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Detecting Coastal Marsh Change from Aerial Imagery using Spectral and Textural Methods: Pascagoula River Estuary, Mississippi, 1955-2014

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DETECTING COASTAL MARSH CHANGE FROM AERIAL IMAGERY USING SPECTRAL AND TEXTURAL METHODS: PASCAGOULA RIVER ESTUARY, MISSISSIPPI, 1955-2014

by

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ABSTRACT

As sea level rise accelerates, coastal marsh ecosystems are increasingly vulnerable. Vertical accretion rates must exceed or keep pace with rates of sea level rise to prevent transition to open water or inland migration of marsh vegetation. While some marsh systems along the northern Gulf of Mexico coast have remained stable, others, e.g., the marshes of the Louisiana Gulf Coast, have experienced high rates of conversion to open water. This study examined the historical extent of intertidal marsh at the mouth of the Pascagoula River in Jackson County, Mississippi to determine whether marsh extent changed during the period 1955-2014 and to ascertain rates of change. Marsh extent was mapped at 3 meters GSD using spectral and textural aerial image data for image dates of February 13, 1955 (black and white), February 12, 1996 (color-infrared), and October 5-16, 2014 (color-infrared). Waterways represented in the imagery were classified using a near-infrared band threshold for 1996 and 2014 and a CV-band threshold for 1955. Land cover was classified into three groups–marsh, woodland/shrubs, and unvegetated–using a Maximum Likelihood Classifier. Change detection analysis revealed a net marsh loss of 1314.4 ha (19.9%) between 1955 and 2014. Classified marsh extent decreased by 1068.3 ha (16.1%) between 1955 and 1996, and 246.1 ha (4.4%) between 1996 and 2014. Linear regression of marsh extent with year yielded a slope of -22.9 ha/year with a coefficient of determination of $r^2 = 0.98$. The results indicate that marsh extent will continue to decrease in the Pascagoula River Estuary.

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LIST OF ABBREVIATIONS

AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
CV	Coefficient of Variation
NERR	National Estuarine Research Reserve
GLCM	Gray-Level Co-Occurrence Matrix
GSD	Ground Sample Distance
IPCC	Intergovernmental Panel on Climate Change
ISODATA	Iterative Self-Organizing Data Analysis Technique
MARIS	Mississippi Automated Resource Information System
MEM	Marsh Equilibrium Model
ML	Maximum Likelihood
MODIS	Moderate Resolution Imaging Spectroradiometer
NAIP	National Agriculture Imagery Program
NAPP	National Aerial Photography Program
NASA	National Aeronautics and Space Administration
NGS	National Geodetic Survey
NHAP	National High Altitude Photography Program
NOAA	National Oceanic and Atmospheric Administration
RCP	Representative Concentration Pathway
ROI	Region of Interest
SLR	Sea Level Rise
SPOT	Satellite Pour l'Observation de la Terre
TM	Thematic Mapper
USGS	United States Geological Survey

CHAPTER I - INTRODUCTION

Research statement

Intertidal marshes provide nesting, foraging, and nursery habitat for many avian and aquatic species (Cho, 2011, p. 7; Mississippi Department of Marine Resources, 1998; Partyka & Peterson, 2008, p. 1571). Marsh vegetation filters impurities and captures sediment as water flows into the ocean. Coastal marshes also function as hurricane buffers, reducing storm surge impacts to surrounding areas (Bilskie, Hagen, Medeiros, & Passeri, 2014). Coastal marshes are among the most productive ecosystems, with detritus from dead marsh vegetation anchoring the estuarine food web, and they sequester carbon dioxide at high rates (Cho, 2011, p. 7; Hinson et al., 2017, p. 5468; Kennish, 2001, p. 731). Existing at the peripheral zone between salt and fresh water, and the boundary between the terrestrial and marine, the fragile nature of this crucial habitat cannot be overstated. Saltwater inundation or lowered freshwater input can decimate marsh vegetation, sometimes permanently affecting the extent of vegetated area. Conversely, freshwater flooding can also lead to plant stress and marsh die-back (Reed, 2002, pp. 234–237).

Due to their peripheral position, coastal marsh ecosystems are uniquely vulnerable to sea level rise (SLR). As annual average temperatures increase, melting ice sheets and thermal expansion will lead to higher sea levels (Englander, 2018; NASA Jet Propulsion Laboratory, 2018). Measurements for the global rate of SLR vary. The National Oceanic and Atmospheric Administration (NOAA) Laboratory for Satellite Altimetry reports global mean SLR as around 2.9mm per year (Bilskie et al., 2014, p. 927; NOAA Center for Satellite Applications and Research, 2015). Even if carbon emissions are drastically reduced as described by Representative Concentration Pathway (RCP) 2.6, Intergovernmental Panel on Climate Change (IPCC) reports indicate a likely increase in global sea level of between 0.26 and 0.55 meters by 2100. The highest-emission RCP described by the IPCC (RCP8.5) would lead to a likely projected rise in Global Mean Sea Level of between 0.45 and 0.82 meters by 2100 according to the IPCC's 2014 report (IPCC, 2015, pp. 56–60). An anonymous, broad elicitation of international sea-level scientists in 2012 indicated a likely increase of between 0.4 and 0.6 meters by 2100 under the intermediate RCP3 scenario, and 0.7 and 1.2 meters by 2100 under the RCP8.5 scenario (Horton, Rahmstorf, Engelhart, & Kemp, 2014, p. 3). In addition to rising waters, coastal marsh ecosystems also face the threat of destruction by direct human activities. Land reclamation projects, dredging and canal maintenance, shoreline alterations, and pollution all have the potential to impact the health of coastal marsh ecosystems by altering natural biological and geological processes (Kennish, 2001, pp. 733–737; Partyka & Peterson, 2008, pp. 1578–1579; Wu, Biber, & Bethel, 2017, p. 10891). In providing a window into past habitats, remote sensing and the interpretation of historical imagery allow us to see how marsh habitats have changed over time in response to these various factors, as well as predict future habitat change.

Research goals

The goal of the present study was to map and quantify the extent of coastal marsh vegetation in the Pascagoula River Estuary beginning in 1955 and ending in 2014, and to identify any locations with notable degrees of change. Specific research questions included:

1. Did marsh extent change over the study period?
2. Did rates and magnitudes of change in marsh extent vary among different parts of the estuary?

Hypotheses

H_1 – Marsh extent decreased between 1955 and 2014.

H_2 – The decline in marsh extent was more pronounced in the more marine portions of the estuary.

CHAPTER II – LITERATURE REVIEW

Threats to coastal marsh stability

Many hydrologic, chemical, and topographical factors influence the development and maintenance of coastal marsh habitats. For a marsh system to remain stable, the net accumulation of mineral and organic matter (accretion) must be greater than or equal to submergence by coastal waters (Kennish, 2001, p. 731). In addition to eustatic SLR, crustal downwarping, sediment compaction, decomposition of organic matter, and erosion all contribute to submergence (Kennish, 2001, p. 731; Wu, Biber, et al., 2017, p. 10891).

Local sea level rise

Local sea level change involves two components: changes in the vertical position of land masses relative to the sea (subsidence and uplift), and changes in the mass or volume of the world's oceans which change the height of the sea relative to land (eustatic SLR) (Rovere, Stocchi, & Vacchi, 2016, p. 222). The combined effects of these factors result in changes in relative sea level for the area under consideration.

Eustatic sea level rise. Worldwide, eustatic SLR is a main factor in the disappearance of coastal wetlands (Wu, Biber, et al., 2017, p. 10891). Drivers of eustatic sea level change include the thermal expansion or contraction of ocean waters, the melting or freezing of glaciers, changes in salinity which affect water volume, and changes in the volume of water held by ocean basins due to geological factors (Rovere et al., 2016, p. 222). Eustatic SLR is difficult to measure, as local factors must first be isolated (Rovere et al., 2016, p. 222). While there is debate about the rate of global sea-level rise increase, evidence suggests that the rate could be accelerating by up to 0.25 mm per year^2 (Wu, Biber, et al., 2017, p. 10891). NOAA measures sea level based on tide gauge measurements, which are recorded with reference to local fixed elevations on land, and using satellite altimetry (National Oceanic Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services, 2018). The NOAA Laboratory for Satellite Altimetry reports that the change in mean sea level in the Gulf of Mexico is higher than the global average at 3.4mm per year ± 0.4mm between 1992 and 2015, compared with 2.9mm per year ± 0.4mm globally (seasonal signals removed) (NOAA Center for Satellite Applications and Research, 2015).

Subsidence. Relative sea level change, or a change in land height relative to the sea, is caused by land uplift or subsidence and can be the result of a variety of geologic, tectonic, and climatic factors (Rovere et al., 2016). During glacial periods, the weight of ice sheets can cause land masses to subside and displace mantle material laterally, causing uplift at the edge of the ice sheet (Glacial Isostatic Adjustment or GIA). During interglacial periods, these areas rebound in response to melting ice (Rovere et al., 2016, pp. 222–223). The redistribution of sediments can similarly provoke isostatic responses (Rovere et al., 2016, p. 225). Tectonic shifts can also lead to uplift and subsidence. Even in tectonically stable areas, vertical movement of land masses attributable to tectonism may still be detected over millions of years (Rovere et al., 2016, p. 225). Subsidence occurs in many coastal areas when sediment is compacted over time by mechanical, biological, and anthropogenic processes. Sediment compaction plays a particularly large role in coastal subsidence in many highly populated river deltas over the last several millennia (Rovere et al., 2016, p. 225). Additionally, both soil drainage activities and subsurface resource extraction can contribute to high rates of subsidence (Rovere et al., 2016, p. 226).

In many areas along the western Gulf Coast, including the Mississippi River Delta, rates of subsidence outpace rates of climate-driven SLR in contributing to coastal land loss (National Academies of Sciences Engineering and Medicine, 2018, p. 64). Shinkle and Dokka (2004) computed velocities of vertical displacement along the Gulf Coast from Beaumont, Texas to Pensacola, Florida based on data collected between 1920 and 1955 from 2,700 National Geodetic Survey (NGS) benchmarks. They found that subsidence on the Northern Gulf Coast peaks in southwest Louisiana at over 25 mm per year, gradually slowing in the eastward direction until stability is reached around Mobile, AL (Shinkle & Dokka, 2004, pp. 1–14). While they found the rates of subsidence on the Louisiana Gulf Coast to be accelerating in a statistically significant way, they found only weak evidence of acceleration in the subsidence rate at the eastern group of benchmarks between New Orleans, Louisiana and Biloxi, Mississippi (Shinkle & Dokka, 2004, pp. 17–24).

Both natural processes and anthropogenic manipulation, including the extraction of subsurface fluids such as natural gas, contribute to high present-day rates of subsidence along the Louisiana Gulf Coast (Yuill, Lavoie, & Reed, 2009, pp. 23–30). Subsidence in coastal Louisiana is partially attributable to tectonic activity; this is influenced by the geologic development of the Gulf of Mexico Basin, growth faulting resulting from the expansion of the Mississippi River Delta, and the movement of offshore salt deposits (Yuill et al., 2009, pp. 25–26). Subsidence at localized fault zones has been measured as high as 1 meter since the 1960s in south Louisiana (Yuill et al., 2009, p. 26). These high localized subsidence rates likely represent discrete tectonic phenomena, as much lower rates are observed in the same areas over geologic time (Yuill et al., 2009, p. 26).

Dokka (2006) found that tectonic activity was a principal component of subsidence in his measurements of vertical benchmark velocities at Michaud, Louisiana (Dokka, 2006, p. 282). In computing velocities for three closely located geodetic benchmarks at varying depths, the author isolated three components of local subsidence which varied by depth. Following the same computational methodology as Shinkle and Dokka (2004), Dokka (2006) referenced benchmark heights to a precise vertical datum (NAVD88) rather than sea level measurements and estimates which are imprecise and often unconfirmed. This allowed for more precise and accurate measurements of benchmark velocities than informal datums used in many contemporary studies, which tend to underestimate subsidence rates (Dokka, 2006, pp. 283–284). Dokka (2006) found that subsidence at the deepest benchmark (BH1089) accounted for 73% of the total subsidence at the study site between 1969 and 1971 and 50% of subsidence between 1971 and 1977. The depth of this benchmark (-2011 m) permitted the author to rule out compaction and other factors, allowing him to attribute this component of local subsidence to tectonic activity (Dokka, 2006, pp. 282–283). Dokka (2006) similarly attributed vertical movement of benchmarks at the intermediate and shallow depths to compaction (Dokka, 2006, p. 283).

The compaction of recently-deposited Holocene sediments is also frequently cited as the primary factor influencing the high rates of subsidence in the Mississippi River Delta (Yuill et al., 2009, p. 26). Compaction occurs as a natural process as fluvial sediments settle over time, with soil grains expelling fluid and reorganizing to become more tightly packed (Yuill et al., 2009, p. 27). This process is directly influenced by the total weight of the material overlying the compacting sediment (Yuill et al., 2009, p. 27). The decomposition of organic material also contributes to sediment compaction (Yuill et al., 2009, p. 27). Observed subsidence due to the decrease in sediment volume is offset by the continued influx of riverine sediments (Yuill et al., 2009, p. 26). In the Mississippi River Delta, however, sediment trapping in upstream reservoirs and river channelization have decreased this sediment supply to the coastal zone, leading to measurably higher subsidence (Yuill et al., 2009, pp. 26–27). Törnqvist and others (2008) assessed compaction rates of Holocene deposits in the Mississippi Delta, finding that peat deposits exhibited very high compaction rates of up to 5 mm per year over 1,200 to 1,600-year periods (Tornqvist et al., 2008, pp. 173–174). Based on their results, shallow compaction of these deposits is likely a significant factor in high subsidence rates on the Louisiana Gulf Coast, and in other coastal systems with organic-rich deposits (Tornqvist et al., 2008, p. 173).

The development of the modern Mississippi Delta Plain from alluvial deposits over the last 8000 years has exerted weight on the underlying crust ("sediment loading"). This has causing to a downward isostatic adjustment that is greater than the vertical height of the deposited sediment layer, leading to subsidence over time (Yuill et al., 2009, pp. 29–30). Glacial isostatic readjustment since the retreat of the Laurentide Ice Sheet has also caused slow, steady subsidence of the southern half of North America, a result of forebulge collapse (Yuill et al., 2009, pp. 29–30).

González and Törnqvist (2006) reasoned that because Pensacola is located on tectonically stable Upper Pliocene sediments, the change in relative sea level at this tide gauge station as reported by Shinkle and Dokka (2004) should thus reflect changes in eustatic sea level and isostatic adjustment (Gonzalez & Tornqvist, 2006, p. 494; Shinkle & Dokka, 2004). The difference between the rate of global SLR over the 20th century and the rate of relative SLR at the Pensacola tide gauge station is about 0.4 mm; thus, the authors attributed this steady rate of subsidence to the isostatic response of the Gulf Coast region to the melting of the Laurentide Ice Sheet (Gonzalez & Tornqvist, 2006, p. 494)

The withdrawal of subsurface fluids such as petroleum and natural gas can lead to sediment compaction in cases where reservoirs collapse (Kennish, 2001, p. 741; Yuill et al., 2009, p. 30). The removal of fluids also causes pressure changes which can contribute to fault slip, although this appears to play a smaller role than reservoir collapse (Yuill et al., 2009, p. 30).

The decay of organic matter also causes subsidence. When organic matter decomposes, organic carbon oxidizes into carbon dioxide gas, which is more mobile than solid organic matter and can be released into the atmosphere. This leads to decreased soil mass and volume (Yuill et al., 2009, p. 33).

On a local or regional scale, the drainage of surface water from saturated or partially-saturated soils can also speed up subsidence rates, particularly in organic-rich soils. The drainage of surface water can lead to lower biomass production, hindering *in situ* organic accretion as well as decreased sediment trapping abilities (Reed, 2002, p.

234; Yuill et al., 2009, p. 32). When surface water is drained from wetlands, surface temperatures tend to be hotter, speeding up decomposition (Yuill et al., 2009, p. 32). Because decomposition also tends to occur more quickly under aerobic conditions than anaerobic conditions, the removal of surface water in the marsh can further interfere with sediment trapping capabilities by facilitating the faster removal of plant litter (Kirwan, Langley, Guntenspergen, & Megonigal, 2013, p. 1874; Wu, Huang, Biber, & Bethel, 2017, p. 373). Additionally, drier conditions promote compaction by increasing relative overburden pressure (Yuill et al., 2009, p. 33).

Wu and others (2014) reported that negligible subsidence in the Grand Bay National Estuarine Research Reserve (NERR) in Jackson County, Mississippi (Wu, Biber, et al., 2017, p. 10894). Falling in the relatively stable eastern region of Shinkle and Dokka's 2004 benchmarks, most of the Jackson County, Mississippi area experiences low rates of subsidence of less than 5 mm per year (NOAA 2004, 15). Near the mouth of the Pascagoula River, however, rates are higher; at the four benchmarks in the Mississippi Sound offshore from the Pascagoula Estuary, subsidence was between 4.9 and 5.5 mm per year since 1977 (Shinkle & Dokka, 2004, p. 69).

Differences in rates of subsidence cause the rate of local SLR to vary across the Northern Gulf of Mexico. As with many locations along the Gulf Coast, incomplete tide gauge records make it impossible to ascertain exact sea level trends in the Pascagoula River Estuary (National Academies of Sciences Engineering and Medicine, 2018, p. 63; National Oceanic Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services, 2018). The closest NOAA Sea Level Trend station is about 50 km away from the mouth of the Pascagoula River on the eastern side of

Dauphin Island, AL. Tide gauge records indicate that the linear trend in relative sea level change at this station is rising approximately 3.61mm per year ± 0.59mm since 1966. However, at the second closest station, about 70 km away, located just north of the Highway 90 Bridge in Bay St. Louis, Mississippi, the rate of rise since 1978 is about 4.56mm per year ± 0.86mm (National Oceanic Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services, 2018).

The response of marsh vegetation to sea level rise

Feedbacks among marsh inundation, the trapping and deposition of sediment, and vegetation growth can facilitate accretion which balances even moderate levels of sea-level rise of up to 12 mm per year (Wu, Biber, et al., 2017, p. 10891). As marsh platforms are inundated more frequently and for longer periods, more sediment is trapped by vegetation, vegetation growth can be augmented in relatively shallow areas, and organic matter is more efficiently buried (Wu, Biber, et al., 2017, p. 10898).

Vegetation, however, is rapidly drowned in cases where SLR exceeds a critical threshold, beyond which the ecosystem is abruptly and often permanently altered, resulting in unvegetated tidal or subtidal flats (Wu, Biber, et al., 2017, pp. 10891–10892). Whereas this threshold was shown by Kirwan and Megonigal (2013) to be around 7-12 mm per year over geologic time, anthropogenic disturbances such as reduced sediment input, increased nutrient input, increased CO_2 levels, higher temperatures, and a more rapid rate of sea-level rise reduce the natural ability of a coastal wetland ecosystem to respond to SLR. This means that this threshold for coastal marsh collapse may be lower in the present day than the past (Kirwan & Megonigal, 2013, p. 55; Wu, Biber, et al., 2017, p. 10891).

Orson and others (1985) analyzed the various response mechanisms of salt marsh ecosystems to a rise in local sea level. The authors described three possible ways in which salt marshes can be formed: by the accumulation of marine sediments in wetland areas protected from wave action, such as bays and lagoons, by the submergence of upland habitats in response to local SLR, or by the accumulation of fluvial sediments in a river delta (Orson et al., 1985, p. 30). They then evaluated the possible responses of each of these types of systems. Whether a marsh drowns, remains stable, or expands in response to SLR is determined by the rate of accretion in the marsh (Orson et al., 1985, p. 32). If the rate of coastal submergence exceeds the rate of accretion, prolonged submergence will cause oxygen levels to become too low for marsh grasses to survive. The localized death of marsh vegetation can eventually cause a terminal decrease in elevation over the entire marsh system, leading to a conversion to open water as the loss of biomass results in both hindered sediment-trapping capabilities and a reduction in organic deposition from marsh grass detritus (Orson et al., 1985, p. 32).

The authors also explained the conditions under which coastal marshes could expand in response to SLR. If rising sea levels lead to increased marine sediment deposition, vertical accretion can increase at a faster rate than SLR. Plant productivity can also be augmented by the increased availability of nutrients from deposition (Orson et al., 1985, p. 34). This case was illustrated by Flessa and others (1977), who noted a rate of vertical accretion higher than the rate of SLR in a Long Island intertidal marsh which was opened to marine sedimentation in 1803 (Flessa, Constantine, & Cushman, 1977, pp. 172–174). Harrison and Bloom (1977) similarly found a positive correlation between the rate of accretion in a Connecticut salt and the tidal range, and accretion showed a positive relationship with flood activity (Harrison & Bloom, 1977). Orson and others (1984) argued that this type of expansion is possible in a riverine coastal marsh as well, particularly in cases where land use changes have increased the volume of available sediment in river systems. They provided as evidence a high rate of marsh expansion in parts of the eastern United States since colonial times that appears to be linked to increased sedimentation due to land clearing practices. Some Chesapeake Bay marshes have been expanding seaward rapidly, and expansion in localized areas of the Louisiana coastal marshes is also noted (Orson et al., 1985, p. 34). Changes in land use leading to increased deltaic sedimentation do not, however, guarantee the long-term stability or expansion of a marsh system. If artificially high sedimentation rates are not maintained, wetland expansion may be rapidly curtailed (Orson et al., 1985, p. 34).

The third possible response of marsh systems to SLR is lateral displacement, not necessarily resulting in a gain or loss in total extent. In this case, marsh vegetation colonizes inland areas which were previously freshwater marsh or upland habitats while erosion and submersion occurs at the seaward boundary (Orson et al., 1985, pp. 34–35). Schuerch and others (2018) described this space available for lateral migration as “accommodation space,” noting its availability as a key factor in predicting future wetland extent (Schuerch et al., 2018).

Reed (2002) also examined the combined effects of relative SLR and accumulation, specifically analyzing the case of coastal marshes in the Mississippi deltaic plain. The author described the change in salt marsh elevation and coverage as a function of global SLR combined with freshwater input change, organic and inorganic sediment input change, and land subsidence (Reed, 2002, pp. 234–235). Reed attributed the large losses in the marshes of coastal Louisiana, particularly the die-backs in the mid-1950s and in 1974, to imbalances in the rate of marsh elevation change and "extreme water level conditions" under which the necessary rate of accretion cannot be maintained (Reed, 2002, p. 237).

Reed posited that, because of the importance of organic deposits in marsh accretion, the health of the marsh vegetation ultimately controls marsh elevation. Thus, the ecological response of marsh vegetation to SLR is integral to the understanding of marsh response to climate change (Reed, 2002, p. 234). Wu and others (2017) found that marsh biomass reduction has a much larger effect on deposition than reduction in suspended sediment concentration (Wu, Biber, et al., 2017, p. 10898). Although rates of conversion to open water have been high in the coastal marshes of Louisiana over the last century, Reed argued that submergence would have "consumed" these marshes already were they fundamentally unable to cope with SLR through accretion (Reed, 2002, p. 237). This highlights the importance of understanding the ecological and geomorphological processes by which coastal marsh systems maintain elevation and how these processes can be used to predict future marsh response.

DeLaune and others (1983) found evidence to support the hypothesis that marsh erosion will occur if coastal submergence accelerates beyond the capacity of the existing sediment supply to maintain elevation, or if sediment supply decreases. The authors used Caseium 137 dating to study vertical accretion in a brackish to saline *Spartina patens* marsh in the Sabine National Wildlife Refuge in Louisiana, where they noted that inland marshes were not keeping pace with subsidence through vertical accretion (Delaune, Baumann, & Gosselink, 1983, pp. 147, 150–151, 155).

Kirwan and Temmerman (2009) examined the connection between the acceleration in global SLR and marsh submergence. In some cases, such as those where the vegetated platform is abruptly submerged, the relationship between marsh loss and sea-level rise is straightforward. This relationship is typically complicated by a variety of factors, including sediment supply, subsidence rates, vegetation disturbances, and anthropogenic modifications to both the chemical conditions of the substrate and to channel morphology (Kirwan & Temmerman, 2009, p. 1802).

The authors evaluated the ability of two numerical models, the Marsh Equilibrium Model (MEM) of Morris and others (2002) and the Temmerman model, to predict elevation response to sea-level change using historical sea level curves from 1700 to 2002. They used these models to predict changes in marsh elevation in response to various rates of future SLR (Kirwan & Temmerman, 2009, pp. 1802–1803; Morris, Sundareshwar, Nietch, Kjerfve, & Cahoon, 2002). In the MEM, increases in marsh platform elevation are determined by sediment concentration in the water column, vegetation productivity and inundation depth at high tide (Morris et al., 2002). Water depth has a positive influence on vegetation productivity up to a critical value, after which productivity begins to decrease (Kirwan & Temmerman, 2009, p. 1802). The Temmerman model calculates marsh accretion based on mineral sediment deposition, organic accretion, and the rate of compaction of buried sediments (Kirwan & Temmerman, 2009, pp. 1802–1803). In both mathematical models, the authors found that marsh accretion rates tend to increase enough to allow coastal marshes to approach a new steady state in response to a one-time increase in sea level. Experiments with a continuously increasing rate of sea-level rise did not approach equilibrium because of the 20- to 30-year lag between marsh accretion and the increasing rate of sea-level rise (Kirwan & Temmerman, 2009, pp. 1802–1803).

Wu and others (2017) reported a similar result for an increasing rate of SLR, finding in their independently-developed model a shorter lag time between marsh collapse and an increase in sea level as the rate of SLR acceleration increases. With rapid SLR, wetlands are less able to compensate for higher water levels (Wu, Biber, et al., 2017, p. 10898). The authors used a mechanistic model which incorporates the MEM and a simplified hydrodynamic model to explore the ecological thresholds of SLR in the Grand Bay National Estuarine Research Reserve (NERR) in Jackson County, Mississippi. This wetland is marine-dominated, receiving little upland sediment, and is more vulnerable than a riverine-dominated system; thus, an ecological threshold is expected to be reached within 100 years (Wu, Biber, et al., 2017, p. 10892).

In using their model to predict whether marsh habitat would be converted to open water, Wu and others (2017) assumed that salt marsh was converted if elevation dropped below the mean low water elevation (-0.197 m with mean sea level as the datum), which they found to closely approximate the elevation of the lower 2.5% quantile of salt marsh elevation in the Grand Bay NERR (Wu, Biber, et al., 2017, p. 10894).

The authors derived an estimated accretion rate based on elevation, estimated suspended sediment delivery, and estimated accretion via root production (Wu, Biber, et al., 2017, p. 10893). They used a simplified hydrodynamic model to simulate the erosion rate using larger velocities to represent severe storms (Wu, Biber, et al., 2017, p. 10894).

Elevation was updated in the model at each time-step based on the derived erosion and accretion rates along with the rates of SLR and subsidence being modeled (Wu, Biber, et al., 2017, p. 10894). Baseline elevation was determined with a 2005 LiDAR dataset, and biomass was estimated based on elevation and sample measurements (Wu, Biber, et al., 2017, p. 10894). Wetland change was simulated in both 2050 and 2100 with rates of SLR ranging from 4 mm per year to 20 mm per year, which is at the high end of the Intergovernmental Panel on Climate Change's (IPCC) 2013 predictions. They also simulated change with various rates of SLR acceleration using a quadratic equation. The ecological threshold was determined based on the inflection point of a sigmoid function fitted to the relationship between total wetland area and SLR or SLR acceleration (Wu, Biber, et al., 2017, p. 10895).

When sea level change was modeled linearly, Wu and others (2017) found the threshold of rate of SLR to be about 8.5 mm per year, and the rate for 2050 was 11.9 mm per year. In each case, the extent of coastal wetlands began to drop dramatically after the threshold was reached (Wu, Biber, et al., 2017, pp. 10895–10896). When the model included an accelerating rate of SLR, the threshold acceleration rate was found to be 9.62 x 10^{-5} meters per year^2 for 2100 and 3.02 x 10^{-4} meters per year^2 for 2050. Based on these thresholds, the authors estimated that a change in sea level of more than 0.73m between 2000 and 2100 will lead to a total collapse of the Grand Bay NERR coastal wetlands (Wu, Biber, et al., 2017, p. 10897). The current rate of SLR at the Grand Bay NERR was reported as 4.1 mm per year (Wu, Biber, et al., 2017, p. 10898).

In applying the same model to determine thresholds in the Pascagoula River Estuary, Wu (2018) found a higher threshold of SLR and SLR acceleration than in Grand

Bay due to increased sediment availability (Wu, 2018). However, the author found that the slope of the sigmoid function was much higher for Pascagoula than for Grand Bay, meaning that there less response time between the point at which the ecological threshold is reached and the point of ecosystem collapse (Wu, 2018). This difference was attributed to the flatter terrain in Pascagoula, as well as a different response of biomass with elevation – above ground biomass appeared to contribute more to accretion in Grand Bay (Wu, 2018). Due to these differences, the model predicted similar losses in total wetland area at 2050 and 2100 in both estuaries (Wu, 2018).

In examining both general characteristics of coastal marsh-SLR interactions and the specific case of the marshes of the Mississippi Gulf Coast, Bilskie and others (2014) predicted that, as coastal areas reestablish long-term equilibrium in response to SLR, shorelines will erode, and marsh vegetation will either migrate inland or be converted to open water (Bilskie et al., 2014, p. 927). The most important factors threatening the short-term stability of salt-marsh ecosystems are reported to be increased coastal flooding, altered inundation patters, and saltwater intrusion up-estuary (Bilskie et al., 2014, p. 927).

Storm Impacts

Though periodic, hurricane impacts can have long-term geomorphic and ecological effects on marsh ecosystems. Damage from storm surge and wind as well as sediment burial can lead to marsh die-back (Guntenspergen et al., 1995, pp. 324–326). Saltwater inundation can also impact vegetation health. Guntenspergen and others (1995) found that salt burn affected intermediate and fresh zones of the marsh more than salt and brackish marsh in his examination of Hurricane Andrew's impact on Louisiana's marshes in 1992 and 1993 (Guntenspergen et al., 1995, p. 331). The authors also found striking lateral compression of marsh vegetation post-Andrew, where the storm had pushed vegetation against hard barriers such as levees, causing substantial topographical changes (Guntenspergen et al., 1995, p. 329). Storm impacts on marsh vegetation cannot be fully assessed until the following growing season; while some of the impacted sites studied by Guntenspergen and others (1995) showed decline in vegetative cover the year following the storm, some sites showed modest recovery, while some exhibited an increase in marsh vegetated cover in 1993 (Guntenspergen et al., 1995, p. 333).

While burial by storm deposition can cause vegetation death, this type of deposition can ultimately augment aggradation in the marsh and may be the primary source of deposition in some Gulf Coast marshes (Williams, 2012, p. 905). Gutenspergen and others found that vegetation at several sites with thick deposition after Andrew recovered relatively quickly, although the composition of this vegetation was different than other sites (Guntenspergen et al., 1995, p. 337). Williams (2012) estimated that Hurricane Ike deposited 16.2 million metric tons along 160 km of the coastline of Texas and Louisiana (Williams, 2012, p. 905). He found that the thickness of sediment deposition in coastal Texas and Louisiana from Hurricane Ike generally declined with distance inland, but the variation in the magnitude of storm deposition found among their sediment cores suggested that many topographical and weather-related factors determine how sediment is distributed (Williams, 2012, p. 904). The magnitude of storm surge found after Ike, along with the relatively small degree of marsh erosion, supports the hypothesis that hurricane deposition is a primary component of marsh aggradation (Williams, 2012, pp. 904–905).

The presence of marsh vegetation tends to dampen the effect of storm surge by reducing wave energy, providing protection against inland flooding. Bilskie and others (2014) examined the sensitivity of storm surge behavior to changes in sea level, topography, and land use/land cover on the Mississippi Gulf Coast (Bilskie et al., 2014, pp. 927–928). They modeled storm surge based on a 1960, 2005, and projected 2050 sea state and estimated topographical conditions for each year (Bilskie et al., 2014, p. 929). The authors found that, between 1960 and 2005, the magnitude of the increase in maximum storm surge level in the northern part of the Pascagoula River Estuary was greater than the magnitude of SLR (amplified). In contrast, maximum storm surge was deamplified in the intermediate and southernmost parts of the marsh, except for the area immediately south of Highway 90, where water accumulates against the raised roadbed but does not flow over it, resulting in higher storm surge levels on the south side of the roadbed (Bilskie et al., 2014, p. 930). The model predicted storm surge amplification of varying degree across the entire estuary between 2005 and 2050 based on predicted land cover for 2050 and SLR scenarios of 15.2 cm, 30.5 cm, and 45.7 cm (Bilskie et al., 2014, p. 931). This change in response in the intertidal marsh zone was attributed to a decrease in flow resistance as more of the marsh was assumed to be converted to open water (Bilskie et al., 2014, p. 932). The westward migration of the Mississippi-Alabama Barrier Islands also impacted storm surge response in the model; this migration has lessened the protective effect of the barrier islands against flooding in the Pascagoula River Basin since 1960 by changing the flow path of storm surge (Bilskie et al., 2014, pp. 930–932).

This study has important implications for both inland flooding scenarios and for the long-term sustainability of the Pascagoula River coastal marsh. If the marsh vegetation is unable to keep pace with SLR acceleration through accretion or inland migration, the loss of marsh extent will lead to more severe inundation, creating a positive feedback loop which will further increase vegetation stress and conversion to open water.

Anthropogenic Impacts

While some categories of SLR and subsidence can themselves be considered human impacts, human activities on a more localized scale also threaten the health and sustainability of coastal marshes. Kennish (2001) reviewed the impacts of various human modifications on salt marsh habitats at a local scale, discussing how human activities can cause or exacerbate accretion deficits (Kennish, 2001, p. 733).

Land reclamation projects which drain and fill coastal marshes to produce agricultural, residential, or industrial real estate are a primary contributor to destruction of tidal marsh habitat (Kennish, 2001, p. 733). Around 300 hectares of coastal wetland area was reclaimed at the mouth of the East Pascagoula River in 1968 to allow for the construction of a new shipyard on the western riverbank. At a cost of $6 million (over $46 million today), sand was pumped from the channel onto the west bank to raise and level the ground for construction and the adjacent portion of the river was widened and deepened (Bureau of Labor Statistics, 2018; Nelson, 2017).

Grid ditching has historically been employed in many coastal wetlands to control mosquito populations by removing standing water from marsh surfaces (Kennish, 2001, p. 733). While it effectively decreases mosquito breeding habitat, this practice also alters hydrological flow in the marsh (Kennish, 2001, p. 733; Watson et al., 2017, p. 672). Tidal waters penetrate further upland, increasing salinity, so that upper marsh is colonized by low marsh vegetation or invasive species. The restriction of normal sediment delivery also inhibits accretion (Kennish, 2001, p. 733; U.S. Army Corps of Engineers, 2009, p. 99; Watson et al., 2017, pp. 674–675). There is no record of mosquito ditching in the Pascagoula River Estuary, but large tracts of marsh in Hancock County near Ansley, Mississippi have been subject to this practice. This area also suffered scouring during Hurricane Katrina in 2005, and invasive species such as Chinese Tallow Tree have heavily colonized this portion of the Hancock County Marshes (U.S. Army Corps of Engineers, 2009, pp. 98–99). The impoundment of marsh areas, usually for the purpose of wildlife management or saltwater intrusion control, can also impact species composition by altering inundation patterns and reducing salinity. Nearly 10% of Louisiana's coastal wetland area was impounded in 1990 (Kennish, 2001, p. 734). There is no evidence that this type of water management practice has been employed in the Pascagoula River Estuary.

Various human activities upstream from coastal estuaries can affect the health of marsh ecosystems. Upstream agriculture tends to increase sediment delivery to coastal areas. The abandonment of agricultural lands as well as the implementation of soil erosion initiatives in the Mississippi River Watershed in the 1930s led to decreased sedimentation in the Lower Mississippi River (Kennish, 2001, p. 737). Dams, reservoirs, and levee systems also decrease downstream deposition as sediments settle behind these manmade impediments (Kennish, 2001, p. 737). While hydrological modifications to the Mississippi River and its tributaries have severely limited fluvial sediment availability in

Louisiana's estuaries, the Pascagoula river is distinguishable as the largest river system in the contiguous United States with no dams or hydrological impediments (Peterson, Weber, & Partyka, 2007, p. 604).

Channelization and dredging activities, while integral for shipping operations, can also severely alter sediment distribution patterns. The removal of dredged material decreases the sediment available for overbank deposition in the marsh (Kennish, 2001, p. 734). The widening and deepening of channels also allows for greater saltwater intrusion, which alters faunal and floral composition (Kennish, 2001, pp. 734–735). Dredging activities can also impact plant and animal life by increasing turbidity (Kennish, 2001, p. 735). Spoil banks and streamside levees associated with the disposal of dredged material decrease sediment supply to the marsh by lessening overbank flooding, inhibiting deposition and accretion (Kennish, 2001, pp. 734–735). The disposal of dredge spoils in the marsh directly destroys marsh habitat by covering vegetation and elevating the land (Kennish, 2001, p. 735).

While salinity in the Pascagoula River Estuary typically ranges from 0 to 15 psu, salinity levels of over 30 psu have been observed near the mouth of the East Pascagoula River, where channelization allows for saltwater to flow across the Mississippi Sound and upriver into the eastern part of the estuary when freshwater input is low (Christmas & Eleuterius, 1973, pp. 81–82; Peterson et al., 2007, pp. 604–614). Christmas and Eleuterius noted a strong salinity wedge near the Escatawpa Pascagoula confluence, with measurements increasing by 10 to 20 ppt at 5-ft intervals (Christmas & Eleuterius, 1973, pp. 81, 97). While Peterson and others (2007) found temperature and salinity were largely homogeneous between the channelized east distributary and the untouched west distributary from December through March, these profiles to varied significantly over the rest of the year (Peterson et al., 2007, p. 610).

The Pascagoula River remains undammed and the estuary contains large stretches of unspoiled, natural marsh, but areas of the shoreline are heavily altered and threatened by pollution, particularly south of the Escatawpa river (Mississippi Department of Marine Resources, 1998; Partyka & Peterson, 2008, pp. 1570–1571). Marsh vegetation is threated by urban development that involves dredging and fill as well as byproduct pollution, and industrial pollution from the Escatawpa river is a primary concern (Mississippi Department of Marine Resources, 1998). Interstate-10, MS-Highway 90, the CSX Railroad Bridge, and Ingalls Shipyard are the only major anthropogenic features within the estuary. Aside from the construction of Interstate-10 in the early 1980s, the expansion of Ingalls Shipyard in 1968, and the rerouting of the Highway 90 causeway sometime between 1940 and 1955, there has been little to no construction to the interior of the marsh since the 1940s. The west distributary of the Pascagoula River remains relatively unspoiled, and development bordering this area of the marsh is largely residential (Peterson & Partyka, 2006, p. 750; Peterson et al., 2007, p. 604). The east distributary is bordered by Ingalls shipyard at the mouth of the river and is dredged periodically from the Escatawpa river confluence to the Mississippi Sound, with the maintained canal extending up the Escatawpa River (Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, & Office of Coast Survey, 2015; Peterson et al., 2007, p. 604).

The future diversion of water from the Pascagoula River or its tributaries could also be disastrous to the ecosystem, resulting in increased saltwater intrusion from the

Mississippi Sound as well as a decrease the dilution of pollutants from upstream (Mississippi Department of Marine Resources, 1998). Plans to expand the Strategic Petroleum Reserve (SPR) at Richton, Mississippi in 2006 were met with strong local opposition due to concerns about salinification and oil spills and ultimately canceled in 2011 (Department of Energy, 2006a, 2006b; Kirgan, 2011) More recently, the US Army Corps of Engineers (USACE) studied a proposal to dam several tributaries of the Pascagoula River create two artificial lakes in George County, Mississippi. The stated primary purpose of project was drought resiliency, but the lakes would also have been used for real estate development and recreation. The project was unanimously opposed by the Pascagoula city council in February 2017. The USACE have not completed their environmental impact statement or issued a record of decision (Muller & Zilbermints, 2017; Pat Harrison Waterway District & George County Board of Supervisors, 2016).

Measuring wetland change using remote sensing

Data

Wide-scale mapping of coastal wetland habitats using remotely sensed image data began in the late 1960s, when the value of coastal wetland habitats began to be recognized and legislation was designed to protect and monitor these areas (Hardisky, Gross, & Klemas, 1986, p. 453). Aerial and satellite image data provide a window into past habitats as well as allowing for a synoptic view of the landscape not afforded by *in situ* field observations. However, the availability of imagery with both high spatial and temporal resolution constrains our ability to map vegetation change in estuarine zones. Satellite remote sensing systems such as Landsat’s Thematic Mapper (TM) obtain imagery at a very high temporal resolution. Multispectral satellite image data have been used to map large wetland areas, such as the Chesapeake Bay Watershed. Hyperspectral data such as from the Advanced Visible Infrared Imaging Spectrometer (AVIRIS) have also been effectively used to discriminate among specific wetland vegetation classes (Klemas, 2013, pp. 1017–1018). However, the spatial complexity of marsh ecosystems, particularly in critical or rapidly-changing sites, typically requires higher-resolution data than Landsat imagery (30 meters GSD) affords (Ghosh, Mishra, & Gitelson, 2016, p. 40; Higinbotham, Alber, & Chalmers, 2004, p. 671; Klemas, 2013, p. 1017).

Multispectral SPOT (Systeme Pour L'Observation de la Terre) satellite imagery, available at 6 or 10 meters GSD, is also used in many vegetation mapping studies. The SPOT satellites also collect higher-resolution panchromatic imagery, as fine as 1.5 meters GSD (Jensen, 2015, p. 602; Klemas, 2013, p. 1017). This type of commercial data, however is not typically available free of charge. Historical aerial film imagery is available at no charge or at a relatively low cost (around $30 per frame) from government agencies such as the United States Geological Survey (USGS) and is typically available at a decadal timescale. The availability of multispectral aerial image data varies, but the high spatial resolution of this imagery, typically around 1 meter GSD, makes it an excellent tool for mapping past habitats (Jeter & Carter, 2016, p. 985). Modern airborne, georeferenced digital camera imagery provides many technological benefits over aerial film photography, including improved quality, faster processing, and extremely fine spatial resolution (Klemas, 2013, p. 1018). However, this type of data collection is only feasible for small-scale projects and does not provide a historical perspective (Klemas, 2013, p. 1018).

Spectral Features

Wetland mapping is typically accomplished using multispectral or hyperspectral data (Klemas, 2013, p. 1018). Color-infrared photography is widely used because it provides contrast between upland and wetland vegetation at a fine spatial scale (Hardisky et al., 1986, p. 453). Vegetation exhibits unique spectral properties in the visible and infrared wavelengths (Klemas, 2013, p. 1019). As with most vegetation, radiance in the red wavelengths is negatively related to live marsh biomass, while near-infrared radiance is positively related (Hardisky et al., 1986, pp. 454–455). The spectral properties of both water and vegetation in the near infrared portion of the electromagnetic spectrum make infrared imagery particularly useful for the study of wetland habitats. Water absorbs infrared radiation very efficiently. Water bodies reflect virtually no infrared radiation aside from cases of specular reflection, high sediment concentrations, or very shallow water where bottom reflectance can be sensed (Jensen, 2006, p. 421). While healthy vegetation tends to reflect strongly in the near-infrared, the vegetative characteristics and physical structure of marsh grasses, particularly their vertical orientation, tend to result in a lower spectral signature across all wavelengths than other vegetated canopies, allowing for differentiation between marsh grasses and other types of vegetation such as trees and shrubs (Bartlett & Klemas, 1981, p. 1695; Jensen, 2006, p. 359). Ghosh and others found a reduced red-edge presence compared with terrestrial vegetation in their *in situ* measurements of spectral reflectance in tidal wetlands in the Northern Gulf of Mexico, attributed to perennial inundation as well as canopy structure and vegetation density. The same effect was also noted for spectral reflectance data derived from MODIS satellite imagery of the same areas (Ghosh et al., 2016, p. 49). *Juncus roemerianus*, the dominant vegetation species in Mississippi's gulf coast marshes, exhibits particularly low reflectance in the visible wavelengths owing to its dark brown foliage, making it even more visually distinguishable from other vegetation types in aerial imagery (Eleuterius, 1976, p. 289; Higinbotham et al., 2004, pp. 672–673).

The variety of plant morphologies present in salt and brackish marshes produces canopy architectures which have different reflectance characteristics. Canopy architecture influences how much light penetrates the canopy as well as the percentage of leaf surfaces which are oriented horizontally to reflect incident radiation (Hardisky et al., 1986, p. 456). Canopy types can be divided into broadleaf, gramineous, and leafless. In broadleaf canopies, composed of plants with largely horizontal leaves such as *Iva*, *Polygonum*, and *Solidago*, the relationship between live biomass and the red to near-infrared vegetation index is strongest, with the vegetation index increasing more as biomass increases, because horizontal surfaces reflect the most incident radiation. The increase in reflectance with biomass, while still positive, is not as strong in gramineous canopies, which have a more random distribution of reflective surfaces, and leafless canopies, which have mostly vertically oriented vegetation (Hardisky et al., 1986, p. 456).

The biophysical characteristics of marsh vegetation, which can vary due to plant health, phenology, canopy moisture, and environmental disturbances, affect the spectral signature (Carter, 1993, p. 239; Jensen, 2006, pp. 362–363; Jensen, Olson, Schill, Porter, & Morris, 2002, p. 30). Living plant material reflects solar radiation differently than dead plant material (Lorenzen & Jensen, 1988, p. 345). Dead biomass (plant litter) and soil reflectance are the two of the most important environmental factors which influence marsh canopy reflectance (Hardisky et al., 1986, p. 455). The presence of dead biomass tends to increase visible reflectance, whereas the presence of soil, particularly dark, wet soil as is typical in a marsh habitat, will decrease near-infrared reflectance (Hardisky et al., 1986, p. 455). Canopy orientation and density influences the amount of reflectance from these sources. Soil reflectance does not contribute much to total reflectance unless the marsh canopy is very sparse. Environmental influences such as tidal changes and wind can influence the position and orientation of dead material in a marsh canopy, thereby changing how strongly it influences the spectral signal of the canopy (Hardisky et al., 1986, p. 455). Solar angle, influenced by latitude, date, and time of day, can also change spectral reflectance of the marsh canopy (Hardisky et al., 1986, pp. 455–456).

Bartlett and Klemas (1981) found that marsh canopy reflectance in visible portion of the spectrum depends on the relative proportions of live and dead biomass in the canopy (Bartlett & Klemas, 1981, p. 1697; Jensen et al., 2002, p. 30). They also found that infrared reflectance was dependent on the amount of vegetation present and its growth form (Bartlett & Klemas, 1981, p. 1702; Jensen et al., 2002, p. 30).

Lorenzen and Jensen (1987) found similar results in their assessment of seasonal changes in biomass and spectral reflectance in two coastal wetlands in Denmark. Using *in situ* reflectance and biomass data, the authors evaluated the impact of live, dead, and total biomass on changes in reflectance in the blue, green, red and near-infrared wavelengths (Lorenzen & Jensen, 1988, p. 346). Two sets of measurements were taken at each study site, in March and June and May and June. Live vegetation absorbs a large proportion of incident visible radiation. Lorenzen and Jensen found that the proportion of living biomass was negatively correlated with reflectance in the red, green and blue wavelengths (Lorenzen & Jensen, 1988, p. 349). Similarly, Carter (1993) found that reflectance increases consistently across the visible portion of the spectrum when plants are under stress, in both a variety of species and stress conditions (Carter, 1993, p. 242). However, Carter found that infrared reflectance was less responsive to stress and did not change with a similarly consistent pattern. Increases in infrared reflectance in response to stress appeared to be most closely related to the degree of leaf dehydration resulting from the stress conditions when examined across species (Carter, 1993, pp. 239, 242–243). Lorenzen and Jensen (1987) found a positive curvilinear relationship between near-infrared reflectance and total biomass as well as green biomass (Lorenzen & Jensen, 1988, p. 345).

Because of these reflectance changes, an awareness of the health and phenology of the vegetation present as well as species represented in the imagery is crucial when assessing marsh habitats using remote sensing. During winter months, vegetation may have died back, causing the proportion of reflectance from soil or dead biomass to increase relative to reflectance from green biomass.

Remotely-sensed imagery can be used not only to map areal extent of wetlands, but to quantify biomass, productivity, and other biophysical data in wetland areas by using image data to extrapolate *in situ* measurements to a large area (Hardisky et al., 1986, p. 453). Jensen and others (2002) used high-resolution, multi-band aerial photography of the ACE Basin National Estuarine Research Reserve in South Carolina to map *Spartina alterniflora* salt marsh as well as assess four biophysical characteristics: biomass, leaf-area-index, and chlorophyll *a* and *b* content (Jensen et al., 2002, p. 28).

Remote sensing provides a less destructive and time-consuming way of measuring these biophysical characteristics. Thus, the authors hoped to ascertain a possible relationship between individual bands of image data and these (Jensen et al., 2002, pp. 28–30). Four-band color-infrared imagery was acquired September 23, 1999 using an ADAR digital camera at 0.7 meters GSD. Reflectance characteristics of a gray calibration target were collected at the same time as the imagery, and an empirical line calibration was performed to compute spectral reflectance from the image data. These reflectance values, along with red simple ratio (SR), normalized difference vegetation index (NDVI) and soil-adjusted vegetation index (SAVI) bands, were regressed against *in situ* biophysical observations (Jensen et al., 2002, pp. 32–33).The near infrared, SR, SAVI, and NDVI bands all showed positive correlations with all four measured biophysical parameters. However, the authors found that the near-infrared band was most strongly correlated (r^2 = 0.81) with these parameters (Jensen et al., 2002, p. 33).

Ghosh and others (2016) monitored tidal wetland biophysical characteristics in the northern Gulf of Mexico on a fine temporal scale using 250 and 500m GSD Moderate Resolution Imaging Spectroradiometer (MODIS) data (Ghosh et al., 2016, p. 40). The authors compared MODIS data with *in situ* measurements of reflectance, biomass, leaf chlorophyll content, vegetation fraction, and leaf area index over several months during the 2010 and 2011 growing seasons in order to model these biophysical characteristics across the Gulf of Mexico Coast at 8-day intervals between 2000 and 2016 (Ghosh et al., 2016, pp. 41–43; Mishra, Ghosh, & Gitelson, n.d.). Based on their modeling, they found that peak growth and photosynthetic activity occurred in the Pascagoula River Estuary in

August or September, with a period of senescence occurring from October until the following March or April (Mishra et al., n.d.).

Higinbotham and others (2004) visually interpreted both spectral and textural image features to manually classify marsh vegetation in two Georgia estuaries. The authors used January 1993 USGS black and white Digital Orthophoto Quarter Quads, April 1974 USGS color-infrared aerial photos, and January 1953 black and white aerial photos. Ground surveys were completed in October 1999 and July 2000 to assess accuracy (Higinbotham et al., 2004, p. 673). They identified four marsh zones—salt marsh, *Juncus*, brackish marsh, and fresh marsh—based on the primary vegetation type, finding that vegetation composition in both estuaries was primarily driven by salinity (Higinbotham et al., 2004, p. 670). The authors also found an increase in the total area of brackish marsh from January 1953 and April 1974 which was largely reversed when between April 1974 and January 1993. Shifts took place largely between areas classified as *Juncus* and areas classified as either fresh or brackish marsh (Higinbotham et al., 2004, pp. 676–680). This study highlights the importance of phenology when using remote sensing to detect vegetative changes. While these interim changes may well be attributable to the dynamic nature of the marsh ecosystem, it also seems that seasonal changes in reflectance of brackish and freshwater marsh species in the study area should be examined. Because the authors identified *Juncus* marsh based on its low visible reflectance, the spectral signature of other marsh species in winter imagery could have been similar to *J. roemerianus*.

Phenology. Phenological cycles place an important limitation on our ability to understand habitat change over time through remote sensing. While multi-year data obtained during the same season is not always available, multi-seasonal data must be used with caution. Temporal changes in the characteristics of land cover classes can lead to systematic misclassification of land cover when different image dates are examined, as seasonal variations in spectral reflectance can cause separate land cover classes to have a similar spectral signature at some points during the year. Eleuterius and Caldwell (1984) directly observed 196 species of flowering plants in Mississippi's tidal marshes over a 15-year period to determine flowering phenology. They found the peak flowering period occurs in July, but peak flowering is later in brackish and saline marshes (August and September, respectively) (Eleuterius & Caldwell, 1984, p. 172). While the authors observed peak flowering of *Spartina alterniflora* and *Phragmites australis* from September to November and September to October, peak flowering of *Juncus roemerianus* was observed from January to May (Eleuterius & Caldwell, 1984, p. 174). Butera (1978) found June and September to be the optimum months for the discrimination of six species of marsh vegetation based on their spectral separability, with April and May also exhibiting high separability. These species included *Baccharis halimifolia*, *Spartina patens*, *Spartina alterniflora*, *Distichis spicata*, and *Juncus roemerianus* (Butera, 1978, pp. 9–10). The author examined marshes nearby Lake Borgne, Louisiana using Landsat MSS imagery from 7 different months, acquired from 1974 to 1977 (Butera, 1978, pp. 2–4). In addition to identifying times peak of separability among all 5 species, Butera determined the optimum month for detection for specific species based on their seasonal spectral characteristics, finding that *J. roemerianus* was most accurately detected in April, and *S. alterniflora* in May (Butera, 1978, p. 10).

Within-year variation in vegetated cover may be incorrectly assumed to represent long-term change (O'Hara, King, Cartwright, King, & Member, 2003, p. 2008). O'Hara and others (2003) used multi-year, multi-seasonal Landsat-5 and Landsat-7 images to classify land cover along the Mississippi Gulf Coast (O'Hara et al., 2003, p. 2005). The authors analyzed imagery from February and September 1991 and February and July 2000. They found that the spectral profiles of each land cover type—including Bottomland Hardwood, Coastal Marsh, Deciduous, Freshwater Marsh, and High- and Low-Density Urban areas—varied predictably between the leaf-on and leaf-off imagery (O'Hara et al., 2003, pp. 2007–2009). In all land cover categories, reflectance in bands 1-6 (representing wavelengths from 0.45 micrometers to 1.75 micrometers and 10.4 to 12.5 micrometers) tended to be lower in the February imagery, with the exception of higher shortwave infrared and thermal reflectance in February in the Bottomland Hardwood land cover class (O'Hara et al., 2003, p. 2008). The Coastal Marsh and Freshwater Marsh Categories both exhibited depressed spectral reflectance in the winter; a distinctive peak in the leaf-on reflectance curve of Freshwater Marsh in the near-infrared band was missing in the leaf-off reflectance curve, causing the spectral profiles of the two land cover categories to appear more similar in the winter imagery than in the summer/fall (O'Hara et al., 2003, p. 2008). The relatively low spatial resolution of Landsat imagery means that these results should be applied to higher-resolution data with caution. However, these results provide justification for grouping marsh vegetative classes in classifications using multi-seasonal imagery as well as illustrating the importance of the possible impacts of phenology on classification accuracy.

Textural features

The inclusion of information on the spatial variability in pixel brightness values is an important aspect of image classification which facilitates the separation of texturally homogeneous marsh areas from other habitat types, such as woodland and shrubland (Haralick, Shanmugam, & Dinstein, 1973, pp. 617–618; Jeter & Carter, 2016, pp. 986–987; Nicholson, 2017, pp. 8–10). Textural features can assist in the identification of marsh vegetation even during senescence because they measure spatial variability instead of simple leaf reflectance characteristics, which tend to change seasonally. Textural analysis also allows for the discrimination of habitat types in the years prior to the 1970s for which only panchromatic imagery was available (Haralick et al., 1973, pp. 617–618; Jeter & Carter, 2016, pp. 986–987; Nicholson, 2017, pp. 8–10). The ENVI texture filter computes second-order statistics using a co-occurrence matrix to calculate local texture values within a moving window of a user-specified size (Harris Geospatial Solutions, 2018). Within this window, the relationship between a central cell and each of its nearest neighbors is examined in terms of value, distance, and direction. These textural features contain information about the spatial distribution of tonal variations within a single band of an image (Haralick et al., 1973, p. 612).

Jeter and Carter (2016) used computed texture bands contrast, correlation, energy, and entropy in a Maximum Likelihood (ML) classification to identify habitat types at 1 meter GSD on Horn Island, Mississippi. The study used panchromatic aerial imagery from October 1940 and May-August 2010 (Jeter & Carter, 2016, pp. 985–989). Change detection analysis between the two classification images indicated a consistent increase in the extent of water and marsh areas over the study period (Jeter & Carter, 2016, pp. 989–992).

Similarly, Nicholson (2017) used computed textural features (mean, variance, entropy, angular second moment, and homogeneity) in her study of habitat change in the Grand Bay NERR in Jackson County, Mississippi (Nicholson, 2017, p. 13). The author used ML classifications to compare land cover for image dates February 13, 1955, February 19, 1992, and October 16, 2014 (Nicholson, 2017, p. 12). Land cover was divided into four classes—woodland, water, marsh, and salt panne. The author found a decrease in marsh extent in the Grand Bay NERR of approximately 5% between 1955 and 2014 (Nicholson, 2017, p. 11).

Classification methods

Thematic information such as land use and land cover categories can be extracted from remotely sensed image data using a variety of pattern recognition methods (Jensen, 2015, p. 361). Image classification methods can be parametric, nonparametric, or nonmetric, depending on the assumptions the user can make about the statistical distribution of the data values (Jensen, 2015, p. 361). Most classification schemes process an image on a pixel-by-pixel basis (per-pixel classification), but newer object-based classification methods are based on the analysis of homogeneous patches rather than single pixels (Jensen, 2015, p. 362).

Classification logic can also be hard or fuzzy. Hard classification methods produce crisp boundaries, but should include fuzzy class definitions since these hard boundaries encompass transitional zones (Jensen, 2015, pp. 362, 376). Fuzzy logic can sometimes extract more precise land-cover information by accounting for the heterogeneous mixture of land cover types that might be represented in a single pixel, but fuzzy classifications schemes are usually developed for specific sites and may not be transferable to other environments (Jensen, 2015, pp. 362, 376).

Classification logic can be unsupervised, where land cover types are not known *a priori*, or supervised, where fieldwork, visual interpretation and personal experience of the analyst inform the classification using training sites, or Regions of Interest (ROIs) (Jensen, 2015, p. 362).These training sites should be representative of each class across the study area, else they can be geographically stratified to represent different class conditions in different parts of the study area (Jensen, 2015, p. 376). The value in each band for each pixel in the training Region of Interest (ROI) is analyzed statistically to provide spectral information about the land cover class (Jensen, 2015, p. 378). Information is typically narrowed down using statistical and graphical analysis to determine the most appropriate and relevant bands to use for classification (feature selection) (Jensen, 2015, p. 382).

When training data are available and data values for each class can be assumed to be normally distributed, a Maximum Likelihood (ML) classification algorithm is typically used (Jensen, 2015, p. 398). In this method, an *n*-dimensional multivariate normal density function is computed based on the training data which approximates the probability density for each class within the feature space (Jensen, 2015, p. 399). The probability that each unknown pixel belongs to a specific class is calculated using this function, and the pixel is assigned to the class to which it most likely belongs based on these probabilites (Jensen, 2015, pp. 399–401).

In some cases where ground reference data is unavailable, researchers have derived training data for use in a supervised classification. In their class-learning method, O'Hara and others (2003) used an unsupervised ISODATA (Iterative Self-Organizing Data Analysis) technique to discern the spectral characteristics of land cover classes over a subset of their study area along the Mississippi Gulf Coast. They then used these characteristics to select training data for a supervised ML classification applied over the entire study area (O'Hara et al., 2003, pp. 2009–2011). Jeter and Carter (2016) derived training data for their study of decadal habitat change on Horn Island, Mississippi by comparing the textural features of their two datasets. A 2010 ground survey provided training data for the 2010 classification. The coefficient of variation (CV), which is unitless and independent of brightness value, was then computed for both sets of imagery. The range of the CV values of each land cover class was then used to select 1940 ground reference data (Jeter & Carter, 2016, p. 989). Nicholson used a similar method for selecting training data historical images of the Grand Bay NERR (Nicholson, 2017, p. 14).

The Pascagoula River Estuary

To date, there has been no comprehensive study of the historical extent of marsh vegetation in the Pascagoula River Estuary. The vegetative characteristics of this ecosystem, however, have been well-documented since the 1970s. The Pascagoula River Marsh Preserve, as defined by the Mississippi Department of Marine Resources (MDMR) in 1998, covers approximately 4,500 ha at the mouth of the Pascagoula River in Jackson County, Mississippi (Mississippi Department of Marine Resources, 1998). Christmas

(1973) reported 19,467 total acres (7,878 ha) of fresh and salt marsh associated with the entire Pascagoula River system in 1973 based on the measurement of USGS topographic maps (Christmas, 1973, p. 15). Eleuterius (1973) reported 13,340 acres (5,399 ha) of *Juncus roemerianus*-dominated salt marsh associated with the Pascagoula River (Christmas & Eleuterius, 1973). The area mapped in the present study was smaller than the area examined by Christmas (1973), as the inland portions of several tributaries (the Escatawpa river and Bluff Creek) along with the associated freshwater marsh areas, were not considered (Figure 1) (Christmas, 1973, pp. 30–31).

The *Cooperative Gulf of Mexico Estuarine Inventory and Study* (1973) provided the first comprehensive study of Mississippi's estuaries, detailing the biology, sedimentology, and hydrology in the major estuaries of Mississippi's Gulf Coast (Christmas, 1973, p. 31). In this volume, Eleuterius described the species composition and zonation patterns in the Pascagoula River Estuary as well as related ecological information such as salinity levels (Eleuterius, 1973, pp. 172–187). Eleuterius also addressed various topics regarding the ecology, biology, and phenology of coastal marsh vegetation in Mississippi in a large body of related literature, including extensive research on *Juncus roemerianus*, the dominant plant species in Mississippi's coastal marshes (Eleuterius, 1975, 1976, 1984; Eleuterius & Caldwell, 1985).

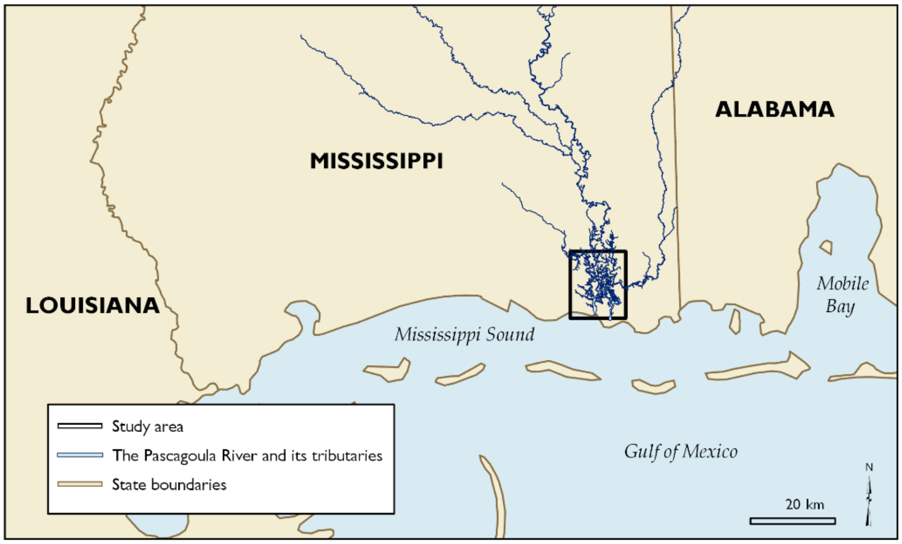


Figure 1. Location of Study Area

The present area of study, defined by the black rectangle on the map, encompasses the intertidal zone of the Pascagoula River Estuary and its immediate freshwater boundaries. The estuary is located in Jackson County, Mississippi at approximately 30°27' N, 88°34' W.

The estuaries of the Mississippi Gulf Coast are home to over 300 species of emergent plants, but Black Needle Rush (*Juncus roemerianus*) dominates the Pascagoula salt marsh, with Smooth Cordgrass (*Spartina alterniflora*) appearing in narrow, disjunct bands bordering waterways (Eleuterius, 1973, p. 152; Mississippi Department of Marine Resources, 1998). The Pascagoula River Estuary includes a range of aquatic plant habitats, including shallow coastal waters, marsh, and freshwater swamp (Cho, 2011, p. 5).

According to Eleuterius' 1973 study, *Juncus roemerianus* made up 45.3% of the total plant population over the entire growing season, composing 57.8% of the surveyed marsh in April, 42.1% in June and 43.7% in August (Eleuterius, 1973, p. 155). Coverage was higher in more saline areas, ranging from 50-60% at the intermediate/brackish stations in April to nearly 100% at the most saline station in June, when *J. roemerianus* coverage tends to peak (Eleuterius, 1973, p. 156). *J. roemerianus* did not occur at all at the inland freshwater station. *Sagittaria lancifolia, Spartina patens, Spartina alterniflora*, and *Spartina cynosuroides* together made up 28.5% of the total population over the entire growing season (Eleuterius, 1973, p. 155). *S. lancifolia* occurred more frequently in the freshwater marsh, decreasing in density as salinity increased. *S. patens* and *S. cynosuroides* were found in the brackish regions of the marsh, and *S. alterniflora* appeared from the brackish to the most saline areas (Eleuterius, 1973, p. 155).

The Pascagoula River marsh can be divided into zones ranging from most saline to least based on vegetation types, which are strongly dependent on salinity levels. These are described by Eleuterius as the saline, brackish, intermediate, and freshwater marsh (Eleuterius, 1973, pp. 159–160). They can also be described as the tidal salt marsh, the tidal oligohaline marsh (including both brackish and low-salinity "intermediate" marsh), and freshwater marsh (Cho, 2011, pp. 5–9).

The most saline region of the Pascagoula River marsh, the tidal salt marsh, is vegetated almost exclusively by *J. roemerianus* (Eleuterius, 1973, pp. 173–174). Tidal salt marshes are formed in the intertidal zone of low-energy, protected coastal areas. They are dominated by rooted grasses, rushes, and sedges that can tolerate the harsh conditions which exist in the coastal zone, including moderate to high salinity levels, tidal fluctuation, and temperature extremes (Cho, 2011, p. 7). In the case of the Pascagoula salt marsh, *J. roemerianus* is bordered by *Spartina alterniflora*, which Eleuterius found to exhibit distinct zonation, occurring in a narrow, discontinuous band along the boundary between *J. roemerianus* stands and open water bodies (Cho, 2011, p. 7; Eleuterius, 1973, pp. 173–174). *Spartina patens, Schoenoplectus americanus* (syn.

Scirpus olneyi) and *Schoenoplectus robustus* can also occur at the periphery of the saline marsh interspersed among *J. roemerianus* (Eleuterius, 1973, p. 173).

The tidal oligohaline marsh is similarly dominated by non-woody, salt-tolerant plants, but due to lower salinity levels exhibits higher degrees of productivity and animal, plant and microbe biodiversity (Cho, 2011, p. 8). *S. alterniflora* decreases and terminates in the brackish zone as salinity levels drop and river banks become steeper due to erosion from natural flow and water traffic. While *J. roemerianus* still dominates, monospecific stands begin to give way to increasing species diversity (Eleuterius, 1973, p. 173). Secondary species in this zone include *Cladium jamaicense, S. cynosuroides, S. patens, Sagittaria lancifolia* and *Schoenoplectus americanus,* which are also found interspersed with *J. roemerianus* in more saline areas, as well as *Limonium caroliniana*, *Boltonia asteroides, Ludwigia sphaerocarpa*, *Lythrum lineare, Ipomoea purpurea,* and *Polygonum setaceum* (Cho, 2011, p. 8; Eleuterius, 1973, p. 1973).

The lowest-salinity reaches of the tidal oligohaline marsh, which Eleuterius describes as the intermediate marsh, marks the upper limit of *J. roemerianus*. In this area of the marsh, a natural levee along the Pascagoula river becomes increasingly pronounced, inhabited by *Phragmites australis* (Common Reed) in almost pure stands along with the shrub *Baccharis halimifolia* (Eleuterius, 1973, pp. 173–174, 177; Peterson & Partyka, 2006, p. 750). *Schoenoplectus tabernaemontani* occupies relatively deep water (Eleuterius, 1973, p. 174). Many freshwater species are found intermixed with *J. roemerianus* in this zone, including *Cladium jamaicense, Eleocharis cellulose, Schoenoplectus americana, Sagittaria lancifolia, Pontederia cordata, Crinum americanum* and *Iris virginica*. The more salt-tolerant *Spartina patens, Spartina* *cynosuroides, Schoenoplectus americanus,* and *Schoenoplectus robustus* are absent (Eleuterius, 1973, p. 153).

Peterson and Partyka (2006) surveyed the main channels and bayous of the Lower Pascagoula River basin to map the occurrence of the invasive *Phragmites australis*. They mapped 48.9 hectares of coverage. 47.2% of this extent was monospecific stands, while 27.2% and 26.6% of coverage was designated as mixed-tree or mixed-marsh, respectively (Peterson & Partyka, 2006, pp. 749–750). The authors found *P. australis* colonized higher elevation ground along the east distributary while favoring the low salinity reaches of the west distributary (Peterson & Partyka, 2006, p. 750). The difference in the pattern of coverage between the east and west distributaries was attributed to differences in habitat modification which result in greater salinity intrusion in the east distributary (Peterson & Partyka, 2006, p. 750). Despite favoring fresh or low-salinity water, *P. australis* can germinate in salinities of up to 20 psu and thus aggressively colonizes disturbed areas (Peterson & Partyka, 2006, pp. 748, 750). The bulk of mapped coverage exists in the brackish and intermediate portions of the estuary, although *P. australis* occurrences were noted in all zones of both the east and west distributaries (Peterson & Partyka, 2006, p. 751). While *P. australis* is likely a native species to the gulf coast, it is possible that coverage has increased over time due to its invasive nature (Peterson & Partyka, 2006, p. 754).

At its inland boundary, the estuary is bordered by freshwater swamp, which is dominated by woody vegetation and trees. Soil conditions are moist, and shallow, standing water is common. The water tends to be slightly acidic and low in nutrients (Cho, 2011, p. 10). Freshwater tidal forests are typically associated with high-flow river systems with gradual elevation gradients and generally mark the inland limit of tidal influence in estuarine ecosystems (C. J. Anderson, Lockaby, & Click, 2013, pp. 1–2). *Taxodium distichum* (Bald Cypress), *Taxodium ascendens* (Pond Cypress) and *Nyssa aquatica* (Water Tupelo) are typical of the Mississippi Cypress-Tupelo swamp (Cho, 2011, p. 10). The vegetation survey completed for the present study found *T. distichum* dominates wooded areas at the inland boundary of the marsh.

Mooneyhan and Criss (2014) used high-resolution Quickbird imagery from 2007/2008 and WorldView imagery from 2011 to map ecological communities in the Hancock County Marsh Preserve and the Pascagoula River Marshes Preserve using an unsupervised ISODATA classification (Mooneyhan & Criss, 2014, pp. 1–2). Their classification included four band color-infrared data along with a calculated NDVI band, and the output classes were manually defined according to the Mississippi Natural Heritage Program (MNHP) Ecological Communities List. The fifty classes produced by the classification algorithm were also grouped into broader categories, including water, mudflats, soil/sand, low marsh, intermediate-high marsh, shrub/scrub and trees (Mooneyhan & Criss, 2014, pp. 3–5). A change detection was not performed between the two sets of imagery because of the noticeable amount of seasonal variability in the imagery, which was acquired over several months. Because of the fineness of the land cover classes, soil saturation conditions could have also accounted for some of the variability in the classifications (Mooneyhan & Criss, 2014, p. 5).

While marsh vegetation in the estuary has been well-characterized by these studies, they do not provide a comprehensive view of the change in marsh extent over time, and the extent of marsh vegetation before 1972 is not addressed in the literature. A synoptic study of land cover in the Pascagoula River Estuary since the 1950s to determine the trajectory and magnitude of marsh change will inform further research on the biogeography of the estuary as well as aid in restoration and conservation decision-making.

While coastal marsh ecosystems provide a host of valuable ecosystem services, these habitats are increasingly vulnerable to human impacts on both a global and local scale. Rising sea levels and other aspects of climate change push the limits of natural biofeedbacks that preserve marsh substrate elevation, and human interventions in coastal wetlands hinder natural marsh maintenance processes to produce impacts far beyond the immediately visible damage caused by direct destruction. The remote sensing of marsh habitats presents many unique challenges but can provide crucial historical insight. This type of analysis is integral to our understanding of both the past and future of these fragile ecosystems in the face of rising seas and other anthropogenic threats.

CHAPTER III - METHODS

Image Analysis

Data and preprocessing

Three sets of aerial image data were selected based on resolution and image clarity. The earliest available high-resolution aerial imagery of the Pascagoula River Estuary was obtained using panchromatic film by the USGS February 13, 1955 at a scale of 1:23,600. The individual frames were digitized at 1000 dpi. Sixteen frames were needed to cover the study area. These were acquired from the USGS at no cost (U.S. Geological Survey, n.d.-a).

The National Aerial Photography Program (NAPP) collected three-band color-infrared film imagery of the area on February 12, 1996 at a scale of 1:40,000. This imagery was digitized at 1000 dpi (U.S. Geological Survey, n.d.-a). Nine frames were needed to cover the study area, which were acquired from USGS at a cost of $30 per frame.

The National Agriculture Imagery Program (NAIP) collected four-band color-infrared imagery October 5 and 16, 2014 and November 2016, but cloud cover over the study site in 2016 made the 2014 images a superior dataset for this study. This imagery was collected using a Leica ADS100 digital pushbroom sensor at a spatial resolution of 1 meter GSD. Airborne GPS data was acquired at the time of collection for geopositioning. The reported horizontal accuracy is ± 4 meters at 95% confidence (Mississippi Automated Resource Information System, n.d.-a). Nine digital ortho quad tiles were needed to cover the study area. These were downloaded from the Mississippi Automated

Resource Information System (MARIS) (Mississippi Automated Resource Information System, n.d.-c).

Each individual frame from the 1955 and 1996 datasets was georeferenced using ArcMap in NAD83, Zone 16N, to the 2014 NAIP dataset with an RMSE of 1.5 or less. The edges of each frame and fiducial marks were removed and each dataset was mosaicked in ENVI. Shadowing from large trees was misinterpreted in initial classifications as water, so all three mosaics were resampled to 3 meters GSD to minimize the effects of shadows by averaging darker, shadowed pixels into brighter woodland pixels. This size was chosen based on visual inspection and the discernable size of treetops in the original imagery. This was the largest pixel size that could be used without smoothing woodland areas to an extent at which they were not readily distinguishable from other types of vegetation based on apparent texture.

The study area was selected based on distance from the Pascagoula River, elevation, and the known extent of present-day marsh. An elevation mask was developed from a 2-foot contour map of Mississippi's coastal counties derived from digital aerial stereo photography obtained in spring 2007 (Mississippi Automated Resource Information System, n.d.-b). The contour map was obtained from MARIS at no cost. The closest elevation contour which contained all marsh visible in each image date was 7 feet (2.13 meters). This polyline was extracted and simplified for use as the study area boundary. The maximum Monthly Mean High High Water Levels observed since October 2005 at the Pascagoula NOAA Lab (NOAA Station ID 8741533) and since February 2008 at the Port of Pascagoula (NOAA Station ID 8741041) both fall well within this boundary at 2.03 feet (0.62 meters) and 1.99 feet (0.61 meters) (Center for Operational Oceanographic Products and Services, 2018).

The availability of high-quality, high-resolution imagery constrained the current study. Because high-water events can influence the classification of marsh vegetation, care was taken to avoid imagery obtained during or after flood or storm events (Campbell & Wang, 2018, p. 5173). The USGS obtained the earliest available color-infrared imagery of the area of workable quality and resolution in November 1979. However, this imagery was not suitable for comparison to the other datasets used in the study as it was taken shortly after Hurricane Frederic, which made landfall at Dauphin Island, Alabama September 12, 1979 and caused extensive damage to the marsh which is evident in the imagery (Barry 2016). The National High Altitude Photography Program (NHAP) obtained three-band color infrared aerial imagery of the area April 9, 1980, but the data is of too poor quality for analysis. Small streams in the imagery are indistinguishable from marsh vegetation, particularly in the northern part of the marsh. This may in part be attributable to high water levels at the time of image aquisition, but is more likely due to degradation of the film which has affected the quality of the near-infrared band. The blue cast in the imagery indicates degradation prior to processing which is typical of color-infrared photography acquired using high-speed film (U.S. Geological Survey, n.d.-b).

A 2016 field study completed between May 21 and June 10, 2016, provided ground reference data for the 2014 classification. Primary and secondary plant species were recorded at 40 randomly-selected points throughout the Pascagoula River Marsh and photos were taken in each cardinal direction (Appendix A).

While Jeter and Carter (2016) and Nicholson (2017) used only panchromatic image data, in the case of the Pascagoula River Marsh, the inclusion of the near-infrared band as a classification input provided much greater accuracy in the detection of waterways and the tree line than the use of textural data alone (Higinbotham et al., 2004; Jeter & Carter, 2016; Klemas, 2013, p. 1018; Nicholson, 2017). Thus, multispectral data were included in cases where they were available.

Textural image features were calculated for all three datasets using ENVI's texture filter. For 2014 and 1996, a panchromatic average of the available spectral bands was computed for use as the input band. Unsupervised ISODATA classifications were created from the 2014 imagery to test for the most effective moving window size. Window sizes 7x7, 11x11, 15x15, and 19x19 were tested. The accuracy of each window size was assessed by a confusion matrix using ground truth ROIs chosen based on the 2016 field study data. The 15x15 classification exhibited the highest overall accuracy at 81.7% and was thus chosen for subsequent analysis (Appendix B). Based on visual inspection, this window size also most accurately characterized the tree line at the northern boundary of the marsh and produced the least noisy classification image.

Table 1 *Coefficient of Correlation Values for Texture Bands (2014 NAIP Imagery)*

	Variance	Homogeneity	Contrast	Dissimilarity	Entropy	Second Moment	Correlation
Variance	1	-0.49	0.89	0.79	0.53	-0.38	-0.07
Homogeneity	-0.49	1	-0.66	-0.81	-0.81	0.87	0.6
Contrast	0.89	-0.66	1	0.95	0.64	-0.46	-0.27
Dissimilarity	0.79	-0.81	0.95	1	0.81	-0.61	-0.47
Entropy	0.53	-0.81	0.64	0.81	1	-0.8	-0.56
Second Moment	-0.38	0.87	-0.46	-0.61	-0.8	1	0.43
Correlation	-0.07	0.6	-0.27	-0.47	-0.56	0.43	1

The textural features used in the ML classifications were homogeneity, entropy, and correlation. These were chosen from the seven texture indices produced by ENVI's Texture Filter. Feature selection was based on correlation analysis (Table 1). The redundant bands second Moment, dissimilarity, and contrast were eliminated so that no two remaining bands correlated with an R-value greater than 0.85 (Jensen, 2015, pp. 382–392). The variance band was also ultimately removed from the classification scheme because it highlighted stream edges, leading to the systematic misclassification of boundaries between marsh and water as woodland/shrubs — the land cover class with the highest textural variability. The selected texture bands (homogeneity, entropy, and correlation) were layer stacked with the image spectral bands for each dataset for use as ML inputs.

Habitat Classification

2014. Training data for the 2014 classification were chosen using the 2016 vegetation survey (Appendix A). Based on the survey data, four habitat types were defined: marsh, woodland/shrubs, unvegetated, and water. While it is possible to further divide the marsh and woodland/shrub habitat types based on the plant species present, the study was limited to these broad definitions due to the lack of spectral information for the first study year.

Water was classified using a band threshold in the infrared band, which was calculated using the training data. All pixels below a threshold of 3 standard deviations greater than the mean infrared brightness value of the training pixels and all pixels below this threshold were selected ($\mu = 2.74$, $\sigma = 3.96$). This file was then edited for accuracy based on the survey data and knowledge of the study area. Some shadows in wooded areas that were not averaged out by resampling were selected by this process and were manually removed from the final water classification. Bright pixels representing specular reflectance from the surface of the water were also manually removed. Once these manual corrections were completed, a water mask was created for use in the ML land cover classification.

ENVI's Maximum Likelihood Classification tool was used to categorize land cover into three groups: marsh, woodland/shrubs, and unvegetated. Water was masked during classification along with all areas outside the 7-foot contour line. The input bands for the classification included the infrared, green, and blue bands, along with the texture bands homogeneity, entropy, and correlation. Because a red band was not available for the 1996 dataset, this band was omitted from the 2014 classification.

The Sieve Classes tool in ENVI was used to remove noise in the classifications, improving visual accuracy by removing misclassified pixels within clearly homogeneous habitats (Jensen, Cowen, Althausen, Narumalani, & Weatherbee, 1993, p. 1043). Classified areas smaller than three pixels were coded as No Data and then replaced with the value of the majority neighboring class using the Majority Filter tool in ArcMap. Misclassified areas were corrected in ArcMap based on visual interpretation of the imagery and knowledge of the study area. Ingalls Shipbuilding, the largest urban feature within the contour boundary, was manually classified as "unvegetated" during post-classification processing, as many high-reflectance, high-variability pixels, such as the edges of buildings, were incorrectly classified as woodland/shrubs, and low-reflectance, low-variability pixels, such as parking lots, were incorrectly classified as marsh. The boundary of the road network surrounding the shipyard as detected by the ML classification from each study year was used as the boundary for the complex.

After these manual corrections were completed, the water classification raster was added to the ML classification raster to produce a final classification image.

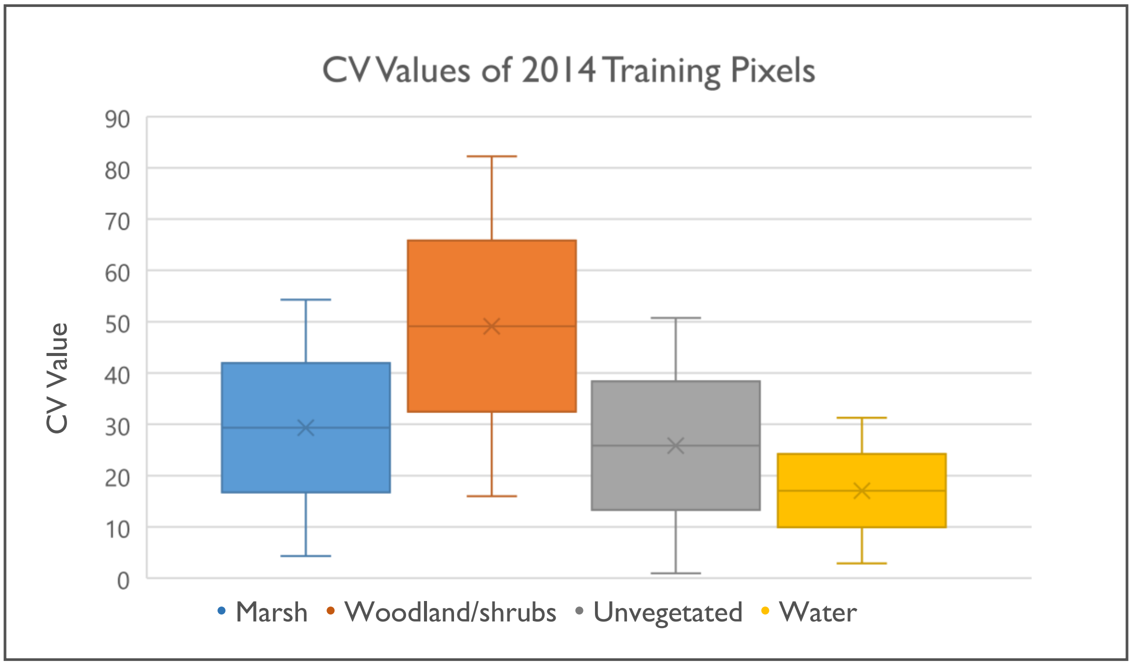


Figure 2. Box and whisker plot: CV Values of 2014 Training Pixels

The CV values for each 2014 training ROI were computed using ENVI's ROI tool. In the absence of in situ ground reference data for the two historical classifications, the CV of each habitat type was used for selecting training pixels. Because of overlap in these CV ranges, the training pixels were selected for the two historical datasets using the mean 2014 CV value plus and minus one standard deviation rather than the full range (Table 2).

In the absence of *in situ* reference data for the 1996 and 1955 image datasets, historical training data were derived using the CV values of each 2014 habitat class. Because CV is a unitless statistic, it can be assumed that the CV value range for each habitat type remains constant across time. Thus, this statistic could be used as a proxy for *in situ* reference data (Jeter & Carter, 2016, p. 989). The CV band was computed for each image dataset by dividing the square root of the variance band by the mean band and multiplying by 100 (Figure 2). The mean and standard deviation of the CV values of each 2014 training ROI were calculated using ENVI's ROI tool. Because of the degree of overlap in the CV ranges, the mean CV of the 2014 training pixels, plus and minus one standard deviation, was used as a guide for selecting training pixels for the 1996 and 1955 classifications rather than the full range (Table 2) (Jeter & Carter, 2016, p. 989).

Table 2 *Coefficient of Variation Statistics for 2014 Training Pixels*

Class (pixels)	Min	Max	Mean	Standard Deviation
Marsh (222925)	4.3	54.3	15.1	5.8
Unvegetated (9319)	1.0	50.7	8.2	8.6
Woodland/shrubs (181959)	16.0	82.3	32.6	7.5
Water (220705)	2.9	31.3	9.7	4.3

The CV values and descriptive statistics for each 2014 training ROI were computed using ENVI's ROI tool. Training pixels were selected for the two historical datasets using the mean 2014 CV value plus and minus one standard deviation.

1996. As in the 2014 dataset, water was classified in the 1996 imagery using the near-infrared band. Training regions were selected based on the known historical location of waterways, and all pixels below a threshold of 1 standard deviation above the mean of the near-infrared brightness values for the training regions were selected ($\mu = 45.41$, $\sigma = 28.70$). The classification file was manually corrected in the same way as the 2014 classification. Because of greater variability in brightness values in the 1996 imagery, more extensive correction was needed than for 2014. At the marine boundary of the study area, large areas which were classified as water in the 2014 image were not selected by this procedure in the 1996 image. Since it was unclear whether the image difference reflects high turbidity or exposed sand due to a lower tidal stage, the classified shoreline was left unaltered.

Land cover was classified as marsh, woodland/shrubs, or unvegetated using ENVI's Maximum Likelihood classifier using the same methods and input bands as for 2014. Accuracy was improved for both the 1996 and 1955 datasets by reclassifying individual image sections within the mosaic which differed slightly in their brightness values (C. P. Anderson, Carter, & Funderburk, 2016, p. 6)**.** These effects could be due to atmospheric haze, camera angle, or other factors. Polygons were created for areas which appeared to exhibit high inaccuracy, and training data specific to each region was chosen within each polygon using the same method as the original classification. The area outside each polygon was masked during classification. The sieve classes tool was used to remove noise, and after small manual corrections were made, the locally reclassified areas were added back to the original ML classification raster. Once corrections were completed, the water classification was added to produce the final classification image.

1955. In the absence of multispectral data, the methodology for classifying the 1955 imagery was largely based on image texture. The CV band was used to classify water, as it highlights low-variability water bodies in a manner similar to near-infrared reflectance. Training regions were selected based on the known historical location of waterways. A threshold of 3 standard deviations from the mean of the training dataset was used ($\mu = 6.3$, $\sigma = 1.4$). This yielded a close approximation of the center pixels of each major waterway once misclassified areas were removed.

As the textural variability of brightness values tends to be high at shorelines, the CV band exhibits high values in the 15 pixels on either side of the water boundary. Thus, the CV threshold did not select pixels close to the shoreline as part of the water class. However, for large waterways, the size of this high-CV edge is predictable, as it is a function of the window size. To account for the high-CV edges that were not classified by the CV threshold, a 22-meter (approximately 7 pixels) buffer was applied to the water polygons to approximate the true edges of the large waterways. This value was calculated by multiplying the window size (15 pixels) by the pixel size (3 meters), and dividing by two, to include only the "inside" half of the shoreline. Small streams could not be extracted using CV; at a stream size of 15 pixels across or less, there is no low-variability center. These small streams were manually digitized.

Land cover was classified using the same methods as for the 2014 and 1996 datasets, with the exception of the input bands. In the absence of multispectral image data, only the panchromatic band was used in the classification, along with the three computed texture bands. Post-processing of the classification data was completed using the same methods as 1996, with several areas locally reclassified to improve accuracy, and manual corrections made based on visual interpretation of the imagery.

Accuracy was assessed for each classification year using ENVI's confusion matrix tool. A pixel-by-pixel change detection was completed for each of the three intervals (1955-2014, 1955-1996, and 1996-2014).

Analysis of Land Cover Change

The classification maps were subdivided into four zones, equidistant from north to south, to assess regional variations in the magnitude of land cover change (Figure 3). Linear regressions of marsh extent over time were performed using the total area of marsh habitat in each year, both for the entire study area and for each zone of the study area.

Figure 3. Study Area Zones

The estuary was divided into four equidistant zones from north to south for change detection analysis, with Zone 1 at the marine boundary of the study area and Zone 4 being the most inland zone.

To examine the rate of marsh change attributable to solely environmental factors other than direct destruction, major anthropogenic features which were constructed or altered during the study period were masked for a second set of analyses (Figure 4).

These features included Ingalls west shipyard, Interstate-10, Highway 90 and the CSX railroad bridge. The mask was constructed using the union of the extent of each urban feature in each image dataset so that the same mask could be used across all three study years. 315.7 hectares were masked in Zone 1 and 20.2 hectares were masked in Zone 3; Zones 2 and 4 did not contain any major anthropogenic features. With these features masked, change detection analysis and linear regression of marsh area, both over the entire study area and by zone, were performed a second time.

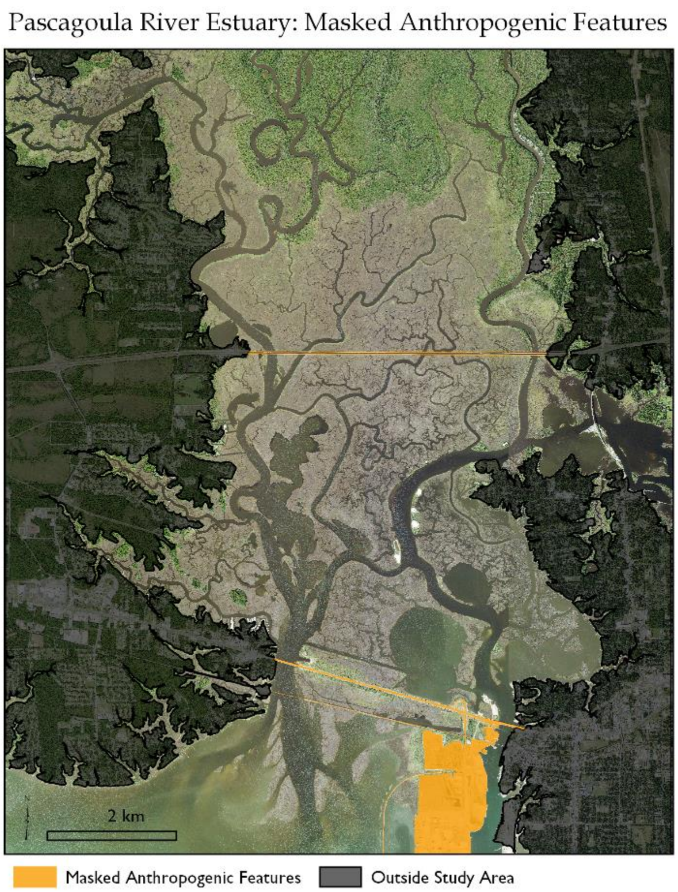


Figure 4. Anthropogenic features masked for change detection

Map shows major anthropogenic features masked during analysis. These features included Ingalls west shipyard, Interstate-10, US Highway 90 and the CSX railroad bridge. The mask was constructed to cover the entire extent of each feature in every study year so that the same mask could be applied in every year.

CHAPTER IV – RESULTS

Image Analysis

Classified habitat maps were produced for each image date, with land cover classified as marsh, woodland/shrubs, unvegetated, or water (Figures 5, 6, and 7). Overall classification accuracy was 99.2% for 1955, 99.1% for 1996, and 99.9% for 2014 (Appendix C). Kappa coefficients were 0.988 for 1955, 0.978 for 1996, and 0.999 for 2014. Table 3 shows the total extent of each habitat class for each image date, while Table 4 shows the extent of each habitat class for each image date when anthropogenic features (Figure 4) were not considered.

Table 3 *Pascagoula River Estuary: Habitat Extent in Each Study Year (hectares)*

	Marsh	Woodland/Shrubs	Unvegetated	Water
1955	6621.0	1827.6	449.0	4072.7
1996	5552.6	2369.8	532.1	4506.5
2014	5306.6	2475.2	402.9	4779.4

Extents in hectares for each habitat class in each year of the study. The geographic extent of the marsh class decreased over both intervals of the study, while the extent of both the woodland/shrubs class and the water class increased over both intervals. The extent of the unvegetated class, the smallest habitat class in the study area, increased between 1955 and 1996, then decreased between 1996 and 2014.

Table 4 *Pascagoula River Estuary: Habitat Extents with Anthropogenic Features Masked (hectares)*

	Marsh	Woodland/Shrubs	Unvegetated	Water
1955	6491.8	1823.5	296.2	4016.3
1996	5541.3	2366.9	217.9	4497.5
2014	5300.4	2473.7	76.7	4775.8

When anthropogenic features were masked for analysis, the directions of change in marsh extent, woodland/shrub extent, and water extent remained the same. However, the measured loss in marsh extent between the first and second image dates was reduced as a result of the mask, highlighting the extent of marsh destroyed by construction activities. The extent of the unvegetated class outside the masked areas decreased over both intervals rather than increasing between 1955 and 1996 as in Table 3.

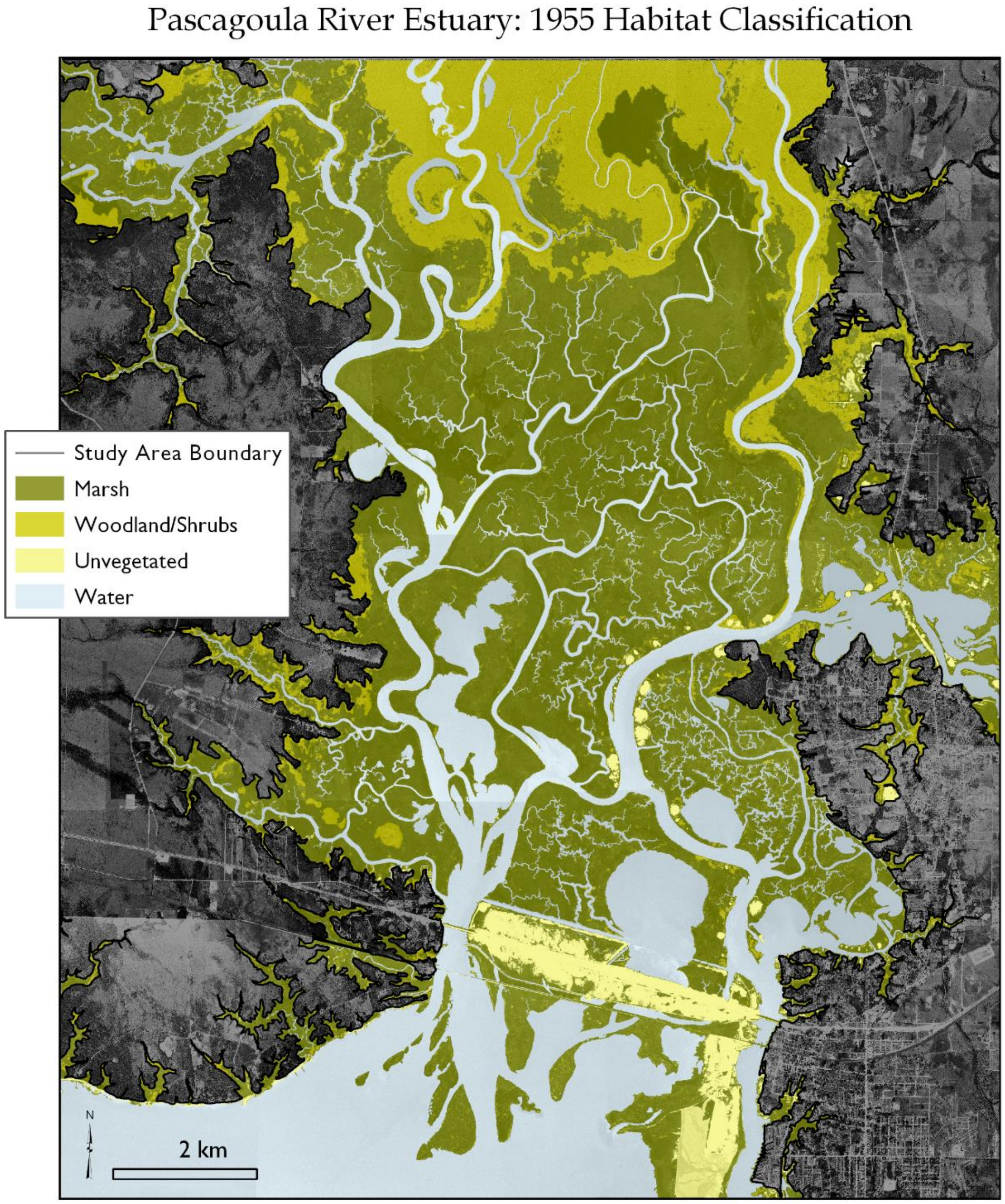


Figure 5. 1955 Habitat Classification Map

Habitat extents were mapped for marsh (dark green), woodland/shrubs (bright green), unvegetated (yellow), and water (light blue) land cover classes for image date February 13, 1955.

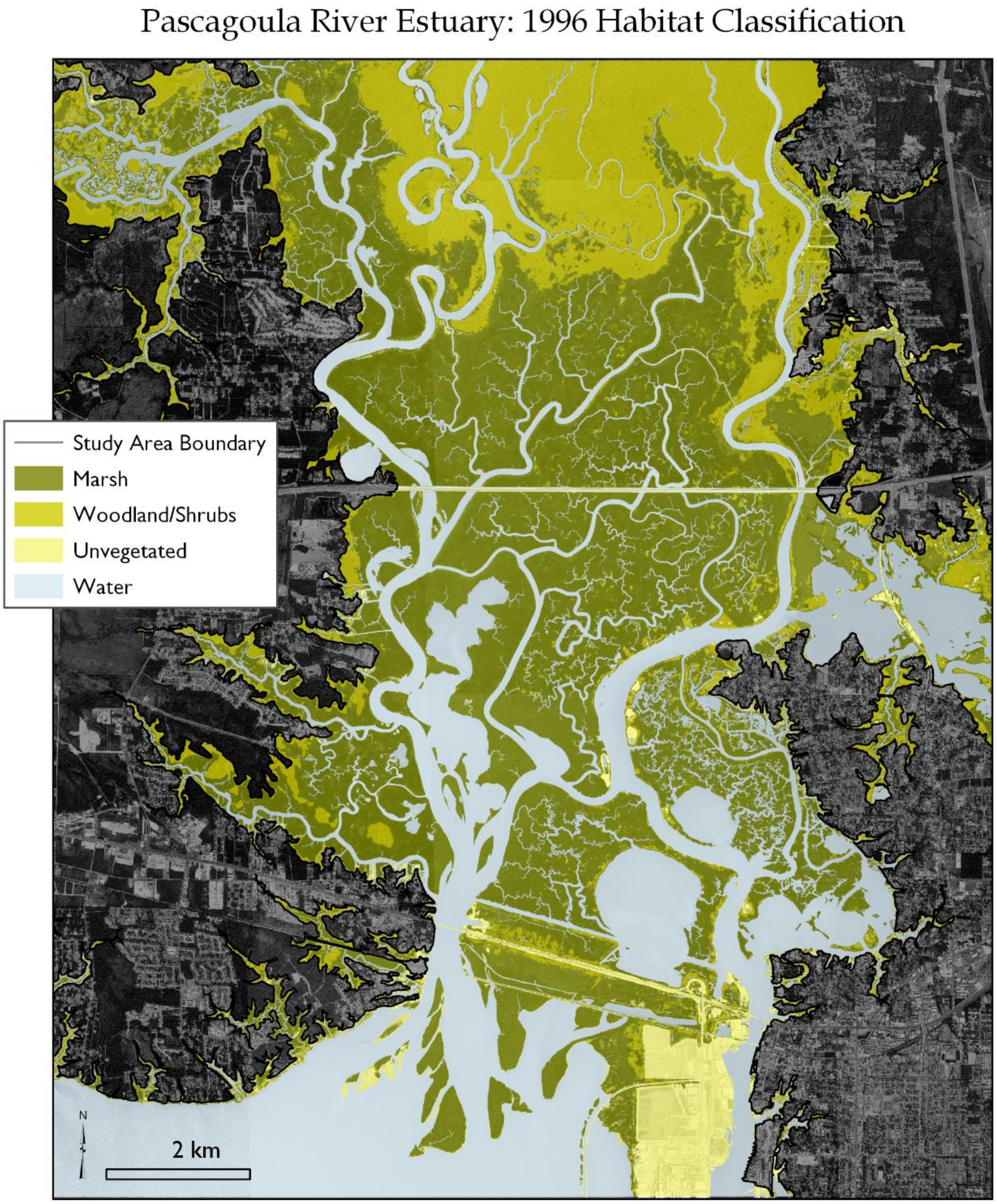


Figure 6. 1996 Habitat Classification Map

Habitat extents were mapped for marsh (dark green), woodland/shrubs (bright green), unvegetated (yellow), and water (light blue) land cover classes for image date February 12, 1996.

Pascagoula River Estuary: 2014 Habitat Classification

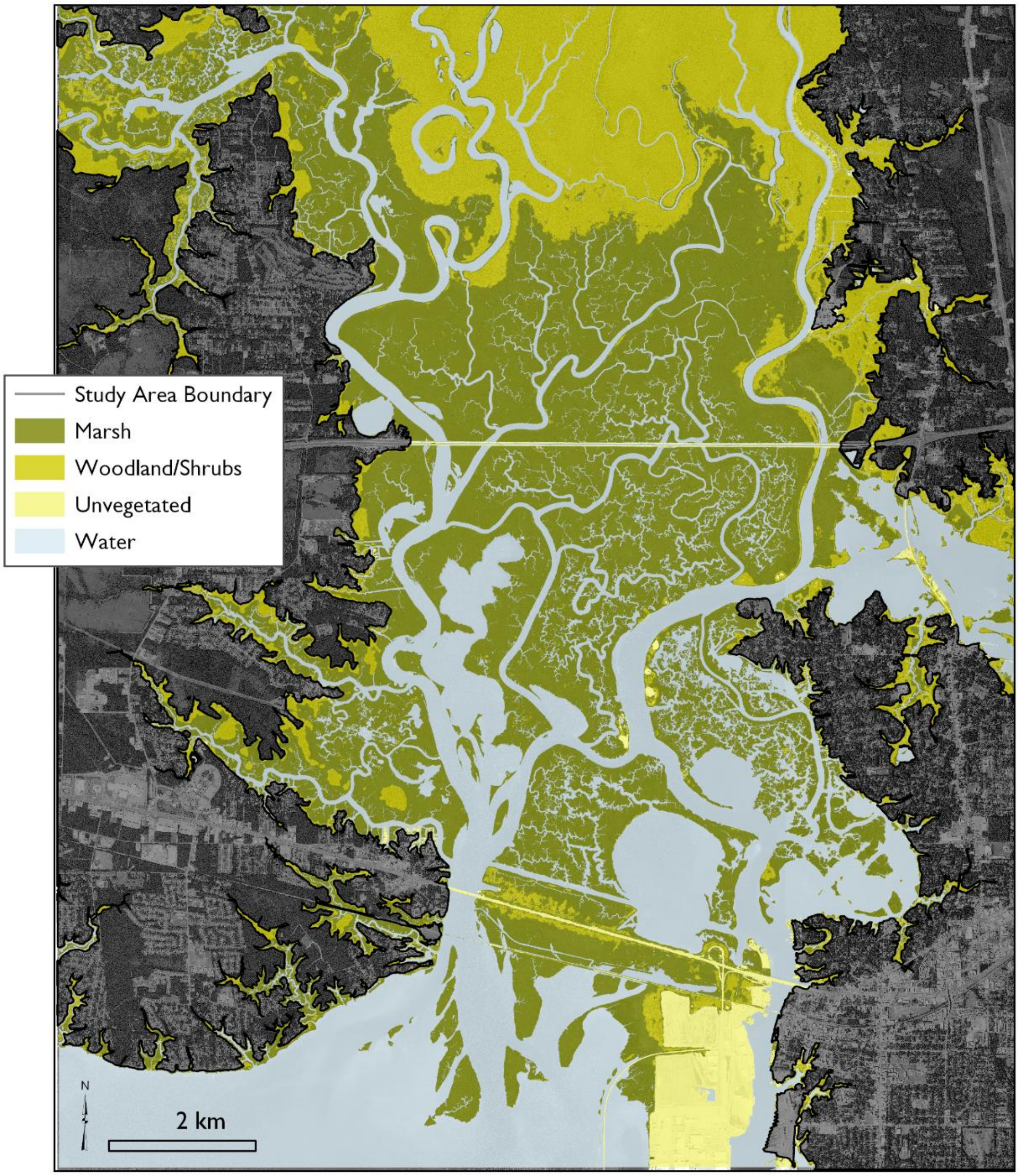


Figure 7. 2014 Habitat Classification Map

Habitat extents were mapped for marsh (dark green), woodland/shrubs (bright green), unvegetated (yellow), and water (light blue) land cover classes for image dates October 5 and October 16, 2014.

Analysis of Land Cover Change

Change detection

Change detection analysis of the three classification maps (Figures 5, 6, and 7) revealed a total loss in classified marsh extent of 19.9% (1,314.4 ha) between 1955 and 2014 (Table 3) (Figure 8). The water class increased by 706.7 ha or 17.4% (Figure 9), the woodland/shrub class increased by 647.6 ha or 35.4% (Figure 10), and the unvegetated class decreased by 46.1 ha or 10.3% (Figure 11) (Appendix D).

Classified marsh extent decreased by 1068.3 ha (16.1%) between 1955 and 1996, and 246.1 ha (4.4%) between 1996 and 2014. When anthropogenic features were masked, the marsh extent lost during the first interval of the study became 950.5 ha (14.6%), and the marsh extent lost during the second interval became 241.0 ha (4.4%) for a total net marsh loss of 1191.5 ha (18.4%) between 1955 and 2014 (Table 4).

Marsh conversion to woodland/shrubs and to water made up similar proportions of the total marsh area lost, with a net 10.0% of the 1955 marsh extent (662.2 ha) converted to water by 2014, and a net 9.8% (650.8 ha) converted to woodland/shrubs. Between 1955 and 1996, 411.3 ha (6.2%) of the total marsh area was converted to water, with an additional 247.5 ha (4.5%) of marsh converted to water between 1996 and 2014. When anthropogenic features were masked, the total area of marsh lost to water during the first interval dropped by 1 ha, while the area lost in the second interval remained the same. Conversion of marsh to woodland was 593.1 ha (9.0%) in the first interval and 49.6 ha (0.9%) in the second interval. These areas fell by less than 1 hectare each when anthropogenic features were masked.

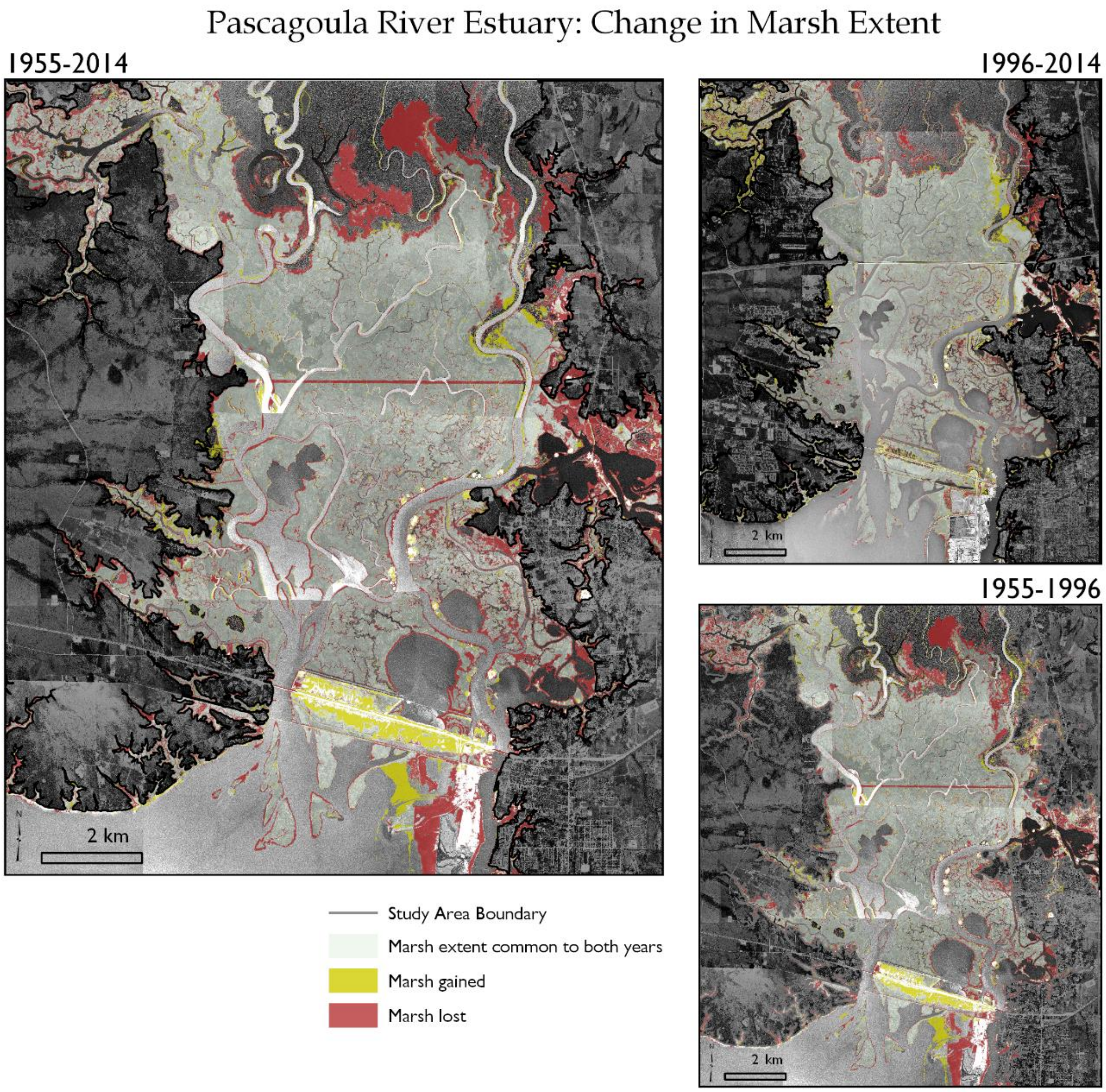


Figure 8. Change in classified marsh extent

Maps illustrate the change in classified marsh extent over each interval of the study: 1955-2014 (the entire study period) 1955-1996, and 1996-2014). The marsh extent that remained constant between each set of image dates is shown in light teal. Marsh lost between the first and second date is shown in red, and marsh gained between the first and second date is shown in green. A net decrease of 1314.4 ha (19.9%) was observed over the entire study period, with a net decrease of 1068.3 ha (16.1%) between 1955 and 1996 and a net decrease of 246.1 ha (4.4%) between 1996 and 2014.

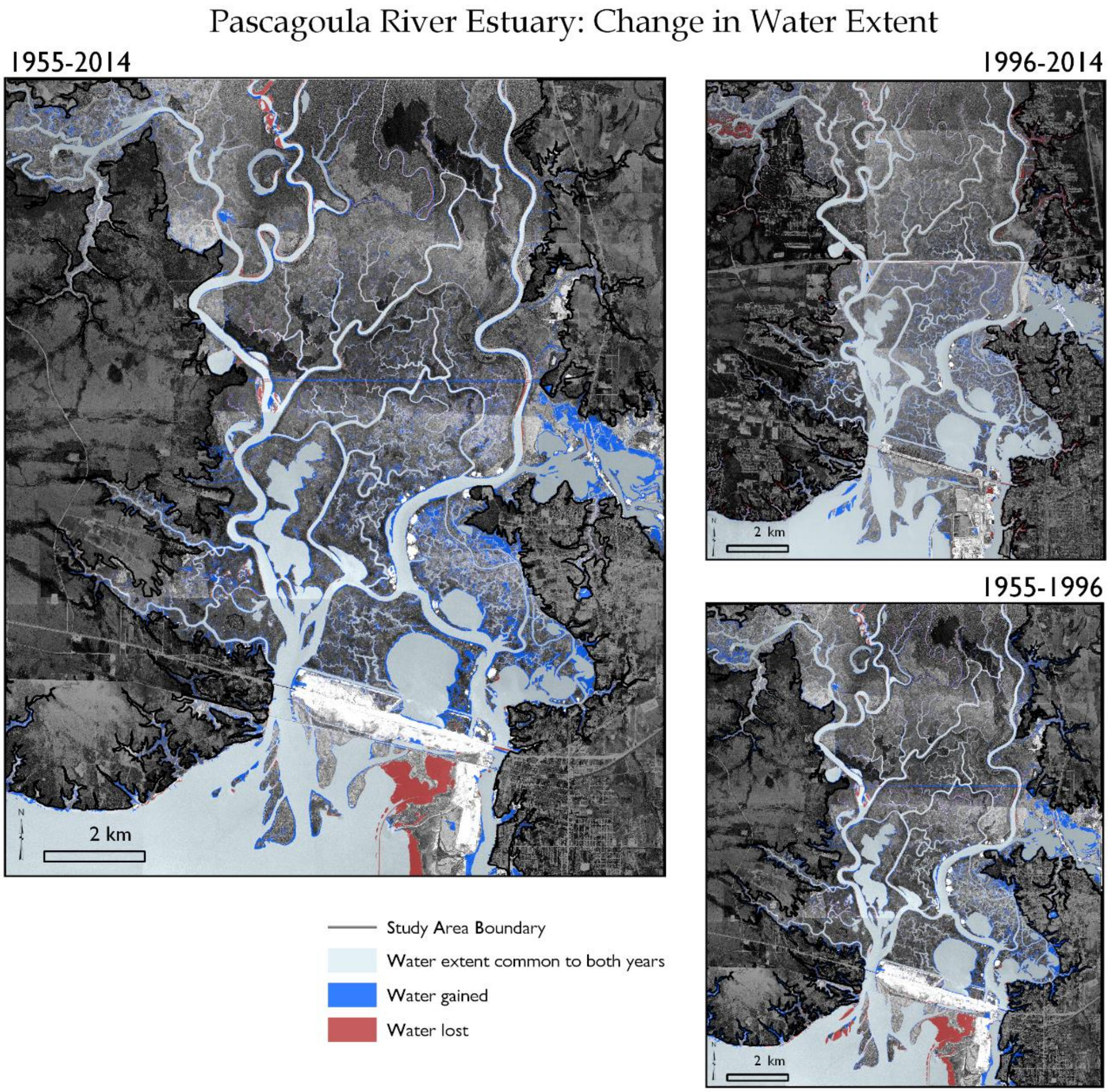


Figure 9. Change in classified water extent

Maps illustrate the change in classified water extent over each interval of the study. The water extent that remained constant between each set of dates is shown in light blue. Water lost over each interval is shown in red, and water gained over each interval is shown in dark blue. A net increase of 706.7 ha (17.4%) was observed over the entire study period, with a net increase of 433.8 ha (10.7%) between 1955 and 1996 and a net increase of 272.9 ha (6.1%) between 1996 and 2014.

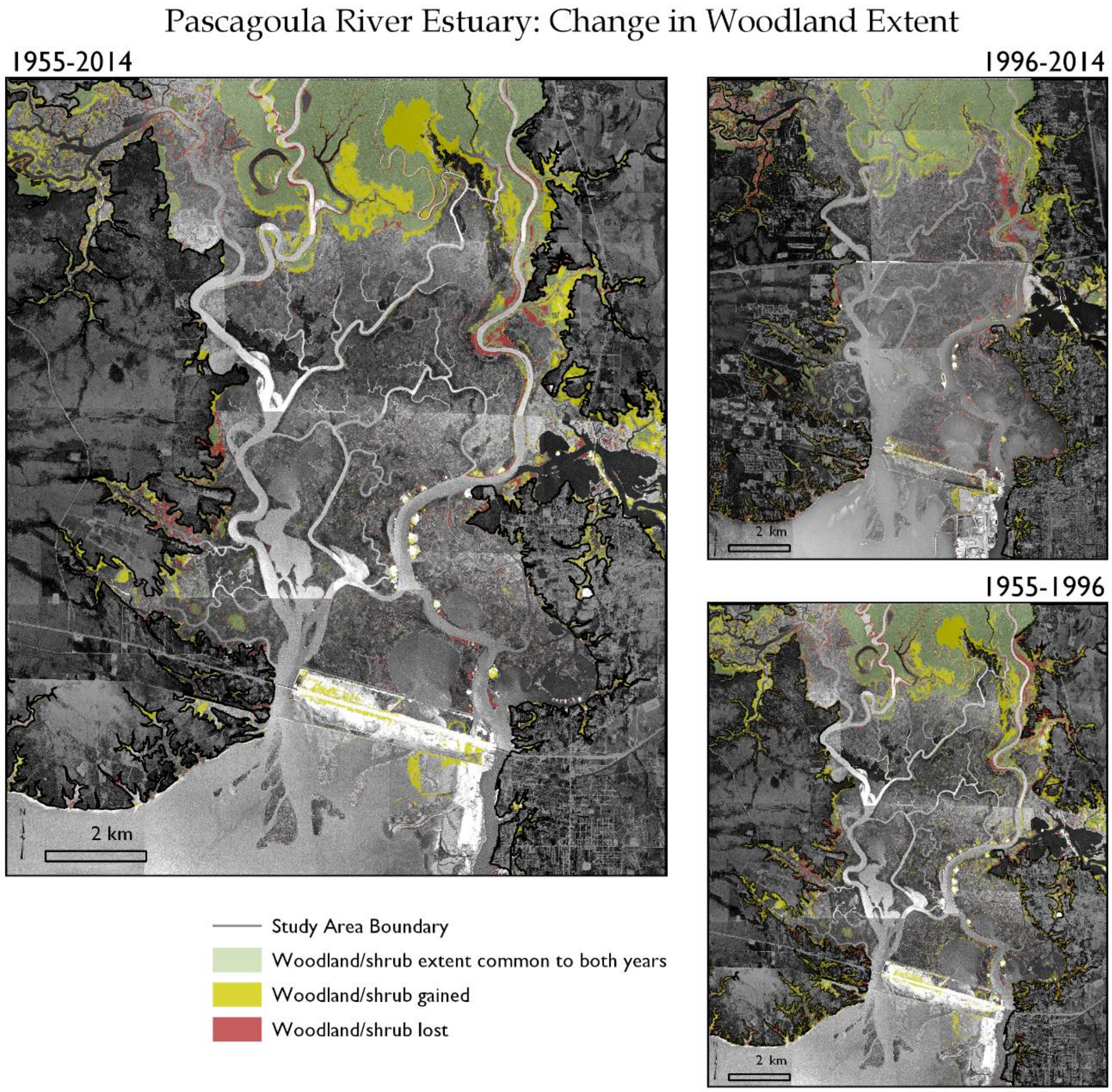


Figure 10. Change in classified woodland/shrub extent

Maps illustrate the change in classified woodland/shrub habitat extent over each interval of the study. The woodland/shrub extent that remained constant between each set of dates is shown in dark green. Woodland/shrub habitat lost between each set of dates is shown in red, and woodland/shrub habitat gained is shown in bright green. A net increase of 647.6 ha (35.4%) was observed over the entire study period, with a net increase of 542.2 ha (29.7%) between 1955 and 1996 and a net increase of 105.4 ha (4.4%) between 1996 and 2014.

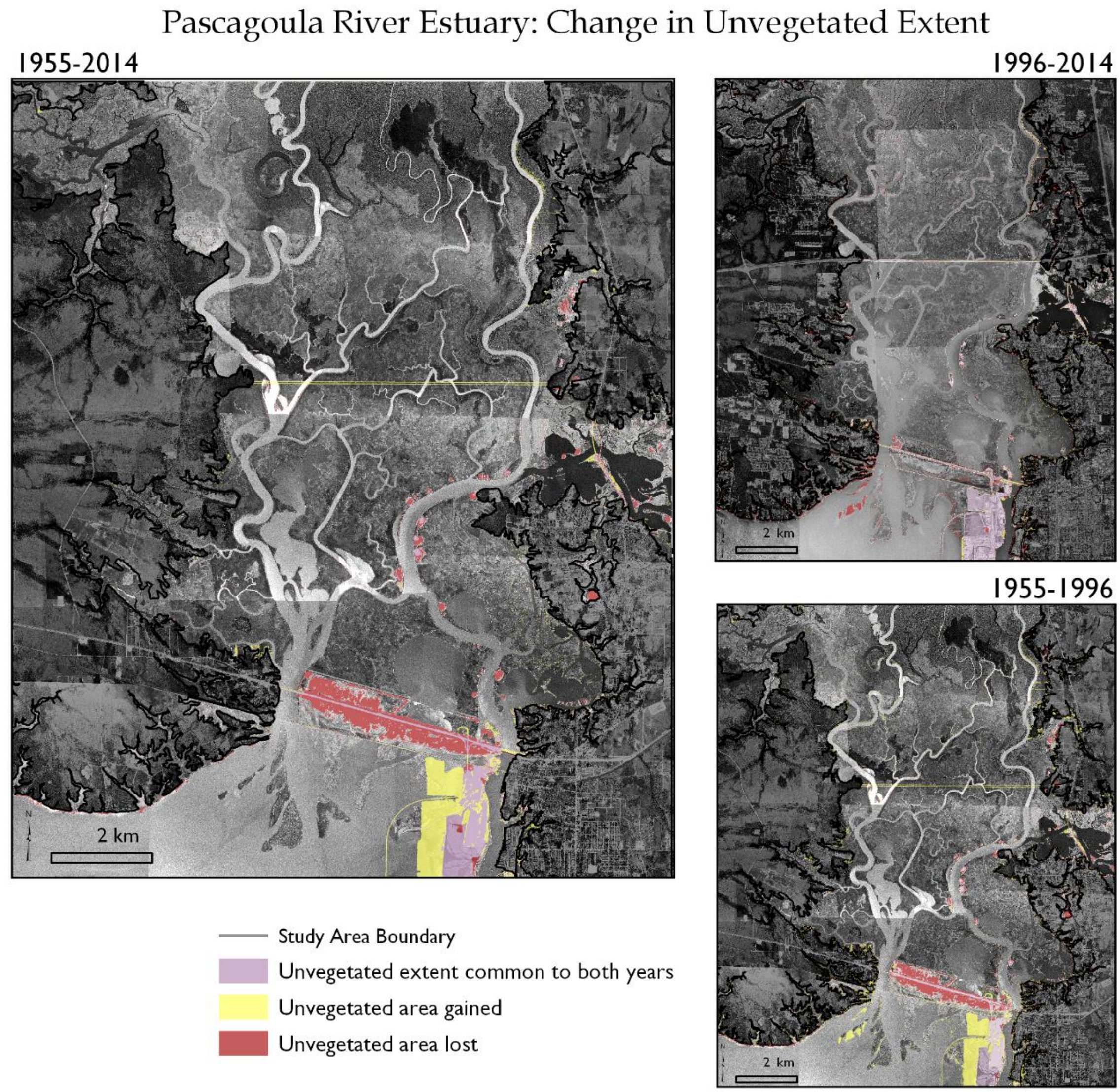


Figure 11. Change in classified unvegetated extent

Maps illustrate the change in classified unvegetated extent over each interval of the study. The unvegetated extent that remained constant between each set of dates is shown in light purple. Unvegetated areas lost between each set of dates are shown in red, and unvegetated areas gained are shown in yellow. A net decrease of 46.8 ha (10.4%) was observed over the entire study period, with a net increase of 83.1 ha (18.5%) between 1955 and 1996 and a net decrease of 129.2 ha (24.3%) between 1996 and 2014.

While conversions to woody vegetation or water accounted for the net decrease in marsh extent, marsh vegetation expanded in unvegetated areas by a net 6.6 ha (<0.01%) between 1955 and 2014. Over the first interval, a net 57.0 ha of marsh (0.9%) was converted to unvegetated land cover. However, when anthropogenic features were masked, a net gain in marsh of 56.7 ha was calculated. Regardless of whether anthropogenic features were masked, the class changes between marsh and unvegetated areas resulted in marsh gains over the 1996-2014 interval. A net 50.6 ha of unvegetated land cover, equivalent to 0.9% of the 1996 marsh extent, was converted to marsh in this interval, or a net 55.4 ha with anthropogenic features masked. The vast majority of inter-class changes between unvegetated and marsh areas took place in Zone 1. These changes are described in further detail below.

When the total study area was considered, every zone exhibited a net loss in marsh extent between 1955 and 2014. However, several zones experienced gains in marsh extent over one of the two time intervals in the study, or both intervals when anthropogenic features were masked.

Zone 1. Marsh extent in Zone 1, the zone containing the smallest marsh area, decreased by 146.7 ha (19.1%) between 1955 and 2014 (Table 5). This included a net change from marsh to water of 87.9 ha (11.5%) and from marsh to woodland/shrubs of 76.2 ha (9.9%) (Appendix D). Between 1955 and 1996, marsh extent decreased by 145.3 ha (18.9%), but between 1996 and 2014, marsh extent only decreased by 1.5 ha (<0.1%). When anthropogenic features were masked, the net marsh loss over the entire study period was 40.6 ha (6.2%), with marsh extent decreasing by 45.5 ha (6.9%) in the first interval and increasing by 4.9 ha (<0.1%) in the second interval.

A net decrease of 20.2 ha in the extent of the water class between 1955 and 1996 was heavily influenced by a land reclamation project which took place in 1968 for the construction of the Ingalls west shipyard (Nelson, 2017). Throughout the rest of Zone 1, shorelines tended to retreat landward (Figure 12). Between 1955 and 1996, a net 44.9 ha (5.9%) of the marsh extent in Zone 1 was converted to water, with an additional 38.5 ha (6.18%) converted between 1996 and 2014 (Appendix E, F). When anthropogenic features were masked, the net marsh area converted to water became 45.8 ha (7.0%) during the first interval and remained 38.5 (6.3%) in the second interval (Appendix H, I). While these figures are less than or equal to the measured marsh extent lost without anthropogenic features masked, the percentages of marsh extent lost rose because the initial area of the marsh class in 1955 and 1996 was smaller as a result of the mask.

Table 5 *Zone 1: Habitat Extent in Each Study Year (hectares)*

	Marsh	Woodland/Shrubs	Unvegetated	Water
1955	767.4	63.6	361.5	1938.5
1996	622.1	167.8	418.8	1918.3
2014	620.6	180.3	335.4	1992.1

Extents in hectares for each habitat class in Zone 1 for each image date. The geographic extent of the marsh class decreased over both intervals of the study, while the extent of the woodland/shrubs class increased over both intervals. The extent of the water class decreased between 1955 and 1996, then increased between 1996 and 2014 for a net increase over the entire study period. The extent of the unvegetated class increased between 1955 and 1996, then decreased between 1996 and 2014 for a net decrease over the entire study period.

Table 6 *Zone 1: Habitat Extents with Anthropogenic Features Masked (hectares)*

	Marsh	Woodland/Shrubs	Unvegetated	Water
1955	658.4	62.5	209.4	1885.1
1996	612.9	166.3	120.3	1911.7
2014	617.8	180.1	24.7	1989.9

When anthropogenic features were masked for analysis in Zone 1, a much smaller net loss in marsh extent was observed over the entire study period. The geographic extent of the marsh class outside the masked areas decreased between 1955 and 1996, but increased slightly between 1996 and 2014. The extent of the water class outside the masked areas increased over both intervals of the study, as areas affected by the 1968 land reclamation project were not included in the analysis. The extent of the unvegetated areas outside the masked areas decreased over both intervals. The extent of the woodland/shrub class was not heavily affected by the mask, exhibiting increases over both intervals as in Table 5.

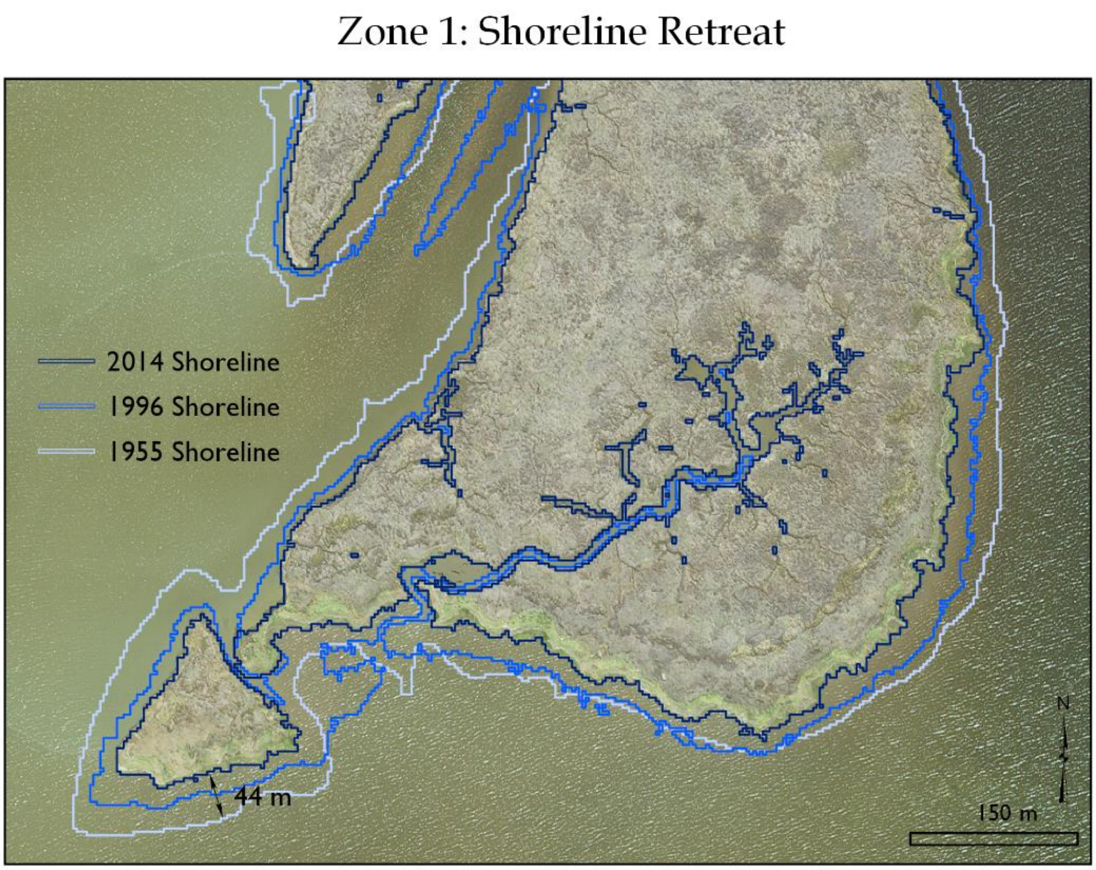


Figure 12. Shoreline retreat in Zone 1 of the study area

Map shows the classified shoreline in for each image date, illustrating the extent of shoreline lost at an island at the marine boundary of the marsh. The 1955 shoreline is shown in light blue, the 1996 shoreline is shown in medium blue, and the 2014 shoreline is shown in navy.

Conversions between the marsh and woodland/shrub class were negative during the first interval but positive in the second. A net 66.9 ha of marsh (9.1% of the 1955 marsh extent) were converted to woody vegetation between the first two image dates, while a net 2.0 ha of the woodland/shrub class (0.3% of the 1996 marsh extent) was converted to marsh between the second two image dates. When anthropogenic features were masked, the net change between the marsh and woodland/shrub classes became 69.7 ha (10.6%) marsh lost during the first interval, and 2.1 ha (0.3%) marsh gained in the second interval.

The magnitude of the inter-class changes between marsh and unvegetated areas is high in Zone 1 compared with the other three zones, with 120.3 ha of 1955 marsh becoming unvegetated land cover in 2014 and 140.3 ha of 1955 unvegetated land cover classified as marsh in 2014. The changes between the two classes resulted in a net gain in marsh over the entire study period of 20 ha (0.03% of the 1955 marsh extent in Zone 1).

Between 1955 and 1996, a net marsh loss to unvegetated land cover of 27 ha (3.5%) was measured. However, when anthropogenic features were masked, the net change from unvegetated land cover to marsh became positive, with 73.5 ha of the unvegetated class converted to marsh. The 1955 image was acquired before the construction of Ingalls west shipyard in 1968 (Nelson, 2017). This land reclamation project accounts for some of the marsh area converted to unvegetated land cover between the first two image dates. However, an even larger portion of Zone 1 was converted from what appears to be bare sand surrounding the Highway 90 causeway in the 1955 image to marsh vegetation in the 1996 image. This unvegetated area may be a result of construction in the area in the early- to mid-1950s, as preliminary analysis of 1940 imagery of the same area indicates that Highway 90 was rerouted between 1940 and 1955. Marsh colonization of this unvegetated expanse offset the losses from construction, resulting in a net gain in marsh extent when anthropogenic features are not considered.

Between 1996 and 2014, class conversions between marsh and unvegetated areas also resulted in net gains in marsh extent. A net 34.6 ha (5.6%) of areas which were unvegetated in 1996 were replaced with marsh vegetation in 2014. When anthropogenic features were removed, this measurement rose to a net 40.9 ha of marsh gained in previously unvegetated areas (6.7%).

Zone 2. Zone 2 exhibited the second highest percent (22.3%) and total area (405.6 ha) of loss over the total study period. Marsh extent decreased by 266.6 ha (14.7%) during the first interval and 139.0 ha (9.0%) in the second interval (Table 7). The extent of unvegetated areas decreased by a net 23.1 ha (47.3%), and the extent of the woodland/shrub class increased by a net 59.2 ha (31.3%).

Table 7 *Zone 2: Habitat Extent in Each Study Year (hectares)*

	Marsh	Woodland/Shrubs	Unvegetated	Water
1955	1814.8	189.4	48.8	1069.6
1996	1548.3	256.8	33.7	1285.2
2014	1409.2	248.6	25.7	1440.6

Extents in hectares for each habitat class in Zone 2 for each image date. The geographic extents of both the marsh class and the unvegetated class decreased over both intervals of the study, while the extent of the water class increased over both intervals. The extent of the woodland/shrub class increased between 1955 and 1996, then decreased between 1996 and 2014 for a net increase over the entire study period.

Conversion to open water was the largest contributing factor to the loss in marsh extent in Zone 2. The extent of classified water increased by 215.7 ha (20.2%) during the first interval and 155.4 ha (12.09%) during the second interval for a total net increase of 371.0 ha (34.7%) between 1955 and 2014. 190 ha of marsh (10.5%) were converted to water between 1955 and 1996, with an additional net 148.4 ha of marsh (9.6%) converted to water between 1996 and 2014 (Appendix E, F). The net change from marsh to water in over the entire study period was 339.0 ha (18.7%) (Appendix D). This zone contains shoreline that is highly disturbed, particularly on the eastern side proximal to the city of Pascagoula, and also contains the bulk of the dredged shipping canal which starts at the mouth of the east distributary and continues upstream into the Escatawpa River (Department of Commerce et al., 2015; Mississippi Department of Marine Resources, 1998; Peterson et al., 2007). Channel expansion is dramatic in this region of the estuary, along both the major distributaries as well as in the smaller channels intersecting the marsh (Figure 9). The area proximal to the city of Pascagoula has experienced particularly heavy losses in marsh extent (Figure 13).

As in Zone 1, conversions between the marsh and woodland/shrub classes resulted in a net marsh loss over the first interval, but a small gain in the second. A net 77.4 ha of marsh (4.3%) was converted to woody vegetation between 1955 and 1996, while a net 9.5 ha (0.1% of the 1996 marsh extent) of woody vegetation was converted to marsh between 1996 and 2014. Some conversion between the marsh and woodland/shrub class is attributable to the growth of woody vegetation in areas where elevation has been increased or maintained by dredge spoil deposits.

Net changes between the marsh class and the unvegetated class were minimal in this zone. A net 0.4 ha (0.02% of the 1955 marsh extent) which was marsh in 1955 was classified as unvegetated in 1996, and there was no net change between 1996 and 2014 between these two classes.

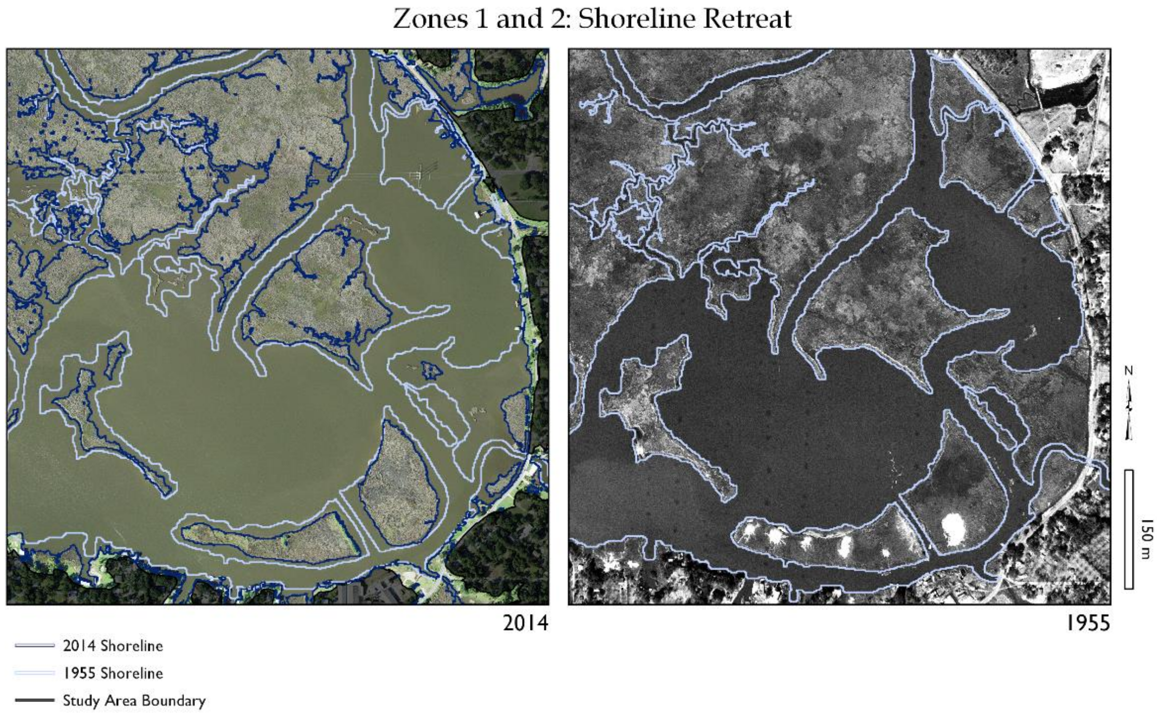


Figure 13. Shoreline retreat in Zones 1 and 2

Map shows the classified shorelines for the 2014 (navy) and 1955 (light blue) image dates, illustrating marsh loss and fragmentation near the city of Pascagoula. The 2014 image is shown at left, and the 1955 image is shown at right.

Zone 3. Between 1955 and 2014, marsh extent in Zone 3 decreased by 291.2 ha (12.7%), while the water class increased by 209.7 ha (34.5%), the woodland/shrub class increased by 81.6 ha (38.4%), and the unvegetated class increased by 0.2 ha (0.6%) (Table 8).

With anthropogenic features (Interstate-10) masked, the measured loss in marsh extent was 277.4 ha (12.1%) and the unvegetated class decreased by 15.1 ha (48.0%) (Table 9). The total extent of the other two habitat classes remained close to the original values.

Table 8 *Zone 3: Habitat Extent in Each Study Year (hectares)*

	Marsh	Woodland/Shrubs	Unvegetated	Water
1955	2301.8	212.3	31.5	608.0
1996	2052.2	306.8	48.1	746.4
2014	2010.6	293.9	31.7	817.7

Extents in hectares for each habitat class in Zone 3 for each image date. The geographic extents of the marsh class decreased over both intervals of the study, while the extent of the water class increased over both intervals. The extent of the woodland/shrub class increased between 1955 and 1996, then decreased between 1996 and 2014 for a net increase over the entire study period. The extent of the unvegetated class increased between 1955 and 1966, then decreased to approximately its original 1955 extent between 1996 and 2014.

Table 9 *Zone 3: Habitat Extents with Anthropogenic Features Masked (hectares)*

	Marsh	Woodland/Shrubs	Unvegetated	Water
1955	2284.7	211.9	31.3	605.6
1996	2050.3	306.5	32.5	744.0
2014	2007.3	293.9	16.3	816.3

As the area masked in Zone 3 was relatively small, the mask did not have a large impact on the magnitudes of change in habitat extents between the three image dates. The direction of change for each habitat type over each interval was the same as in Table 8.

As with Zones 1 and 2, conversions between the marsh and water classes resulted in a net loss in marsh extent over both intervals. A net total of 187.9 ha of marsh (8.2% of the 1955 marsh extent) was converted to water over the entire study period. 119.2 ha of marsh (5.18%) was converted to water between 1955 and 1996, and 69.6 ha of marsh (3.4%) was converted to water between 1996 and 2014. With Interstate-10 masked, these measurements fell by one hectare or less in each interval, leaving the percentages unchanged.

Conversions between the marsh and woodland/shrub classes again resulted in a net loss in marsh between 1955 and 1996 and a net gain in marsh between 1996 and 2014. During the first interval, 111.1 ha (4.8%) of the 1955 marsh class was converted to woodland/shrubs in 1996, while a net 21.2 ha of 1996 woodland/shrub land cover was converted to marsh in 2014. Over the entire study period, a net 87.7 ha (3.8%) of the 1955 marsh class was converted to woodland in 2014.

Class changes between the unvegetated and marsh classes were small in this zone, despite the construction of Interstate-10 during the first interval of the study period. The total net change from marsh habitat to unvegetated habitat was 14.5 ha (0.6%). With Interstate-10 masked, this measurement fell to 1.6 ha (<0.1%). Between 1955 and 1996, 18.3 ha (0.8%) of the 1955 marsh extent was converted to unvegetated land cover, while 6.7 ha (0.3%) were converted from unvegetated to marsh between 1996 and 2014. When Interstate-10 was masked, the net change during the first interval became 5.2 ha (0.2%) of marsh lost to the unvegetated class, and the net change during the second interval became 5.3 ha (0.3%) of marsh gained from the unvegetated class.

Severe open water conversion in the area surrounding the Escatawpa-Pascagoula confluence was balanced in part by a vegetation shift from woodland/shrub to marsh habitat on the banks of the East Distributary. However, the expansion of some wooded areas at the western edge of the study area led to a net gain in woodland/shrub land cover of 81.6 ha. The construction of Interstate-10 contributed to marsh loss in this zone as well. Stream expansion and channel-widening is notable, but does not appear to be as severe in this area as the more southern zones, with the exception of the Escatawpa-Pascagoula confluence (Figure 9).

Zone 4. Percent and areal loss of marsh was greatest in Zone 4, the most inland zone, where classified marsh extent decreased by 468.0 ha (27.0%) between 1955 and 2014 (Table 10). Marsh extent decreased by 404.2 ha (23.3%) between 1955 and 1996, and by 63.8 ha (4.8%) between 1996 and 2014. Over the entire study period, the woodland/shrub class extent increased by 391.3 ha (28.8%), the water class extent increased by 72.9 ha (49.0%), and the unvegetated class extent increased by 3.3 ha (16.0%).

Table 10 *Zone 4: Habitat Extent in Each Study Year (hectares)*

	Marsh	Woodland/Shrubs	Unvegetated	Water
1955	1733.9	1359.8	6.7	456.1
1996	1329.7	1637.3	31.3	556.6
2014	1265.9	1751.1	10.0	529.0

Extents in hectares for each habitat class in Zone 4 for each image date. The geographic extents of the marsh class decreased over both intervals of the study, while the extent of the woodland/shrub class increased over both intervals. The extent of the unvegetated class increased between 1955 and 1996, then decreased between 1996 and 2014 for a small net increase over the entire study period. The extent of the water class increased between 1955 and 1966, then decreased between 1996 and 2014 for a net increase over the entire study period.

The encroachment of woody vegetation into the marsh dominated the loss in marsh extent in Zone 4, with a net 419.2 ha (24.2%) of the 1955 marsh extent classified as woodland/shrubs in 2014 (Appendix D). 490.7 ha of marsh was replaced by woody vegetation. This was only offset by 71.5 ha of marsh migration into previously wooded areas (Figure 14). Between 1955 and 1996, 334.4 ha (19.3%) of the 1955 marsh extent was converted to woody vegetation. An additional 82.2 ha (6.2%) of the 1996 marsh extent was converted to woody vegetation in 2014.

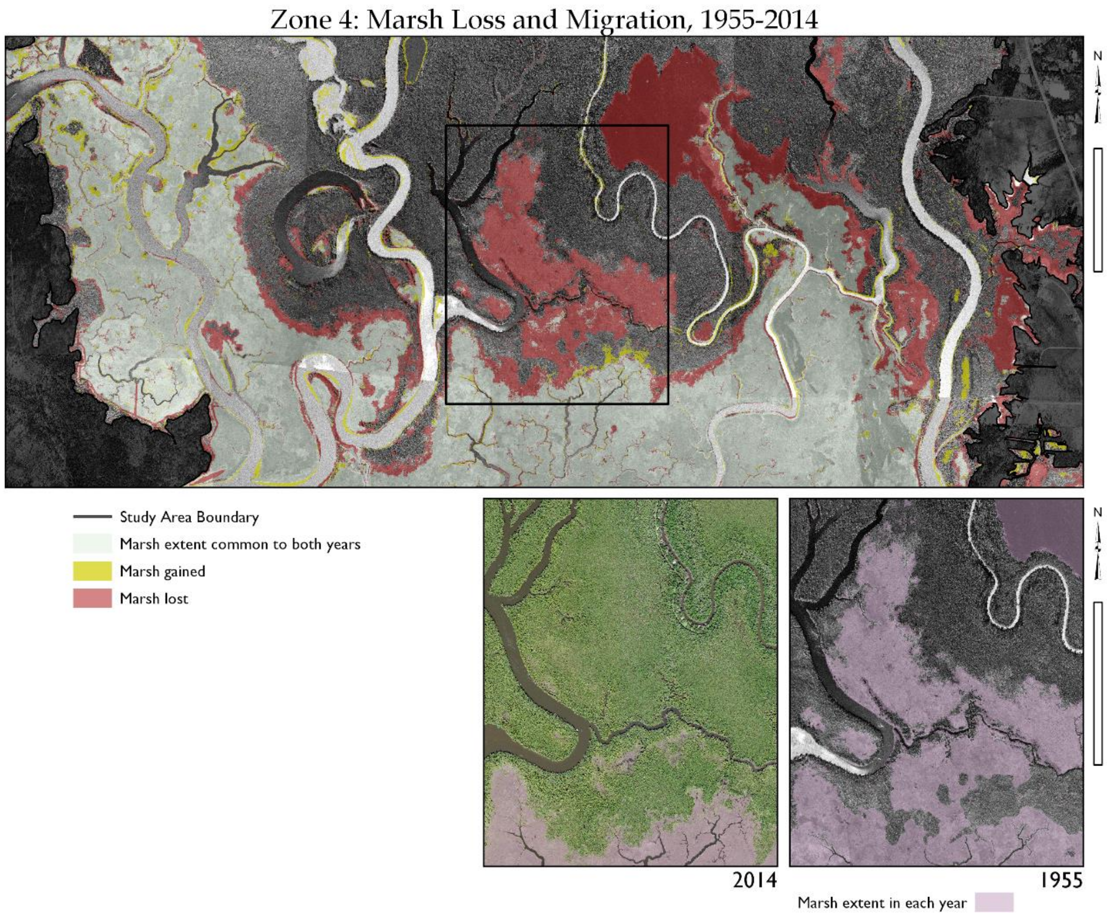


Figure 14. Marsh Loss and Migration in Zone 4

The top map shows areas of marsh gain and loss between 1955 and 2014. The two inset maps (area on top map noted by extent indicator) show the marsh extent in 2014 and 1955. While marsh areas within this rectangle have been largely colonized by woody vegetation since 1955, inland migration of marsh vegetation is notable in the southeast corner of the rectangle.

Open water conversion in this zone was positive over the entire study period, but relatively small in terms of net area compared with the woodland/shrub class changes, with a net 47.4 ha (2.7%) of marsh converted to water between 1955 and 2014. Between 1955 and 1996, a net 57.1 ha (3.29%) of the marsh class was converted to water (Appendix E). Between 1996 and 2014, however, a net 9 ha (0.7% of the 1996 marsh extent) was converted from water marsh (Appendix F). While 45.6 ha of the 1996 marsh class was classified as water in 2014, 54.6 ha of the 1996 water class was classified as marsh, making Zone 4 the only zone to exhibit a positive net marsh conversion between the marsh and water classes over any interval of the study.

This was influenced by a large degree of marsh to water conversion between 1955 and 2014 in the Paige Bayou/Bluff Creek area which was reversed between 1996 and 2014 (Figure 15). Standing water in the marsh or dead vegetation may have led to a misclassification in 1996. There is no river gauge on either waterway to check for local flood conditions, but discharge rates at Graham Ferry, Mississippi on the West Distributary were elevated on the 1996 image date above levels on the 2014 image date (US Department of the Interior & US Geological Survey, 2019). Significant channel migration in the West Distributary between 1955 and 1996 was also noted (Figure 16).

Unvegetated class changes in this zone were minimal at around 3 ha over the study period. During the first interval, 12 ha (0.7%) of marsh was converted to unvegetated land cover, while during the second interval, 9.3 ha (0.7%) of marsh was converted to unvegetated land cover.

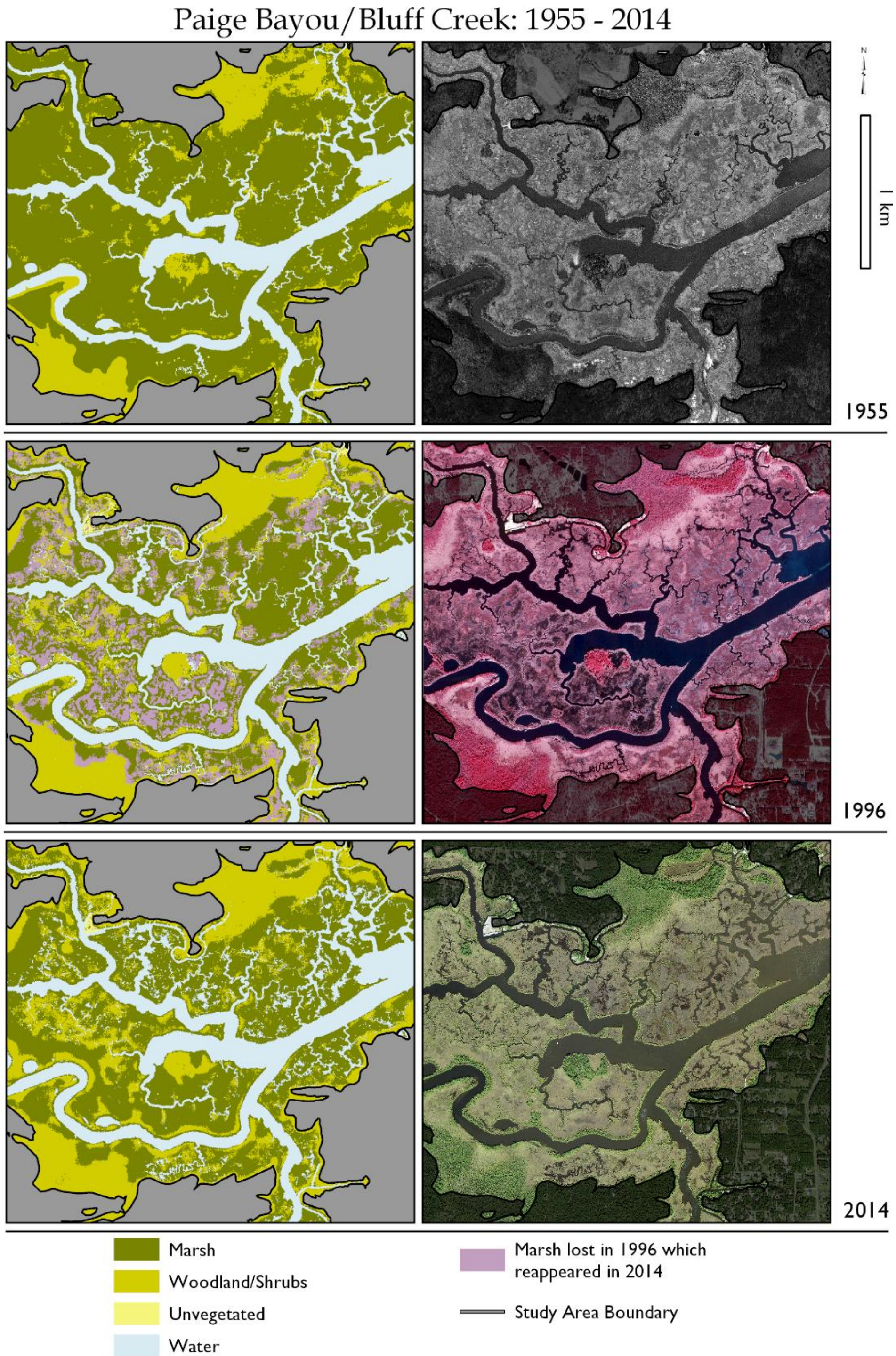


Figure 15. Habitat changes in the Paige Bayou/Bluff Creek area

Map shows the classification maps (left) and imagery (right) for the Bluff Creek/Paige Bayou area in the northwest corner of the study area for each year in the study. The middle classification map shows areas which were classified as marsh in 1955 that changed classes in 1996, but were reclassified as marsh in 2014; these areas are represented in pink.

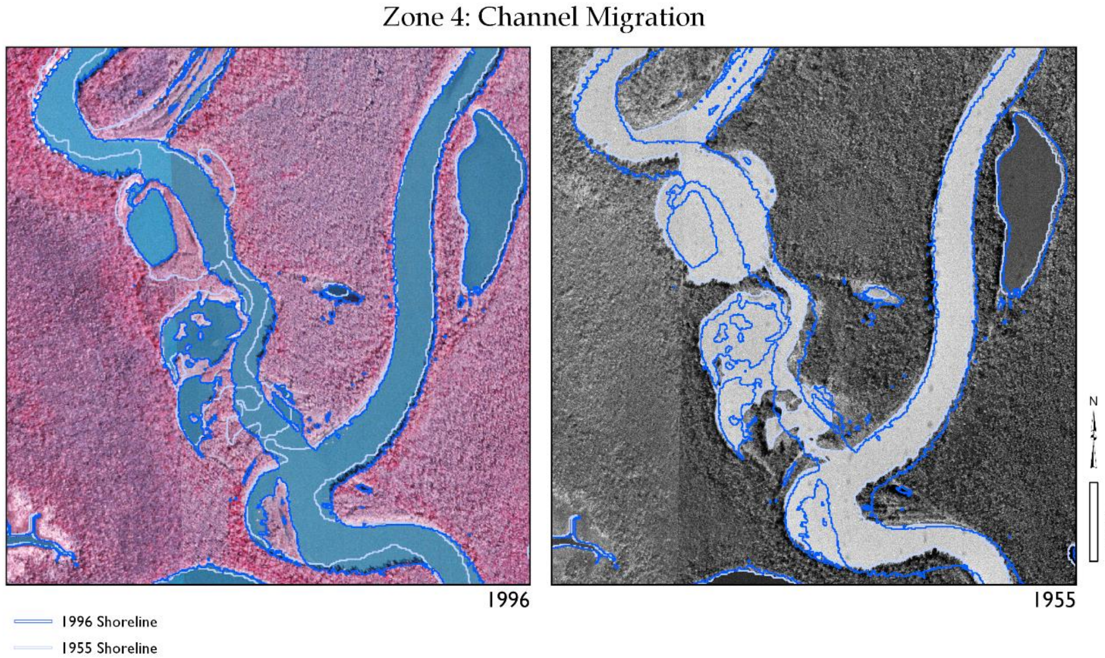


Figure 16. Channel migration in the West Distributary of the Pascagoula River

Maps show the West distributary of the Pascagoula River in 1996 (left) and 1955 (right) at the northern boundary of the study area with the 1996 and 1955 shorelines overlaid in royal blue and light blue. The change in the river's course contributed to a relatively small rate of growth in the water habitat class for Zone 4 during the first interval of the study period.

Rates of change in marsh extent

The rate of change in marsh extent was -0.34% per year when calculated over the entire study area (Table 11). The rate of marsh loss was higher for the first period (1955-1996) than for the second (1996-2014). These rates were -0.39% per year and -0.25% per year. When major anthropogenic features were masked before the change detection, the annual rate of change from 1955-2014 fell to -0.31% (Table 12). The annual rates of change with anthropogenic features masked for 1955-1996 and 1996-2014 were -0.36% and -0.24%.

Table 11 *Annual Rates of Change in Marsh Extent: Entire Study Area*

	1955-1996	1996-2014	1955-2014
Total Study Area	-0.39%	-0.25%	-0.34%
Zone 1	-0.46%	-0.01%	-0.32%
Zone 2	-0.36%	-0.50%	-0.38%
Zone 3	-0.26%	-0.11%	-0.21%
Zone 4	-0.57%	-0.27%	-0.46%

Annual rates of change in marsh extent were calculated for the total study area and for each zone by dividing the percent of marsh extent lost between the two image dates by the number of years between the two image dates.

Table 12 *Annual Rates of Change in Marsh Extent: Anthropogenic Features Masked*

	1955-1996	1996-2014	1955-2014
Total Study Area	-0.36%	-0.24%	-0.31%
Zone 1	-0.17%	0.04%	-0.10%
Zone 2	-0.36%	-0.50%	-0.38%
Zone 3	-0.25%	-0.12%	-0.21%
Zone 4	-0.57%	-0.27%	-0.46%

Annual rates of change in marsh extent, with anthropogenic features masked in each dataset, were calculated for the total study area and for each zone by dividing the percent of marsh extent lost between the two image dates by the number of years between the two image dates. Note: the rates for Zones 2 and 4 are the same in Table 11 and Table 12, as no anthropogenic features were masked in these two zones.

Zone 1. In Zone 1, the rate of annual change in marsh extent was -0.32% between 1955 and 2014 when the total study area was considered, with a rate of change of -0.46% per year between 1955 and 1996 and a rate of change of -0.01% per year between 1996 and 2014 (Table 11). These rates shifted to -0.10% per year (1955-2014), -0.17% per year (1955-1996) and +0.04% per year (1996-2014) when anthropogenic features were masked (Table 12). These features included Ingalls Shipyard, Highway 90, and the CSX railroad. A small strip of marsh was lost in the masked area due to shipyard additions during the 1996-2014 period. In the unmasked portion of the image, however, land cover conversion from woody vegetation and unvegetated shoreline to marsh outpaced marsh conversion to open water for a net positive rate of change in marsh extent between 1996 and 2014.

The rate of conversion from marsh to open water was 0.14% per year during the first interval but increased during the second interval of the study to 0.34% per year. When anthropogenic features were masked, the difference in these rates was slightly less pronounced, but the rates were higher due to the smaller initial marsh area measured as a result of the mask. 0.17% of marsh extent per year was converted to water during the first interval and 0.35% of marsh extent per year was converted to water in the second.

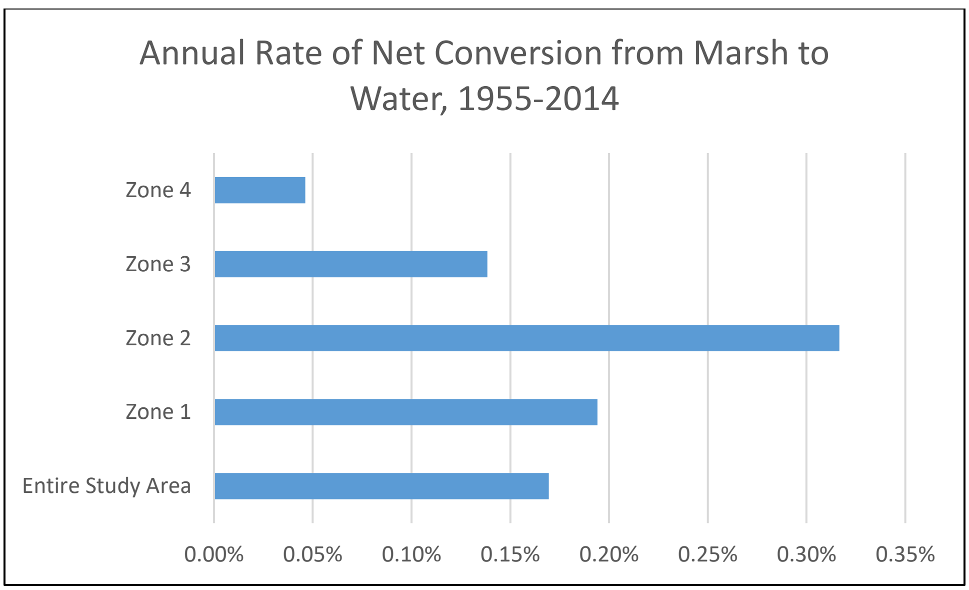


Figure 17. Rates of conversion from marsh to water by Zone

Zone 2 exhibited the highest rate of net change from marsh to water at 0.32% per year. The rate of change for the entire study area was 0.17% per year. The rates for Zones 1, 3, and 4 were 0.19%, 0.14%, and 0.05%.

Zone 2. The second-highest rate of marsh loss was in Zone 2 at -0.38% annually between 1955 and 2014 (Table 11). In this zone, the rate increased during the second time period, from -0.36% (1955-1996) to -0.50% (1996-2014). Because Zone 2 contains no major anthropogenic features, the rates of change were the same for both change detections. The rate of marsh to water conversion in this zone also increased between the first and second interval from 0.26% per year to 0.53% per year. Over the entire study period, the rate of marsh to water conversion was 0.32% per year, the highest among all four zones (Figure 17).

Zone 3. In Zone 3, the rate of marsh change remained constant at -0.21% between 1955 and 2014, regardless of whether anthropogenic features (Interstate-10) were masked (Table 11, 12). When the total study area was considered, the annual rate of change was -0.26% for 1955-1996 and -0.11% for 1996-2014. When Interstate-10 was masked, these rates were -0.25% and -0.12%. As with Zones 1 and 2, the rate of marsh to water conversion increased between the two intervals from 0.13% per year to 0.19% per year. This increase, however, is much less pronounced than in the southern two zones.

Because the construction of the Interstate-10 bridge resulted in a loss in marsh area during the initial period, masking this area led to a slightly lower rate of loss during the 1955-1996 interval. A slightly higher rate of marsh loss was calculated with this area masked for the second period due to a difference in camera angle which allows for a thin strip of marsh to be visible along the south side of the bridge in 2014 that is not visible in the 1996 image.

In addition to removing anthropogenic destruction from the rate of change, masking this feature allows for a more accurate representation of habitat change, as the brightness values do not represent ground reflectance, but the reflectance of the raised bridge above the ground. While the area beneath the Interstate-10 bridge is known to be water in the present day, in the absence of 1996 reference data, masking the area is a more conservative way to accurately represent ground conditions based on the available data. However, the masked area was not large enough in this zone to influence the rate of marsh to water conversion and did not have a large impact on the results for this zone.

Zone 4. Among the four zones, Zone 4 exhibited the highest annual rate of marsh loss at -0.46% between 1955 and 2014 (Table 11). However, the annual rate of loss was much higher in the initial period (-0.57% per year) than in the final period (-0.27% per year). The main driver of marsh loss in this area was the encroachment of woody vegetation. The annual rate of marsh conversion to woody vegetation was 0.47% per year between 1955 and 1996 and 0.34% per year between 1996 and 2014.

The rate of marsh to water conversion between 1955 and 1996 was 0.13% per year, comparable the rate of open water conversion in Zone 3. In contrast with the other three zones, however, Zone 4 exhibited a positive net conversion between marsh and water between the second two image dates, resulting in an annual rate of water conversion to marsh of 0.004% per year. This may have been influenced by the misclassification of marsh vegetation as water in the Bluff Creek area in the 1996 habitat classification due to what appear to be wet soil conditions (Figure 15). Much of this area was classified as marsh in both 1955 and 2014 but classified as water in 1996. These areas contribute to a net gain in marsh areas during the second interval of the study even though they may not represent a true change in land cover.

Regression of marsh extent over time

Linear regression of total marsh extent in hectares with year yielded a slope of -22.9 ha/year with an intercept of 51415 ha (Figure 18). The coefficient of determination (r^2) was 0.98 and the standard error of the regression (S) was 123.4 ha. With anthropogenic features masked, the relationship between marsh extent and year was slightly stronger ($r^2 = 0.99$, S = 97.6 ha) (Figure 19). The slope of the regression equation was -20.7 hectares per year with an intercept of 46953 ha.

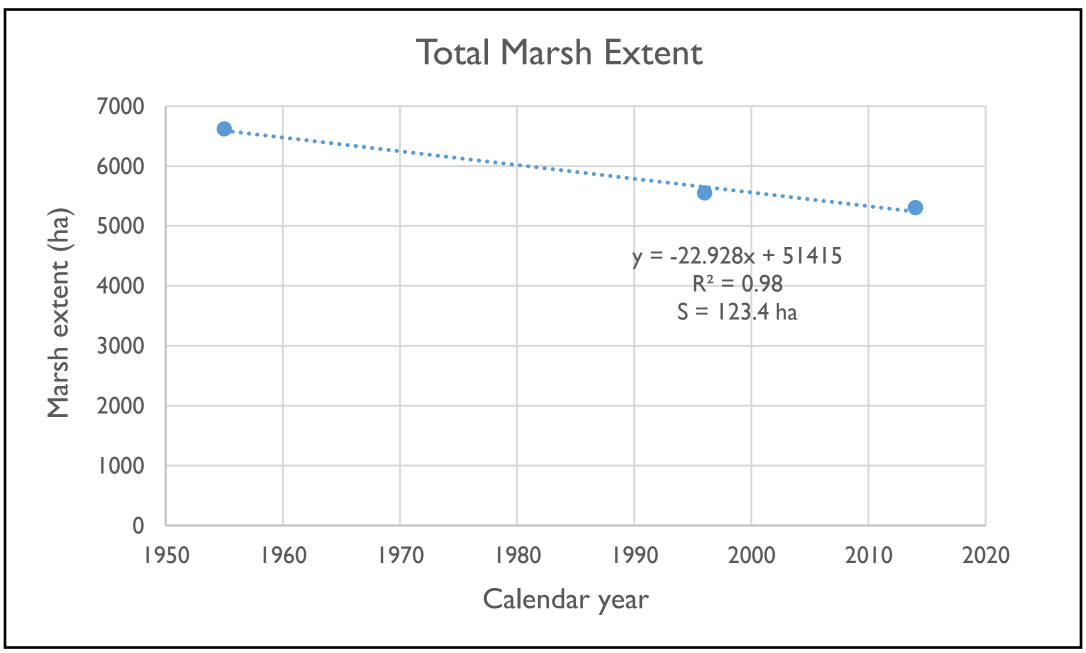


Figure 18. Regression of total marsh extent with calendar year

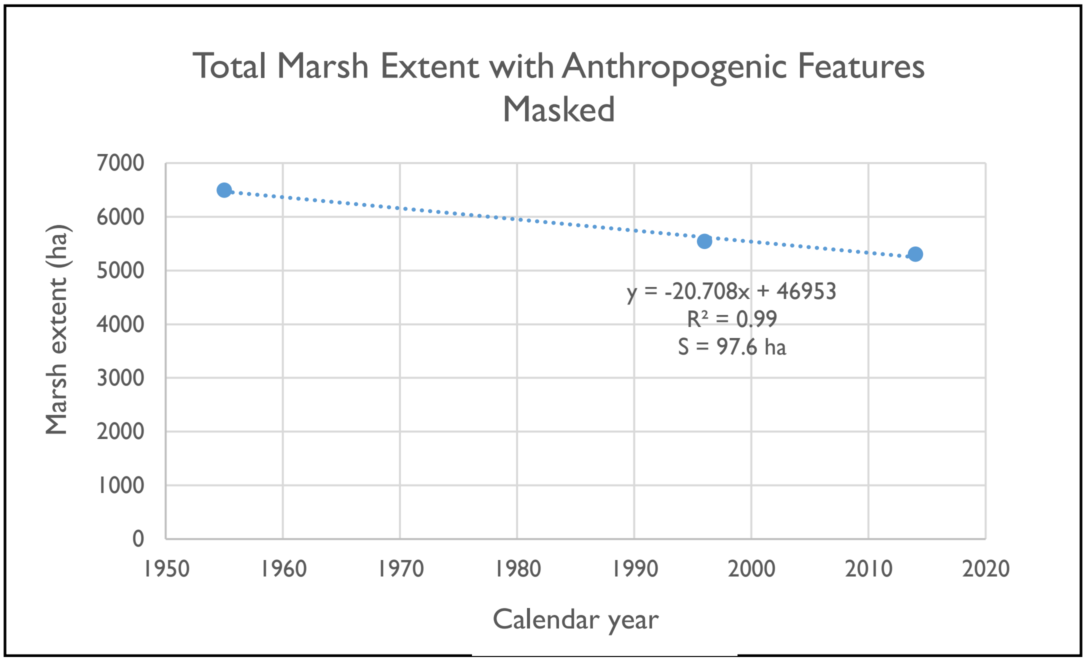


Figure 19. Regression of total marsh extent (anthropogenic features masked) with calendar year

When regression analysis was performed for each zone, marsh extent in Zone 1 exhibited the weakest linear relationship with year. When the entire zone was considered, the slope of the regression equation was -2.7 hectares per year with an intercept of 5976 ha (r^2 = 0.91, S = 34.5 ha) (Figure 20). When anthropogenic features were masked, the r^2 value fell to 0.85 (slope = -0.8 ha/year, intercept = 2140.0 ha, S = 13.8 ha) (Figure 21).

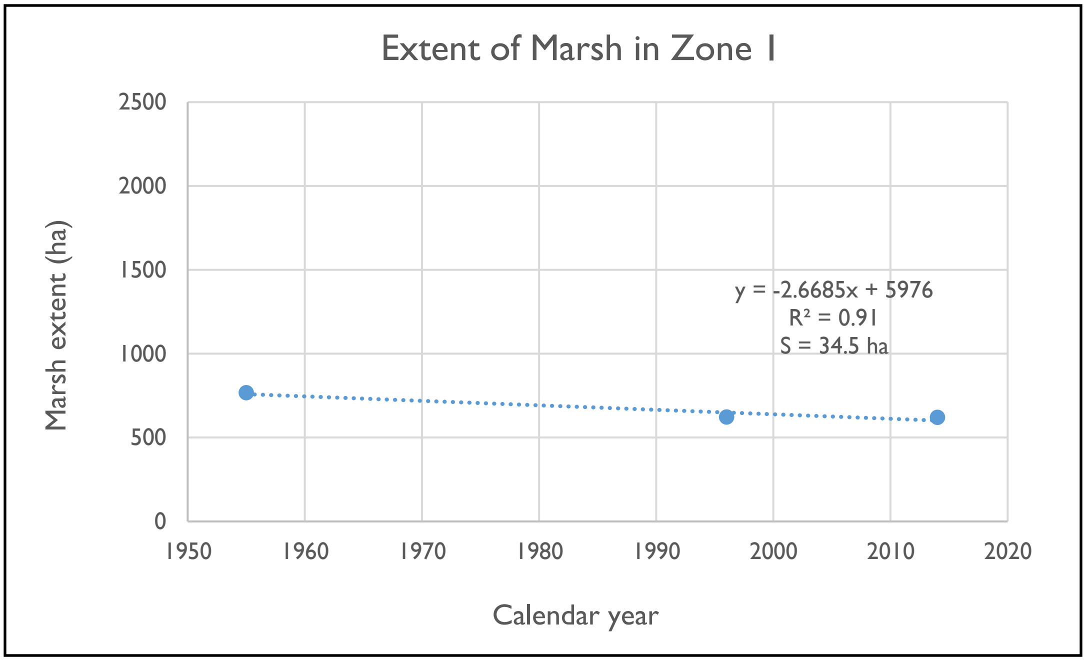


Figure 20. Regression of marsh extent in Zone 1 with calendar year

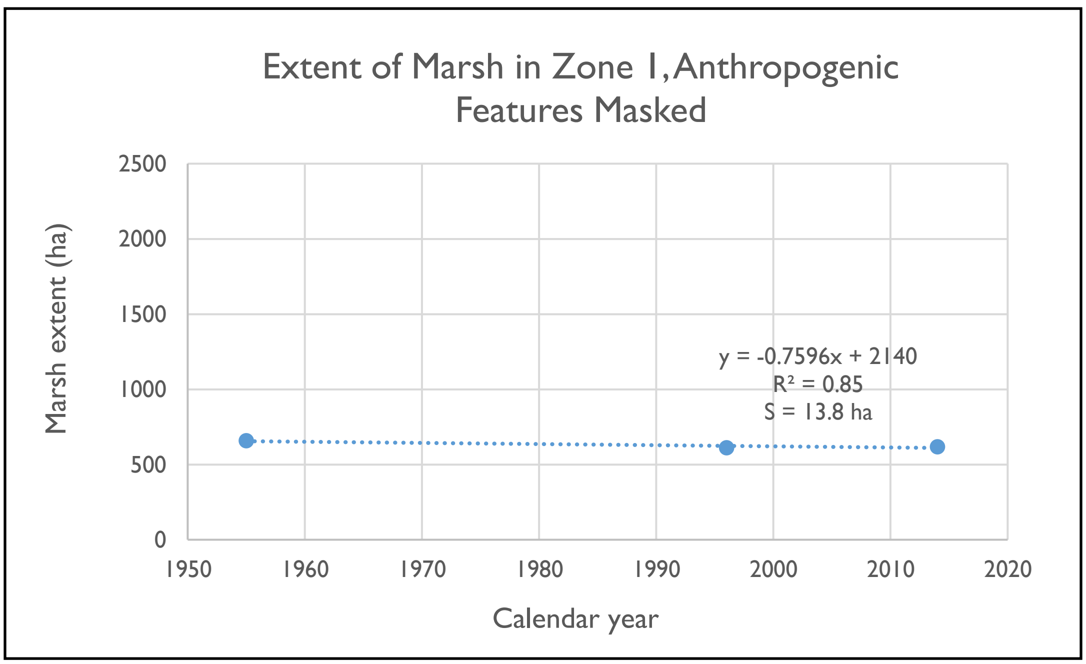


Figure 21. Regression of marsh extent in Zone 1 (anthropogenic features masked) with calendar year

The strongest linear relationships between marsh extent and year were found in the two central zones (Zones 2 and 3). Zone 2 exhibited the strongest relationship (slope = -6.8 ha/year, intercept = 15132 ha, r^2 =0.998, S = 12.2 ha) (Figure 22).

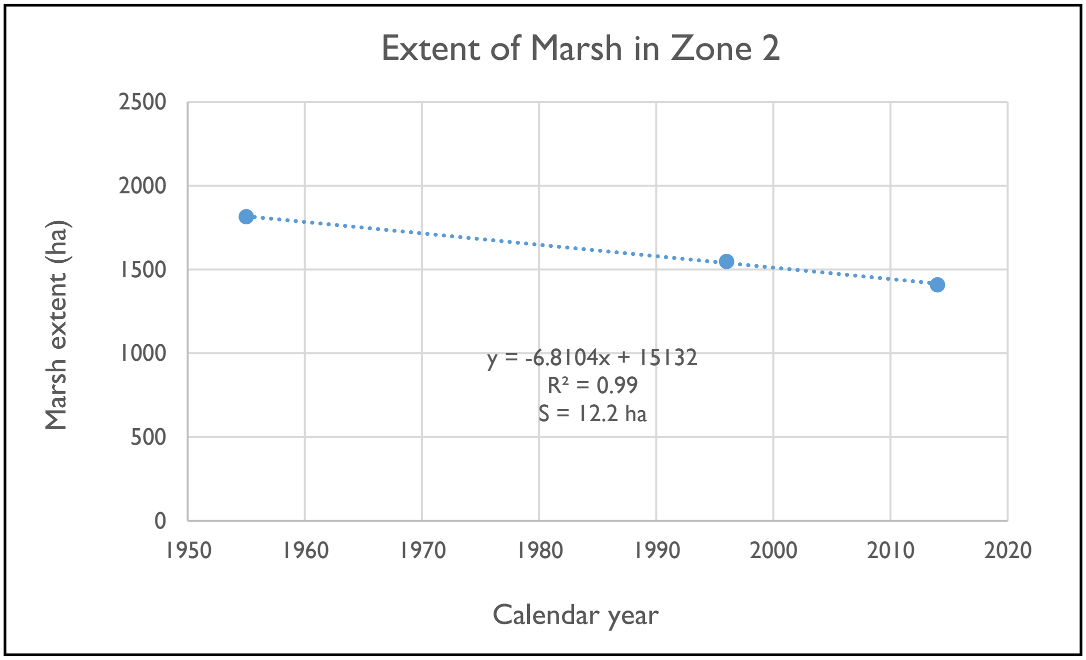


Figure 22. Regression of total marsh extent in Zone 2 of the study area with calendar year.

In Zone 3, the strength of the regression was improved when anthropogenic features were masked. When the entire zone was considered, the slope of the regression equation was -5.1 hectares per year with an intercept of 12329 (r^2 = 0.97, S = 37.6 ha) (Figure 23). With Interstate-10 masked, the slope fell to -4.9 hectares per year with an intercept of 11808 ha (r^2 = 0.98, S = 33.1 ha) (Figure 24).

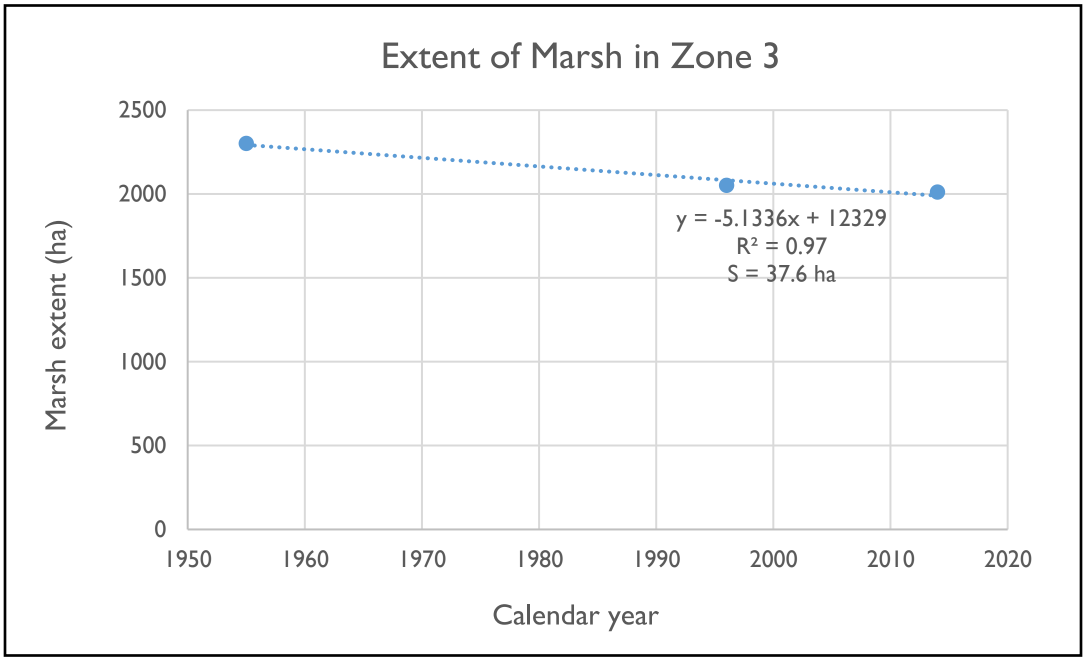


Figure 23. Regression of total marsh extent in Zone 3 with calendar year

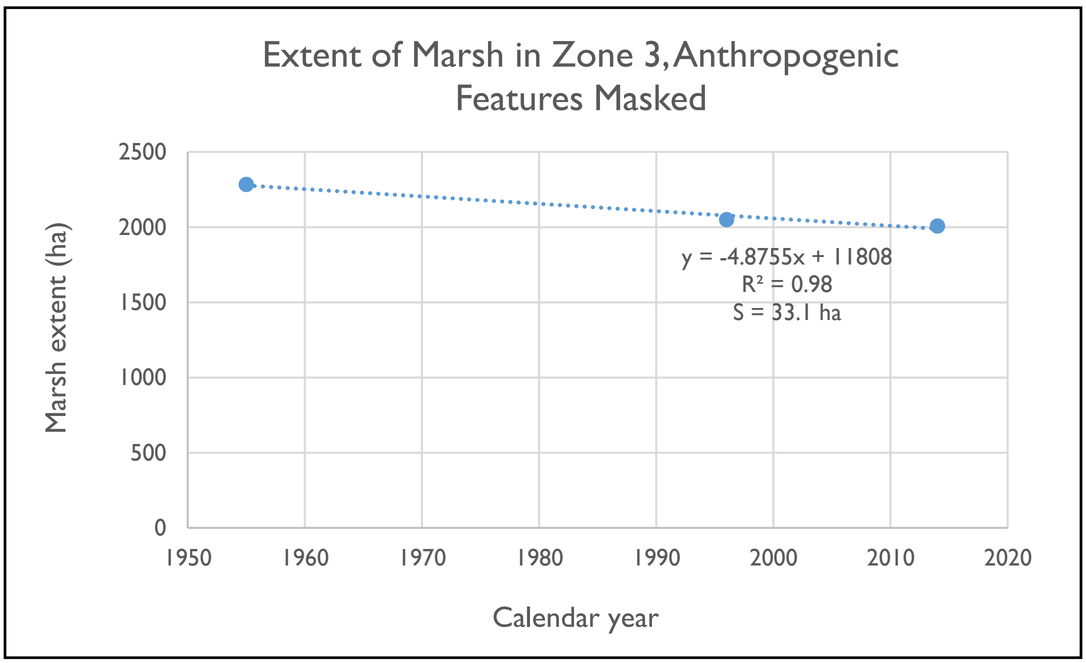


Figure 24. Regression of marsh extent in Zone 3 (anthropogenic features masked) with calendar year

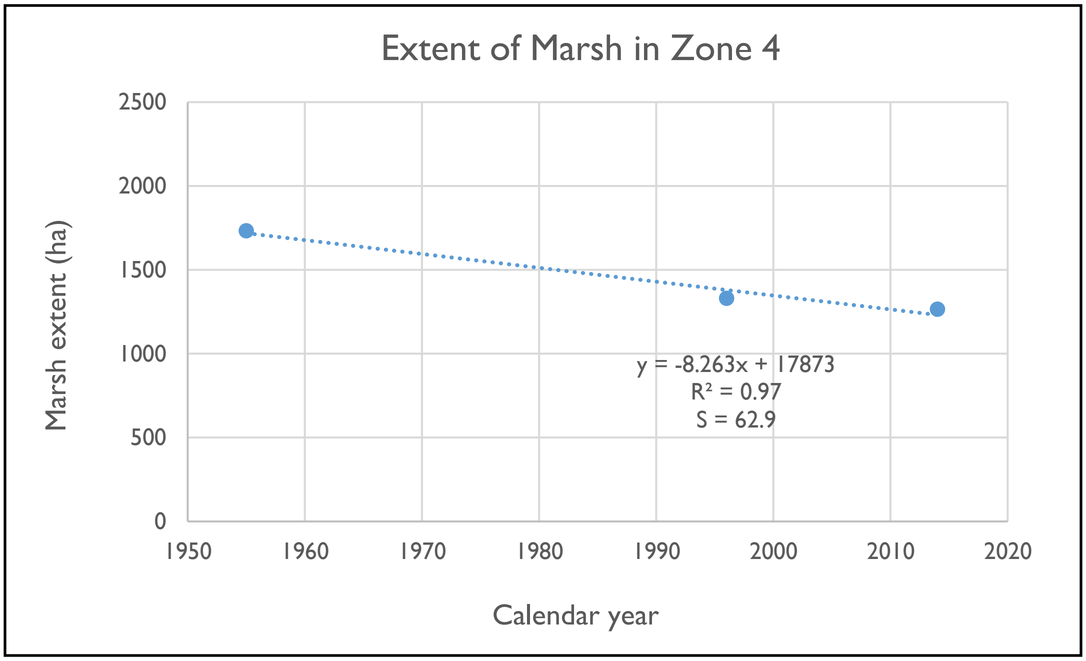


Figure 25. Regression of marsh extent in Zone 4 with calendar year

The greatest slope was observed in Zone 4, the most inland zone, at -8.3 hectares per year (intercept = 17873, r^2 = 0.97, S = 62.9) (Figure 25).

With a coefficient of determination of 0.98 and a low standard error (S), the modeled negative linear relationship between marsh extent and calendar year for the entire study area (both with and without anthropogenic features included) was strong. This relationship was stronger (r^2 =0.99) when anthropogenic features were masked. Additionally, the negative linear relationship between marsh extent and year was strong for the two central zones, particularly when anthropogenic features were masked in Zone 3.

Marsh extent in 2050 was predicted using the regression equation for the entire study area with anthropogenic features masked (y = -20.708x + 46953) (Figure 19). Assuming that no further development or construction replaces marsh inside the study area, marsh extent in 2050 was predicted as 4500.8 ha (Figure 26). This would represent a decrease of 799.5 ha, or 15.1%, between 2014 and 2050, and decrease of 1991.0 ha (almost 20 km^2), or 31.1%, between 1955 and 2050.

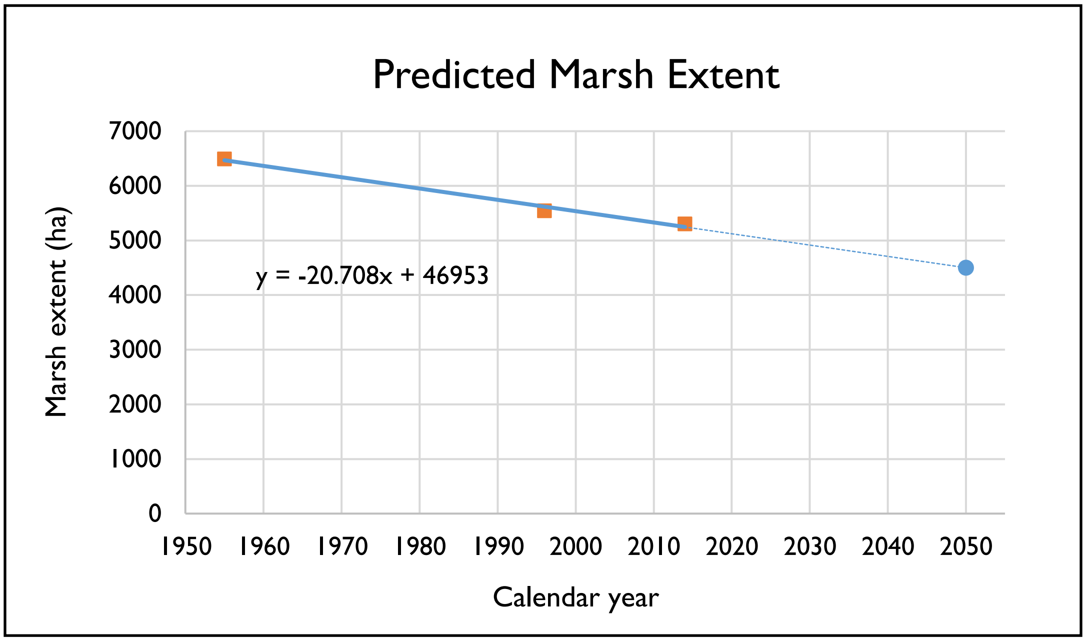


Figure 26. Prediction of Marsh Extent in 2050

Marsh extent in 2050 was predicted based on the results of the regression of total marsh extent with anthropogenic features masked with calendar year. The predicted extent of marsh vegetation in 2050 was 4500.8 ha.

CHAPTER V – DISCUSSION AND CONCLUSIONS

Discussion

Based on the results, marsh extent in the Pascagoula River Estuary can be expected to continue to decline. While the rates of change in marsh extent slowed for Zones 1, 3, and 4 between the first and second intervals of the study, rates of conversion to open water increased in all but the most inland zone of the estuary. While the modeled linear relationship between marsh extent and calendar year was strong, it is likely that the prediction of marsh habitat extent for 2050 underestimates marsh loss, as sea level rise is not expected to proceed linearly, but to accelerate in the coming decades (Wu, Biber, et al., 2017, p. 10891).

The results for Zone 1 conform to our expectations about how sea level rise will affect estuarine boundaries. As shorelines retreated (Figure 26), upland habitats were overtaken by marsh vegetation (Bilskie et al., 2014; Kirwan & Temmerman, 2009; Orson et al., 1985). Outside the masked anthropogenic areas, marsh vegetation overtook unvegetated areas during both intervals of the study, and marsh vegetation also colonized previously wooded areas in the second interval of the study. Coupled with an increase in the total area covered by water, these habitat changes indicate a shift to wetter habitat types over the course of the study period. Contrary to H_2, however, Zone 1, the most marine portion of the estuary, did not exhibit the highest rate of marsh loss during the study period (observed in Zone 4) or even the highest rate of conversion to open water (observed in Zone 2). Additionally, the rate of marsh loss was slower between 1996 and 2014 than 1955 and 1996 because of upland habitat conversions to marsh. However, the increasing rate of marsh to water conversion observed in this zone is likely to eventually lead to a higher rate of overall marsh loss as sea level continues to rise. At higher water levels, marsh vegetation will run out of upland areas to colonize ("accommodation space"), and the ecological threshold described by Wu et al (2017) will be reached (Schuerch et al., 2018; Wu, Biber, et al., 2017).

Based on the calculated rates of change in marsh extent and the linear regression of marsh area over time, the most vulnerable zone of the study area is Zone 2. This portion of the estuary exhibited an increasing rate of marsh loss between the two study intervals, as well increasing rate of marsh to water conversion. The rate of marsh to water conversion was also higher in Zone 3 during the second study interval, although this rate increase was less dramatic and the overall rate of marsh loss was slower in the second interval. For both zones, linear regression indicated a strong negative relationship between marsh extent and year, with a rate of loss of 6.8 hectares per year since 1955 in Zone 2 and 5.1 ha per year in Zone 3 with Interstate-10 masked. Dredging and channelization can potentially hinder marsh accretion by reducing suspended sediment availability as well as impact vegetation health by allowing for increased saltwater intrusion (Kennish, 2001, pp. 734–735). The channelization of the East Distributary, as well as the development of the shoreline along its banks, may thus have contributed to a high rate of loss in the central marsh. Further analysis to assess the differences in marsh change between the east and west portions of the estuary could shed light on whether marsh loss is more significant along the East Distributary than the West.

As in Zone 1, class changes between the woodland/shrub and marsh habitats in Zones 2 and 3 indicate a shift to wetter habitat types over the second interval of the study. The expansion of woodland vegetation at the eastern and western boundaries of the marsh as well as the growth of woody vegetation surrounding relatively high-elevation dredge spoil deposits contributed to a net positive conversion from classified marsh to classified woodland/shrub land cover between 1955 and 1996 in both zones. However, this trend was reversed second interval of the study period, with marsh vegetation replacing a large proportion of previously wooded areas along the banks of the East distributary in Zone 3 as well as some woody vegetation surrounding dredge spoils in Zone 2.

Different factors appeared to influence the habitat changes at the freshwater boundary of the estuary. Colonization by woody vegetation was the dominating factor in loss of marsh extent in Zone 4, while the rate of marsh conversion to open water was lower; this figure may have been influenced by unusually wet soil conditions in 1996 (Figure 15). The interactions between the marsh and woodland land cover classes in this portion of the marsh warrant further study. Marsh vegetation does not appear to have migrated inland as expected under sea level rise conditions except in a few small areas (Figure 14).

Woodland vegetation in the northern part of the study area noted by the 2016 survey was indicative of tidal freshwater swamp habitat. Species composition and forest structure in this transitional zone is sensitive to changes in tidal influence (C. J. Anderson et al., 2013, p. 2). Thus, species diversity and species turnover can be high, in part due to annual fluctuations in salinity which can encourage the growth of salt-tolerant vegetation (C. J. Anderson et al., 2013, p. 9). In their examination of hydrological patterns in the forested wetlands of the Apalachicola River, Anderson and Lockaby (2012) found tidal freshwater swamps to exist within a narrow water level range of ±20 cm of the ground surface, and at salinities of less than 0.5 ppt (C. J. Anderson & Lockaby, 2012, p. 814). It is therefore possible that high rates of overbank sedimentation or storm deposition have increased elevation in this part of the estuary to a degree that has allowed freshwater swamp species such as *T. distichum* to out-compete marsh grass species (Flessa et al., 1977, p. 1803; Harrison & Bloom, 1977; Orson et al., 1985, p. 1934; Williams, 2012, pp. 904–905). However, the colonization of marsh areas by flood-tolerant tree species such as *T. distichum* could also point to a change in chemical or biotic factors, such as a decrease in salinity related to increased freshwater input (C. J. Anderson et al., 2013, p. 2; Cho, 2011, p. 10; Powell, Jackson, & Ardón, 2016, p. 548). More detailed research regarding the plant species present in this area as well as study of past and present sedimentation rates would assist in determining the trajectory of future habitat change at the northern boundary of the estuary.

Overall, the results of the regressions indicate a steady, linear decline in marsh extent in the central portion of the estuary. The regression results for Zones 1 and 4, however, indicate that the change in marsh extent over time is not linear at the northern and southern boundaries of the marsh. In Zone 1, marsh colonization of unvegetated areas between 1955 and 1996 was not echoed in magnitude in the period from 1996 to 2014 because there was less low-elevation area available for marsh vegetation to colonize. Changes in elevation within the study area are small, but the elevation gradient at the periphery of the marsh to the east and west is steep; marsh colonization will not occur past this boundary, which was approximated by the elevation mask for the study area, unless sea level rises to a much higher level (Bilskie et al., 2014; Orson et al., 1985; Wu, Biber, et al., 2017). Thus, it would seem that the availability of accommodation space at the northern boundary of the estuary will be a key factor in determining the future extent of marsh vegetation (Schuerch et al., 2018).

In Zone 4, the rate of marsh loss and the rate of marsh conversion to woody vegetation were both slower during the second interval of the study. These rates of change, however, were still high; the areal extent of marsh converted to woodland between 1996 and 2014 was greater in Zone 4 than the extent of marsh converted to open water in Zone 3 over the same interval. Further inquiry into the mechanisms behind this habitat shift will allow for more a more thorough evaluation of how the inland boundary of marsh vegetation might change in the future.

A planned addition of more sample dates to the study may improve confidence in the observed trends shown in the linear regressions. The inclusion of additional image datasets will also aid in the determination of how much of the differences in the rates of change in marsh extent are a result of differences in hydrological conditions or seasonal variation between image dates, and how much of these differences are attributable to permanent changes in habitat structure and extent.

Ideally, imagery would have been obtained at the same tidal and river stage for each image. However, considering the absence of river gauge data before 1993 and tide gauge data before 2003, imposing this limitation would severely restrict, if not totally prevent, historical study of the area (Jensen et al., 1993, p. 1044; US Department of the Interior & US Geological Survey, 2019). In their guidelines for coastal habitat mapping, The Coastal Change Analysis Program (C-CAP) deems tide heights of greater than three feet above Mean Low Tide (MLT) unacceptable for image acquisition and analysis, while up to two feet above MLT is recommended and MLT or lower is ideal (Dobson et al.

1995, 26). Available data for tide and river gauge heights were compared for each image collection date to evaluate the possible influence of water level on the image classification results.

Eight of the nine frames in the 2014 dataset were obtained October 5, 2014, while the final image was obtained October 16. At USGS Station 02480285 at the West Pascagoula River at Highway 90, the October 5 tidal high was measured via tide gauge as 1.47 feet (0.45 m), the tidal low was 0.34 feet (0.10 m), and the mean tide level was 0.97 (0.30 m) using the NAVD 1988 datum. On October 16, the tidal high was 0.90 feet (0.27 m), the tidal low was 0.01 feet (0.003 m), and the mean tidal height was 0.45 feet (0.14 m) (US Department of the Interior & US Geological Survey, 2019).

No tide gauge information was available for the 1996 image date (February 12) nor for the 1955 image date (February 13). The tidal range in the estuary is typically low. The mean range measured at the Pascagoula NOAA Lab (NOAA Station 8741533) between September 2005 and January 2019 is 1.35 feet (0.41 m), with the diurnal range reported as 1.53 feet (0.47 m) (Center for Operational Oceanographic Products and Services, 2018). Christmas (1973) reports the spring tide range as approximately 2.5 feet (0.76 m) and neap tide range as approximately 1 foot (0.31 m) (Christmas, 1973, p. 25). The average February Mean Tide Height from 2006 to 2018 was -0.05 feet using NAVD 1988 (Center for Operational Oceanographic Products and Services, 2018). Considering this average and the known tide levels for the 2014 image dates, it is possible that the tide was at a lower level in the two historical datasets than in the 2014 dataset. Several areas off the coasts of the marsh islands at the marine boundary of the study area which were classified as water in both the 1955 and 2014 classifications were classified as unvegetated by the ML algorithm in the 1996 classification. These appear to represent either high turbidity or exposed tidal flats, which would indicate a low tidal stage. A lower tide level could theoretically influence the classification of mixed pixels along the shoreline, particularly at the marine boundary of the image. However, the small tidal range in the estuary means that under typical circumstances, even at high tide, the tidal height would not have exceeded the guidelines set forth by the C-CAP in either of the historical images, and it is known to have been within recommended height for the 2014 image date (Campbell & Wang, 2018, p. 5169; Dobson et al., 1995, p. 26; US Department of the Interior & US Geological Survey, 2019). In their assessment of tidal influence on *Spartina alterniflora* classification in Jamaica Bay, New York, Campbell and Wang (2018) found that only 0.0014% of modeled marsh vegetation was inundated at a tidal height of 70.1 cm (2.3 feet) above MLW, a higher tidal stage than represented in the 2014 imagery (Campbell & Wang, 2018, p. 5173). The small tidal range in the estuary gives further assurance that under typical circumstances, even at high tide, tidal waters would not inundate marsh vegetation; differences in tidal stage would more likely be recognizable by the exposure or inundation of unvegetated tidal flats in the imagery, as appears to be the case in the 1996 dataset. Thus, it is unlikely that tidal stage materially influenced the classification of marsh vegetation in this study.

River stage also impacts hydrological conditions in the estuary. At USGS Station 02479310 at Graham Ferry, the river gauge closest to the study area, gauge height on October 5, 2014 ranged between approximately 2.55 feet and 2.92 feet using the NGVD 1929 datum, while discharge ranged between approximately 2300 and 3220 cubic feet per second. On October 16, the river stage was higher, with the gauge height ranging from approximately 3.05 feet to 3.41 feet, while discharge ranged from approximately 2700 to 3820 cubic feet per second (US Department of the Interior & US Geological Survey, 2019). Gauge height information was not available for 1996. However, discharge on February 12, 1996 was measured between approximately 23000 and 19000 cubic feet per second, which could indicate a higher river stage (US Department of the Interior & US Geological Survey, 2019). A comparable discharge rate on February 4, 2019, was associated with a gauge height of between 13.2 and 12.7 feet, which is below the National Weather Service Flood Stage designation of 16 feet. In the 1996 dataset, dark patches in the northwest portion of the marsh surrounding Paige Bayou and Bluff Creek inland from the Pascagoula/Bluff Creek confluence may be an indication of standing water in the marsh at the time of image acquisition (Figure 15). However, no flood gauge exists on either creek to check for flood conditions in this specific area, and these patches could alternately represent reflectance from dark, wet soil as a result of sparse canopy coverage or vegetation die back (Bartlett & Klemas, 1981, p. 1702; Hardisky et al., 1986, p. 455; Jensen et al., 2002, p. 30). While it is not likely that the Pascagoula river exceeded flood stage on February 12, 1996, conditions may have been wetter in the inland part of the study area during the acquisition of the 1996 imagery than at the time of acquisition of the 2014 imagery. It is not possible, however, to tell whether or to what extent this impacted the image classification results.

While no data were available for the 1955 image date at this station, neither was any indication found in the literature that flood conditions occurred during this part of the year. A USGS report on flooding during 1955 describes flooding which began in southern Mississippi April 12, but makes no mention of any flood conditions before that date and indicates normal rates of stream discharge north of the study area previous to the described flooding (Wells, 1962, pp. 84–93).

Imagery acquired in the same month was not available across study years. NAIP acquires “leaf-on” imagery for the purpose of agricultural monitoring (Jensen, 2015, p. 600). It is likely that the October 2014 NAIP imagery represents higher above-ground biomass than a February image from the same year, considering that measurements for above-ground biomass in the estuary tend to peak in August or September (Mishra et al., n.d.). The spectral properties of each habitat type certainly vary between leaf-off and leaf-on periods (Mishra et al., n.d.; O’Hara et al., 2003, p. 2008). However, considering the perennial nature of the dominant salt marsh species in the Pascagoula River Estuary (Eleuterius, 1975, pp. 135–138) and the use of textural features in defining habitat types, the use of multi-seasonal image data, though not ideal, still presents a valid comparison if one assumes that the relative degree of textural variability within each habitat type does not change dramatically throughout the year (Jeter & Carter, 2016, p. 987; Nicholson, 2017, p. 11). Because training data was selected for each habitat type from within the same image, and because it was selected using textural features rather than spectral features, *a priori* knowledge of the exact spectral signature of each vegetation or habitat type was not necessary to classify land cover (Jeter & Carter, 2016; Nicholson, 2017). The spectral signatures of each habitat type need not match exactly across years, because the habitat types were defined based on their CV values rather than their spectral signatures.

Chrysafis and others found that GLCM texture measures computed using a 3x3 moving window produced the most accurate land cover classifications in in the Rhodopes mountain range in Greece when multi-seasonal Sentinel 2 data were incorporated, implying phenological differences in the textural features of the habitats represented in the imagery (Chrysafis, Mallinis, Tsakiri, & Patias, 2019, pp. 6–8). However, the authors also reported similarly high accuracy for single-date imagery when a larger window size (9x9) was used (Chrysafis et al., 2019). Pu and others similarly found a statistically significant increase in classification accuracy when multi-seasonal Pleiades data were used to distinguish among seven urban tree species in Tampa, FL, but this improvement was again described as “modest” in comparison with the best single-date classification results (Pu, Landry, & Yu, 2018, pp. 153–156). Thus, while highlighting the need for further research, these studies do not necessarily invalidate the assumption that the four land cover classes defined in the present study – marsh, woodland and shrubs, water, and unvegetated areas – remain texturally distinguishable from each other throughout the year. More detailed investigation into phenological variations in the textural characteristics of the habitat types present in the Pascagoula River Estuary, including the examination of multi-seasonal imagery from the same year to assess seasonal textural variations, would strengthen confidence in the between-year change detection results.

Conclusions

The present study identified key areas of change within the marsh as well as establishing historical baselines for marsh extent in the estuary. Land cover was classified in the Pascagoula River Estuary at a high spatial resolution (3 meters GSD) using black and white aerial imagery obtained February 13, 1955, and color-infrared aerial imagery obtained February 12, 1996, and October 5-16, 2014. Marsh extent was quantified for each year, along with water, woodland/shrubs, and unvegetated areas. Land cover changes over the study period were assessed for the entire study area and compared among four regions of the estuary, divided from north (inland) to south (marine). The rates of change in marsh extent, both among these four zones and between the two time intervals in the study, were examined, revealing a trend of decreasing rates of marsh loss, but increasing rates of marsh conversion to open water in the two southern, marine zones. Linear regressions of marsh extent with calendar year were performed for the entire study area and for each zone, revealing a strong negative linear relationship of marsh extent with time. Based on the results of the linear regressions, a decrease from the 1955 marsh habitat extent of around 31% is predicted by 2050.

As sea level rises, and with an expected increase in the severity and frequency of tropical storms (Knutson et al., 2010), the problem of conservation in the Pascagoula River Estuary will become increasingly pressing. Bilskie and others (2014) project a greater response in maximum storm surge to sea level rise as more of the central marsh is converted to open water, which will lead to lessened protection from flooding in neighboring areas (Bilskie et al., 2014, p. 932). Fisheries will become increasingly threatened as nursery and feeding areas are lost or become fragmented (Partyka & Peterson, 2008, p. 1579). Thus, the continued decline of the Pascagoula River marsh will have not only ecological, but also cultural and economic ramifications for the Mississippi Gulf Coast.

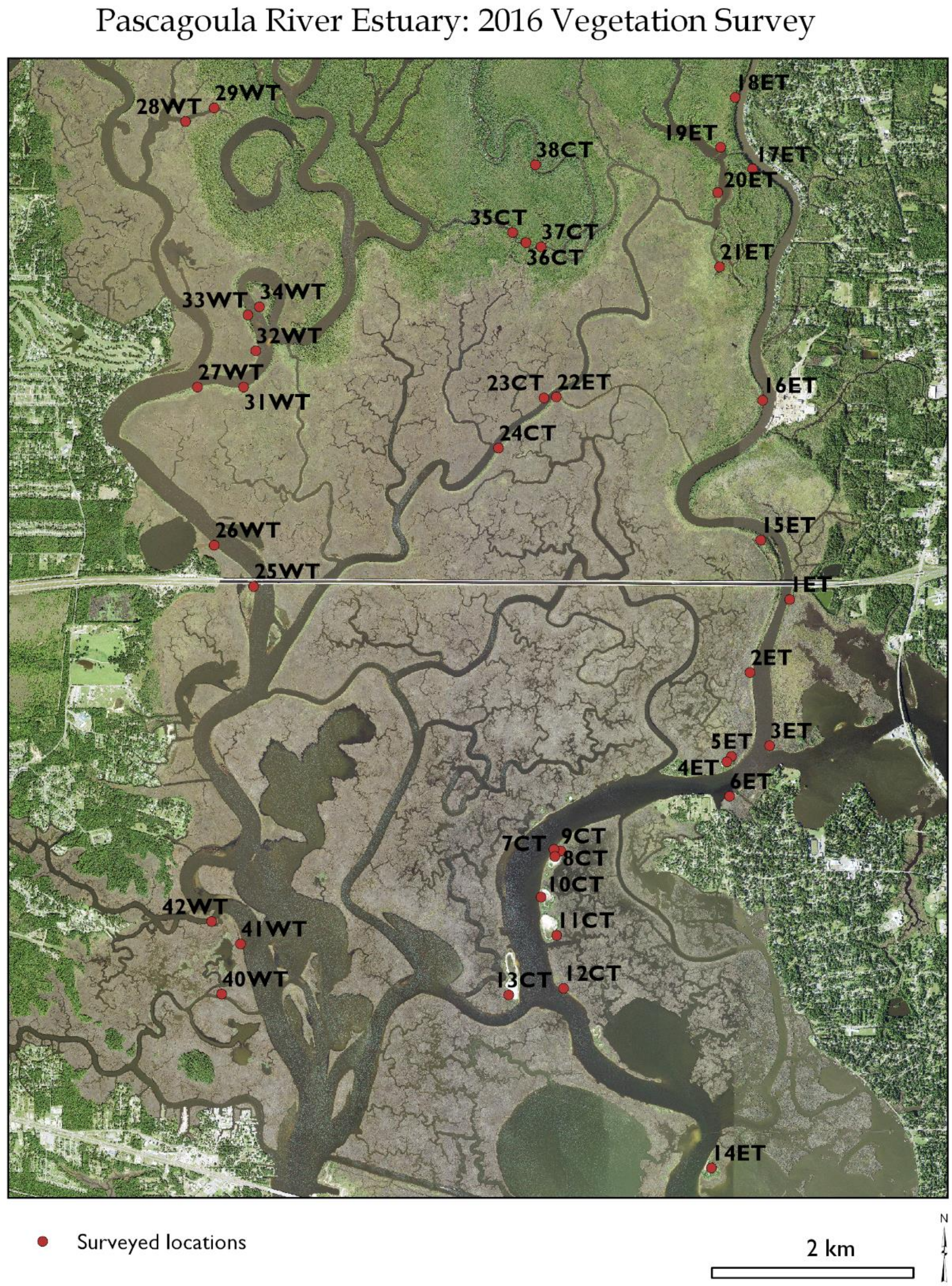
APPENDIX A – Vegetation Survey

Table A1. *Survey of Vegetation in the Pascagoula River Estuary, May 21-June 10, 2016*

Location	Latitude	Longitude	Primary Species	Secondary Species	Plant Community
10CT	30.40985903	-88.58259704	*Imperata cylindrica*	*Pinus taeda, Triadica sebifera, Morella cerifera*	Woodland
11CT	30.40645204	-88.58094497	*Juncus roemerianus, Spartina alterniflora*		Marsh
12CT	30.40171601	-88.58014802	*Juncus roemerianus*	*Baccharis angustifolia*	Marsh
13CT	30.40105401	-88.58580496	*Juncus roemerianus*	*Juncus roemerianus*	Marsh
14ET	30.38581898	-88.56463102	Unidentified grass	*Triadica sebifera, Pinus taeda*	Sand/Debris
15ET	30.44209499	-88.560428	*Sabal minor, Juncus* sp.	*Juncus roemerianus*	Marsh Shrubland
16ET	30.45461001	-88.560444	*Sabal minor*	*Acer rubrum, Mimosa* sp., *Taxodium distichum*	Woodland
17ET	30.47532303	-88.56181503	*Serenoa repens*	Unidentified hardwood trees	Woodland
18ET	30.48169998	-88.56371303	*Serenoa repens, Pinus elliotii*	*Serenoa repens, Quercus nigra, Sweet gum*	Woodland
19ET	30.47721902	-88.56513804	*Serenoa repens, Persea palustris, Morella cerifera*	*Taxodium distichum, Quercus nigra, Acer rubrum*	Woodland
1ET	30.43681003	-88.55735603	*Juncus roemerianus, Iva frutescens*	*Sabal minor and Baccharis* sp.	Marsh Shrubland
20ET	30.47315799	-88.56537399	*Sabal minor, Persea palustris*	Unidentified fern (poss. *Osmunda regalis), Spartina* sp.	Marsh Shrubland
21ET	30.466501	-88.56506696	*Baccharis* sp., *Sabal minor*	*Taxodium distichum, Morella cerifera*	Marsh Shrubland
22ET	30.45465896	-88.58175097	*Phragmites australis*	*Morella cerifera, Baccharis* sp.	Marsh
23CT	30.45454798	-88.583021	*Sagittaria lancifolia, Juncus roemerianus*	*Rubus* sp., *Taxodium distichum*	Marsh
24CT	30.45000901	-88.58765401	*Typha* sp., *Quercus* sp., *Baccharis* sp.	*Morella cerifiera, Phragmites australis*	Marsh Shrubland
25WT	30.43730699	-88.61274197	*Phragmites australis, Morella cerifera*	*Baccharis* sp., *Rubus* sp., *Sagitarria* sp.	Marsh Shrubland
26WT	30.44095103	-88.61687198	*Phragmites australis*	*Juncus roemerianus*	Marsh
27WT	30.45508501	-88.61883997	*Phragmites australis*	*Taxodium distichum, Acer rubrum*	Marsh
28WT	30.47884704	-88.62046899	*Cladium* sp., *Sagittaria* sp.	*Taxodium distichum, Acer rubrum*	Woodland
29WT	30.48009996	-88.61752904	*Sagittaria lancifolia, Schoenoplectus americanus*	*Juncus roemerianus*	Marsh
2ET	30.43022697	-88.561349	*Juncus roemerianus*	*Phragmites australis*	Marsh
31WT	30.45514402	-88.61406798	*Phragmites australis*	*Schoenoplectus americanus*	Marsh
32WT	30.45840902	-88.61286501	*Phragmites australis*	*Juncus roemerianus, Morella cerifera, Taxodium distichum*	Marsh

33WT	30.461598	-88.61373003	*Morella cerifera, Acer* sp.	*Phragmites australis, Taxodium distichum, Sabal minor*	Marsh Shrubland
34WT	30.46235103	-88.61255497	*Sagittaria lancifolia, Nuphar lutea*	*Juncus roemerianus*	Marsh
35CT	30.46932704	-88.586502	*Quercus* sp., *Taxodium distichum, Sweet bay,* unidentified fern	*Acer rubrum, Morella cerifera*	Woodland
36CT	30.46844702	-88.58511002	*Taxodium distichum, Nyssa sylvatica*	*Persea palustris, Morella cerifera, Iva frutescens*	Woodland
37CT	30.46807604	-88.58354403	*Cladium* sp., *Sagittaria* sp., *unidentified fern*	*Taxodium distichum, Baccharis* sp., *Persea palustris, Magnolia virginiana*	Marsh Shrubland
38CT	30.47541599	-88.58424299	*Serenoa repens*	*Persea palustris, Acer rubrum*	Woodland
3ET	30.42369696	-88.55922	*Spartina alterniflora*	*Juncus roemerianus*	Marsh
40WT	30.40077397	-88.61544404	*Juncus romerianus*	*Sagittaria lancifolia*	Marsh
41WT	30.40528502	-88.613568	*Sagittaria lancifolia, Cladium* sp.	*Juncus roemerianus*	Marsh
42WT	30.40724999	-88.616588	*Spartina alterniflora, Sagittaria lancifolia, Juncus roemerianus*		Marsh
4ET	30.42219602	-88.56361899	*Quercus hemisphaerica*	*Quercus nigra*	Sand/Debris
5ET	30.422697	-88.56314398	*Juncus roemerianus*		Marsh
6ET	30.41912204	-88.56328002	*Spartina alterniflora, Juncus roemerianus*	*Phragmites australis and Baccharis* sp.	Marsh
7CT	30.41414998	-88.58134001	*Spartina alterniflora, Mimosa* sp.	*Baccharis angustifolia*	Marsh Shrubland
8CT	30.41351303	-88.58122802	Sand and debris		Sand/Debris
9CT	30.41401704	-88.58063199	*Spartina alterniflora, Juncus roemerianus*	*Morella cerifera*	Marsh

Figure A1. Map of locations surveyed



APPENDIX B – Confusion Matrices for 2014 Unsupervised ISODATA Classifications

Table B1. *Confusion Matrix: 2014 ISODATA Classification, 7x7 window size*

Overall Accuracy	(274021/349007)	78.51%
Kappa Coefficient	0.5584	

Ground Truth (Pixels)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0	0
Class 2 (3 combined)	16715	3028	18037	12416	50196
Class 5 (6 combined)	0	3094	2	13325	16421
Class 1	21748	4947	218755	0	245450
Class 4	30	1335	118	35457	36940
Total	38493	12404	236912	61198	349007

Ground Truth (Percent)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0	0
Class 2 (3 combined)	43.42	24.41	7.61	20.29	14.38
Class 5 (6 combined)	0	24.94	0	21.77	4.71
Class 1	56.5	39.88	92.34	0	70.33
Class 4	0.08	10.76	0.05	57.94	10.58
Total	100	100	100	100	100

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
Class 2 (3 combined)	66.7	56.58	33481/50196	21778/38493
Class 5 (6 combined)	81.16	75.06	13327/16421	9310/12404
Class 1	10.88	7.66	26695/245450	18157/236912
Class 4	4.01	42.06	1483/36940	25741/61198

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
Class 2 (3 combined)	43.42	33.3	16715/38493	16715/50196
Class 5 (6 combined)	24.94	18.84	3094/12404	3094/16421
Class 1	92.34	89.12	218755/236912	218755/245450
Class 4	57.94	95.99	35457/61198	35457/36940

Table B2. *Confusion Matrix: 2014 ISODATA Classification, 11x11 window size*

Overall Accuracy	(278472/347802)	80.07%
Kappa Coefficient	0.577	

Ground Truth (Pixels)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0	0
Class 2 (3 combined)	11510	4102	16548	9887	42047
Class 5 (6 combined)	0	1909	3	6609	8521
Class 1	26983	3378	220355	0	250716
Class 4	0	1817	3	44698	46518
Total	38493	11206	236909	61194	347802

Ground Truth (Percent)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0	0
Class 2 (3 combined)	29.9	36.61	6.98	16.16	12.09
Class 5 (6 combined)	0	17.04	0	10.8	2.45
Class 1	70.1	30.14	93.01	0	72.09
Class 4	0	16.21	0	73.04	13.37
Total	100	100	100	100	100

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
Class 2 (3 combined)	72.63	70.1	30537/42047	26983/38493
Class 5 (6 combined)	77.6	82.96	6612/8521	9297/11206
Class 1	12.11	6.99	30361/250716	16554/236909
Class 4	3.91	26.96	1820/46518	16496/61194

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
Class 2 (3 combined)	29.9	27.37	11510/38493	11510/42047
Class 5 (6 combined)	17.04	22.4	1909/11206	1909/8521
Class 1	93.01	87.89	220355/236909	220355/250716
Class 4	73.04	96.09	44698/61194	44698/46518

Table B3. *Confusion Matrix: 2014 ISODATA Classification, 15x15 window size*

Overall Accuracy	(285175/349007)	81.71%
Kappa Coefficient	0.6119	

Ground Truth (Pixels)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0	0
Class 2 (3 combined)	10430	4901	15930	8454	39715
Class 5 (6 combined)	0	3265	9	2233	5507
Class 1	28063	2564	220969	0	251596
Class 4	0	1674	4	50511	52189
Total	38493	12404	236912	61198	349007

Ground Truth (Percent)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0	0
Class 2 (3 combined)	27.1	39.51	6.72	13.81	11.38
Class 5 (6 combined)	0	26.32	0	3.65	1.58
Class 1	72.9	20.67	93.27	0	72.09
Class 4	0	13.5	0	82.54	14.95
Total	100	100	100	100	100

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
Class 2 (3 combined)	73.74	72.9	29285/39715	28063/38493
Class 5 (6 combined)	40.71	73.68	2242/5507	9139/12404
Class 1	12.17	6.73	30627/251596	15943/236912
Class 4	3.22	17.46	1678/52189	10687/61198

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
Class 2 (3 combined)	27.1	26.26	10430/38493	10430/39715
Class 5 (6 combined)	26.32	59.29	3265/12404	3265/5507
Class 1	93.27	87.83	220969/236912	220969/251596
Class 4	82.54	96.78	50511/61198	50511/52189

Table B4. *Confusion Matrix: 2014 ISODATA Classification, 19x19 window size*

Overall Accuracy	(19879502/28222805)	70.44%
Kappa Coefficient	0.426	

Ground Truth (Pixels)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0	0
Class 2 (3 combined)	1197904	210552	2977660	1007009	5393125
Class 5 (6 combined)	2231	137210	7457	1433556	1580454
Class 1	1859982	584993	16031150	612	18476737
Class 4	40118	62068	157065	2513238	2772489
Total	3100235	994823	19173332	4954415	28222805

Ground Truth (Percent)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0	0
Class 2 (3 combined)	38.64	21.16	15.53	20.33	19.11
Class 5 (6 combined)	0.07	13.79	0.04	28.93	5.6
Class 1	59.99	58.8	83.61	0.01	65.47
Class 4	1.29	6.24	0.82	50.73	9.82
Total	100	100	100	100	100

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
Class 2 (3 combined)	77.79	61.36	4195221/5393125	1902331/3100235
Class 5 (6 combined)	91.32	86.21	1443244/1580454	857613/994823
Class 1	13.24	16.39	2445587/18476737	3142182/19173332
Class 4	9.35	49.27	259251/2772489	2441177/4954415

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
Class 2 (3 combined)	38.64	22.21	1197904/3100235	1197904/5393125
Class 5 (6 combined)	13.79	8.68	137210/994823	137210/1580454
Class 1	83.61	86.76	16031150/19173332	16031150/18476737
Class 4	50.73	90.65	2513238/4954415	2513238/2772489

APPENDIX C – Confusion Matrices for Classification Images

Table C1. *Confusion Matrix: 2014 Classification Image*

Overall Accuracy	(372900/373334)	99.88%
Kappa Coefficient	0.9975	

Ground Truth (Pixels)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	1	1
2014Marsh	44494	60	4	153	44711
2014Unveg	0	887	0	0	887
2014Water	8	0	259729	64	259801
2014Woodland	104	40	0	67790	67934
Total	44606	987	259733	68008	373334

Ground Truth (Percent)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0	0
2014Marsh	99.75	6.08	0	0.22	11.98
2014Unveg	0	89.87	0	0	0.24
2014Water	0.02	0	100	0.09	69.59
2014Woodland	0.23	4.05	0	99.68	18.2
Total	100	100	100	100	100

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
2014Marsh	0.49	0.25	217/44711	112/44606
2014Unveg	0	10.13	0/887	100/987
2014Water	0.03	0	72/259801	4/259733
2014Woodland	0.21	0.32	144/67934	218/68008

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
2014Marsh	99.75	99.51	44494/44606	44494/44711
2014Unveg	89.87	100	887/987	887/887
2014Water	100	99.97	259729/259733	259729/259801
2014Woodland	99.68	99.79	67790/68008	67790/67934

Table C2. *Confusion Matrix: 1996 Classification Image*

Overall Accuracy	(218610/220516)	99.14%
Kappa Coefficient	0.9772	

Ground Truth (Pixels)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	1214	1214
1996Marsh	14235	4	1	611	14851
1996Unveg	1	1224	0	0	1225
1996Water	0	0	169729	28	169757
1996Woodland	41	5	1	33422	33469
Total	14277	1233	169731	35275	220516

Ground Truth (Percent)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	3.44	0.55
1996Marsh	99.71	0.32	0	1.73	6.73
1996Unveg	0.01	99.27	0	0	0.56
1996Water	0	0	100	0.08	76.98
1996Woodland	0.29	0.41	0	94.75	15.18
Total	100	100	100	100	100

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
1996Marsh	4.15	0.29	616/14851	42/14277
1996Unveg	0.08	0.73	1/1225	9/1233
1996Water	0.02	0	28/169757	2/169731
1996Woodland	0.14	5.25	47/33469	1853/35275

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
1996Marsh	99.71	95.85	14235/14277	14235/14851
1996Unveg	99.27	99.92	1224/1233	1224/1225
1996Water	100	99.98	169729/169731	169729/169757
1996Woodland	94.75	99.86	33422/35275	33422/33469

Table C3. *Confusion Matrix: 1955 Classification Image*

Overall Accuracy	(193938/195431)	99.24%
Kappa Coefficient	0.9887	

Ground Truth (Pixels)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	6	6
1955Marsh	42657	0	16	1152	43825
1955Unveg	39	8551	0	2	8592
1955Water	237	0	67193	11	67441
1955Woodland	30	0	0	75537	75567
Total	42963	8551	67209	76708	195431

Ground Truth (Percent)

Class	Test Vector (Marsh)	Test Vector (Unveg)	Test Vector (Water)	Test Vector (Wood/Shrub)	Total
Unclassified	0	0	0	0.01	0
1955Marsh	99.29	0	0.02	1.5	22.42
1955Unveg	0.09	100	0	0	4.4
1955Water	0.55	0	99.98	0.01	34.51
1955Woodland	0.07	0	0	98.47	38.67
Total	100	100	100	100	100

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
1955Marsh	2.67	0.71	1168/43825	306/42963
1955Unveg	0.48	0	41/8592	0/8551
1955Water	0.37	0.02	248/67441	16/67209
1955Woodland	0.04	1.53	30/75567	1171/76708

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
1955Marsh	99.29	97.33	42657/42963	42657/43825
1955Unveg	100	99.52	8551/8551	8551/8592
1955Water	99.98	99.63	67193/67209	67193/67441
1955Woodland	98.47	99.96	75537/76708	75537/75567

APPENDIX D – Change Detection Results, 1955-2014

Table D1. *Change Detection Results, Total Study Area (1955-2014)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	8543030	13700	10236	1748	1132	8569846	8569846
2014 Marsh (5896167 points)	4765	5310508	233866	183464	163564	5896167	5896167
2014 Woodland/Shrubs (2750262 points)	7772	957024	1661372	81825	42269	2750262	2750262
2014 Unvegetated (447702 points)	732	176111	18203	185575	67081	447702	447702
2014 Water (5310484 points)	6802	899292	106997	46246	4251147	5310484	5310484
Class Total	8563101	7356635	2030674	498858	4525193	0	0
Class Changes	20071	2046127	369302	313283	274046	0	0
Image Difference	6745	-1460468	719588	-51156	785291	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.8	0.2	0.5	0.4	0.0	100.0	100.0
2014 Marsh (5896167 points)	0.1	72.2	11.5	36.8	3.6	100.0	100.0
2014 Woodland/Shrubs (2750262 points)	0.1	13.0	81.8	16.4	0.9	100.0	100.0
2014 Unvegetated (447702 points)	0.0	2.4	0.9	37.2	1.5	100.0	100.0
2014 Water (5310484 points)	0.1	12.2	5.3	9.3	93.9	100.0	100.0
Class Total	100.0	100.0	100.0	100.0	100.0	0.0	0.0
Class Changes	0.2	27.8	18.2	62.8	6.1	0.0	0.0
Image Difference	0.1	-19.9	35.4	-10.3	17.4	0.0	0.0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	76887270	123300	92124	15732	10188	77128614	77128614
2014 Marsh (5896167 points)	42885	47794572	2104794	1651176	1472076	53065503	53065503
2014 Woodland/Shrubs (2750262 points)	69948	8613216	14952348	736425	380421	24752358	24752358
2014 Unvegetated (447702 points)	6588	1584999	163827	1670175	603729	4029318	4029318
2014 Water (5310484 points)	61218	8093628	962973	416214	38260323	47794356	47794356
Class Total	77067909	66209715	18276066	4489722	40726737	0	0
Class Changes	180639	18415143	3323718	2819547	2466414	0	0
Image Difference	60705	-13144212	6476292	-460404	7067619	0	0

Table D2. *Change Detection Results, Zone 1 (1955-2014)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19491836	3977	1641	794	255	19498500	19498504
2014 Marsh (5896167 points)	1002	448527	20228	155943	63910	689610	689610
2014 Woodland/Shrubs (2750262 points)	1561	104856	35672	46168	12033	200290	200290
2014 Unvegetated (447702 points)	348	133707	3449	173973	61172	372649	372649
2014 Water (5310484 points)	811	161571	9709	24832	2016485	2213408	2213408
Class Total	19495560	852638	70699	401710	2153855	0	0
Class Changes	3724	404111	35027	227737	137370	0	0
Image Difference	2944	-163028	129591	-29061	59553	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	100.0	0.5	2.3	0.2	0.0	100.0	100.0
2014 Marsh (5896167 points)	0.0	52.6	28.6	38.8	3.0	100.0	100.0
2014 Woodland/Shrubs (2750262 points)	0.0	12.3	50.5	11.5	0.6	100.0	100.0
2014 Unvegetated (447702 points)	0.0	15.7	4.9	43.3	2.8	100.0	100.0
2014 Water (5310484 points)	0.0	19.0	13.7	6.2	93.6	100.0	100.0
Class Total	100.0	100.0	100.0	100.0	100.0	0.0	0.0
Class Changes	0.0	47.4	49.5	56.7	6.4	0.0	0.0
Image Difference	0.0	-19.1	183.3	-7.2	2.8	0.0	0.0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	175426524	35793	14769	7146	2295	175486500	175486536
2014 Marsh (5896167 points)	9018	4036743	182052	1403487	575190	6206490	6206490
2014 Woodland/Shrubs (2750262 points)	14049	943704	321048	415512	108297	1802610	1802610
2014 Unvegetated (447702 points)	3132	1203363	31041	1565757	550548	3353841	3353841
2014 Water (5310484 points)	7299	1454139	87381	223488	18148365	19920672	19920672
Class Total	175460040	7673742	636291	3615390	19384695	0	0
Class Changes	33516	3636999	315243	2049633	1236330	0	0
Image Difference	26496	-1467252	1166319	-261549	535977	0	0

Table D3. *Change Detection Results, Zone 2 (1955-2014)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19497676	2912	2201	309	53	19503148	19503148
2014 Marsh (5896167 points)	1780	1464116	62558	17837	19542	1565833	1565833
2014 Woodland (2750262 points)	2055	137340	120854	14882	1128	276259	276259
2014 Unveg (447702 points)	200	15918	2747	8543	1151	28559	28559
2014 Water (5310484 points)	3219	396211	22076	12628	1166529	1600663	1600663
Class Total	19504932	2016497	210436	54199	1188403	0	0
Class Changes	7256	552381	89582	45656	21874	0	0
Image Difference	-1784	-450664	65823	-25640	412260	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	100.0	0.1	1.0	0.6	0.0	100.0	100.0
2014 Marsh (5896167 points)	0.0	72.6	29.7	32.9	1.6	100.0	100.0
2014 Woodland (2750262 points)	0.0	6.8	57.4	27.5	0.1	100.0	100.0
2014 Unveg (447702 points)	0.0	0.8	1.3	15.8	0.1	100.0	100.0
2014 Water (5310484 points)	0.0	19.6	10.5	23.3	98.2	100.0	100.0
Class Total	100.0	100.0	100.0	100.0	100.0	0.0	0.0
Class Changes	0.0	27.4	42.6	84.2	1.8	0.0	0.0
Image Difference	0.0	-22.3	31.3	-47.3	34.7	0.0	0.0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	175479084	26208	19809	2781	477	175528332	175528332
2014 Marsh (5896167 points)	16020	13177044	563022	160533	175878	14092497	14092497
2014 Woodland (2750262 points)	18495	1236060	1087686	133938	10152	2486331	2486331
2014 Unveg (447702 points)	1800	143262	24723	76887	10359	257031	257031
2014 Water (5310484 points)	28971	3565899	198684	113652	10498761	14405967	14405967
Class Total	175544388	18148473	1893924	487791	10695627	0	0
Class Changes	65304	4971429	806238	410904	196866	0	0
Image Difference	-16056	-4055976	592407	-230760	3710340	0	0

Table D4. *Change Detection Results, Zone 3 (1955-2014)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19466204	2293	1358	107	78	19470038	19470036
2014 Marsh (5896167 points)	1015	2111158	71619	7277	42912	2233981	2233981
2014 Woodland/Shrubs (2750262 points)	1309	169043	136577	17446	2213	326588	326588
2014 Unvegetated (447702 points)	112	23355	5256	2897	3643	35263	35263
2014 Water (5310484 points)	1768	251688	21091	7321	626725	908593	908593
Class Total	19470408	2557537	235901	35048	675571	0	0
Class Changes	4204	446379	99324	32151	48846	0	0
Image Difference	-372	-323556	90687	215	233022	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	100.0	0.1	0.6	0.3	0.0	100.0	100.0
2014 Marsh (5896167 points)	0.0	82.5	30.4	20.8	6.4	100.0	100.0
2014 Woodland/Shrubs (2750262 points)	0.0	6.6	57.9	49.8	0.3	100.0	100.0
2014 Unvegetated (447702 points)	0.0	0.9	2.2	8.3	0.5	100.0	100.0
2014 Water (5310484 points)	0.0	9.8	8.9	20.9	92.8	100.0	100.0
Class Total	100.0	100.0	100.0	100.0	100.0	0.0	0.0
Class Changes	0.0	17.5	42.1	91.7	7.2	0.0	0.0
Image Difference	0.0	-12.7	38.4	0.6	34.5	0.0	0.0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	175195836	20637	12222	963	702	175230342	175230324
2014 Marsh (5896167 points)	9135	19000422	644571	65493	386208	20105829	20105829
2014 Woodland/Shrubs (2750262 points)	11781	1521387	1229193	157014	19917	2939292	2939292
2014 Unvegetated (447702 points)	1008	210195	47304	26073	32787	317367	317367
2014 Water (5310484 points)	15912	2265192	189819	65889	5640525	8177337	8177337
Class Total	175233672	23017833	2123109	315432	6080139	0	0
Class Changes	37836	4017411	893916	289359	439614	0	0
Image Difference	-3348	-2912004	816183	1935	2097198	0	0

Table D5. *Change Detection Results, Zone 4 (1955-2014)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19018448	1763	2686	167	195	19023260	19023258
2014 Marsh (5896167 points)	911	1286652	79431	2393	37200	1406587	1406587
2014 Woodland/Shrubs (2750262 points)	2348	545249	1367866	3298	26894	1945655	1945655
2014 Unvegetated (447702 points)	47	3087	6743	156	1114	11147	11147
2014 Water (5310484 points)	1001	89819	54121	1465	441408	587814	587814
Class Total	19022756	1926570	1510847	7479	506811	0	0
Class Changes	4308	639918	142981	7323	65403	0	0
Image Difference	502	-519983	434808	3668	81003	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	100.0	0.1	0.2	2.2	0.0	100.0	100.0
2014 Marsh (5896167 points)	0.0	66.8	5.3	32.0	7.3	100.0	100.0
2014 Woodland/Shrubs (2750262 points)	0.0	28.3	90.5	44.1	5.3	100.0	100.0
2014 Unvegetated (447702 points)	0.0	0.2	0.4	2.1	0.2	100.0	100.0
2014 Water (5310484 points)	0.0	4.7	3.6	19.6	87.1	100.0	100.0
Class Total	100.0	100.0	100.0	100.0	100.0	0.0	0.0
Class Changes	0.0	33.2	9.5	97.9	12.9	0.0	0.0
Image Difference	0.0	-27.0	28.8	49.0	16.0	0.0	0.0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	171166032	15867	24174	1503	1755	171209340	171209322
2014 Marsh (5896167 points)	8199	11579868	714879	21537	334800	12659283	12659283
2014 Woodland/Shrubs (2750262 points)	21132	4907241	12310794	29682	242046	17510895	17510895
2014 Unvegetated (447702 points)	423	27783	60687	1404	10026	100323	100323
2014 Water (5310484 points)	9009	808371	487089	13185	3972672	5290326	5290326
Class Total	171204804	17339130	13597623	67311	4561299	0	0
Class Changes	38772	5759262	1286829	65907	588627	0	0
Image Difference	4518	-4679847	3913272	33012	729027	0	0

APPENDIX E – Change Detection Results, 1955-1996

Table E1. *Change Detection Results, Total Study Area (1955-1996)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	8543092	15388	11223	2036	1668	8573407	8573407
1996 Marsh (6169581 points)	7624	5519068	291288	170836	180765	6169581	6169581
1996Woodland (2633067 points)	6630	950252	1574062	71030	31093	2633067	2633067
1996 Unveg (591204 points)	1484	234133	33687	216820	105080	591204	591204
1996 Water (5007202 points)	4271	637794	120414	38136	4206587	5007202	5007202
Class Total	8563101	7356635	2030674	498858	4525193	0	0
Class Changes	20009	1837567	456612	282038	318606	0	0
Image Difference	10306	-1187054	602393	92346	482009	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.766	0.209	0.553	0.408	0.037	100	100
1996 Marsh (6169581 points)	0.089	75.022	14.344	34.245	3.995	100	100
1996Woodland (2633067 points)	0.077	12.917	77.514	14.239	0.687	100	100
1996 Unveg (591204 points)	0.017	3.183	1.659	43.463	2.322	100	100
1996 Water (5007202 points)	0.05	8.67	5.93	7.645	92.959	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.234	24.978	22.486	56.537	7.041	0	0
Image Difference	0.12	-16.136	29.665	18.511	10.652	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	76887828	138492	101007	18324	15012	77160663	77160663
1996 Marsh (6169581 points)	68616	49671612	2621592	1537524	1626885	55526229	55526229
1996Woodland (2633067 points)	59670	8552268	14166558	639270	279837	23697603	23697603
1996 Unveg (591204 points)	13356	2107197	303183	1951380	945720	5320836	5320836
1996 Water (5007202 points)	38439	5740146	1083726	343224	37859283	45064818	45064818
Class Total	77067909	66209715	18276066	4489722	40726737	0	0
Class Changes	180081	16538103	4109508	2538342	2867454	0	0
Image Difference	92754	-10683486	5421537	831114	4338081	0	0

Table E2. *Change Detection Results, Zone 1 (1955-1996)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19491844	4927	1764	1055	516	19500108	19500104
1996 Marsh (6169581 points)	1074	453081	20767	136797	79479	691198	691198
1996Woodland (2633067 points)	1335	98395	29107	46626	10967	186430	186430
1996 Unveg (591204 points)	699	166826	7483	197513	92788	465309	465309
1996 Water (5007202 points)	609	129409	11578	19719	1970105	2131420	2131420
Class Total	19495560	852638	70699	401710	2153855	0	0
Class Changes	3716	399557	41592	204197	183750	0	0
Image Difference	4544	-161440	115731	63599	-22435	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.981	0.578	2.495	0.263	0.024	100	100
1996 Marsh (6169581 points)	0.006	53.139	29.374	34.054	3.69	100	100
1996Woodland (2633067 points)	0.007	11.54	41.17	11.607	0.509	100	100
1996 Unveg (591204 points)	0.004	19.566	10.584	49.168	4.308	100	100
1996 Water (5007202 points)	0.003	15.177	16.376	4.909	91.469	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.019	46.861	58.83	50.832	8.531	0	0
Image Difference	0.023	-18.934	163.695	15.832	-1.042	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	175426596	44343	15876	9495	4644	175500972	175500936
1996 Marsh (6169581 points)	9666	4077729	186903	1231173	715311	6220782	6220782
1996Woodland (2633067 points)	12015	885555	261963	419634	98703	1677870	1677870
1996 Unveg (591204 points)	6291	1501434	67347	1777617	835092	4187781	4187781
1996 Water (5007202 points)	5481	1164681	104202	177471	17730945	19182780	19182780
Class Total	175460040	7673742	636291	3615390	19384695	0	0
Class Changes	33444	3596013	374328	1837773	1653750	0	0
Image Difference	40896	-1452960	1041579	572391	-201915	0	0

Table E3. *Change Detection Results, Zone 2 (1955-1996)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19497696	3005	2255	318	57	19503332	19503330
1996 Marsh (6169581 points)	3531	1602091	72121	17416	25169	1720328	1720328
1996Woodland (2633067 points)	1778	158107	112234	12201	1029	285349	285349
1996 Unveg (591204 points)	273	16961	6209	13257	737	37437	37437
1996 Water (5007202 points)	1649	236333	17617	11007	1161411	1428017	1428017
Class Total	19504928	2016497	210436	54199	1188403	0	0
Class Changes	7232	414406	98202	40942	26992	0	0
Image Difference	-1598	-296169	74913	-16762	239614	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.963	0.149	1.072	0.587	0.005	100	100
1996 Marsh (6169581 points)	0.018	79.449	34.272	32.133	2.118	100	100
1996Woodland (2633067 points)	0.009	7.841	53.334	22.511	0.087	100	100
1996 Unveg (591204 points)	0.001	0.841	2.951	24.46	0.062	100	100
1996 Water (5007202 points)	0.008	11.72	8.372	20.308	97.729	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.037	20.551	46.666	75.54	2.271	0	0
Image Difference	-0.008	-14.687	35.599	-30.927	20.163	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	175479264	27045	20295	2862	513	175529988	175529970
1996 Marsh (6169581 points)	31779	14418819	649089	156744	226521	15482952	15482952
1996Woodland (2633067 points)	16002	1422963	1010106	109809	9261	2568141	2568141
1996 Unveg (591204 points)	2457	152649	55881	119313	6633	336933	336933
1996 Water (5007202 points)	14841	2126997	158553	99063	10452699	12852153	12852153
Class Total	175544352	18148473	1893924	487791	10695627	0	0
Class Changes	65088	3729654	883818	368478	242928	0	0
Image Difference	-14382	-2665521	674217	-150858	2156526	0	0

Table E4. *Change Detection Results, Zone 3 (1955-1996)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19466208	2557	1463	102	192	19470522	19470520
1996 Marsh (6169581 points)	1548	2160148	58905	13590	46029	2280220	2280220
1996Woodland (2633067 points)	1137	182389	144638	9781	2960	340905	340905
1996 Unveg (591204 points)	242	33927	8081	5621	5592	53463	53463
1996 Water (5007202 points)	1270	178516	22814	5954	620798	829352	829352
Class Total	19470404	2557537	235901	35048	675571	0	0
Class Changes	4196	397389	91263	29427	54773	0	0
Image Difference	116	-277317	105004	18415	153781	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.978	0.1	0.62	0.291	0.028	100	100
1996 Marsh (6169581 points)	0.008	84.462	24.97	38.775	6.813	100	100
1996Woodland (2633067 points)	0.006	7.131	61.313	27.907	0.438	100	100
1996 Unveg (591204 points)	0.001	1.327	3.426	16.038	0.828	100	100
1996 Water (5007202 points)	0.007	6.98	9.671	16.988	91.892	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.022	15.538	38.687	83.962	8.108	0	0
Image Difference	0.001	-10.843	44.512	52.542	22.763	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	175195872	23013	13167	918	1728	175234698	175234680
1996 Marsh (6169581 points)	13932	19441332	530145	122310	414261	20521980	20521980
1996Woodland (2633067 points)	10233	1641501	1301742	88029	26640	3068145	3068145
1996 Unveg (591204 points)	2178	305343	72729	50589	50328	481167	481167
1996 Water (5007202 points)	11430	1606644	205326	53586	5587182	7464168	7464168
Class Total	175233636	23017833	2123109	315432	6080139	0	0
Class Changes	37764	3576501	821367	264843	492957	0	0
Image Difference	1044	-2495853	945036	165735	1384029	0	0

Table E5. *Change Detection Results, Zone 4 (1955-1996)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19018460	2142	3378	188	352	19024520	19024516
1996 Marsh (6169581 points)	1343	1303609	139432	3018	30088	1477490	1477490
1996Woodland (2633067 points)	2022	510955	1287743	2404	16137	1819261	1819261
1996 Unveg (591204 points)	193	16337	11893	414	5962	34799	34799
1996 Water (5007202 points)	739	93527	68401	1455	454272	618394	618394
Class Total	19022760	1926570	1510847	7479	506811	0	0
Class Changes	4300	622961	223104	7065	52539	0	0
Image Difference	1756	-449080	308414	27320	111583	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.977	0.111	0.224	2.514	0.069	100	100
1996 Marsh (6169581 points)	0.007	67.665	9.229	40.353	5.937	100	100
1996Woodland (2633067 points)	0.011	26.521	85.233	32.143	3.184	100	100
1996 Unveg (591204 points)	0.001	0.848	0.787	5.535	1.176	100	100
1996 Water (5007202 points)	0.004	4.855	4.527	19.454	89.633	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.023	32.335	14.767	94.465	10.367	0	0
Image Difference	0.009	-23.31	20.413	365.289	22.017	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	171166140	19278	30402	1692	3168	171220680	171220644
1996 Marsh (6169581 points)	12087	11732481	1254888	27162	270792	13297410	13297410
1996Woodland (2633067 points)	18198	4598595	11589687	21636	145233	16373349	16373349
1996 Unveg (591204 points)	1737	147033	107037	3726	53658	313191	313191
1996 Water (5007202 points)	6651	841743	615609	13095	4088448	5565546	5565546
Class Total	171204840	17339130	13597623	67311	4561299	0	0
Class Changes	38700	5606649	2007936	63585	472851	0	0
Image Difference	15804	-4041720	2775726	245880	1004247	0	0

APPENDIX F – Change Detection Results, 1996-2014

Table F1. *Change Detection Results, Total Study Area (1996-2014)*

Pixel Counts	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	8568144	893	303	170	336	8569846	8569846
2014 Marsh (5896167 points)	1376	5253918	397471	93359	150043	5896167	5896167
2014 Woodland/Shrubs (2750262 points)	1839	452612	2166198	46025	83588	2750262	2750262
2014 Unvegetated (447702 points)	181	37163	10656	379628	20074	447702	447702
2014 Water (5310484 points)	1867	424995	58439	72022	4753161	5310484	5310484
Class Total	8573407	6169581	2633067	591204	5007202	0	0
Class Changes	5263	915663	466869	211576	254041	0	0
Image Difference	-3561	-273414	117195	-143502	303282	0	0

Percentages	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	99.939	0.014	0.012	0.029	0.007	100	100
2014 Marsh (5896167 points)	0.016	85.158	15.095	15.791	2.997	100	100
2014 Woodland/Shrubs (2750262 points)	0.021	7.336	82.269	7.785	1.669	100	100
2014 Unvegetated (447702 points)	0.002	0.602	0.405	64.213	0.401	100	100
2014 Water (5310484 points)	0.022	6.889	2.219	12.182	94.926	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.061	14.842	17.731	35.787	5.074	0	0
Image Difference	-0.042	-4.432	4.451	-24.273	6.057	0	0

Area (Square Meters)	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	77113296	8037	2727	1530	3024	77128614	77128614
2014 Marsh (5896167 points)	12384	47285262	3577239	840231	1350387	53065503	53065503
2014 Woodland/Shrubs (2750262 points)	16551	4073508	19495782	414225	752292	24752358	24752358
2014 Unvegetated (447702 points)	1629	334467	95904	3416652	180666	4029318	4029318
2014 Water (5310484 points)	16803	3824955	525951	648198	42778449	47794356	47794356
Class Total	77160663	55526229	23697603	5320836	45064818	0	0
Class Changes	47367	8240967	4201821	1904184	2286369	0	0
Image Difference	-32049	-2460726	1054755	-1291518	2729538	0	0

Table F2. *Change Detection Results, Zone 1 (1996-2014)*

Pixel Counts	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	19498084	181	57	87	96	19498504	19498504
2014 Marsh (5896167 points)	607	561228	57441	52629	17705	689610	689610
2014 Woodland/Shrubs (2750262 points)	512	55215	115802	14232	14529	200290	200290
2014 Unvegetated (447702 points)	157	14146	3975	342892	11479	372649	372649
2014 Water (5310484 points)	745	60428	9155	55469	2087611	2213408	2213408
Class Total	19500104	691198	186430	465309	2131420	0	0
Class Changes	2020	129970	70628	122417	43809	0	0
Image Difference	-1600	-1588	13860	-92660	81988	0	0

Percentages	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	99.99	0.026	0.031	0.019	0.005	100	100
2014 Marsh (5896167 points)	0.003	81.196	30.811	11.311	0.831	100	100
2014 Woodland/Shrubs (2750262 points)	0.003	7.988	62.116	3.059	0.682	100	100
2014 Unvegetated (447702 points)	0.001	2.047	2.132	73.691	0.539	100	100
2014 Water (5310484 points)	0.004	8.743	4.911	11.921	97.945	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.01	18.804	37.884	26.309	2.055	0	0
Image Difference	-0.008	-0.23	7.434	-19.914	3.847	0	0

Area (Square Meters)	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	175482756	1629	513	783	864	175486536	175486536
2014 Marsh (5896167 points)	5463	5051052	516969	473661	159345	6206490	6206490
2014 Woodland/Shrubs (2750262 points)	4608	496935	1042218	128088	130761	1802610	1802610
2014 Unvegetated (447702 points)	1413	127314	35775	3086028	103311	3353841	3353841
2014 Water (5310484 points)	6705	543852	82395	499221	18788499	19920672	19920672
Class Total	175500936	6220782	1677870	4187781	19182780	0	0
Class Changes	18180	1169730	635652	1101753	394281	0	0
Image Difference	-14400	-14292	124740	-833940	737892	0	0

Table F3. *Change Detection Results, Zone 2 (1996-2014)*

Pixel Counts	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	19502660	340	62	31	58	19503150	19503148
2014 Marsh (5896167 points)	139	1457974	71172	12194	24354	1565833	1565833
2014 Woodland/Shrubs (2750262 points)	163	60583	196927	9164	9422	276259	276259
2014 Unvegetated (447702 points)	9	12203	2484	11136	2727	28559	28559
2014 Water (5310484 points)	363	189228	14704	4912	1391456	1600663	1600663
Class Total	19503336	1720328	285349	37437	1428017	0	0
Class Changes	676	262354	88422	26301	36561	0	0
Image Difference	-188	-154495	-9090	-8878	172646	0	0

Percentages	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	99.997	0.02	0.022	0.083	0.004	100	100
2014 Marsh (5896167 points)	0.001	84.75	24.942	32.572	1.705	100	100
2014 Woodland/Shrubs (2750262 points)	0.001	3.522	69.013	24.478	0.66	100	100
2014 Unvegetated (447702 points)	0	0.709	0.871	29.746	0.191	100	100
2014 Water (5310484 points)	0.002	11	5.153	13.121	97.44	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.003	15.25	30.987	70.254	2.56	0	0
Image Difference	-0.001	-8.981	-3.186	-23.715	12.09	0	0

Area (Square Meters)	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	175523940	3060	558	279	522	175528350	175528332
2014 Marsh (5896167 points)	1251	13121766	640548	109746	219186	14092497	14092497
2014 Woodland/Shrubs (2750262 points)	1467	545247	1772343	82476	84798	2486331	2486331
2014 Unvegetated (447702 points)	81	109827	22356	100224	24543	257031	257031
2014 Water (5310484 points)	3267	1703052	132336	44208	12523104	14405967	14405967
Class Total	175530024	15482952	2568141	336933	12852153	0	0
Class Changes	6084	2361186	795798	236709	329049	0	0
Image Difference	-1692	-1390455	-81810	-79902	1553814	0	0

Table F4. *Change Detection Results, Zone 3 (1996-2014)*

Pixel Counts	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	19469728	180	39	26	65	19470040	19470036
2014 Marsh (5896167 points)	288	2062160	109029	15193	47311	2233981	2233981
2014 Woodland/Shrubs (2750262 points)	141	85452	219287	9257	12451	326588	326588
2014 Unvegetated (447702 points)	4	7801	1521	21651	4286	35263	35263
2014 Water (5310484 points)	362	124627	11029	7336	765239	908593	908593
Class Total	19470522	2280220	340905	53463	829352	0	0
Class Changes	794	218060	121618	31812	64113	0	0
Image Difference	-486	-46239	-14317	-18200	79241	0	0

Percentages	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	99.996	0.008	0.011	0.049	0.008	100	100
2014 Marsh (5896167 points)	0.001	90.437	31.982	28.418	5.705	100	100
2014 Woodland/Shrubs (2750262 points)	0.001	3.748	64.325	17.315	1.501	100	100
2014 Unvegetated (447702 points)	0	0.342	0.446	40.497	0.517	100	100
2014 Water (5310484 points)	0.002	5.466	3.235	13.722	92.27	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.004	9.563	35.675	59.503	7.73	0	0
Image Difference	-0.002	-2.028	-4.2	-34.042	9.555	0	0

Area (Square Meters)	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	175227552	1620	351	234	585	175230360	175230324
2014 Marsh (5896167 points)	2592	18559440	981261	136737	425799	20105829	20105829
2014 Woodland/Shrubs (2750262 points)	1269	769068	1973583	83313	112059	2939292	2939292
2014 Unvegetated (447702 points)	36	70209	13689	194859	38574	317367	317367
2014 Water (5310484 points)	3258	1121643	99261	66024	6887151	8177337	8177337
Class Total	175234698	20521980	3068145	481167	7464168	0	0
Class Changes	7146	1962540	1094562	286308	577017	0	0
Image Difference	-4374	-416151	-128853	-163800	713169	0	0

Table F5. *Change Detection Results, Zone 4 (1996-2014)*

Pixel Counts	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	19022804	182	139	20	117	19023260	19023258
2014 Marsh (5896167 points)	339	1172505	159782	13291	60670	1406587	1406587
2014 Woodland/Shrubs (2750262 points)	974	251100	1633123	13285	47173	1945655	1945655
2014 Unvegetated (447702 points)	7	2992	2667	3901	1580	11147	11147
2014 Water (5310484 points)	397	50711	23550	4302	508854	587814	587814
Class Total	19024520	1477490	1819261	34799	618394	0	0
Class Changes	1716	304985	186138	30898	109540	0	0
Image Difference	-1262	-70903	126394	-23652	-30580	0	0

Percentages	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	99.991	0.012	0.008	0.057	0.019	100	100
2014 Marsh (5896167 points)	0.002	79.358	8.783	38.194	9.811	100	100
2014 Woodland/Shrubs (2750262 points)	0.005	16.995	89.768	38.176	7.628	100	100
2014 Unvegetated (447702 points)	0	0.203	0.147	11.21	0.256	100	100
2014 Water (5310484 points)	0.002	3.432	1.294	12.362	82.286	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.009	20.642	10.232	88.79	17.714	0	0
Image Difference	-0.007	-4.799	6.948	-67.967	-4.945	0	0

Area (Square Meters)	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrubs (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	171205236	1638	1251	180	1053	171209340	171209322
2014 Marsh (5896167 points)	3051	10552545	1438038	119619	546030	12659283	12659283
2014 Woodland/Shrubs (2750262 points)	8766	2259900	14698107	119565	424557	17510895	17510895
2014 Unvegetated (447702 points)	63	26928	24003	35109	14220	100323	100323
2014 Water (5310484 points)	3573	456399	211950	38718	4579686	5290326	5290326
Class Total	171220680	13297410	16373349	313191	5565546	0	0
Class Changes	15444	2744865	1675242	278082	985860	0	0
Image Difference	-11358	-638127	1137546	-212868	-275220	0	0

APPENDIX G – Change Detection Results with Anthropogenic Features Masked, 1955-2014

Table G1. *Change Detection Results, Total Study Area with Anthropogenic Features Masked (1955-2014)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	8924132	10913	7882	1359	566	8944852	8944852
2014 Marsh (5896167 points)	4694	5304985	233764	182493	163344	5889280	5889280
2014 Woodland/Shrubs (2750262 points)	7273	956315	1660959	81783	42265	2748595	2748595
2014 Unvegetated (447702 points)	538	43048	16548	19483	5627	85244	85244
2014 Water (5310484 points)	6785	897893	106977	44029	4250806	5306490	5306490
Class Total	8943422	7213154	2026130	329147	4462608	0	0
Class Changes	19290	1908169	365171	309664	211802	0	0
Image Difference	1430	-1323874	722465	-243903	843882	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.784	0.151	0.389	0.413	0.013	100	100
2014 Marsh (5896167 points)	0.052	73.546	11.537	55.444	3.66	100	100
2014 Woodland/Shrubs (2750262 points)	0.081	13.258	81.977	24.847	0.947	100	100
2014 Unvegetated (447702 points)	0.006	0.597	0.817	5.919	0.126	100	100
2014 Water (5310484 points)	0.076	12.448	5.28	13.377	95.254	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.216	26.454	18.023	94.081	4.746	0	0
Image Difference	0.016	-18.354	35.657	-74.102	18.91	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	80317188	98217	70938	12231	5094	80503668	80503668
2014 Marsh (5896167 points)	42246	47744865	2103876	1642437	1470096	53003520	53003520
2014 Woodland/Shrubs (2750262 points)	65457	8606835	14948631	736047	380385	24737355	24737355
2014 Unvegetated (447702 points)	4842	387432	148932	175347	50643	767196	767196
2014 Water (5310484 points)	61065	8081037	962793	396261	38257254	47758410	47758410
Class Total	80490798	64918386	18235170	2962323	40163472	0	0
Class Changes	173610	17173521	3286539	2786976	1906218	0	0
Image Difference	12870	-11914866	6502185	-2195127	7594938	0	0

Table G2. *Change Detection Results, Zone 1 with Anthropogenic Features Masked (1955-2014)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19842756	3945	1639	776	240	19849356	19849356
2014 Marsh (5896167 points)	991	446401	20217	155000	63884	686493	686493
2014 Woodland/Shrubs (2750262 points)	1561	104700	35663	46157	12033	200114	200114
2014 Unvegetated (447702 points)	209	15026	2182	8066	1971	27454	27454
2014 Water (5310484 points)	800	161469	9709	22637	2016430	2211045	2211045
Class Total	19846316	731541	69410	232636	2094558	0	0
Class Changes	3560	285140	33747	224570	78128	0	0
Image Difference	3040	-45048	130704	-205182	116487	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.982	0.539	2.361	0.334	0.011	100	100
2014 Marsh (5896167 points)	0.005	61.022	29.127	66.628	3.05	100	100
2014 Woodland/Shrubs (2750262 points)	0.008	14.312	51.38	19.841	0.574	100	100
2014 Unvegetated (447702 points)	0.001	2.054	3.144	3.467	0.094	100	100
2014 Water (5310484 points)	0.004	22.072	13.988	9.731	96.27	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.018	38.978	48.62	96.533	3.73	0	0
Image Difference	0.015	-6.158	188.307	-88.199	5.561	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	178584804	35505	14751	6984	2160	178644204	178644204
2014 Marsh (5896167 points)	8919	4017609	181953	1395000	574956	6178437	6178437
2014 Woodland/Shrubs (2750262 points)	14049	942300	320967	415413	108297	1801026	1801026
2014 Unvegetated (447702 points)	1881	135234	19638	72594	17739	247086	247086
2014 Water (5310484 points)	7200	1453221	87381	203733	18147870	19899405	19899405
Class Total	178616844	6583869	624690	2093724	18851022	0	0
Class Changes	32040	2566260	303723	2021130	703152	0	0
Image Difference	27360	-405432	1176336	-1846638	1048383	0	0

Table G3. *Change Detection Results, Zone 3 with Anthropogenic Features Masked (1955-2014)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19488640	2294	1358	107	78	19492478	19492476
2014 Marsh (5896167 points)	1012	2107816	71558	7263	42718	2230367	2230367
2014 Woodland/Shrubs (2750262 points)	1309	169026	136576	17446	2210	326567	326567
2014 Unvegetated (447702 points)	82	9017	4876	2718	1391	18084	18084
2014 Water (5310484 points)	1765	250394	21071	7299	626439	906968	906968
Class Total	19492808	2538547	235439	34833	672836	0	0
Class Changes	4168	430731	98863	32115	46397	0	0
Image Difference	-332	-308180	91128	-16749	234132	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.979	0.09	0.577	0.307	0.012	100	100
2014 Marsh (5896167 points)	0.005	83.032	30.393	20.851	6.349	100	100
2014 Woodland/Shrubs (2750262 points)	0.007	6.658	58.009	50.085	0.328	100	100
2014 Unvegetated (447702 points)	0	0.355	2.071	7.803	0.207	100	100
2014 Water (5310484 points)	0.009	9.864	8.95	20.954	93.104	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.021	16.968	41.991	92.197	6.896	0	0
Image Difference	-0.002	-12.14	38.706	-48.084	34.798	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	175397760	20646	12222	963	702	175432302	175432284
2014 Marsh (5896167 points)	9108	18970344	644022	65367	384462	20073303	20073303
2014 Woodland/Shrubs (2750262 points)	11781	1521234	1229184	157014	19890	2939103	2939103
2014 Unvegetated (447702 points)	738	81153	43884	24462	12519	162756	162756
2014 Water (5310484 points)	15885	2253546	189639	65691	5637951	8162712	8162712
Class Total	175435272	22846923	2118951	313497	6055524	0	0
Class Changes	37512	3876579	889767	289035	417573	0	0
Image Difference	-2988	-2773620	820152	-150741	2107188	0	0

APPENDIX H – Change Detection Results with Anthropogenic Features Masked, 1955-1996

Table H1. *Change Detection Results, Total Study Area with Anthropogenic Features Masked (1955-1996)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	8924178	12575	8856	1608	1058	8948275	8948275
1996 Marsh (6169581 points)	7490	5514568	291118	166760	177081	6157017	6157017
1996 Woodland/Shrubs (2633067 points)	6272	949287	1573710	70527	30089	2629885	2629885
1996 Unvegetated (591204 points)	1229	103775	32097	54304	50658	242063	242063
1996 Water (5007202 points)	4253	632949	120349	35948	4203722	4997221	4997221
Class Total	8943422	7213154	2026130	329147	4462608	0	0
Class Changes	19244	1698586	452420	274843	258886	0	0
Image Difference	4853	-1056137	603755	-87084	534613	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.785	0.174	0.437	0.489	0.024	100	100
1996 Marsh (6169581 points)	0.084	76.452	14.368	50.664	3.968	100	100
1996 Woodland/Shrubs (2633067 points)	0.07	13.16	77.671	21.427	0.674	100	100
1996 Unvegetated (591204 points)	0.014	1.439	1.584	16.498	1.135	100	100
1996 Water (5007202 points)	0.048	8.775	5.94	10.922	94.199	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.215	23.548	22.329	83.502	5.801	0	0
Image Difference	0.054	-14.642	29.798	-26.457	11.98	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	80317602	113175	79704	14472	9522	80534475	80534475
1996 Marsh (6169581 points)	67410	49631112	2620062	1500840	1593729	55413153	55413153
1996 Woodland/Shrubs (2633067 points)	56448	8543583	14163390	634743	270801	23668965	23668965
1996 Unvegetated (591204 points)	11061	933975	288873	488736	455922	2178567	2178567
1996 Water (5007202 points)	38277	5696541	1083141	323532	37833498	44974989	44974989
Class Total	80490798	64918386	18235170	2962323	40163472	0	0
Class Changes	173196	15287274	4071780	2473587	2329974	0	0
Image Difference	43677	-9505233	5433795	-783756	4811517	0	0

Table H2. *Change Detection Results, Zone 1 with Anthropogenic Features Masked (1955-1996)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19842760	4871	1762	1000	457	19850852	19850852
1996 Marsh (6169581 points)	1071	450360	20722	132758	76139	681050	681050
1996 Woodland/Shrubs (2633067 points)	1335	98141	29105	46143	10002	184726	184726
1996 Unvegetated (591204 points)	550	51087	6281	35187	40576	133681	133681
1996 Water (5007202 points)	599	127082	11540	17548	1967384	2124153	2124153
Class Total	19846316	731541	69410	232636	2094558	0	0
Class Changes	3556	281181	40305	197449	127174	0	0
Image Difference	4536	-50491	115316	-98955	29595	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.982	0.666	2.539	0.43	0.022	100	100
1996 Marsh (6169581 points)	0.005	61.563	29.854	57.067	3.635	100	100
1996 Woodland/Shrubs (2633067 points)	0.007	13.416	41.932	19.835	0.478	100	100
1996 Unvegetated (591204 points)	0.003	6.983	9.049	15.125	1.937	100	100
1996 Water (5007202 points)	0.003	17.372	16.626	7.543	93.928	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.018	38.437	58.068	84.875	6.072	0	0
Image Difference	0.023	-6.902	166.137	-42.536	1.413	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	178584840	43839	15858	9000	4113	178657668	178657668
1996 Marsh (6169581 points)	9639	4053240	186498	1194822	685251	6129450	6129450
1996 Woodland/Shrubs (2633067 points)	12015	883269	261945	415287	90018	1662534	1662534
1996 Unvegetated (591204 points)	4950	459783	56529	316683	365184	1203129	1203129
1996 Water (5007202 points)	5391	1143738	103860	157932	17706456	19117377	19117377
Class Total	178616844	6583869	624690	2093724	18851022	0	0
Class Changes	32004	2530629	362745	1777041	1144566	0	0
Image Difference	40824	-454419	1037844	-890595	266355	0	0

Table H3. *Change Detection Results, Zone 3 with Anthropogenic Features Masked (1955-1996)*

Pixel Counts	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	19488648	2558	1463	102	192	19492962	19492960
1996 Marsh (6169581 points)	1545	2158508	58843	13568	45685	2278149	2278149
1996 Woodland/Shrubs (2633067 points)	1137	182084	144628	9779	2921	340549	340549
1996 Unvegetated (591204 points)	213	19390	7714	5446	3383	36146	36146
1996 Water (5007202 points)	1266	176007	22791	5938	620655	826657	826657
Class Total	19492806	2538547	235439	34833	672836	0	0
Class Changes	4158	380039	90811	29387	52181	0	0
Image Difference	154	-260398	105110	1313	153821	0	0

Percentages	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	99.979	0.101	0.621	0.293	0.029	100	100
1996 Marsh (6169581 points)	0.008	85.029	24.993	38.952	6.79	100	100
1996 Woodland/Shrubs (2633067 points)	0.006	7.173	61.429	28.074	0.434	100	100
1996 Unvegetated (591204 points)	0.001	0.764	3.276	15.635	0.503	100	100
1996 Water (5007202 points)	0.006	6.933	9.68	17.047	92.245	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.021	14.971	38.571	84.365	7.755	0	0
Image Difference	0.001	-10.258	44.644	3.769	22.862	0	0

Area (Square Meters)	Unclassified	1955 Marsh (7356635 points)	1955 Woodland/Shrubs (2030674 points)	1955 Unvegetated (498858 points)	1955 Water (4525193 points)	Row Total	Class Total
Unclassified	175397832	23022	13167	918	1728	175436658	175436640
1996 Marsh (6169581 points)	13905	19426572	529587	122112	411165	20503341	20503341
1996 Woodland/Shrubs (2633067 points)	10233	1638756	1301652	88011	26289	3064941	3064941
1996 Unvegetated (591204 points)	1917	174510	69426	49014	30447	325314	325314
1996 Water (5007202 points)	11394	1584063	205119	53442	5585895	7439913	7439913
Class Total	175435254	22846923	2118951	313497	6055524	0	0
Class Changes	37422	3420351	817299	264483	469629	0	0
Image Difference	1386	-2343582	945990	11817	1384389	0	0

APPENDIX I – Change Detection Results with Anthropogenic Features Masked, 1996-2014

Table I1. *Change Detection Results, Total Study Area with Anthropogenic Features Masked (1996-2014)*

Pixel Counts	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrub (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	8943183	880	297	156	336	8944852	8944852
2014 Marsh (5896167 points)	1359	5252709	397405	87785	150022	5889280	5889280
2014 Woodland/Shrubs (2750262 points)	1790	452233	2165137	45860	83575	2748595	2748595
2014 Unvegetated (447702 points)	79	26219	8610	40185	10151	85244	85244
2014 Water (5310484 points)	1864	424976	58436	68077	4753137	5306490	5306490
Class Total	8948275	6157017	2629885	242063	4997221	0	0
Class Changes	5092	904308	464748	201878	244084	0	0
Image Difference	-3423	-267737	118710	-156819	309269	0	0

Percentages	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrub (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	99.943	0.014	0.011	0.064	0.007	100	100
2014 Marsh (5896167 points)	0.015	85.313	15.111	36.265	3.002	100	100
2014 Woodland/Shrubs (2750262 points)	0.02	7.345	82.328	18.945	1.672	100	100
2014 Unvegetated (447702 points)	0.001	0.426	0.327	16.601	0.203	100	100
2014 Water (5310484 points)	0.021	6.902	2.222	28.124	95.116	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.057	14.687	17.672	83.399	4.884	0	0
Image Difference	-0.038	-4.348	4.514	-64.784	6.189	0	0

Area (Square Meters)	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrub (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	80488647	7920	2673	1404	3024	80503668	80503668
2014 Marsh (5896167 points)	12231	47274381	3576645	790065	1350198	53003520	53003520
2014 Woodland/Shrubs (2750262 points)	16110	4070097	19486233	412740	752175	24737355	24737355
2014 Unvegetated (447702 points)	711	235971	77490	361665	91359	767196	767196
2014 Water (5310484 points)	16776	3824784	525924	612693	42778233	47758410	47758410
Class Total	80534475	55413153	23668965	2178567	44974989	0	0
Class Changes	45828	8138772	4182732	1816902	2196756	0	0
Image Difference	-30807	-2409633	1068390	-1411371	2783421	0	0

Table I2. *Change Detection Results, Zone 1 with Anthropogenic Features Masked (1996-2014)*

Pixel Counts	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrub (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	19848944	178	57	79	96	19849356	19849356
2014 Marsh (5896167 points)	593	560070	57422	50721	17687	686493	686493
2014 Woodland/Shrubs (2750262 points)	512	55098	115800	14175	14529	200114	200114
2014 Unvegetated (447702 points)	59	5294	2294	15554	4253	27454	27454
2014 Water (5310484 points)	742	60410	9153	53152	2087588	2211045	2211045
Class Total	19850850	681050	184726	133681	2124153	0	0
Class Changes	1906	120980	68926	118127	36565	0	0
Image Difference	-1494	5443	15388	-106227	86892	0	0

Percentages	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrub (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	99.99	0.026	0.031	0.059	0.005	100	100
2014 Marsh (5896167 points)	0.003	82.236	31.085	37.942	0.833	100	100
2014 Woodland/Shrubs (2750262 points)	0.003	8.09	62.687	10.604	0.684	100	100
2014 Unvegetated (447702 points)	0	0.777	1.242	11.635	0.2	100	100
2014 Water (5310484 points)	0.004	8.87	4.955	39.76	98.279	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.01	17.764	37.313	88.365	1.721	0	0
Image Difference	-0.008	0.799	8.33	-79.463	4.091	0	0

Area (Square Meters)	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrub (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	178640496	1602	513	711	864	178644204	178644204
2014 Marsh (5896167 points)	5337	5040630	516798	456489	159183	6178437	6178437
2014 Woodland/Shrubs (2750262 points)	4608	495882	1042200	127575	130761	1801026	1801026
2014 Unvegetated (447702 points)	531	47646	20646	139986	38277	247086	247086
2014 Water (5310484 points)	6678	543690	82377	478368	18788292	19899405	19899405
Class Total	178657650	6129450	1662534	1203129	19117377	0	0
Class Changes	17154	1088820	620334	1063143	329085	0	0
Image Difference	-13446	48987	138492	-956043	782028	0	0

Table I3. *Change Detection Results, Zone 3 with Anthropogenic Features Masked (1996-2014)*

Pixel Counts	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrub (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	19492168	180	39	26	65	19492480	19492476
2014 Marsh (5896167 points)	288	2062160	109029	11579	47311	2230367	2230367
2014 Woodland/Shrubs (2750262 points)	141	85452	219287	9236	12451	326567	326567
2014 Unvegetated (447702 points)	4	5730	1165	9594	1591	18084	18084
2014 Water (5310484 points)	362	124627	11029	5711	765239	906968	906968
Class Total	19492962	2278149	340549	36146	826657	0	0
Class Changes	794	215989	121262	26552	61418	0	0
Image Difference	-486	-47782	-13982	-18062	80311	0	0

Percentages	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrub (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	99.996	0.008	0.011	0.072	0.008	100	100
2014 Marsh (5896167 points)	0.001	90.519	32.016	32.034	5.723	100	100
2014 Woodland/Shrubs (2750262 points)	0.001	3.751	64.392	25.552	1.506	100	100
2014 Unvegetated (447702 points)	0	0.252	0.342	26.542	0.192	100	100
2014 Water (5310484 points)	0.002	5.471	3.239	15.8	92.57	100	100
Class Total	100	100	100	100	100	0	0
Class Changes	0.004	9.481	35.608	73.458	7.43	0	0
Image Difference	-0.002	-2.097	-4.106	-49.97	9.715	0	0

Area (Square Meters)	Unclassified	1996 Marsh (6169581 points)	1996 Woodland/Shrub (2633067 points)	1996 Unvegetated (591204 points)	1996 Water (5007202 points)	Row Total	Class Total
Unclassified	175429512	1620	351	234	585	175432320	175432284
2014 Marsh (5896167 points)	2592	18559440	981261	104211	425799	20073303	20073303
2014 Woodland/Shrubs (2750262 points)	1269	769068	1973583	83124	112059	2939103	2939103
2014 Unvegetated (447702 points)	36	51570	10485	86346	14319	162756	162756
2014 Water (5310484 points)	3258	1121643	99261	51399	6887151	8162712	8162712
Class Total	175436658	20503341	3064941	325314	7439913	0	0
Class Changes	7146	1943901	1091358	238968	552762	0	0
Image Difference	-4374	-430038	-125838	-162558	722799	0	0

APPENDIX J – Linear Regressions of Marsh Extent over Time

Table J1. *Regression of Marsh Extent with Calendar Year, Total Study Area*

SUMMARY

Year	*Marsh Extent (ha)*
1955	6620.9715
1996	5552.6229
2014	5306.5503

Regression Statistics	
Multiple R	0.99217034
R Square	0.984401983
Adjusted R Square	0.968803966
Standard Error	123.4184179
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	961309.0763	961309.0763	63.11071396	0.079716891
Residual	1	15232.10587	15232.10587		
Total	2	976541.1822			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	51415.0194	5738.988724	8.958898836	0.070767116	-21505.74631	124335.7851	15180.47065	87649.56815
Year	-22.92789832	2.88610881	-7.944225196	0.079716891	-59.59938775	13.7435911	-41.15007219	-4.705724455

RESIDUAL OUTPUT

Observation	*Predicted Area*	*Residuals*	*Standard Residuals*
1	6590.978177	29.99332257	0.343684227
2	5650.934346	-98.31144619	-1.126520522
3	5238.232176	68.31812362	0.782836295

PROBABILITY OUTPUT

Percentile	*Area*
16.66666667	5306.5503
50	5552.6229
83.33333333	6620.9715

Table J2. *Regression of Marsh Extent with Calendar Year, Zone 1*

SUMMARY

Year	*Marsh Extent (ha)*
1955	767.3742
1996	622.0782
2014	620.649

Regression Statistics	
Multiple R	0.95716709
R Square	0.916168838
Adjusted R Square	0.832337677
Standard Error	34.51891223
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	13022.19621	13022.19621	10.92873843	0.187002066
Residual	1	1191.555301	1191.555301		
Total	2	14213.75151			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	5975.994591	1605.138451	3.723039958	0.167051806	-14419.2232	26371.21238	-4158.450734	16110.43992
Year	-2.668546919	0.807216122	-3.305864248	0.187002066	-12.92520024	7.588106397	-7.765108934	2.428015095

RESIDUAL OUTPUT

Observation	*Predicted Area*	*Residuals*	*Standard Residuals*
1	758.985364	8.388836019	0.343684227
2	649.5749403	-27.49674028	-1.126520522
3	601.5410957	19.10790427	0.782836295

PROBABILITY OUTPUT

Percentile	*Area*
16.66666667	620.649
50	622.0782
83.33333333	767.3742

Table J3. *Regression of Marsh Extent with Calendar Year, Zone 2*

SUMMARY

Year	*Marsh Extent (ha)*
1955	1814.8473
1996	1548.2952
2014	1409.2497

Regression Statistics	
Multiple R	0.99912507
R Square	0.998250905
Adjusted R Square	0.99650181
Standard Error	12.19059982
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	84815.75135	84815.75135	570.7242998	0.026632595
Residual	1	148.6107239	148.6107239		
Total	2	84964.36207			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	15132.09167	566.8660814	26.69429723	0.023837384	7929.375178	22334.80815	11553.04009	18711.14325
Year	-6.810374316	0.285074125	-23.88983675	0.026632595	-10.43258452	-3.188164114	-8.610261508	-5.010487125

RESIDUAL OUTPUT

Observation	*Predicted Area*	*Residuals*	*Standard Residuals*
1	1817.809877	-2.962577215	-0.343684227
2	1538.58453	9.710669759	1.126520522
3	1415.997793	-6.748092545	-0.782836295

PROBABILITY OUTPUT

Percentile	*Area*
16.66666667	1409.2497
50	1548.2952
83.33333333	1814.8473

Table J4. *Regression of Marsh Extent with Calendar Year, Zone 3*

SUMMARY

Year	*Marsh Extent (ha)*
1955	2301.7833
1996	2052.198
2014	2010.5829

Regression Statistics	
Multiple R	0.985633228
R Square	0.97147286
Adjusted R Square	0.94294572
Standard Error	37.61859004
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	48192.27885	48192.27885	34.05433745	0.108042854
Residual	1	1415.158316	1415.158316		
Total	2	49607.43716			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	12328.81603	1749.27428	7.047960498	0.089727892	-9897.821117	34555.45317	1284.332891	23373.29916
Year	-5.133593274	0.879701312	-5.835609432	0.108042854	-16.31125825	6.044071703	-10.68780876	0.420622217

RESIDUAL OUTPUT

Observation	*Predicted Area*	*Residuals*	*Standard Residuals*
1	2292.641176	9.142124207	0.343684227
2	2082.163852	-29.96585157	-1.126520522
3	1989.759173	20.82372736	0.782836295

PROBABILITY OUTPUT

Percentile	*Area*
16.66666667	2010.5829
50	2052.198
83.33333333	2301.7833

Table J5. *Regression of Marsh Extent with Calendar Year, Zone 4*

SUMMARY

Year	*Marsh Extent (ha)*
1955	1733.913
1996	1329.741
2014	1265.9283

Regression Statistics	
Multiple R	0.984523444
R Square	0.969286411
Adjusted R Square	0.938572823
Standard Error	62.89901763
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	124855.9621	124855.9621	31.55887843	0.112148636
Residual	1	3956.286419	3956.286419		
Total	2	128812.2486			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	17872.7779	2924.820778	6.110725837	0.103265381	-19290.59373	55036.14952	-593.8137193	36339.36952
Year	-8.26299269	1.470877784	-5.617728939	0.112148636	-26.95226695	10.42628157	-17.54974952	1.023764143

RESIDUAL OUTPUT

Observation	*Predicted Area*	*Residuals*	*Standard Residuals*
1	1718.62719	15.28581032	0.343684227
2	1379.844489	-50.10348937	-1.126520522
3	1231.110621	34.81767906	0.782836295

PROBABILITY OUTPUT

Percentile	*Area*
16.66666667	1265.9283
50	1329.741
83.33333333	1733.913

APPENDIX K – Linear Regressions with Anthropogenic Features Masked

Table K1. *Regression of Marsh Extent with Calendar Year, Total Study Area*

SUMMARY

Year	*Marsh Extent (ha)*
1955	6491.8386
1996	5541.3153
2014	5300.352

Regression Statistics	
Multiple R	0.993979721
R Square	0.987995685
Adjusted R Square	0.97599137
Standard Error	97.61259004
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	784204.5069	784204.5069	82.3033781	0.06989105
Residual	1	9528.217735	9528.217735		
Total	2	793732.7246			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	46953.11765	4539.010978	10.34434988	0.061352109	-10720.48514	104626.7204	18294.93021	75611.30509
Year	-20.70844041	2.282645985	-9.072120926	0.06989105	-49.71220764	8.295326819	-35.12049996	-6.296380864

RESIDUAL OUTPUT

Observation	*Predicted Area*	*Residuals*	*Standard Residuals*
1	6468.116647	23.72195293	0.343684227
2	5619.07059	-77.75529017	-1.126520522
3	5246.318663	54.03333724	0.782836295

PROBABILITY OUTPUT

Percentile	*Area*
16.66666667	5300.352
50	5541.3153
83.33333333	6491.8386

Table K2. *Regression of Marsh Extent with Calendar Year, Zone 1*

SUMMARY

Year	*Marsh Extent (ha)*
1955	658.3869
1996	612.945
2014	617.8437

Regression Statistics	
Multiple R	0.920835755
R Square	0.847938488
Adjusted R Square	0.695876975
Standard Error	13.75502608
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1055.037459	1055.037459	5.576286034	0.255015877
Residual	1	189.2007426	189.2007426		
Total	2	1244.238201			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	2139.999592	639.6123121	3.345776108	0.184895337	-5987.045397	10267.04458	-1898.353612	6178.352797
Year	-0.759568009	0.321657842	-2.361416108	0.255015877	-4.846618406	3.327482387	-2.790435697	1.271299678

RESIDUAL OUTPUT

Observation	*Predicted Area*	*Residuals*	*Standard Residuals*
1	655.0441336	3.342766351	0.343684227
2	623.9018453	-10.95684526	-1.126520522
3	610.2296211	7.61407891	0.782836295

PROBABILITY OUTPUT

Percentile	*Area*
16.66666667	612.945
50	617.8437
83.33333333	658.3869

Table K3. *Regression of Marsh Extent with Calendar Year, Zone 3*

SUMMARY

Year	*Marsh Extent (ha)*
1955	2284.6923
1996	2050.3341
2014	2007.3303

Regression Statistics	
Multiple R	0.98759481
R Square	0.975343509
Adjusted R Square	0.950687018
Standard Error	33.14936486
Observations	3

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	43468.7102	43468.7102	39.55727172	0.100379912
Residual	1	1098.880391	1098.880391		
Total	2	44567.59059			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90.0%*	*Upper 90.0%*
Intercept	11808.28141	1541.45414	7.660481819	0.082637119	-7777.75048	31394.31331	2075.923003	21540.63983
Year	-4.875521801	0.7751896	-6.289457188	0.100379912	-14.72523957	4.974195965	-9.769876311	0.01883271

RESIDUAL OUTPUT

Observation	*Predicted Area*	*Residuals*	*Standard Residuals*
1	2276.636293	8.056006635	0.343684227
2	2076.7399	-26.40579953	-1.126520522
3	1988.980507	18.34979289	0.782836295

PROBABILITY OUTPUT

Percentile	*Area*
16.66666667	2007.3303
50	2050.3341
83.33333333	2284.6923

REFERENCES

Anderson, C. J., & Lockaby, B. G. (2012). Seasonal patterns of river connectivity and saltwater intrusion in tidal freshwater forested wetlands. *River Research and Applications*, *28*(2012), 814–826. https://doi.org/10.1002/rra.1489

Anderson, C. J., Lockaby, B. G., & Click, N. (2013). Changes in Wetland Forest Structure, Basal Growth, and Composition across a Tidal Gradient. *The American Midland Naturalist*, *170*(1), 1–13.

Anderson, C. P., Carter, G. A., & Funderburk, W. R. (2016). The Use of Aerial RGB Imagery and LIDAR in Comparing Ecological Habitats and Geomorphic Features on a Natural versus Man-Made Barrier Island. *Remote Sensing*, *8*(7), 602. https://doi.org/10.3390/rs8070602

Bartlett, D. S., & Klemas, V. (1981). In Situ Spectral Reflectance Studies of Tidal Wetland Grasses. *Photogrammetric Engineering and Remote Sensing*, *47*(12), 1695–1703.

Bilskie, M. V., Hagen, S. C., Medeiros, S. C., & Passeri, D. L. (2014). Dynamics of sea level rise and coastal flooding on a changing landscape. *Geophysical Research Letters*, *41*, 927–934. https://doi.org/10.1002/2013GL058759

Bureau of Labor Statistics. (2018). CPI Inflation Calculator. Retrieved November 15, 2018, from https://www.bls.gov/data/inflation_calculator.htm

Butera, M. K. (1978). *A Determination of the Optimum Time of Year for Remotely Classifying Marsh Vegetatin from landsat Multispectral Scanner Data*.

Campbell, A., & Wang, Y. (2018). Examining the influence of tidal stage on salt marsh mapping using high-spatial-resolution satellite remote sensing and topobathymetric

LiDAR. *IEEE Transactions on Geoscience and Remote Sensing*, *56*(9). https://doi.org/10.1109/TGRS.2018.2810503

Carter, G. A. (1993). Responses of Leaf Spectral Reflectance to Plant Stress. *American Journal of Botany*, *80*(3), 239–243. Retrieved from https://www.jstor.org/stable/2445346

Center for Operational Oceanographic Products and Services. (2018). NOAA Tides & Currents. Retrieved January 31, 2019, from https://tidesandcurrents.noaa.gov/

Cho, H. J. (2011). *Aquatic Plants of the Mississippi Coast*. (H. J. Cho, P. Biber, & J. D. Caldwell, Eds.). Jackson, MS: Jackson State University.

Christmas, J. Y. (1973). Area Description. In J. Y. Christmas (Ed.), *Cooperative Gulf of Mexico Estuarine Inventory and Study, Mississippi* (pp. 1–72). Ocean Springs, MS: State of Mississippi Gulf Coast Research Laboratory.

Christmas, J. Y., & Eleuterius, L. N. (1973). Hydrology. In J. Y. Christmas (Ed.), *Cooperative Gulf of Mexico Estuarine Inventory and Study, Mississippi* (pp. 74–137). Ocean Springs, MS: State of Mississippi Gulf Coast Research Laboratory.

Chrysafis, I., Mallinis, G., Tsakiri, M., & Patias, P. (2019). Evaluation of single-date and multi-seasonal spatial and spectral information of Sentinel-2 imagery to assess growing stock volume of a Mediterranean forest. https://doi.org/10.1016/j.jag.2018.12.004

Delaune, R. D., Baumann, R. H., & Gosselink, J. G. (1983). Relationships among vertical accretion, coastal submergence, and erosion in a Louisiana Gulf Coast Marsh. *Journal of Sedimentary Petrology*, *53*(1), 147–157. https://doi.org/10.1306/212F8175-2B24-11D7-8648000102C1865D

Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, & Office of Coast Survey. (2015). Coastal Maintained Channels in US Waters. Silver Spring, MD: NOAA's Ocean Service, Office of Coast Survey. Retrieved from https://nauticalcharts.noaa.gov/data/gis-data-and-services.html#enc-direct-to-gis

Department of Energy. (2006a). DOE Takes Next Steps to Expand Strategic Petroleum Reserve to One Billion Barrels. Retrieved May 1, 2018, from https://energy.gov/articles/doe-takes-next-steps-expand-strategic-petroleum-reserve-one-billion-barrels

Department of Energy. (2006b, December 8). DOE Takes Next Steps to Expand Strategic Petroleum Reserve to One Billion Barrels. Retrieved from https://www.energy.gov/articles/doe-takes-next-steps-expand-strategic-petroleum-reserve-one-billion-barrels

Dobson, J. E., Bright, E. A., Ferguson, R. L., Field, D. W., Wood, L. L., Haddad, K. D., … Thomas, J. P. (1995). *NOAA Coastal Change Analysis Program (C-CAP): Guidance for Regional Implementation*. https://doi.org/NOAA Technical Report NMFS 123

Dokka, R. K. (2006). Modern-day tectonic subsidence in coastal Louisiana. *Geology*, *34*(4), 281–284. https://doi.org/10.1130/G22264.1

Eleuterius, L. N. (1973). The Marshes of Mississippi. In J. Y. Christmas (Ed.), *Cooperative Gulf of Mexico Estuarine Inventory and Study, Mississippi* (pp. 147–190). Ocean Springs, MS: State of Mississippi Gulf Coast Research Laboratory.

Eleuterius, L. N. (1975). The Life History of the Salt Marsh Rush, Juncus roemerianus.

Bulletin of the Torrey Botanical Club, *102*(3), 135–140. Retrieved from http://www.jstor.org/stable/2484735

Eleuterius, L. N. (1976). The Distribution of Juncus roemerianus in the Salt Marshes of North America. *Chesapeake Science*, *17*(4), 289–292. Retrieved from https://www.jstor.org/stable/1350516

Eleuterius, L. N. (1984). Autecology of the Black Needlerush Juncus roemerianus. *Gulf Research Reports*, *7*(4), 339–350. https://doi.org/10.18785/grr.0704.05

Eleuterius, L. N., & Caldwell, J. D. (1984). Flowering phenology of tidal marsh plants in Mississippi. *Castanea*, *49*, 172–179.

Eleuterius, L. N., & Caldwell, J. D. (1985). Soil Characteristics ofSpartina alterniflora, Spartina patens, Juncus roemerianus, Scirpus olneyi, and Distichlis spicata Populations at One Locality in Mississippi. *Gulf Research Reports*, *8*(1), 27–33. https://doi.org/10.18785/grr.0801.05

Englander, J. (2018). Rising Seas and Changing Coastlines. *2018 Bays and Bayous Symposium: Navigating Waves of Change*. Mobile, AL.

Flessa, K. W., Constantine, K. J., & Cushman, M. (1977). Sedimentation Rates in a Coastal Marsh Determined from Historical Records. *Chesapeake Science*, *18*(2), 172–176. Retrieved from https://www.jstor.org/stable/1350858

Ghosh, S., Mishra, D. R., & Gitelson, A. A. (2016). Long-term monitoring of biophysical characteristics of tidal wetlands in the northern Gulf of Mexico - A methodological approach using MODIS. *Remote Sensing of Environment*, *173*, 39–58. https://doi.org/10.1016/j.rse.2015.11.015

Gonzalez, J. L., & Tornqvist, T. E. (2006). Coastal Louisiana in Crisis: Subsidence or Sea

Level Rise? *Eos*, *87*(45), 493–508.

Guntenspergen, G. R., Cahoon, D. R., Grace, J., Steyer, G. D., Fournet, S., & Foote, A. L. (1995). Disturbance and Recovery of the Louisiana Coastal Marsh Landscape from the Impacts of Hurricane Andrew. *Journal of Coastal Research*, (Special Issue No. 21), 324–339. Retrieved from https://www.jstor.org/stable/25736018

Haralick, R. M., Shanmugam, K., & Dinstein, I. (1973). Textural Features for Image Classification. *IEEE Transactions on Systems, Man, and Cybernetics*, *SMC-3*(6), 610–621. https://doi.org/10.1109/tsmc.1973.4309314

Hardisky, M. A., Gross, M. F., & Klemas, V. V. (1986). Remote Sensing of Coastal Wetlands. *BioScience*, *36*(7), 453–460. Retrieved from https://www.jstor.org/stable/1310341

Harris Geospatial Solutions. (2018). Texture Filters. Retrieved February 6, 2019, from https://www.harrisgeospatial.com/docs/TextureFilters.html

Harrison, E. Z., & Bloom, A. L. (1977). Sedimentation rates on tidal salt marshes in Connecticut. *Journal of Sedimentary Research*, *47*(4), 1484–1490. https://doi.org/10.1306/212F739C-2B24-11D7-8648000102C1865D

Higinbotham, C. B., Alber, M., & Chalmers, A. G. (2004). Analysis of Tidal Marsh Vegetation Patterns in Two Georgia Estuaries Using Aerial Photography and GIS. *Estuaries*, *27*(4), 670–683.

Hinson, A. L., Feagin, R. A., Eriksson, M., Najjar, R. G., Herrmann, M., Bianchi, T. S., … Boutton, T. W. (2017). The spatial distribution of soil organic carbon in tidal wetland soils of the continental United States. *Global Change Biology*, *23*(12), 5468–5480. https://doi.org/10.1111/gcb.13811

Horton, B. P., Rahmstorf, S., Engelhart, S. E., & Kemp, A. C. (2014). Expert assessment of sea-level rise by AD 2100 and AD 2300. https://doi.org/10.1016/j.quascirev.2013.11.002

IPCC. (2015). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (R. K. Pachauri & L.A. Meyer, Eds.). Geneva, Switzerland: IPCC. Retrieved from http://www.ipcc.ch.

Jensen, J. R. (2006). *Remote Sensing of the Environment: An Earth Resource Perspective* (2nd ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Jensen, J. R. (2015). *Introductory Digital Image Processing: A Remote Sensing Perspective* (4th ed.). Glenview, IL: Pearson Education, Inc.

Jensen, J. R., Cowen, D. J., Althausen, J. D., Narumalani, S., & Weatherbee, O. (1993). An Evaluation of the CoastWatch Change Detection Protocol in South Carolina. *Photogrammetric Engineering & Remote Sensing*, *59*(June), 1039–1046.

Jensen, J. R., Olson, G., Schill, S. R., Porter, D. E., & Morris, J. (2002). Remote sensing of biomass, leaf-area-index, and chlorophyll a and b content in the ACE basin national estuarine research reserve using sub-meter digital camera imagery. *Geocarto International*, *17*(3), 27–36. https://doi.org/10.1080/10106040208542241

Jeter, G. W., & Carter, G. A. (2016). Habitat change on Horn Island, Mississippi, 1940-2010, determined from textural features in panchromatic vertical aerial imagery. *Geocarto International*, *31*(9), 985–994. https://doi.org/10.1080/10106049.2015.1094527

Kennish, M. J. (2001). Coastal Salt Marsh Systems in the U. S.: A Review of

Anthropogenic Impacts. *Journal of Coastal Research*, *17*(3), 731–748. Retrieved from http://www.jstor.org/stable/4300224

Kirgan, H. (2011, September 23). Proposed Richton salt dome project is dead as funding for environmental impact statement is cancelled. *Gulflive.Com*. Retrieved from http://blog.gulflive.com/mississippi-press-news/2011/09/proposed_richton_salt_dome_pro.html

Kirwan, M. L., Langley, J. A., Guntenspergen, G. R., & Megonigal, J. P. (2013). The impact of sea-level rise on organic matter decay rates in Chesapeake Bay brackish tidal marshes. *Biogeosciences*, *10*, 1869–1876. https://doi.org/10.5194/bg-10-1869-2013

Kirwan, M. L., & Megonigal, J. P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, *504*(December 2013), 53–60. https://doi.org/10.1038/nature12856

Kirwan, M. L., & Temmerman, S. (2009). Coastal marsh response to historical and future sea-level acceleration. *Quaternary Science Reviews*, *28*(17–78), 1801–1808. https://doi.org/10.1016/j.quascirev.2009.02.022

Klemas, V. (2013). Remote Sensing of Coastal Wetland Biomass: An Overview. *Journal of Coastal Research*, *29*(5), 1016–1029. https://doi.org/10.2112/JCOASTRES-D-12-00237.1

Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., … Sugi, M. (2010). Tropical cyclones and climate change. *Nature Geoscience*, *3*(3), 157–163. https://doi.org/10.1038/ngeo779

Lorenzen, B., & Jensen, A. (1988). Reflectance of Blue, Green, Red and Near Infrared

Radiation from Wetland Vegetation Used in a Model Discriminating Live and Dead Above Ground Biomass. *The New Phytologist*, *108*(3), 345–355. Retrieved from https://www.jstor.org/stable/2433304

Mishra, D. R., Ghosh, S., & Gitelson, A. A. (n.d.). MS Coastal Marsh Synthesis Task 3: Biophysical Models. Retrieved March 4, 2019, from https://sites.google.com/view/ms-coastal-marsh-synthesis/task-3-biophysical-models

Mississippi Automated Resource Information System. (n.d.-a). 2016 National Agriculture Imagery Program (NAIP). Retrieved January 2, 2019, from https://www.maris.state.ms.us/HTM/DownloadData/NAIP_2016.html

Mississippi Automated Resource Information System. (n.d.-b). MDEM 2007 Coastal Region Base Mapping Data. Retrieved February 27, 2019, from https://www.maris.state.ms.us/HTM/DownloadData/MDEM2007CoastalBaseMapping.html

Mississippi Automated Resource Information System. (n.d.-c). Raster Images. Retrieved January 2, 2019, from https://www.maris.state.ms.us/HTM/DownloadData/RasterImages.html

Mississippi Department of Marine Resources. (1998). Pascagoula River Marsh Preserve. Retrieved January 18, 2019, from http://www.dmr.ms.gov/index.php/mississippi-gems/248-pascagoula-river

Mooneyhan, D. S., & Criss, G. A. (2014). *Ecological communities of the Hancock County Marshes and Pascagoula River Marshes Coastal Preserves*.

Morris, J. T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B., & Cahoon, D. R. (2002). Responses of coastal wetlands to rising sea level. *Ecology*, *83*(10), 2869–2877.

https://doi.org/10.1890/0012-9658(2002)083[2869:ROCWTR]2.0.CO;2

Muller, W., & Zilbermints, R. (2017, February 3). Pascagoula City Council votes to oppose Lake George project. *SunHerald*. Retrieved from http://www.sunherald.com/news/local/counties/jackson-county/article130644979.html

NASA Jet Propulsion Laboratory. (2018). Global Climate Change: Vital Signs of the Planet. Retrieved March 10, 2018, from https://climate.nasa.gov

National Academies of Sciences Engineering and Medicine. (2018). *Understanding the Long-Term Evolution of the Coupled Natural-Human Coastal System: The Future of the U.S. Gulf Coast*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25108

National Oceanic Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services. (2018). Sea Level Trends. Retrieved October 25, 2018, from https://tidesandcurrents.noaa.gov/sltrends/

Nelson, K. (2017, April 9). 50 years ago, a modern shipyard changed Mississippi's struggling economy. *SunHerald*. Retrieved from https://www.sunherald.com/latest-news/article143546249.html

Nicholson, H. M. (2017). *Textural Analysis of Historical Aerial Photography to Determine Change in Coastal Marsh Extent: Site fo the Present-Day Grand Bay National Estuarine Research Reserve (GBNERR) 1955-2014*. The University of Southern Mississippi.

NOAA Center for Satellite Applications and Research. (2015). Laboratory for Satellite Altimetry/Sea Level Rise. Retrieved October 25, 2018, from https://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/

O'Hara, C. G., King, J. S., Cartwright, J. H., King, R. L., & Member, S. (2003). Multitemporal Land Use and Land Cover Classification of Urbanized Areas Within Sensitive Coastal Environments. *IEEE Transactions on Geoscience and Remote Sensing*, *41*(9), 2005–2014. https://doi.org/10.1109/TGRS.2003.816573

Orson, R., Panageotou, W., Leatherman, S. P., Orsona, R., Panageotoub, W., & Stephen, P. (1985). Response of Tidal Salt Marshes of the U. S. Atlantic and Gulf Coasts to Rising Sea Levels. *Journal of Coastal Research*, *1*(1), 29–37. Retrieved from https://www.jstor.org/stable/4297007

Partyka, M. L., & Peterson, M. S. (2008). Habitat Quality and Salt-Marsh Species Assemblages along an Anthropogenic Estuarine Landscape, *24*(6), 1570–1581. https://doi.org/10.2112107-0937

Pat Harrison Waterway District, & George County Board of Supervisors. (2016). Pascagoula River Drought Resiliency Project EIS. Retrieved July 1, 2018, from https://www.georgecountylakeseis.com/en/homepage

Peterson, M. S., & Partyka, M. L. (2006). Baseline Mapping of Phragmites australis (Common Reed) in Three Coastal Mississippi Estuarine Basins. *Southeastern Naturalist*, *5*(4), 747–756. Retrieved from http://www.jstor.org/stable/3878063

Peterson, M. S., Weber, M. R., & Partyka, M. L. (2007). Integrating in situ quantitative geographic information tools and size-specific, laboratory-based growth zones in a dynamic river-mouth estuary. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *618*, 602–618. https://doi.org/10.1002/aqc

Powell, A. S., Jackson, L., & Ardón, M. (2016). Disentangling the effects of drought, salinity, and sulfate on baldcypress growth in a coastal plain restored wetland. *Restoration Ecology*, *24*(4), 548–557. https://doi.org/10.1111/rec.12349

Pu, R., Landry, S., & Yu, Q. (2018). Assessing the potential of multi-seasonal high resolution Pléiades satellite imagery for mapping urban tree species. *Int J Appl Earth Obs Geoinformation*, *71*, 144–158. https://doi.org/10.1016/j.jag.2018.05.005

Reed, D. J. (2002). Sea-Level Rise and Coastal Marsh Sustainability: Geological and Ecological Factors in the Mississippi Delta Plain. *Geomorphology*, *48*(1), 233–243. https://doi.org/10.1016/s0169-555x(02)00183-6

Rovere, A., Stocchi, P., & Vacchi, M. (2016). Eustatic and Relative Sea Level Changes. *Current Climate Change Reports*, 221–231. https://doi.org/10.1007/s40641-016-0045-7

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M. L., Wolff, C., Lincke, D., … Brown, S. (2018). Future response of global coastal wetlands to sea-level rise. *Nature*. https://doi.org/10.1038/s41586-018-0476-5

Shinkle, K. D., & Dokka, R. K. (2004). *Rates of vertical displacement at benchmarks in the Lower Mississippi Valley and the Northern Gulf Coast*. Silver Spring, MD. https://doi.org/NOAA Technical Report NOS/NGS 50

Tornqvist, T. E., Wallace, D. J., Storms, J. E. A., Wallinga, J., Van Dam, R. L., Blaauw, M., … Snijders, E. M. A. (2008). Mississississippi Delta Subsidence Primarily Caused by Compaction of Holocene Strata. *Current Climate Change Reports*, *1*(2008), 173–176. https://doi.org/10.1038/ngeo129

U.S. Army Corps of Engineers. (2009). *Comprehensive Plan and Integrated*

Programmatic Environmental Impact Statement: Volume 2 - Appendix A: Environmental.

U.S. Geological Survey. (n.d.-a). EarthExplorer - Home. Retrieved January 2, 2019, from https://earthexplorer.usgs.gov/

U.S. Geological Survey. (n.d.-b). USGS EROS Archive - Aerial Photography - National High Altitude Photography (NHAP). Retrieved January 2, 2019, from https://www.usgs.gov/centers/eros/science/usgs-eros-archive-aerial-photography-national-high-altitude-photography-nhap?qt-science_center_objects=0#qt-science_center_objects

US Department of the Interior, & US Geological Survey. (2019). USGS Water Data for USA. Retrieved February 4, 2019, from https://nwis.waterdata.usgs.gov/nwis

Watson, E. B., Wigand, C., Davey, E. W., Andrews, H. M., Bishop, J., & Raposa, K. B. (2017). Wetland Loss Patterns and Inundation-Productivity Relationships Prognosticate Widespread Salt Marsh Loss for Southern New England. *Estuaries and Coasts*. https://doi.org/10.1007/s12237-016-0069-1

Wells, J. V. B. (1962). *Summary of Floods in the United States During 1955*. Washington, DC. https://doi.org/Geological Survey Water-Supply Paper 1455-B

Williams, H. F. L. (2012). Magnitude of Hurricane Ike storm surge sedimentation: implications for coastal marsh aggradation. *Earth Surface Processes and Landforms*, *37*, 901–906. https://doi.org/10.1002/esp.3252

Wu, W. (2018). Predicting the impact of sea-level rise on coastal wetlands: implications for coastal wetland restoration. *2018 Bays and Bayous Symposium: Navigating Waves of Change*. Mobile, AL.

Wu, W., Biber, P., & Bethel, M. (2017). Thresholds of sea- -level rise rate and sea-level rise acceleration rate in a vulnerable coastal wetland. *Ecology and Evolution*, *7*, 10890–10903. https://doi.org/10.1002/ece3.3550

Wu, W., Huang, H., Biber, P., & Bethel, M. (2017). Litter Decomposition of *Spartina alterniflora* and *Juncus roemerianus* : Implications of Climate Change in Salt Marshes. *Journal of Coastal Research*, *332*. https://doi.org/10.2112/JCOASTRES-D-15-00199.1

Yuill, B., Lavoie, D., & Reed, D. J. (2009). Understanding Subsidence Processes in Coastal Louisiana. *Journal of Coastal Research*, (Special Issue No. 54), 23–37. https://doi.org/10.2112/SI54-012.1.intensity