop an impediment to wetland migration.

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<sup>6</sup> A notable exception has been the work of James Titus of the EPA, who has been publishing on wetland migration and the socioeconomic advantages of a retreat policy for over two decades. For example, see (Titus 1998, 2011).

The questions that we considered for each alternative's wetland migration assessment include:

- Does a policy alternative allow landowners to armor their property?
- Does a policy alternative allow landowners to develop their property?

### Flood Risk

Another key criterion, especially important to the draft Master Plan (CPRA January 2012), is for projects to reduce flooding risk. Flood risk reduction is one of the two primary decision criteria of the Master Plan and one of the primary benefits of each and every wetland migration policy alternative. The 2012 Draft Master Plan assumes that coastal areas will see an annual population increase of 0.67 percent (CPRA January 2012). This increase will bring more people and other assets to the coast that will then be at risk to flooding during natural hazards such as Hurricanes Katrina and Rita. By reducing this increase or even reducing the net assets on the coast, flooding risk will also be reduced. This criterion is very similar to the wetland migration issue of minimizing development to discourage levee use as both seek to reduce assets in an area. Despite this, this criterion is included because it has its own distinct goal separate of wetland migration.

The question that we considered for each alternative's flood risk reduction assessment is:

- What effect will the alternative have on the accumulation of assets in an area?

### Equity

The 2012 Draft Master Plan explicitly addresses the issue of social equity with the decision criterion "Distribution of Risk Across All Socio-Economic Groups". The plan states, "The intent of this criterion was to make sure that the draft plan did not increase flooding risks for low income citizens, and instead, distributed risk reduction across income levels" (CPRA January 2012, p.136).

For the alternatives in this project, we wanted to make sure that all of their effects did not impact lower income groups more than others.

Another equity issue that was of concern was an alternative's effect on property rights. Did a policy directly limit rights, did it offer alternatives, was it voluntary, or does it have no effect? Due to the likelihood of takings, all of the alternatives that were regulatory were only applied to new landowner contracts and all rights for current property owners are grandfathered in. However, this does not take away the effect of reducing a landowner's future rights, which are still being deliberated in court cases.

The questions that we considered for each alternative's equity assessment include:

- Does a policy alternative disproportionately affect lower income groups?
- To what degree does a policy alternative curtail a landowner's property rights?

### Adaptability

Any wetland migration policy that proceeds from our assessments of the available alternatives will need to be nested inside of the larger, comprehensive Master Plan. The intentional coupling of natural and anthropogenic forces means that any action taken in one part of the system will have a cascade of impacts in other parts of the system. Moreover, the adaptive nature of the Master Plan means that project priorities can shift every five years based on any number of political, economic, or scientific reasons (CPRA January 2012). For example, the current range of uncertainties in environmental drivers may be narrowed or resolved in the future. The most notable of these is the 2012 Draft Master Plan's use of 0.27 meter and 0.45 meter 100 year expected GSLR rates, both of which are low compared to what other scientists are predicting (Rahmstorf 2007, Pfeffer et al. 2008, Grinstead et al. 2009, CPRA January 2012). The design of a wetland migration policy will need to account for the ability of the alternative to adapt with the Master Plan in the future.

The question that we considered for each alternative's adaptability assessment is:

- Can the policy alternative be revised or cancelled if need be?

### Political Feasibility

Gauging the political feasibility of a given policy instrument requires a review of several legal and regulatory precedents. The legal precedent behind a policy design must respect property rights and be robust enough to withstand takings claims. To judge this, each alternative was assessed for its use in Louisiana or other states and how it withstood challenges. As well, there was a general consideration of the popular sentiment for an alternative. Each alternative will be included in a Master Plan that must make it out of the CPRA and be passed and signed by the state legislature and governor respectively. There must be enough popular sentiment to push the alternative through this process and not be cut out during any part of it.

The questions that we considered for each alternative's political feasibility assessment include:

- What are the legal and legislative precedent in Louisiana and other states for the alternatives?
- What is the popular sentiment for the alternative?

## Policy Alternatives

This section analyzes six policy alternatives that could be used to facilitate wetland migration. The policy alternatives are split into two groups of similar characteristics: regulatory programs and voluntary options. The main difference between the two is that regulatory programs require compliance by law whereas voluntary options do not and participation is at will. Each alternative's analysis includes an overview of the policy instrument followed by an assessment of the ability of each alternative to satisfy the policy criteria. While more alternatives could have been analyzed, we focused on these six because of their overall effectiveness in satisfying the criteria, especially wetland migration and flood risk.

## Regulatory Programs

### ***Rolling Easements***

For this report, rolling easements will be defined as a regulation that prevents shoreline armoring along all tidally influenced waters and reverts permanently inundated property back to the state. Besides being written into law, this regulation is further codified by being written into all land contracts in the coastal zone. This makes it very similar to the Texas Open Beach Act which also prevents shoreline armoring, but only applies this to beaches, making the rolling easements in this paper even stricter (Texas Natural Resources Code Annotated 61.001-.178). While protections aren't allowed, development is allowed. The point of this is that the landowner can realize the full benefit of the land before it is inundated (USCCSP 2009). On the other hand, the entire risk of land loss is on the owner.

The main example of a regulatory rolling easement in the U.S. is the Texas Open Beaches Act. First created from the state's common law, it was later codified as a state regulation in 1959, amended in 1985, and became part of the state constitution in 2009 (McLaughlin 2011, Texas Natural Resources Code Annotated 61.001-.178). It's most current form prevents armoring along the beach so that water can move inland unimpeded which has the result of allowing the beach to migrate inland as well. This keeps the beach wide and healthy for the enjoyment of all the citizens in the state. The constitutional law is very popular in Texas as it passed with 77 percent of the vote; although it must be noted that this was for a law that would only affect beaches and does not apply to estuaries or rivers like the rolling easements as will be discussed later (McLaughlin 2011). Legal challenges had not been successful until recently as courts found that there was an implied dedication due to the public's long history of use (McLaughlin 2011). Recently, though, the Texas Supreme Court has overturned part of the law saying that when nature erodes the beach on the shore and pushes the beach inland, property owners whose land is not the beach do not lose their property (Severance

vs. Patterson 2011). This obviously will have caused a large stir among rolling easement proponents in the state.

While other states prevent shoreline armoring, they usually don't guarantee that the property line will also move inland. Rhode Island has a regulation that prevents that shoreline armoring and also might push back where new development can occur behind dunes when SLR occurs (CPRA 2011a, Rhode Island Coastal Resources Management Program Rules 210.7(C)(2)&(A)(2)). Their regulation uses a setback for development behind dunes, but the size of the setback is determined by the amount and rate that the beach moves inland (Rhode Island Coastal Resources Management Program Rules 210.7(C)(2)&(A)(2)). While this isn't quite like the rolling easement discussed in this report, it is very limited as it only applies to areas behind dunes and provides an example of preventing protections and pushing development back as SLR occurs.

#### *Wetland Migration*

These rolling easements allow water to migrate inland unimpeded by coastal armoring. As the water moves inland with SLR, the wetlands will also be able to migrate inland as the environment changes. The other factor to consider is development, which is completely allowed in this regulation. Allowing development is good for the landowners who can't protect their land, but high development may spur officials to protect the land with armoring (CPRA January 2012). The opposing force to this high development is that future landowners will be aware that they cannot build protections against SLR. This may be a disincentive for landowners who want their investments to last longer and have protections (Titus 1998).

#### *Flood Risk*

Rolling easements may increase flood risk rather than decrease it, because it prevents coastal armoring in any way. Although, it will make landowners completely aware of the possibility of flooding which may serve to reduce land ownership along the coast, reducing the flood risk (Titus 1998).

#### *Equity*

As a regulation, this policy affects all homeowners equally who choose to have land along the coast. Low income persons will not be disproportionately affected. However, rolling easements take away a landowner's right to armor their land. Even though landowners must agree to this before purchasing their property, this still creates an equity issue such as the one that Texas currently has to deal with (Severance v. Patterson 2011).

#### *Adaptability*

As a regulation, rolling easements are not permanent and can be changed or cancelled at any time.

### *Political Feasibility*

Rolling easements have been used in other states such as Texas and Rhode Island, though not in the same way or for the same purpose as within this report. While this gives the regulation some precedent, applying the lessons from these states to Louisiana may be limited given its different history and legal background. While the regulatory precedent from other states is not strong, rolling easements would fit in with the 2012 Draft Master Plan which recognized land use planning tools as “an essential ingredient in reducing flood risk” (CPRA January 2012). Applying land use planning to wetland migration would not be a big step, and many Louisiana parishes already employ land use plans (Lafourche Parish 1982).

The one precedent that most rolling easements share is that they are especially unpopular to most coastal property owners because they do not want water to inundate their land (Titus 2011). This may be why new rolling easement regulations have never occurred outside of Texas, and are usually only allowed to apply to certain areas. Applying the strict rolling easement within this study to the whole coastal zone is likely to be very unpopular.

### ***Density Restrictions***

Density restrictions are a type of zoning regulation that limit the amount of development in an area. This policy has been used as a retreat and hazard mitigation policy in several states because it reduces the overall cost and amount of development that can be damaged (USCCSP 2009). First, by keeping some land undeveloped, this land will be cheaper to acquire in the future and will have few if any assets that can be damaged (USCCSP 2009). Second, by having less development overall, the eventual cost of moving or abandoning those structures will also be reduced (USCCSP 2009). The other side to the cost issue is that by reducing development, the greatest economic benefit of the land is not realized, lowering the lands total economic output.

Maryland is one state that uses density restrictions by limiting development to one home per acre within 305 meters of the shore in most coastal areas (USCCSP 2009). This rule has been in place since the 1980s and was originally enacted to reduce runoff pollution. As the threat of SLR has increased, though, the state is now using it as part of its plan to prepare for possible SLR near the coast (Maryland House Bill 973-2008).

Likewise, New Jersey has a state plan where development is discouraged in rural planning areas and on land with valuable ecosystems, which include wetlands (New Jersey State Planning Commission 2001).

### *Wetland Migration*

Density restrictions have no effect on preventing armoring. The only effect they may have is to lower the incentive to armor as there will be less developed land to protect. Density restrictions directly minimize

development in an area. While this may directly assist wetland migration by reducing the amount of developed land that will either impede migration or covers land that would then become wetlands, it may be most important to Louisiana in that it will reduce the likelihood of state protection of the land (CPRA January 2012, USCCSP 2009). While the scope of this paper mostly answers whether or not development is minimized, the effectiveness of density restrictions will depend on how long until migration or inundation is likely to occur. If these are imminent then density restrictions will be less effective because it is likely too late for these to affect much change as current development will be grandfathered in.

#### *Flood Risk*

By reducing the amount of land per area that can be developed, flood risk will also be minimized.

#### *Equity*

When the number of residents is restricted in an area, this forces out lower income individuals as properties rise in price due to scarcity (Pollakowski and Wachter 1990). The caveat to this is that if the land is not seen as desirable, it may have little to no impact since density would remain low anyways. This could not be assessed for Louisiana so the caveat is not included in our analysis. We can confidently say, though, that these regulations take away the landowner's right to develop their property. Like rolling easements, new landowners will be aware of the restrictions before purchase, but it may create issues in the future.

#### *Adaptability*

As a regulation, density restrictions are not permanent and can be changed or cancelled at any time.

#### *Political Feasibility.*

Density Restrictions have been used in other states to achieve most of the same goals as they would achieve in Louisiana. Besides their use in Maryland and New Jersey for retreat policy, they are also a common regulation across the U.S. for other purposes and their use would not be a surprise. Besides their use in other states, density restrictions would fit in with the 2012 Draft Master Plan which recognized land use planning tools as "an essential ingredient in reducing flood risk" (CPRA January 2012). Applying land use planning to wetland migration would not be a big step and many Louisiana parishes already employ land use plans (Lafourche Parish 1982).

There are counteracting forces that may impact the popularity of density restrictions. On the one hand, they may displace lower income people and make it harder for Louisiana to have a working coast where they are implemented. On the other, property prices may rise and their use is common enough to not raise eyebrows.

### ***Transferable Development Rights***

A Transferable Development Rights (TDR) program is a more complex regulatory tool that would limit development in a vulnerable area, referred to as a “sending” area, and direct it to a protected or upland area, referred to as the “receiving” area (Titus 2011). To compensate for development restrictions, landowners are given development rights in excess of zoning limits in the receiving area (Titus 2011). The specific design of a TDR program can vary in its selection of restrictions and awards. The severity of restrictions ranges from a combination of density zoning, rolling easements, and no rebuild after destruction of property by a storm, to the sole limitation of density zoning. Typically, the landowner will be awarded an amount of supplementary development units in the receiving area that is equal to the amount prevented on the property in the sending area (Titus 2011). In addition, some TDR designs award bonus development units in the receiving area to landowners that relinquish property rights in the sending area to either the state or a land trust organization (Monroe County Growth Management Division 2009). Ideally, there will be an equal amount of supply and demand between a given parish’s sending and receiving areas, but ultimately this will be dependent on the prevailing geography and regional flood protection infrastructure.

TDRs have been used for several decades and for various purposes. Most of these purposes have been to protect valuable uses of land such as agriculture or sensitive ecosystems, both of which face being bought for higher development. New Jersey created the Pinelands Protection Act in 1979 which gave credits to a landowner depending on where they developed (Juergensmeyer et al. 1998). These could then be spent or sold and were used for further development in receiving areas. Montgomery County in Maryland also created a TDR program to deal with losing agricultural land when the county began to rapidly develop (Juergensmeyer et al. 1998). Montgomery County’s TDR program protects agricultural land while allowing dense development along roads.

TDRs have faced several legal battles in the late 1990s. These cases dealt with a variety of issues but usually had to do with one of the following: programs run by agencies that did not have the regulatory authority, the purpose or value of the program was not properly explained, or the program did not include land uses for the sending areas meaning that the land was deprived all usefulness making the program a taking (Juergensmeyer et al. 1998). These legal battles served to improve the nature of TDRs and fixed these problems. Successful use of TDRs may be seen in cities like Washington D.C., which has used them to fuel a responsible development boom recently in the city (Fruehling 2007).

### ***Wetland Migration***

The effect of TDRs on wetland migration depends on the design of the program. Less restrictive designs allow property armoring, but density limits prevent the buildup of assets and value, in turn making

engineered protection less likely. Moreover, development opportunities in the receiving area are more likely to attract investment from a landowner. TDRs reduce development in certain areas by making them the sending areas. While development as a whole may change either way, TDRs are a smart regulation that uses carrots and sticks to push development away from areas where officials want less.

### *Flood Risk*

If sending areas are areas of coastal hazards, reducing development there will also reduce the assets at risk of future destruction.

### *Equity*

In terms of social equity, TDR programs will suffer the same downfalls as density restrictions. By restricting development, the supply of housing will remain mostly static, which will adversely affect low-income individuals and renters (Bures and Kanapaux 2011). TDR programs were developed for the explicit purpose of fairly compensating landowners for their ostensible loss of development rights. Under a TDR program, an individual is restricted from developing land in the sending area but granted excess development privileges in the receiving area. A case can be made that the landowner may face unfair restrictions if property armoring and rebuilding is not allowed in the sending area. On the other end of the spectrum, an equally valid argument can be made that a landowner may be given gratuitous benefits if the density restriction allows for some development and armoring is allowed along with the supplementary development rights that are awarded in the receiving area. However, the flexibility of a TDR program should be counted as a strength because careful design will result in reasonable equity for landowners.

### *Adaptability*

As a regulation, TDRs are not permanent and can be changed or cancelled at any time.

### *Political Feasibility*

Many Louisiana parishes employ land use plans that include density zones for the purpose of directing development to desired areas.<sup>7</sup> Thus, the basic concept of a TDR program should already be familiar to local officials. Moreover, St. Tammany is already investigating using TDRs in their own parish to conserve sensitive habitats (Hamauei 2011). The willingness of the State to provide grants in support of local land use planning should alleviate political tension and encourage participation by parishes. The CPRA recognizes land use planning tools like TDRs as “an essential ingredient in reducing flood risk” (CPRA January 2012). Moreover, in keeping with the Master Plan, an appropriately designed TDR scheme will be able to “direct development

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<sup>7</sup> For example, see the code of ordinances for St. Mary Parish at <<http://library1.municode.com/default-test/home.htm?infobase=19950>>.

away from high hazard areas and help preserve the natural functions of floodplains and other critical areas” (CPRA January 2012). Lastly, TDR programs are not new or radical in nature. TDRs have been used for several decades and their ongoing success in areas like Monroe County in the Florida Keys and Washington D.C. show they are a tested regulation that will continue to be used (Fruehling 2007, Monroe County Growth Management Division 2009).

Like density restrictions, there are counteracting forces that may impact TDRs popularity. Depending on the specific design and distance between sending and receiving areas, they may displace lower income people and make it harder for Louisiana to have a working coast where they are implemented. On the other, property prices may rise and their use is common enough to not raise eyebrows.

## Voluntary Options

### **Conservation Easements**

Instead of buying the land directly, conservation easements buy the right to develop the land from the landowner (USCCSP 2009). This keeps the land undeveloped so that the sea or wetlands can migrate onto the land unimpeded. These can also be used to create buffer zones around property, rivers, or current wetlands that the water can move onto over time (USCCSP 2009). While landowners can still use the land, the uses that are allowed are restricted to those that don’t involve structures or hard surfaces. Conservation organizations or the government can own conservation easements.

Conservation easements have been used for several years in Maryland where conservation organizations have bought development rights from property owners along coastal bays (MALPF 2003). To maintain agricultural use of land, conservation easements have been used around Virginia Beach since 1979 (City Council of Virginia Beach 2003). The Nature Conservancy (TNC) has been using conservation easements to protect land since 1961 when they bought their first conservation easement at the Gallup Salt Marsh in Connecticut (Conservation Easements at TNC 2011). Today, TNC has conservation easements on more than two million acres of land (Conservation Easements at TNC 2011).

### *Wetland Migration*

This rule allows water to migrate inland unimpeded by coastal armoring (USCCSP 2009). Due to this, conservation easements allow almost the total migration of wetlands on land with these easements. Impediments will still occur from already developed land that is left in the way, but if this is sparse it will not seriously impact migration. Additionally, these easements prevent development, which will discourage levees.

### *Flood Risk*

As conservation easements restrict development, the assets at risk to flooding will also be restricted.

### *Equity*

Because this policy is optional, it only affects the people who choose to partake in it. Due to this, it will not disproportionately affect low-income individuals. While this alternative takes away a landowners right to develop their land, whether or not they sell this right is entirely optional. Being optional, it does not take away the right to develop without permission or compensation.

### *Adaptability*

Once a landowner has sold their right to develop their land, that right belongs to the entity that bought it. The only way to get the right back is to buy it, though this transaction must be agreeable to the entity that bought the right.

### *Political Feasibility*

States like Maryland and conservation organizations like TNC have been using conservation easements successfully to protect land for decades. While the land can still be used for some beneficial purposes, they halt any impacts that development might have, which for Louisiana is stopping armoring and the reducing the likelihood that levees would be used. Add to this the fact that Louisiana has shown that they are interested in directly acquiring land to meet their goals in the 2012 Draft Master Plan and the step to acquiring just development rights seems very feasible. Also, since this policy is optional most landowners will not feel imposed upon by a new restriction of rule.

### ***Defeasible Estates***

In common law, property ownership continues in perpetuity. A defeasible estate is a contract between two entities, one of which currently owns the land, and a second, who will gain ownership when a specific event occurs, termed a “reverter” (Titus 2011). The second entity’s future interest in the land can be sold or donated to any other entity, such as a land trust organization or the government (Titus 2011).

For wetland migration, two specific events, or reverters, are appropriate. The most straightforward event is a RSLR of a predetermined amount. In this case, the owner sells the future interest of the land to a buyer, but retains ownership until the agreed upon amount of RSLR occurs. Since the primary goal of a defeasible estate in Louisiana would be to facilitate wetland migration, RSLR should be set to trigger a reverter at about the same time that the new owner would otherwise look to defend the property against the rising sea (Titus 2011). The exact amount of RSLR chosen for the reverter will depend on the elevation of the parcel being sold (Titus 2011).

Another event closely aligned with nonstructural projects in the 2012 Draft Master Plan is a predicted 100-year flood depth greater than a predetermined amount. As proposed, the current nonstructural program uses a flood depth of greater than 18 feet to qualify properties for voluntary acquisition (CPRA January 2012). This is also a logical threshold to use as a reverter in a defeasible estate. A clear way to describe such an arrangement is that land is owned by a buyer “for as long as it takes the predicted 100-year flood depth to reach a base flood elevation of 18 feet as found on the Federal Emergency Management Agency’s (FEMA) Digital Flood Insurance Rate Maps” (CPRA January 2012 p.65). The elevation of a given parcel is taken into account with FEMA’s flood insurance maps.

### *Wetland Migration*

The prospect of wetland migration is good for both RSLR and flood depth reverters. A carefully chosen RSLR amount, one that triggers a reverter before the property is affected, would negate the need for the property to be armored since the first landowner would lose their interest in the land before protection was ever needed. The flood depth reverter ostensibly functions as protection, because it is specifically designed to avoid a certain level of flood risk. Thus, it is safe to assume that protection is unlikely as long as the buyer of the defeasible estate is comfortable with the amount of risk inherent to the flood depth reverter.

On the other hand, given the adaptive nature of the Master Plan, it is possible that CPRA protection priorities would shift in the face of growing density and, subsequently, result in the construction of a regional levee. The additional flood protection provided by the levee would lower the modeled 100-year flood depth and effectively postpone a flood depth reverter. The RSLR reverter would remain unchanged as the proximity to open water and level of flood protection does not factor into observed RSLR. Since time to reversion may be extended with a flood depth reverter then additional development is also possible. Nevertheless, the flood depth reverter would primarily be responsible for moderating growth, not stimulating it.

### *Flood Risk*

On one side, defeasible estates may increase flood risk as their primary goal is to provide a mechanism for development. However, the possibility of a reverter may lead the market to demand housing that is smaller and cost-conscious. This is because buyers will be less willing to make substantial investments for non-permanent, contingent ownership. Future flood risk increases can be offset in this way.

This outcome is further influenced by what type of reverter is used. RSLR is a change that, ultimately, cannot be avoided and whose rate of change can be reliably forecasted in the near term (i.e. 10 years into the future). Flood depth is more dynamic and will be greatly influenced by not just SLR but a range of climate change variables as well as the success or failure of restoration efforts as wetlands attenuate storm surge. The success of a marsh creation project or the announcement of a new river diversion may embolden

developers or defeasible estate owners to add more value to a property. Therefore, defeasible estates with a flood depth reverter can be considered not as good at reducing flood risk as those with a RSLR reverter.

### *Equity*

Defeasible estates provide good equity for low-income individuals, renters and fair mechanism for responsible developers. For one thing, the alternative is completely voluntary so landowners will know what they are agreeing to beforehand. Also, the possibility of a reverter keeps housing demand low that, in turn, keeps prices stable. This outcome favors low-income individuals and renters that often have trouble keeping up with a rising cost of living often manifests in coastal communities.

Setting up a defeasible estate is a voluntary action taken by all parties—the developer, the buyer, and the third party purchaser of the future interest. Thus, it cannot be considered as a limitation on property rights in any way. For responsible developers that understand the urgency of the wetland loss crisis, defeasible estate planning is a way to exercise value in their property that they would otherwise be reluctant to pursue (Titus 2011).

### *Adaptability*

Once a landowner has sold the future interest in the land, that interest belongs to the entity that bought it. The only way to get the right back is to buy it; though this transaction must be agreeable to the entity that bought the right. For defeasible estates, adaptability also depends on the type of reverter used to arrange the future interest agreement. Since RSLR is not impacted by additional restoration or protection projects, properties with a RSLR reverter will not be adaptable to changes in the Master Plan. However, flood depth is influenced by protection projects so properties with flood depth reverters are somewhat adaptable. For example, if the CPRA installs a levee that a property with a flood depth reverter receives extra protection from, then time to reversion is extended and additional development opportunities can be realized.

### *Political Feasibility*

One problem that could occur is that some states put limits on the length of time that reverters or forfeiture provisions apply (Rupert 2012). Other states took away the ability of landowners to even create defeasible estates (Titus 2011). On the other hand, many of these states that put restrictions on defeasible estates, do not apply these restrictions when the owner of the future interest is the state government or a conservation organization (Titus 2011). Even more, the federal government through the Supremacy Clause is not beholden to the state laws and their restrictions on defeasible estate use. If Louisiana has any restrictions on defeasible estates, then the state would have to rewrite its rules.

Despite some states putting restrictions on their use, courts have upheld the use of reverters (Titus 2011).

Louisiana has also shown that they are interested in directly acquiring land to meet their goals in the Master

Plan (CPRA January 2012). So if Louisiana can use defeasible estates, the courts will back their use and Louisiana has shown that it has an interest in using acquisition of property or property rights as a tool in its efforts to prepare for SLR.

Besides being voluntary, the possibility of a reverter satisfies several different, and sometimes opposing, points of view at the same time. Climate change skeptics don't believe SLR will rise at an accelerated rate over the next century, and therefore are prime candidates for the purchase of a defeasible estate. To this group, a discount in price based on the possibility of sea level rising a substantial amount in their lifetime is well worth the risk. Most conservation non-governmental organizations (NGOs) and land trusts believe in climate change and consider treatment of the issue a core objective, which make them prime purchasers of future interests. This group views the possibility of a reverter based on RSLR as a cost effective investment. Original landowners turned developers will also be pleased by a defeasible estate arrangement no matter their motivation, be it as a cautious optimist or a reluctant pessimist.

### ***Voluntary Acquisition***

Voluntary acquisitions purchase property from willing landowners and remove the development on the land (USCCSP 2009). These can be advantageous for landowners if protections would be expensive and if the protections would eventually fail in the long-term. With the buyout money, landowners can vacate their vulnerable land and can relocate. Buyout programs transfer the risk of SLR from the landowner to the public since they pay the buyout (USCCSP 2009) and are best used as part of a larger planned retreat so that landowners don't buy vulnerable properties and then expect to be bailed out.

This policy alternative is unique in that it is the only one that is currently in the 2012 Draft Master Plan (CPRA January 2012). In the 2012 Draft Master Plan, it will be used where structures would need to be elevated more than 18 feet to be above projected flood depths. Voluntary acquisitions have also been used in many other instances. They are popular in states because they don't incur any possible takings because they provide full compensation to landowners and are optional. Places like Virginia Beach, Virginia and Barnegat Light, New Jersey have used them to buy large amount of the land near the coast (USCCSP 2009).

### ***Wetland Migration***

Voluntary acquisitions reduce the number of landowners, thus reducing the amount of coastal protections that may occur (USCCSP 2009). As well, development on the land is also removed so that water movement and wetland migration are completely unimpeded. By acquiring land and removing development from it, this alternative will minimize the development that might encourage levee use.

### *Flood Risk*

As this policy reduces the amount of assets in possible flood prone areas, it will reduce flood risk. How many buyouts occur will determine the level of flood risk that is reduced.

### *Equity*

Since this policy is optional, it only affects the people who choose to partake in it. Due to this, it will not disproportionately affect low-income individuals. While this alternative takes away a landowners land, whether or not they sell this right is entirely optional. Being optional, it does not take away the right to develop without permission or compensation.

### *Adaptability*

Once a landowner has sold their land, it belongs to the entity that bought it. The only way to get the land back is to buy it; although, this transaction must be agreeable to the entity that bought the right.

### *Political Feasibility*

This alternative has the strongest precedent in that it is currently included in the 2012 Draft Master Plan and has been used in other states successfully. While what properties are acquired in Louisiana may change if it is applied to wetland migration, this is a minor shift in its use. Because this policy is optional most landowners will not feel imposed upon by a new restriction of rule. Also, as it is already included in the 2012 Draft Master Plan and major outcries have not come forth, it is reasonable to think it is popular enough to pass in the next Master Plan.

## Policy Matrix

The results of the policy alternatives analysis are summarized in the proceeding matrices.

TABLE 23. POLICY MATRIX: REGULATORY PROGRAMS

<b>Criteria</b>	<i>Sub-Criteria</i>	<i>Rolling Easements</i>	<i>Density Restrictions</i>	<i>Transferable Development Rights</i>
<b>Wetland Migration</b>	<i>Prevent property armor</i>	Good - Prevents armoring	Poor - Allows armoring	Neutral - Allows armoring, but incentives make the receiving area more likely to attract investment
	<i>Minimize Development</i>	Neutral - Development allowed but less likely	Good - Minimizes development	Good - Minimizes development
<b>Flood Risk</b>	<i>Minimize Assets at Risk</i>	Neutral - Development allowed but is less likely	Good - Minimizes development	Good - Minimizes development
<b>Equity</b>	<i>Social Equity</i>	Good - Effects landowners equally	Poor - Low income displacement possible	Neutral - Displacement possible in sending area, but benefits possible in receiving area
	<i>Protection of Property Rights</i>	Poor - Restricts right to protect property	Poor - Limits right to develop	Neutral - Restricts right to develop in sending area but compensates in receiving area
<b>Adaptability</b>	<i>Flexibility of Alternative</i>	Good - Rule can be repealed or revised	Good - Rule can be repealed or revised	Good - Rule can be repealed or revised
<b>Political feasibility</b>	<i>Regulatory Precedent</i>	Neutral - Precedent from other states, but in various contexts	Good - Used effectively in other states; Louisiana supports land use planning	Good - Used effectively in other states; proposed in St. Tammany Parish; LA supports land use planning
	<i>Popular Sentiment</i>	Poor - Unpopular with landowners	Neutral - Benefits higher income individuals; hurts low-income individuals	Neutral - Benefits higher income individuals; hurts low-income individuals

TABLE 24. POLICY MATRIX ANALYSIS: VOLUNTARY OPTIONS

<b>Criteria</b>	<i>Sub-Criteria</i>	<i>Conservation Easements</i>	<i>Defeasible Estates</i>	<i>Voluntary Acquisition</i>
<b>Wetland Migration</b>	<i>Prevent property armor</i>	Good - Prevents armoring	Neutral - Allows armoring but likelihood depends on time to reversion	Good - Prevents or removes armoring on acquired land
	<i>Minimize Development</i>	Good - Restricts development	Neutral - Allows development; likelihood depends on time to reversion and type of reverter	Good - Removes development
<b>Flood Risk</b>	<i>Minimize Assets at Risk</i>	Good - Restricts development	Neutral - Allows development; likelihood depends on time to reversion and type of reverter	Good - Removes development
<b>Equity</b>	<i>Social Equity</i>	Good - Voluntary, no unwanted impact	Good - Voluntary, no unwanted impact	Good - Voluntary, no unwanted impact
	<i>Protection of Property Rights</i>	Good - Voluntary, no unwanted impact	Good - Voluntary, no unwanted impact	Good - Voluntary, no unwanted impact
<b>Adaptability</b>	<i>Flexibility of Alternative</i>	Poor - Bound by legal contract	Neutral - Bound by legal contract, but reverter may be flexible	Poor - Transfer of ownership to state
<b>Political feasibility</b>	<i>Regulatory Precedent</i>	Good - Precedent as conservation tool	Good - Historical precedent in other contexts; future interest by reversion upheld by courts	Good - Precedent set in LA via Draft Master Plan; currently used in other states
	<i>Popular Sentiment</i>	Good - Voluntary	Good - satisfies diverse and opposing views on SLR	Good - Voluntary; currently part of 2012 Master Plan

### Stylized Policy Matrix

To aid in the discussion of the policy analysis results, the matrices have been colored to represent the individual outcome of each alternative analyzed with respect to the criteria and sub-criteria. Intuitively, the green boxes represent good results, while the red boxes represent poor results. The gray boxes represent “gray areas,” meaning results depend on more nuanced details uncovered by the alternatives analysis and therefore cannot be explicitly labeled as bad or good.

TABLE 25. STYLIZED POLICY MATRIX: REGULATORY PROGRAMS

<b>Criteria</b>	<b>Sub-Criteria</b>	<i>Rolling Easements</i>	<i>Density Restrictions</i>	<i>Transferable Development Rights</i>
<b>Wetland Migration</b>	<i>Prevent property armor</i>	Green	Red	Gray
	<i>Minimize Development</i>	Gray	Green	Green
<b>Flood Risk</b>	<i>Minimize Assets at Risk</i>	Gray	Green	Green
<b>Equity</b>	<i>Social Equity</i>	Green	Red	Gray
	<i>Protection of Property Rights</i>	Red	Red	Gray
<b>Adaptability</b>	<i>Flexibility of Alternative</i>	Green	Green	Green
<b>Political feasibility</b>	<i>Regulatory Precedent</i>	Gray	Green	Green
	<i>Popular Sentiment</i>	Red	Gray	Gray

TABLE 26. STYLIZED POLICY MATRIX: VOLUNTARY OPTIONS

<b>Criteria</b>	<b>Sub-Criteria</b>	<i>Conservation Easements</i>	<i>Defeasible Estates</i>	<i>Voluntary Acquisition</i>
<b>Wetland Migration</b>	<i>Prevent property armor</i>			
	<i>Minimize Development</i>			
<b>Flood Risk</b>	<i>Minimize Assets at Risk</i>			
<b>Equity</b>	<i>Social Equity</i>			
	<i>Protection of Property Rights</i>			
<b>Adaptability</b>	<i>Flexibility of Alternative</i>			
<b>Political feasibility</b>	<i>Regulatory Precedent</i>			
	<i>Popular Sentiment</i>			

### ***Regulatory Programs vs. Voluntary Options***

The stylized matrices reveal clear differences between the results of regulatory programs and voluntary options. In particular, there appears to be less favorable outcomes in the regulatory programs matrix as indicated by the comparative abundance of green boxes in the voluntary programs matrix. Since voluntary options do not impose rules and restrictions on landowners against their will, the equity and political feasibility criteria received uniformly positive outcomes. Therefore, this result is not surprising, but in regards to facilitating wetland migration it is a bit misleading. We can only expect a certain level of participation in voluntary options. The CPRA expects only 10 percent of eligible landowners to participate in voluntary acquisition, translating to only 3 percent of the total nonstructural projects being planned (CPRA 2012 *Appendix G-2*). On the other hand, while the regulatory programs may appear to be more challenging to implement and potentially less effective than voluntary options, they will have a much larger net impact as mandates that require compliance by law. This makes regulatory programs integral to any mix of policy alternatives.

### **Applying the Policy Matrix: Potential for Wetland Migration**

As an effective way to further discuss the policy alternatives analysis, we used the regulatory programs matrix in conjunction with key wetland migration findings from the GIS analysis. The following such discussion provides a glimpse into how stakeholders and policy makers might use the matrices as tools for investigating alternatives and implementing the most appropriate and efficient mix of policy alternatives for a given circumstance.

A reoccurring theme in our findings is how the unique geophysical conditions of each parish influence the biophysical processes of wetlands. The SLAMM results relating to wetland migration are no different. For the purpose of estimating potential for wetland migration, we want to focus on areas where wetlands would be naturally created from dry land as opposed to shifts in wetland vegetation types. In the context of this analysis, we have defined wetland gain, or wetland migration, as the conversion of dry undeveloped land to a wetland of any type from 2007 to 2100. We found a range of total wetland migration across the case study parishes with Lafourche gaining only 20 square miles, Vermilion gaining the most at 76 square miles and St. Mary falling in between as usual, but much closer to Lafourche with 28 square miles of wetlands gained (Table 27).

TABLE 27. THE PERCENT OF WETLAND LOSS OFFSET BY WETLAND GAIN (MIGRATION). (VALUES REPRESENT A 1.5 GSLR BY 2100 WITH LOW SUBSIDENCE AND NO DIKE PROTECTION.)

Parish	Wetland Gain (sq mi)	Wetland Loss (sq mi)	% Loss Offset by Gain
Vermilion	76	165	46%
St. Mary	28	106	26%
Lafourche	20	497	4%

Another reoccurring theme also seen in this subset of SLAMM data is a continued net loss of wetlands by 2100 in all three case study parishes. Driven by high rates of subsidence, we expect Lafourche Parish to experience the largest amount of total wetland loss at 497 square miles. In this instance, St. Mary Parish represents the other extreme at 106 square miles of wetland loss. Lastly, we expect Vermilion Parish to see slightly more wetland loss than St. Mary Parish at 165 square miles. It is the magnitude of total wetland loss in relation to wetland gain that will have important implications for the use of the policy matrix as a wetland migration decision support.

The percent of wetland loss offset by wetland gain indicates how much of an impact wetland migration will have in a given parish and helps to control for differences in total spatial extent. In Lafourche Parish, we expect wetland gain to offset only 4 percent of the nearly 500 square miles of total loss by 2100. Wetland gain in Vermilion Parish is projected to provide the greatest offset to wetland loss at 46 percent. St. Mary Parish returns to its more familiar position of being in between the two with wetland gain offsetting 26 percent of total wetland loss by 2100. These findings suggest that wetland migration can indeed make substantial offsets to wetland loss in Vermilion Parish. It is also clear that, in Lafourche Parish, there is little potential for wetland migration to buffer against wetland loss.

We can now use these findings in consultation with our stylized policy matrix to investigate which regulatory program alternatives would be appropriate given each extreme (Table 25). In Vermilion Parish, potential for wetland migration is high so we would look to the wetland migration criteria first to see which alternatives contribute to that goal. Since our scenario includes no dike protection we can further concentrate on the “prevent property armor” sub-criteria. Of the three regulatory programs, rolling easements is the only one to receive an undoubtedly favorable (green) outcome because it prevents property armor. Pursuing this alternative would give Vermilion Parish the best opportunity to facilitate the high potential for wetland migration to offset future wetland losses. Looking down the column for rolling easements reveals less favorable outcomes (red) for equity and political feasibility indicating that some policy makers may consider this alternative to be impractical from an implementation standpoint. A good second choice for Vermilion

Parish is TDRs. This program receives a neutral rating (gray) for its ability to prevent property armor because it decreases the likelihood that property owners will armor their vulnerable property by providing an incentive to invest in other, less vulnerable areas. Most important in this scenario, TDRs have more favorable outcomes in the equity and political feasibility criteria making their implementation more practical.

In Lafourche Parish, there is virtually no potential for wetland migration to offset wetland loss. Therefore, we can completely discount the wetland migration criterion and focus on the flood risk criterion instead. This time both density restrictions and TDRs meet the criteria and provide favorable outcomes because they limit development in areas of concern. However, limiting development has drawbacks as reflected by the poor results for density restrictions in the equity criteria. Given that the state expects a 0.67 percent annual rate of growth, restricting development will gradually decrease housing supply and, in turn, increase housing costs for low-income individuals and renters. In addition, limiting development without compensation curtails property rights. Therefore, once again, TDRs are a more practical alternative due to their ability to compensate property owners for density restrictions and their ability to alleviate housing supply pressures by allowing development in less vulnerable areas to account for the annual growth rate.

## **Mitigating Induced Risk: Wetland Migration Policy Behind Flood Protection**

There is one important difference between the potential wetland migration scenarios discussed above and the current setting in coastal Louisiana. Many areas, including Vermilion Parish, are currently protected by levees and several more flood protection projects are part of the 2012 Master Plan and expected to be completed over the next 50 years. This does not prevent a wetland migration policy, or more specifically, our policy maker's decision support tool from being applicable. The 2012 Master Plan uses flood risk reduction as one of its primary criteria and we recognized early in the development of our wetland policy framework that all of our alternatives not only worked towards preventing impediments to wetland migration, but they also functioned to effectively minimize flood risk too. Therefore, wetland migration alternatives can be strategically deployed in many areas to mitigate "Induced Risk," one of the main reservations that the CPRA has about providing high levels of flood protection infrastructure. Specifically, the 2012 Master Plan states:

We do not want construction of new hurricane protection systems to encourage unwise development in high risk areas, as has occurred in the past. Such development increases overall levels of risk and diminishes the effectiveness of the protection structures themselves. This phenomenon is called 'Induced Risk,' and it runs counter to the master plan's objectives of sustaining wetland ecosystems and reducing the flood risks borne by coastal communities. (p. 161)

Consider the same scenario for Vermilion Parish as above, but with dike protection this time. In this example, levees act as a barrier to wetland migration and translate to low potential for wetland migration to offset total wetland loss by 2100. Once again, we would look to focus on the flood risk criterion. It's important to realize that in most cases wetland migration benefits will still be accruing at the same time. In this case, a logical choice for a policy maker would be to implement a TDR policy to send development away from a levee footprint. Another option would be for parish governments to encourage land trusts to purchase conservation easements by cutting legal red tape, expediting easement applications, or providing tax incentives. It may take a century or more to capture the potential conservation value of properties behind flood protection structures by way of their destruction or removal, but land trusts are non-profit organizations with long-term visions making such a strategy feasible with the right incentives.

Yet this begs the question: why would such expensive flood protection infrastructure ever be removed? Levees may be abandoned and removed in the future for several reasons. Accelerated RSLR may result in skyrocketing maintenance costs or render protection obsolete altogether. After all, the Master Plan considers a less optimistic scenario, but it does not include the upper bounds of GSLR estimates. As our review of current SLR literature previously noted, recent indicators of glacial melting suggest we are more likely to experience the upper bounds of previous estimates. Moreover, during the public review period for the 2012 Draft Master Plan, the residents of Lake Charles, LA have voiced their desire to forgo planned levee protection (Wold 2012). This makes public opposition to levees a reason for levee removal in the future as well. These scenarios validate the use of wetland migration policy alternatives behind structural protections for their mitigation of induced risk in the near term as well as their wetland migration benefit in the long term.

## Policy Analysis Conclusion

Results from the policy analysis indicate that voluntary options hold many advantages over regulatory programs, most notably with the equity and political feasibility criteria. Yet, the at-will nature of voluntary options also means that low participation levels will prevent these alternatives from facilitating adequate wetland migration. In contrast, regulatory programs require compliance by law making them more challenging to implement but more effective at facilitating wetland migration. Thus, regulatory programs are a necessary component of any wetland migration policy.

The exploratory framework of our policy model proved to be applicable in scenarios with and without flood protection, as well as in adaptive circumstances such as recent revisions to flood management strategies in Lake Charles, LA. Applying the policy model in scenarios where dike and levee protection is removed reveals

that rolling easements would only be appropriate in Vermillion or St. Mary parish where potential for wetland migration is high. In Lafourche parish, where potential for wetland migration is low, an emphasis on minimizing flood risk suggests that transferable development rights would be the best alternative to pursue. Applying the policy model in areas where dikes and levees are present also favors transferable development rights as the optimal policy alternative. Moreover, this final demonstration suggests that a wetland migration policy can serve to address the CPRA priority of minimizing “induced risk,” while also adapting to changes in flood protection planning.

## Recommendations for Further Research

Efforts to model RSLR and wetland migration across Louisiana's coast should be continued throughout the future. As models typically fall short of representing the full spectrum of a process, future efforts should adapt with the availability of finer resolution data, improved methodology, or newly acquired knowledge regarding the process of RSLR and wetland migration.

The policy analysis could benefit from further research to fine-tune the equity and political feasibility criteria at local scales. TDR programs show much promise in balancing wetland migration and flood risk priorities with property rights, but many uncertainties exist in the specific design of the program. Effective designs will be able to direct development away from vulnerable areas without sending investment and tax revenue out of a parish. However, the availability of dry, undeveloped land in less vulnerable areas may be limited within a given jurisdiction. Parish-specific models that integrate geospatial data with economic models are needed to test the viability of TDR programs where they are considered for implementation. If parish boundaries prove to be a constraint on TDR programs then the CPRA will need to take on a coast wide supervisory role and provide support to parishes with more sending areas than receiving areas.

The Lake Charles example illustrates the need to perform community-based interviews with stakeholders to gain a more precise understanding of popular sentiment for wetland migration. Lake Charles is probably not the only community with opinions that run counter to traditional thinking. Interviews should be conducted with citizens, business interests, and local officials to provide more accurate and fine-grained assessments of political feasibility. The framework of the policy model with this type of exploration and flexibility in mind and will therefore serve as a useful tool in guiding future research.

## References

1990. Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA). 302(9).
1991. Texas Natural Resources Code Annotated. 61.001-.178.
2008. Living Shoreline Protection Act. Maryland General Assembly. .
- 2011a. Rhode Island Coastal Resources Management Program (RICRMP). 210.7 (C2 and A2).
- 2011b. Severance v. Patterson, No. 09-0387. Supreme Court of Texas.
- Akumu, C. E., S. Pathirana, S. Baban, and D. Bucher. 2011. Examining the potential impacts of sea level rise on coastal wetlands in north-eastern NSW, Australia. *Journal of Coastal Conservation* **15**:15-22.
- Ambrose, S. 2001. Man vs Nature: The Great Mississippi Flood Of 1927. National Geographic Society. [http://news.nationalgeographic.com/news/2001/05/0501\\_river4.html](http://news.nationalgeographic.com/news/2001/05/0501_river4.html). November 15, 2011.
- Ardoin, L., A. Beall, R. Brouillette, J. Cowan, M. Deshotels, N. Johnson, J. Porthouse, and J. Russell. 2007. Integrated Ecosystem Restoration and Hurricane Protection: Louisiana's Comprehensive Master Plan for a Sustainable Coast. Baton Rouge, LA.
- Autin, W. J. 2002. Landscape evolution of the Five Islands of south Louisiana: scientific policy and salt dome utilization and management. *Geomorphology* **47**:227-244.
- Bardach, E. 2012. A practical guide for policy analysis. 4th edition. CQ Press, Thousand Oaks, CA.
- Barras, J. A. 2006. Land area change in coastal Louisiana after the 2005 hurricanes-a series of three maps. U.S. Geological Survey Open-File Report 06-1274.
- Barras, J. A. 2009. Land area change and overview of major hurricane impacts in coastal Louisiana, 2004-08. Page 6 Map 3080 scale 1:250,000, U.S. Geological Survey Scientific Investigations, .
- Barras, J. A., J. C. Bernier, and R. A. Morton. 2008. Land area change in coastal Louisiana: A multidecadal perspective (from 1956 to 2006). U.S. Geological Survey Scientific Investigations Map 3019, scal 1:250,000:14.
- Bass, A. S. and R. E. Turner. 1997. Relationships between salt marsh loss and dredged canals in three Louisiana estuaries. *Journal of Coastal Research* **13**:895-903.
- Baumann, R. H., J. W. Day Jr., and C. A. Miller. 1984. Mississippi deltaic wetland survival: sedimentation versus coastal submergence. *Science* **224**:1093-1095.
- Blum, M. D. and H. H. Roberts. 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience* **2**:488-491.
- Britsch, L. D. and J. B. Dunbar. 1993. Land loss rates: Louisiana coastal plain. *Journal of Coastal Research* **9**:324-338.
- Bures, R. and W. Kanapaux. 2011. Historical Regimes and Social Indicators of Resilience in an Urban System: the Case of Charleston, South Carolina. *Ecology and Society* **16**.
- Buster, N. A. and C. W. Holmes. 2001. Gulf of Mexico Origin, Waters, and Biota: Volume 3, Geology. Texas A&M Press, College Station, Texas.
- Cahoon, D. R., D. J. Reed, and J. W. Day Jr. 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. *Marine Geology* **128**:1-9.
- Cahoon, D. R., D. J. Reed, A. S. Kolker, M. M. Brinson, J. C. Stevenson, S. Riggs, R. Christian, E. Reyes, C. Voss, and D. Kunz. 2009. Coastal Wetland Sustainability. Pages 57-72 Coastal Sensitivity to Sea Level Rise: A Focus on the Mid-Atlantic Region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [(authors)Titus, J.G., K.E. Anderson, D.R. Cahoon, D.B. Gesch, S.K. Gill, B.T. Gutierrez, E.R. Thieler, S.J. Williams]. U.S. Environmental Protection Agency, Washington DC.
- Carter, J., A. Foote, and A. Johnson-Randall. 1999. Modeling the effects of nutria (*Myocastor coypus*) on wetland loss. *Wetlands* **19**:209-219.
- Chen, H. and R. G. Pontius. 2011. Sensitivity of a Land Change Model to Pixel Resolution and Precision of the Independent Variable. *Environmental Modeling & Assessment* **16**:37-52.
- Chu-Agor, M. L., R. Munoz-Carpena, G. Kiker, A. Emanuelsson, and I. Linkov. 2011. Exploring vulnerability of coastal habitats to sea level rise through global sensitivity and uncertainty analyses. *Environmental Modelling & Software* **26**:593-604.
- Church, J. A., N. J. White, T. Aarup, W. S. Wilson, P. L. Woodworth, C. M. Dominques, J. R. Hunter, and K. Lambeck. 2008. Understanding global sea levels: past, present, and future. *Sustainable Science* **14**:698-716.
- City Council of Virginia Beach. 2003. Comprehensive Plan: Planning Document. City Council of Virginia Beach, VA.

- Clemen, R. T. and T. Reilly. 2001. Making Hard Decisions with DecisionTools. Duxbury, Pacific Grove, CA.
- Clough, J. S. 2010. A White Paper on Data Requirements and Data Inventory for Alaska SLAMM Analyses. Warren Pinnacle Consulting, Inc., Warren, VT.
- Clough, J. S. 2012. SLAMM Forum. <http://warrenpinnacle.com/SLAMMFORUM>. January 2012.
- Clough, J. S., P. Glick, A. Polaczyk, and B. Nunley. 2011. Sea-Level Rise and Coastal Habitats in Southeastern Louisiana: An Application of the Sea Level Affecting Marshes (SLAMM) Model. National Wildlife Federation.
- Clough, J. S., R. A. Park, and R. Fuller. 2010. SLAMM 6 beta Technical Documentation: Release 6.0.1 beta. Warren Pinnacle Consulting, Inc.
- Coleman, J., H. Roberts, and G. Stone. 1988. Mississippi River delta: an overview. *Journal of Coastal Research* **14**:698-716.
- Coleman, J. M., H. H. Roberts, and G. W. Stone. 1998. Mississippi River delta: an overview. *Journal of Coastal Research* **14**:698-716.
- Couvillion, B. 2010. Landcover Data. Personal communication.
- Couvillion, B. R., J. A. Barras, G. D. Steyer, W. Sleavin, M. Fischer, H. Beck, N. Trahan, B. Griffin, and D. Heckman. 2011. Land area change in coastal Louisiana from 1932 to 2010. U.S. Dept. of the Interior, U.S. Geological Survey, Reston, Va.
- CPRA. 2007. Integrated Ecosystem Restoration and Hurricane Protection: Louisiana's Comprehensive Master Plan for a Sustainable Coast. Coastal Protection and Restoration Authority (CPRA).
- CPRA. 2011a. Coastal Crisis: Land Loss. Governor's Office of Coastal Activities. Coastal Protection and Restoration Authority (CPRA).  
<http://coastal.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&pid=112&printer=1>. October 10, 2011.
- CPRA. 2011b. Louisiana Coastal Ports of Louisiana. Twin Parish and Vermilion Port Profiles.  
<http://portsoflouisiana.org/>. February 19, 2012.
- CPRA. 2012. Louisiana's Comprehensive Master Plan for a Sustainable Coast. Coastal Protection and Restoration Authority (CPRA).
- CPRA. January 2012. Louisiana's Comprehensive Master Plan for a Sustainable Coast (Draft). Coastal Protection and Restoration Authority (CPRA).
- Day, J. W., D. F. Boesch, E. J. Clairain, G. P. Kemp, S. B. Laska, W. J. Mitsch, K. Orth, H. Mashriqui, D. J. Reed, L. Shabman, C. A. Simenstad, B. J. Streever, R. R. Twilley, C. C. Watson, J. T. Wells, and D. F. Whigham. 2007. Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science* **315**:1679-1684.
- DeLaune, R. D. and S. R. Peseshki. 1994. The influence of subsidence and saltwater intrusion on coastal marsh stability: Louisiana, Gulf Coast, U.S.A. *Journal of Coastal Research*:77-89.
- DeMarco, K., J. Mouton, and J. W. Pahl. 2011. Recommendations for anticipating sea-level rise impacts on Louisiana coastal resources during project planning and design. Louisiana Applied Coastal Engineering & Science (LACES) Division, Coastal Protection and Restoration Authority of Louisiana.
- Ford, M. and J. Nyman. 2011. Preface: an overview of the Atchafalaya River. *Hydrobiologia* **658**:1-5.
- Frazier, D. E. 1967. Recent deltaic deposits of the Mississippi River: their development and chronology. *Gulf Coast Association of Geological Societies Transactions* **27**:287-315.
- Fruehling, D. 2007. TDR 101. *Washington Business Journal*,  
<http://www.bizjournals.com/washington/stories/2007/08/20/focus9.html?page=all>. August 20, 2007.
- Glick, P., J. Clough, A. Polaczyk, and B. Nunley. 2011. Sea-Level Rise and Coastal Habitats in Southeastern Louisiana: An Application of the Sea Level Affecting Marshes Model (SLAMM). National Wildlife Federation.
- Gonzalez, J. L. and T. E. Törnqvist. 2006. Coastal Louisiana in crisis: Subsidence or sea level rise? *EOS Transactions* **87**:493-550.
- Grinsted, A., J. Moore, and S. Jevrejeva. 2009. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics* **34**:461-472.
- Hamauei, M. 2011. Ordinance to amend the St. Tammany Parish unified development code, Volume 1 (Zoning) by amending Article 2, definitions and create a section 6.07 transfer of development rights overlay. *in* S. T. P. C. Ordinance, editor. 4486.

- Han, W., G. A. Meehl, B. Rajagopalan, J. T. Fasullo, A. Hu, J. Lin, W. G. Large, J.-w. Wang, X.-W. Quan, L. L. Trenary, A. Wallcraft, T. Shinoda, and S. Yeager. 2010. Patterns of Indian Ocean sea-level change in a warming climate. *Nature Geoscience* **3**:546-550.
- Hebert, M. C. 1997. Coastal Restoration Under CWPPRA and Property Rights Issues. *Louisiana Law Review* **57**:1165-1211.
- Hendrick, R. 1994. A Heuristic Approach to Policy Analysis and the Use of Sensitivity Analysis. *Public Productivity and Management Review* **18**:37-55.
- IPCC. 2001. *Climate Change 2001: The Scientific Basis*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.
- IPCC. 2007a. *Climate Change 2007: Synthesis Report*, Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.
- IPCC. 2007b. *Climate Change 2007: Synthesis report, Summary for policy makers*. Cambridge University Press, Cambridge.
- Jessen, A. S. 2006. Louisiana and the Coastal Zone Management Act in the Wake of Hurricane Katrina: A Renewed Advocacy for a More Aggressive Use of the Consistency Provision to Protect and Restore Coastal Wetlands. *Ocean and Coastal Law Journal* **12**:133-160.
- Juergensmeyer, J. C., J. C. Nicholas, and B. D. Leebrick. 1998. Transferable Development Rights and Alternatives After Suitum. *Urban Lawyer* **30**:441-451.
- Kolker, A. S., M. A. Allison, and S. Hameed. 2011. An evaluation of subsidence rates and sea-level variability in the northern Gulf of Mexico. *Geophysical Research Letters* **38**.
- LA Department of Natural Resources, T. A. D. 2010. *Louisiana Energy Facts Annual Report*. Baton Rouge, LA.
- LA Department of Wildlife and Fisheries. 2006. *The Economic Benefits of Fisheries, Wildlife and Boating Resources in the State of Louisiana*. Baton Rouge, LA.  
[http://www.wlf.louisiana.gov/sites/default/files/pdf/publication/32728-economic-benefits-fisheries-wildlife-and-boating-resources-state-louisiana-2006/southwick\\_2006\\_final\\_final\\_report\\_5-27-08\\_0.pdf](http://www.wlf.louisiana.gov/sites/default/files/pdf/publication/32728-economic-benefits-fisheries-wildlife-and-boating-resources-state-louisiana-2006/southwick_2006_final_final_report_5-27-08_0.pdf). April 25, 2012.
- LA Department of Wildlife and Fisheries. 2010. *2009-2010 Annual Report*, Baton Rouge, LA: Louisiana Department of Wildlife and Fisheries.
- LA Department of Wildlife and Fisheries. 2011. *Waterfowl Population Estimates in Louisiana's Coastal Zone Below U.S. Highway 90 and on Catahoula Lake*. Baton Rouge, LA.  
[http://www.wlf.louisiana.gov/sites/default/files/pdf/waterfowl\\_survey/33575-January%202011%20Survey/waterjan2011.pdf](http://www.wlf.louisiana.gov/sites/default/files/pdf/waterfowl_survey/33575-January%202011%20Survey/waterjan2011.pdf). April 25, 2012.
- Lafourche Parish. 1982. *Lafourche LCP*.
- Lafourche Parish Government. 2012. About Lafourche. <http://www.lafourchegov.org/default.aspx>. February 19, 2012.
- LDNR. 2011. *Louisiana Coastal Program: Assessment and Strategy 2011-2015*. Louisiana Department of Natural Resources (LDNR).
- Louisiana Wetland Protection Panel. April 1987. *Saving Louisiana's coastal wetlands: The need for a long-term plan of action*. Library of Congress, US Environmental Protection Agency. Louisiana Geological Survey. Grand Terre Island, LA.
- LSU AgCenter. 2011. *Louisiana Rice Acreage by Variety Summary 2011*.  
<http://www.lsuagcenter.com/MCMS/RelatedFiles/{9AFBF0E0-289F-40DE-AFDE-31AF15483BA2}/2011-Rice-Acreage-Survey-summary.pdf>. February 2012.
- Mac, M. J., A. O. Paul, C. E. P. Haecker, and P. D. Doran. 1998. Status and Trends of the Nation's Biological Resources. Pages 385-437, US Department of the Interior, US Geologic Survey Biological Resources Division.
- MALPF. 2003. *Maryland's land conservation programs: Protecting the Chesapeake Bay Watershed*. Maryland Agricultural Land Preservation Foundation (MALPF).
- McLaughlin, R. J. 2011. Rolling Easements as a response to sea level rise in coastal Texas: Current status of the law after *Severance v. Patterson*. *Journal of Land Use and Environmental Law* **26**:365-394.

- McLeod, E., B. Poulter, J. Hinkel, E. Reyes, and R. Salm. 2010. Sea-level rise impact models and environmental conservation: A review of models and their applications. *Ocean & Coastal Management* **53**:507-517.
- Meckel, T. A., U. S. ten Brink, and S. J. Williams. 2006. Current subsidence rates due to compaction of Holocene sediments in southern Louisiana. *Geophysical Research Letters* **33**.
- Monroe County Growth Management Division. 2009. A Layman's Guide to Residential ROGO. A New Era in Growth Management: The Tier System, Key West, FL. <http://www.floridakeyskeywestrealestate.com/pdf/laymansguideROGO.pdf>. March 2012.
- Morris, J. T., P. V. Sundareshwar, C. T. Nietch, B. Kjerfve, and D. R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology* **83**:2869-2877.
- Morton, R. A. and J. C. Bernier. 2010. Recent Subsidence-Rate Reductions in the Mississippi Delta and Their Geological Implications. *Journal of Coastal Research* **26**:555-561.
- New Jersey State Planning Commission. 2001. The New Jersey State Development and Redevelopment Plan: Infrastructure Needs Assessment.
- Nicholls, R. and A. Cazenave. 2010. Sea-level rise and its impact on coastal zones (June, pg 1517, 2007). *Science* **329**:628-628.
- Nicholls, R. J., S. E. Hanson, J. A. Lowe, R. A. Warrick, X. Lu, A. J. Long, and T. R. Carter. 2011. Constructing sea-level scenarios for impact and adaptation assessment of coastal area: a guidance document. Supporting Material, Intergovernmental Panel on Climate Change Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA), 47p.
- NOAA Tides & Currents. 2012. Tidal Datums. <http://tidesandcurrents.noaa.gov/>. January 2012.
- OCPR. 2011. Louisiana's Coastal Crisis. <http://coastal.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&nid=152&pnid=0&pid=112&catid=0&elid=0>. November 15, 2011.
- Park, R. A., M. S. Trehan, P. W. Mousel, and R. C. Howe. 1989. The effects of sea level rise on US coastal wetlands. US Environmental Protection Agency, Washington, D.C.
- Penland, S. and J. R. Suter. 1989. The geomorphology of the Mississippi River chenier plain. *Marine Geology* **90**:231-258.
- Pfeffer, W. T., J. T. Harper, and S. O'Neel. 2008. Kinematic constraints on glacier contributions to the 21st-century sea-level rise. *Science* **321**:1340-1343.
- Pollakowski, H. O. and S. M. Wachter. 1990. The effects of land-use constraints on housing prices. *Land Economics*, University of Wisconsin Press **66**:315-324.
- Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* **315**:368-370.
- Rignot, E., I. Velicogna, M. R. van den Broeke, A. Monaghan, and J. T. M. Lenaerts. 2011. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters* **38**.
- Rupert, T. 2012. Use of future interests in land as a sea-level rise adaptation strategy in Florida. Florida Sea Grant College Program.
- Saltelli, A. and M. Saisana. 2007. Settings and methods for global sensitivity analysis--a short guide. *Proceedings in Applied Mathematics and Mechanics* **7**:2140013-2140014.
- Sasser, C. E., J. G. Gosselink, E. M. Swenson, C. M. Swarzenski, and N. C. Leibowitz. 1996. Vegetation, Substrate and Hydrology in Floating Marshes in the Mississippi River Delta Plain Wetlands, USA. *Vegetatio* **122**:129-142.
- Sasser, C. E., M. D. Materne, J. M. Visser, G. O. Holm, and E. Evers. 2007. Restoring Freshwater Floating Marsh in Coastal Louisiana. *Louisiana Agriculture Magazine* **Spring 2004**.
- Schilmoeller, G. 2006. Invoking the Fifth Amendment to Preserve and Restore the Nation's Wetlands in Coastal Louisiana. *Tulane Environmental Law Journal* **19**:317-338.
- Smith, J. M., M. A. Cialone, T. V. Wamsley, and T. O. McAlpin. 2010. Potential impact of sea level rise on coastal surges in southeast Louisiana. *Ocean Engineering* **37**:37-47.
- Syvitski, J. P. M., A. J. Kettner, I. Overeem, E. W. H. Hutton, M. T. Hannon, G. R. Brakenridge, J. Day, C. Vorosmarty, Y. Saito, L. Giosan, and R. J. Nicholls. 2009. Sinking deltas due to human activities. *Nature Geoscience* **2**:681-686.
- The Greater Lafourche Port Commission. 2012. About Us. [www.portfourchon.com](http://www.portfourchon.com). February 19, 2012.
- Titus, J. G. 1998. Rising seas, coastal erosion, and the takings clause: How to save wetlands and beaches without hurting property owners. *Maryland Law Review* **57**:1279-1399.

- Titus, J. G. 2011. Rolling Easements. Climate Ready Estuaries Program, EPA.  
<http://www.epa.gov/cre/downloads/rollingeasementsprimer.pdf>.
- TNC. 2011. Conservation Easements at The Nature Conservancy. *in* T. N. Conservancy, editor. Conservation Easements,  
<http://www.nature.org/aboutus/privatelandsconservation/conservationeasements/conservation-easements-at-the-nature-conservancy.xml>. April 13, 2012.
- Törnqvist, T. E., D. J. Wallace, J. E. A. Storms, J. Wallinga, R. L. van Dam, M. Blaauw, M. S. Derksen, C. J. W. Klerks, C. Meijneken, and E. M. A. Snijders. 2008. Mississippi Delta subsidence primarily caused by compaction of Holocene strata. *Nature Geoscience* **1**:173-176.
- Turner, R. E., J. J. Baustian, E. M. Swenson, and J. S. Spicer. 2006. Wetland sedimentation from Hurricanes Katrina and Rita. *Science* **314**:449-452.
- U.S. Census Bureau. 2009. Louisiana QuickFacts from the US Census Bureau.  
<http://quickfacts.census.gov/qfd/states/22000.html>. April 25, 2012.
- U.S. Census Bureau. 2010. American Fact Finder. Washington, D.C.  
<http://factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml>. February 2012.
- U.S. Department of Commerce, N., NMFS,. 2009. Fisheries of the United States, 2008. Silver Springs, MD.
- U.S. EPA. 2012. The Mississippi-Atchafalaya River Basin (MARB). U.S. EPA Office of Wetlands, Oceans, and Watersheds. <http://water.epa.gov/type/watersheds/named/msbasin/marb.cfm>. January 22, 2012.
- USACE. 2004. Coastal Overwash Part 1: Overview of the Processes. Regional Sediment Management (RSM) Demonstration Program Technical Note, <http://www.wes.army.mil/rsm/pubs/pdfs/rsm-tn-14.pdf>. February 15, 2012.
- USACE. 2009. Waterway Data: Principle Ports of the United States., Navigation Data Center.  
<http://www.ndc.iwr.usace.army.mil/data/datappor.htm>. April 25, 2012.
- USACE New Orleans District. 2004. Louisiana Coastal Area (LCA) Near-Term Ecosystem Restoration Plan: Evolution of Coastal Restoration in Louisiana.
- USCCSP. 2009. Coastal Sensitivity to sea-rise: A focus on the Mid-Atlantic region. Synthesis and Assessment Product 4-1. U.S. Climate Change Science Program (USCCSP).
- USGS. 2008. Freshwater-Saltwater Interactions along the Atlantic Coast. USGS,  
<http://water.usgs.gov/ogw/gwrp/saltwater/salt.html>. November 15, 2011.
- Vermilion Parish Tourist Commission. 2012. Vermilion Parish Tourist Commission: About Us. Abbeville, LA.  
<http://www.mostcajun.com/>. February 19, 2012.
- Wold, A. 2012. Public suggestions included in coastal restoration plan. *The Advocate*. Capital City Press LLC, Baton Rouge, LA <http://theadvocate.com/home/2310981-125/public-suggestions-included-in-coastal>. March 16, 2012.
- Yu, S.-Y., T. E. Törnqvist, and P. Hu. 2012. Quantifying Holocene lithospheric subsidence rates underneath the Mississippi Delta. *Earth and Planetary Science Letters* **331-332**:21-30.
- Yuill, B., D. Lavoid, and D. J. Reed. 2009. Understanding subsidence processes in coastal Louisiana. *Journal of Coastal Research* **Special Issue No. 54**:23-36.