Assessing the impact of Hurricane Katrina on the coastal wetland of St. Bernard, Louisiana

Rukumani Rimal

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ASSESSING THE IMPACT OF HURRICANE KATRINA ON THE COASTAL WETLAND OF ST. BERNARD, LOUISIANA

by

RUKUMANI RIMAL

Under the Direction of Lawrence Kiage, Ph.D.

ABSTRACT

The wetlands of the coastal Louisiana have been disappearing at an alarming rate. The rate was further accelerated during the Hurricane Katrina. Hurricane Katrina converted a large area of wetland into open water by bulk removal of vegetation, flooding, and killing of plants through the salt water inundation. The aim of this study was to quantify wetland loss rates in a high salinity wetland of St. Bernard Parish, Louisiana before and after Hurricane Katrina made landfall. Change-detection-mapping and analysis, using Landsat TM images, was used for generating the change matrices. Images from 1990 and 2010 were analyzed to estimate total wetland loss and the wetland loss contributed by Hurricane Katrina over the 20-year period. The analysis revealed that wetland loss in the study area during Hurricane Katrina accounted for over half (65%) of the total land lost over a 20-year period (1990 to 2010). The annual net loss of wetland to water during 2003-2004, 2004-2005 and 2005-2006 were estimated to be 10.82 km², 15.42 km² and 36.06 km² respectively, which is 26.45 %, 24.80% and 48.76% of total changes in four years (2003-2006). Vegetation disturbances were mapped using Normalized Difference Vegetation Index (NDVI).

Keywords: Landsat TM, Coastal Louisiana, NDVI, wetland loss, high salinity wetland
Assessing the Impact of Hurricane Katrina on the Coastal Wetland of St. Bernard, Louisiana

By

Rukumani Rimal

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In the College of Arts and Sciences

Georgia State University

2017
ASSESSING THE IMPACT OF HURRICANE KATRINA ON THE COASTAL WETLAND
OF ST. BERNARD, LOUISIANA

by

RUKUMANI RIMAL

Committee Chair: Lawrence Kiage

Committee: Brian K Meyer
Dajun Dai

Electronic Version Approved:
Office of Graduate Studies
College of Arts and Sciences
Georgia State University
December 2017
DEDICATION

This work is dedicated to my parents, Govinda Prasad Rimal and Sita Rimal, and my husband Suresh Nath Neupane, who always helped me in my academic career. And a special dedication to my son Vrishank Krishna Neupane.
ACKNOWLEDGEMENTS

I would like to thank Dr. Lawrence Kiage for motivating, supporting, and providing valuable guidance in my efforts to completing this Thesis. His guidance and suggestions have always helped me improve and look for the best in me. My special thanks to the committee members Dr. Brian K. Meyer and Dr. Dai for their invaluable support and guidance.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS.............................................................................................................. 6

LIST OF FIGURES .................................................................................................................. 10

LIST OF EQUATIONS .............................................................................................................. 12

1 INTRODUCTION..................................................................................................................... 13

1.1. Background ..................................................................................................................... 13

1.2. Wetland loss in Louisiana............................................................................................... 13

   1.2.1. Anthropogenic causes of land loss in Louisiana ...................................................... 16

   1.2.2. Natural causes of wetland loss in Louisiana ........................................................... 17

1.3. Restoration and protection of wetlands ........................................................................ 18

1.4. Assessing effects of Hurricanes on the coastal wetlands .............................................. 19

1.5. Types of Wetland and their response to Hurricanes ...................................................... 21

1.6. History of major Hurricanes in Louisiana .................................................................... 22

1.7. Hurricane Katrina ........................................................................................................... 23

1.8. Hurricane Katrina and its effect on the coastal wetlands of Louisiana ......................... 24

1.9. Research Question and Objectives ............................................................................... 26

2 THE STUDY AREA............................................................................................................... 29

2.1. Dynamics of the study area ........................................................................................... 31

2.2. Significance of the Study ............................................................................................... 33

4 METHODS ............................................................................................................................ 35

3.1. Data acquisition ............................................................................................................. 35
3.2. Pre-processing of data ........................................................................................................... 36
  3.2.1. Geometric correction ........................................................................................................ 36
  3.2.2. Radiometric correction ..................................................................................................... 38
3.3. Unsupervised classification .................................................................................................... 40
3.4. Land Use or Land Cover Change (LULC) detection mapping ........................................... 41
3.5. Normalized Difference Vegetation Index (NDVI) .............................................................. 41

4 RESULTS .................................................................................................................................. 43
  4.1. Radiometric enhancement .................................................................................................... 43
  4.2. Color composites .................................................................................................................. 43
  4.3. Land Use/Land Cover maps ................................................................................................ 47
  4.4. Change detection map ........................................................................................................ 54
  4.5. NDVI ................................................................................................................................ 59
  4.6. Statistics of NDVI ............................................................................................................... 60
  4.7. Z-test ................................................................................................................................ 66

5 DISCUSSION ............................................................................................................................. 69

6 CONCLUSION ............................................................................................................................. 77

REFERENCES ............................................................................................................................... 81
LIST OF TABLES

Table 1: Land area in Coastal Louisiana, Coastal Wetlands Planning, Protection, and Restoration Act Program (1932-2010), Source: Couvillion et al. (2011) ...................... 15

Table 2: The land areas in Pontchartrain basin as defined by the Coastal Wetlands Planning, Protection and Restoration Act Program (2013.), 1932–2010. ...................... 32

Table 3: Attribute of the Landsat imagery used in the study…………………………………………………………. 35

Table 4: RMSE obtained during geometric correction ................................................................. 38

Table 5: Area/ percentage changed in the study area ................................................................. 56

Table 6: Statistics of Z-test for 2005 and 2006 NDVI samples ..................................................... 67

Table 7: Statistics of Z-test for 2004 and 2005 NDVI samples ..................................................... 67

Table 8: Statistics of Normalized Difference Vegetation Index for the study area ............ 68
LIST OF FIGURES

Figure 1: Map showing coastal Louisiana, land loss and predicted gain. Source: Modified from La Coast, U.S. Geologic Society (2008) .......................................................... 16

Figure 2: Aerial images, displaying land lost near Mississippi bird foot delta from 1932 to 2011 .............................................................................................................. 18

Figure 3: Pictures showing the damage in the wetlands of coastal Louisiana post-Katrina landfall ........................................................................................................... 21

Figure 4: A map of Louisiana-showing the path of Hurricane Katrina in 2005 ............ 24

Figure 5: MODIS, Terra images of Mississippi river channel pre- and post- Katrina, False color composite, 2005 ......................................................................................... 25

Figure 6: An aerial image is showing a small portion of Louisiana coastal area before and after Hurricane Katrina ...................................................................................... 26

Figure 7: Map showing study area ............................................................................ 30

Figure 8: An image is showing types of wetland in southwestern Louisiana .......... 31

Figure 9: Flowchart of geometric correction process that was employed in this study ...... 37

Figure 10: Schematic sketch of solar radiation components in flat terrain for Atmospheric and Topographic correction (ATCOR) 2 model ................................................. 39

Figure 11: An example of satellite scene (Landsat TM 5) of the study area in false color RGB (Red, Green, Blue) before and after applying ATCOR 2 model .............. 43

Figure 12: An example of true Color Composite (TCC) ................................................. 44

Figure 13: An example of false color IR ................................................................. 45

Figure 14: Spectral scatter plot of reflectance value (Digital Number) in the Red band on the x-axis and the NIR band on the y-axis .......................................................... 46
Figure 15: Land cover map of 2003

Figure 16: Land cover map of 2004

Figure 17: Land cover map of 2005

Figure 18: Land cover map of 2006

Figure 19: Land cover map of 1990

Figure 20: Land cover Map of 2010

Figure 21: LULC change maps of the study area derived from the Landsat TM 5 images of 2003, 2004, 2005, 1990 and 2010

Figure 22: Area graph of the change matrices

Figure 23: NDVI maps for the year 2003, 2004, 2005 and 2006 derived from Landsat TM 5 images of the study area

Figure 24: Map showing the maximum and minimum value of NDVI for each pixel from 2004-2006.

Figure 25: Map showing the difference between the highest value of NDVI and lowest value of NDVI from 2003-2006.

Figure 26: NDVI maps for 1990 and 2010

Figure 27: NDVI statistics for whole study area
LIST OF EQUATIONS

Equation 1: Calculation of Root Mean Square error per GCP...

Equation 2: Transmittance value in each pixel

Equation 3: Surface reflectance for each pixel

Equation 4: Calculation of Normalized Difference Vegetation Index
1 INTRODUCTION

1.1. Background

Diverse and complex natural processes integrated with human failures alter coastal wetlands physically, biologically and chemically (White & Kaplan, 2017). The wetlands in coastal Louisiana are not an exception. Coastal Louisiana is facing many serious environmental problems such as subsidence, erosion, and bio-deterioration and has been subjected to a greater risk of wetland loss and ecological damage due to the anthropogenic as well as natural causes. The natural causes of wetland loss include extreme weather events like hurricanes, subsidence, abandoned river delta, and the anthropogenic causes of wetland loss include, but are not limited to, construction of impoundment, dredging, spoil disposing and land reclamation (Mitsch, Straškraba, & Jorgensen, 2012). The loss of Louisiana’s wetlands also took place as they were covered by fill materials or separated by spoil banks (Mitsch, Straškraba, & Jorgensen, 2012).

The Louisiana coastal plain accounts for 40% of the US wetlands and 80% of the total loss (Penland et al., 1990). Barras and Dunbar (year), using time series analysis method, estimated that the Louisiana coast has been losing land at the rate of 25 to 35 square miles per year (Dunbar et al., 1992; Barras et al., 1994). The most recent rate of land loss estimated by Couvillion et al. (2011) indicates a minimum loss of 16.5 square miles per year.

1.2. Wetland loss in Louisiana

Many of the fragile wetlands in coastal Louisiana have been converted to open water by subsidence, dredging canals, and erosion. About 4,600 km$^2$ of low lying wetlands in Louisiana were converted into open water from 1932 to 2004 (USGS, 2016). Louisiana accounts for the highest rate of land loss in the whole United States, with almost about 80 percent of the total wetland loss (Louisiana Ecological Services, 2016). Nearly 1.1 million acres had been lost by the
beginning of the 20th century from the impacts of natural and anthropogenic causes (Templet & Meyer-Arendt, 1988). Penland et al. (1990) identified that coastal Louisiana lost landmass of nearly 2,000 square miles from 1932 to 2010 (USGS, 2010; Penland et al., 1990). Louisiana loses the land nearly the size of Manhattan Island every year (USGS, 2010).

Barras et al. (2005) and Duxbury and Dickinson (2007) stated the loss rate of 40-60 km²/year during 1970’s (Duxbury & Dickinson, 2007; Barras et al., 2005). Templet and Meyer-Arendt (1988) identified the catastrophic wetland disappearance rate of 150 km²/yr during the 1980’s (Templet & Meyer-Arendt, 1988). The loss during 1970’s and 1980’s was attributed to the aggregate effect of subsidence and erosion of both anthropogenic and natural process, and hurricanes. However, with the restoration and protection efforts, the annual loss rates slowed down by the beginning of 1990’s (Louisiana Ecological Services, 2016). The rate decelerated to an estimated rate of 30 km²/year from late 1980 to 2004 due to the restoration efforts implemented (USGS, 2010). However, when the regular wetland loss process was augmented by the storms of 2005 and 2008, the cumulative effects led to the loss of land equal to the size of Chicago (Barras and Morton, 2008). The most recent loss rates identified by Barras et al. (2010) were 33.07 km² from 2009 to 2010 and 53.48 km² from 2008 to 2009 (Barras et al., 2010). Still, it is projected that Louisiana’s coast will continue to lose land at the rate of about 6,600 acres per year (10 sq. miles) over the next 50 years, resulting in another 330,000 acres of wetlands being lost, an area almost equivalent to size of the state of Rhode Island (Barras et al., 2005). Lack of proper restoration efforts can result in the loss of one-third of 1930’s Louisiana coastal wetland by 2050 (Tibbetts, 2006). Table 1 below shows the total area of coastal Louisiana in square miles over the 1932 to 2010 time period, strongly indicating that the coastal land area is decreasing significantly.
<table>
<thead>
<tr>
<th>Decimal Date</th>
<th>Coastal land area (square miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1932</td>
<td>7,545.92</td>
</tr>
<tr>
<td>1956</td>
<td>7,104.28</td>
</tr>
<tr>
<td>1973.9</td>
<td>6,749.68</td>
</tr>
<tr>
<td>1975.7</td>
<td>6,534.90</td>
</tr>
<tr>
<td>1977.4</td>
<td>6,265.65</td>
</tr>
<tr>
<td>1985.1</td>
<td>5,985.12</td>
</tr>
<tr>
<td>1988.1</td>
<td>6,139.65</td>
</tr>
<tr>
<td>1990.8</td>
<td>6,020.31</td>
</tr>
<tr>
<td>1995.7</td>
<td>5,842.57</td>
</tr>
<tr>
<td>1998.2</td>
<td>5,748.43</td>
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<tr>
<td>1999.9</td>
<td>5,924.58</td>
</tr>
<tr>
<td>2002.2</td>
<td>5,867.61</td>
</tr>
<tr>
<td>2004.9</td>
<td>5,816.89</td>
</tr>
<tr>
<td>2006.8</td>
<td>5,607.89</td>
</tr>
<tr>
<td>2008.8</td>
<td>5,451.75</td>
</tr>
<tr>
<td>2009.8</td>
<td>5,459.78</td>
</tr>
<tr>
<td>2010.8</td>
<td>5,662.71</td>
</tr>
</tbody>
</table>

Figure 1 highlights the area that has been gained and lost since 1932 to 2000. It also highlights the areas of predicted loss and gain between 2000 and 2050 which illustrates the huge possibility of the large area being lost to water soon.
1.2.1. Anthropogenic causes of land loss in Louisiana

The anthropogenic causes of land loss are mostly due to interventions in the wetland ecology and construction of levees, impoundments, and dredging. Levees limit sediment supply to the wetland floodplain in the coastal regions, hence unable to meet the supply to compensate the recent loss rates. Before human settlement increased significantly in the area and construction of levees were very limited, Mississippi River flow provided enough sediment supply to the Louisiana coastal region (Twilley et al., 2016). The rapid construction of levees in past few decades has limited the sediment supply to the coastal region. By 2007 there were about 3,620 km of levees constructed in coastal Louisiana and few hundred kilometers were under current construction (Conner, Doyle, & Krauss, 2007). Oil and gas industries’ infrastructures are also
responsible for the wetland loss in the Louisiana coastal area. Huge networks of the pipelines, production setup, canals and dredging possess serious threats to coastal Louisiana. Excavated materials from the wetlands produced by these industries are dredged onto the bank. These banks stop the flow of sediments and water, resulting in the death of the plants in the wetlands (LCPRA, 2004). Canals formed by oil and gas industries allow salt water intrusion into the wetland system, which alters the salinity. The intrusion of saline water results in the death of plants, primarily in the freshwater wetlands (low salinity) and increases the erosion rate (McKee & Mendelssohn, 1989). Highly saline wetlands can comparatively tolerate saline water intrusions.

1.2.2. Natural causes of wetland loss in Louisiana

Weather-related catastrophic events are the foremost natural causes of wetland loss in the Louisiana coast. Other substantial causes of wetland loss in coastal Louisiana are global climate change and sea level rise. Global climate change is not only expected to increase coastal storm events but also accelerate sea level rise. The current global mean sea level rise is about 1.7 mm/yr (Church & White, 2006), however it may vary in both regional and local scale. A US Army Corps of Engineers tide gauge in Eugene Island documented the sea level rise at the rate of 1.19 cm/yr from 1946 to 1988 (Penland and Ramsay, 1990). Houma tide gauge data documented a sea level rise rate of 1.09 cm/yr for the same study period (Penland and Ramsay, 1990). Increasing sea level can submerge the coastal region. Furthermore, Intergovernmental Panel on Climate Change estimates that global sea level rise is supposed to increase the subsidence hazard rate in the coastal Louisiana region (Day et al., 2008).

The other substantial natural causes of wetland loss are high energy storms and hurricanes. The high-energy storm events are capable of eroding and removing the coastal
wetlands, which contribute to the higher wetland loss rate in the year they occur. Besides the direct removal, the storm surge also favors the salt water intrusion that ultimately kills vegetation and helps further erosion of barrier shorelines.

Figure 2 below shows the land loss condition in the Mississippi bird foot delta of coastal Louisiana in the last 79 years, from 1932 to 2011, resulted from the combined effect of natural and anthropogenic factors. The aerial imagery depicted below shows the huge loss of land to water over the years.

Figure 2: Aerial images, displaying land lost near Mississippi bird foot delta from 1932 to 2011. New built up land since 1932 is displayed in green color.

1.3. Restoration and protection of wetlands

With the legislative initiatives to control the wetland loss in the coastal region, the Coastal Wetland Planning, Protection and Restoration Act (CWPPRA) was enacted in 1990 for the restoration of the wetlands in the coastal region. According to the Louisiana government, nearly 70% of the funds are allocated to the projects in coastal Louisiana for the restoration and protection of wetlands. Since the 1990s, $30-$80 million has been allocated annually for the restoration projects in Louisiana alone. There were about 155 CWPPRA coastal restoration
projects enacted as of 2011 that demonstrated the different techniques of wetland restoration with the aim of involving local communities in restoration activities. The projects were mostly funded through CWPPRA. Currently 108 projects have been completed that has benefitted almost 100,000 acres (LACPR, 2009).

1.4. Assessing the effects of Hurricanes on coastal wetlands

Land loss in coastal Louisiana is a complex phenomenon and cannot be attributed to a single factor. However, considering their erosional strength, extreme weather events like hurricanes have a significant role in the wetland removal process. Lovejoy et al. (2013) observed that the effects of hurricanes Katrina and Rita in 2005 eroded 527 km² of coastal wetlands and transformed the wetland into open water bodies (Lovejoy et al., 2013). Lovejoy et al. (2013) used high-resolution satellite images (QuickBird, IKONOS, and Geoeye-1) to assess the loss of land in two different study areas. The two areas that Lovejoy et al. (2013) studied are the southwestern part of Chenier Plain and eastern delta plain of Delacroix. The Chenier Plain was impacted by Rita (2005) and Ike (2008), whereas the Delacroix area was impacted by Katrina (2005) and Gustav (2008). The study found the broadening of existing open water bodies and erosion of fringing wetland areas due to the extreme storms in both places. The study was based on the Change Detection Analysis and the Fractional Water Classification methods. According to Lovejoy et al. (2013), Hurricane Ike increased the rate of land loss by 7.9% in the Hackberry area, whereas Hurricane Katrina in Delacroix reduced the landmass by 4.9% of the total area. In the Hackberry area, the initial land loss rate estimated was 5.8% during Rita, which further augmented to 7.9% during Hurricane Ike.

Barras et al. (2009) also studied the impact of several hurricanes in the coastal region and revealed that land loss can be increased significantly during high-intensity hurricanes and
worsens during recurring events of such hurricanes. Their research found that Hurricanes Katrina, Rita, Gustav, and Ike transformed 328 square miles of wetlands into open water in just four years, between 2004 and 2008. That is why the loss during that period exceeded the total loss from 25 years’ period (1978-2004) (Barras, 2009). Their study is based on the Change Analysis method using satellite images. Figure 3 shows the flooded condition of the coastal wetlands and the blown away tufts post-Hurricane Katrina. When a major hurricane strikes the coast, it can cause severe damage to the wetlands by both flooding and complete removal processes. The erosion of the wetlands also depends upon the vegetation condition. Shallowly rooted vegetation can easily be blown away versus deeply rooted vegetation.
Figure 3: Pictures showing the damage in the wetlands of coastal Louisiana post-Katrina landfall. Pictures (a), (b), (c) and (d) of figure show the flooded condition of the Louisiana coastal wetlands after Hurricane Katrina landfall. Figures (a), (d), and (c) are the typical cases of salt water intrusion into the wetlands and flooding. Figure (b) and (d) shows the blown away tuft during Hurricane Katrina. Complete removal of shallow-rooted wetlands occurs when hit by strong Hurricane like Katrina. Figure (e) shows the blown away tuft deposited at the settlement area.


1.5. Types of Wetland and Response to Hurricanes

Howes et al. (2010) noted that the high salinity wetlands were less prone to the damage than the low salinity wetlands following significant storm events. The vegetation that grows in
low salinity wetlands are mostly shallow rooted and can be eroded easily. On one hand, vegetation of the high salinity wetlands can somehow tolerate the salt water inundation produced from the storm surge, which makes them less susceptible to plant mortality and erosion. On the other hand, low salinity wetlands tend to die easily from the salt water intrusion and can be eroded without much effort.

### 1.6. History of major Hurricanes in Louisiana

The historic record of memorable and most destructive hurricanes of the 20th century on the Louisiana Coast include Andrew (1992), Camille (1969), Betsy (1965) and Audrey (1957) (Roth, 2010). The most destructive hurricanes of the 21st century that made landfall in Louisiana are Lili (2002), Katrina (2005), Rita (2005) and Gustav (2008) (Roth, 2010). Hurricane Lili developed as a tropical storm in the Atlantic and soon converted into a category four, however, the storm weakened to the category one before making the landfall in the Vermilion Parish of Louisiana on October 3, 2002. Hurricane Lili with wind speeds of 120 mph caused a total of one billion in economic damage. The category three Hurricane Rita made landfall in Louisiana on September 20, 2005. Hurricane Rita caused economic damage of $18 billion throughout its path and a total of 125 fatalities, 113 happened in Texas alone. However, the estimated damage in Louisiana caused by Rita was $8 billion with one fatality. Another major hurricane to hit Louisiana during the 21st century was the category two Hurricane Gustav, which made landfall in Louisiana on September 1, 2008. The estimated damage caused by Gustav was $10 billion and 153 fatalities. At the time, Hurricane Katrina (2005) was the deadliest and the most destructive storm with the total economic damage of $108 billion, of which $75 billion worth of damage took place in New Orleans and Mississippi. The human casualties exceeded more than 1,200. The costliest hurricane in the US history, Katrina not only caused the tangible damage worth
billions but also caused intangible ecological and environmental damages in Louisiana ("Hurricanes in History," 2016) (www.noaa.org).

1.7. Hurricane Katrina

One of the costliest disasters in the history of USA, Katrina formed on August 23, 2005, in the Bahamas as a tropical storm and converted into a hurricane after two days. The most impacted states by Hurricane Katrina were Florida, Mississippi, Louisiana, and Texas.

The tropical depression, which formed 200 miles southeast of Bahamas, strengthened significantly, traveled from the northwest Bahamas, and then turned to southern Florida, soon to become a hurricane near Miami on August 25, 2005 (NOAA). According to NOAA, Hurricane Katrina reached the category five intensity on the Saffir-Simpson scale on August 28, 2005. The wind speed reached 175 mph with the measured central pressure of 902 mb at a location 195 miles southeast of the tail of the Mississippi River. Hurricane Katrina made its first landfall in Hallandale Beach and Aventura on August 25 and slowly strengthened to the category five hurricane over the warm water of the Gulf of Mexico. However, the hurricane weakened to a category three hurricane when it made its second landfall in southeastern Louisiana on August 29, 2005 (NOAA). The hardest hit parishes were St. Bernard Parish, Plaquemines Parish, Orleans Parish, St. Tammany Parish, Terrebonne Parish and Washington Parish. Hurricane Katrina induced a large change in soil and vegetation. Figure 4 shows the track of Hurricane Katrina in the State of Louisiana and its coastal area and parishes.
Figure 4: A map of Louisiana showing the path of Hurricane Katrina in 2005.

1.8. Hurricane Katrina and its effect on the coastal wetlands of Louisiana

A report by the US Geological Survey’s National Wetland Research Center in 2005 stated that coastal Louisiana lost more than 217 square miles of land that was transformed into water by the episodic events of Katrina and Rita (Barras et al., 2005). Some areas experienced permanent loss by the direct removal of the wetlands by strong winds. The rest of the changes were transitory, causing immediate flooding, and removal of aquatic vegetation. Continuous assessment of the impacted area is very crucial to learn the recovery status after the landfall (Barras, 2005). An assessment by using satellite images seems to be a very promising method mainly when the areas impacted is large and not easily accessible like coastal Louisiana.
Figures 5 and 6 below show the pre-and post-Katrina satellite images of coastal Louisiana and also include the study area. The damages at the coastal region seem well-pronounced in the MODIS (Terra images). Figure 6 shows the flooded condition of a coastal area where noticeable land is under water after Hurricane Katrina. These images justify how dynamic, as well as vulnerable these coastal wetlands are during hurricanes.

Figure 5: MODIS, Terra images of Mississippi river channel pre- and post- Katrina, False color composite. It also includes the study area. Source: NASA earth observation, MODIS Rapid Response team, 2005. http://earthobservatory.nasa.gov
1.9. Research Question and Objectives

When accelerated by the episodic events of hurricanes between 2004 and 2006, 70% of the cumulative coastal wetland loss from 1978 to 2004 (26 years) occurred in only a 3-year period. Louisiana solely accounted for 80% of the total loss in the entire United States during Hurricane Katrina (Tibbetts, 2006). Previous studies such as Howes et al. (2010) and Barras et al., (2008) have suggested the spatial relation between the salinity types of the wetlands and the extent of the hurricane-induced loss identified on the satellite images of the coastal area. They further suggested that vegetation types control the resiliency of these wetlands during destructive hurricanes. The deep-rooted high salinity wetlands are more resilient than the shallow-rooted low salinity wetlands (Howes et al., 2010; Barras, Bernier, & Morton, 2008). Additionally, when salt water from the storm surge intrudes into the wetlands, it causes the enhanced mortality of the low salinity wetlands without much efforts versus the high salinity wetlands. However, the
extent and the degree of resiliency/damages in such high-salinity environment is yet to be understood explicitly, and very limited studies are available. This study was designed to investigate the impacts of the high-intensity hurricanes on high salinity regime wetlands such as St. Bernard Parish, on the Pontchartrain Basin. Specifically, the study aims to answer the following research questions:

a) Do high salinity wetlands remain unchanged, even during high-intensity hurricanes?

b) To what extent are high salinity wetlands impacted by intense hurricanes?

c) How does the impact of intense hurricanes on high salinity wetlands compare with the overall wetland loss in coastal Louisiana?

To find the answers to the research questions, a sample study area of predominantly high salinity wetlands was identified on the Louisiana coast in such a way that the area selected lay on the path of Hurricane Katrina and was one of the hardest hit; hence the loss can be readily identified on satellite imagery. This wetland is also among very few wetlands that are distinctly classified as a higher salinity wetland. Otherwise, finding higher salinity wetlands is itself very challenging as salinity condition does not have a clear boundary. In addition to that, the study area was hit by Hurricane Katrina as a category three hurricane. Hence it would be an ideal area to study the wetland’s resiliency during strong hurricanes.

The specific objectives of the study were:

1.1 To use the Landsat TM 5 data to identify and quantify land cover types mainly Land/Wetland and Water in the study area.

1.2 To test the effectiveness of the Time Series Analysis method for quantifying the wetland loss/recovery.
1.3 To compare the annual loss rates during Hurricane Katrina with a year before/after the landfall.

1.4 To understand if Hurricane Katrina accounted for the bulk of the changes from the decadal loss perspectives.

1.5 To identify and quantify vegetation disturbance and test the statistical significance of Normalized Difference Vegetation Indices (NDVI).
2 THE STUDY AREA
The study area is centered mainly in St. Bernard Parish of the Pontchartrain basin, located in southeastern Louisiana in the northern Gulf of Mexico. This wetland is located southeast of New Orleans and southwest of Chandelier Plain and surrounded by Lake Borgne in the east and Chandelier Sound on the West. This area was selected as a sample for the study as it is predominantly saline (more than 95%) and can truly represent the high salinity wetland of the coast to fulfill the research objective of understanding the resiliency of the high salinity wetlands during high-intensity hurricanes, in this case, Hurricane Katrina. Also, the study area lies on the Hurricane Katrina track; and therefore, represents one of the hardest hit wetland areas along the Louisiana Coast. Figure 7 shows the study area map with Louisiana parishes and the coastline of Louisiana.
Figure 7: Map showing study area, the black line in the middle of the map shows the nominal track of Hurricane Katrina in the coastal Louisiana, polygons in brown are the Louisiana parishes. Satellite image overlaid on the map is the study area in Louisiana coastline.
2.1. Dynamics of the study area

The St. Bernard wetland lies on the eastern part of the St. Bernard Parish within the Pontchartrain Basin. This basin consists of 483,390 acres of wetlands; the fresh wetlands of 38,500 acres, the brackish wetland of 116,800 acres, the intermediate wetland of 28,600 acres and rest are saline (www.lacoast.gov). Fresh and intermediate wetlands are low salinity wetlands whereas brackish and saline wetlands are high salinity (Howes et al., 2010). For the salinity regime classes, the Howes et al. (2010) publication and the map produced by USGS were used as the reference. Vegetation in the high salinity regime is mostly characterized by deeply rooted vegetation and the vegetation in low salinity wetlands has relatively shallow rooting. That is why saline wetlands mostly remain resilient during the high-intensity storm, which prevents loss, even during the high-intensity hurricanes (Howes et al., 2010). Figure 8 below shows the types of wetlands in southwestern Louisiana.

Figure 8: An image showing types of wetland in southwestern Louisiana, Source: USGS. The circle shows the study area.
Pontchartrain Basin alone has lost almost 66,000 acres of wetlands to water since 1932.

Table 2 is a summary of total land areas in Pontchartrain basin from 1990 to 2010 as published by Coastal Wetlands Planning, Protection and Restoration Act Program (Coastal Wetlands Planning and Restoration Act Program, 2013). The dates are given in the decimal dating system, which is derived by dividing the day of the year in which image was obtained by the number of the days.

Table 2: The land areas in Pontchartrain basin as defined by the Coastal Wetlands Planning, Protection and Restoration Act Program (2013.), 1932–2010.

<table>
<thead>
<tr>
<th>Date</th>
<th>Land area in Square miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990.8</td>
<td>970.8</td>
</tr>
<tr>
<td>1995.7</td>
<td>934.51</td>
</tr>
<tr>
<td>1998.2</td>
<td>961.99</td>
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<td>1999.9</td>
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<td>2002.2</td>
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<td>2004.9</td>
<td>936.71</td>
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<tr>
<td>2006.8</td>
<td>912.33</td>
</tr>
<tr>
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<td>900.98</td>
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<td>903.23</td>
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<tr>
<td>2010.8</td>
<td>910.96</td>
</tr>
</tbody>
</table>

According to Dunbar et al. (1992), Pontchartrain Basin has lost 8% of the land masses as it was converted into the open water bodies since 1932, which is more than 76,000 acres of land (Dunbar et al. 1992). Barras et al. (1994) studied the land loss rate and concluded that this basin could alone lose 1,250 acres of the land every year lacking restorative action (Barras et al. 1994). Based on the study conducted by Louisiana Coastal Wetland Conservation and Restoration Task
Force (1993), Department of Natural Resources and Coastal Restoration Division, the State of Louisiana determined that if no restorative efforts are performed to save the wetlands, this basin will lose additional 23% of landmass by 2040 ("Louisiana Coastal Wetland Functions and Values," 1997).

2.2. Significance of the Study

Hurricane Katrina-induced effects converted 517 km$^2$ of coastal wetlands into open water in Louisiana. The northeastern wetlands suffered greater assaults, as they lie close to the storm track. Corresponding to the entire coastal area, the study region, being one of the hardest hit, also has a potential to lose wetland at an accelerated rate during Hurricane Katrina. The available studies on wetland loss conditions mostly focus on large areas, encompassing nearly the entire coastal Louisiana and are not specific to the types of wetland. Not enough research has been done to understand the salinity regime’s response to the hurricanes. In this case, the effort is made to understand the wetland loss condition in only high salinity regime by using a predominantly saline wetland as a sample study area. Hence, this study will help us to explicitly understand high salinity regimes response during devastating hurricanes, in this case, Hurricane Katrina.

Also, this study only uses medium-resolution satellite imagery to investigate the land loss effect caused by Hurricane Katrina on a sample site with a specific salinity regime (based on the USGS classification). This paper will also examine the suitability of coarser resolution imagery in identifying the land to water conversion in a smaller area, especially when the study region lies on the coast and has an indistinct boundary of land and water. The previous studies conducted in smaller regions (e.g., Lovejoy et al., 2010), have used coarse imagery only in
concurrence with finer images. So, this study will also help us on identifying the challenges, limitations, and usefulness of using coarser resolution images alone for such kind of research
3 METHODS

3.1. Data acquisition

Table 3 is a summary of the attributes of the Landsat data that were utilized in this study. The Landsat TM 5 images of 1990, 2003 to 2006, and 2010 with scenes that cover the study areas were acquired from the Landsat archive of the USGS Earth Explorer FTP portal. These data covered the periods before and after the landfall of Hurricane Katrina.

Table 3: Attribute of the Landsat imagery used in the study

<table>
<thead>
<tr>
<th>Acquisition date</th>
<th>Sensor</th>
<th>Spatial Resolution (meters)</th>
<th>No. of Bands*</th>
<th>Sun elevation</th>
<th>Sun azimuth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-10-20</td>
<td>TM 5</td>
<td>30</td>
<td>6</td>
<td>43.27</td>
<td>146.86</td>
</tr>
<tr>
<td>2004-11-07</td>
<td>TM 5</td>
<td>30</td>
<td>6</td>
<td>38.69</td>
<td>152.85</td>
</tr>
<tr>
<td>2005-10-25</td>
<td>TM 5</td>
<td>30</td>
<td>6</td>
<td>42.78</td>
<td>151.26</td>
</tr>
<tr>
<td>2006-10-28</td>
<td>TM 5</td>
<td>30</td>
<td>6</td>
<td>42.57</td>
<td>153.76</td>
</tr>
<tr>
<td>2000-11-1</td>
<td>TM 5</td>
<td>30</td>
<td>6</td>
<td>37.6</td>
<td>144.68</td>
</tr>
<tr>
<td>2010-11-08</td>
<td>TM 5</td>
<td>30</td>
<td>6</td>
<td>39.00</td>
<td>154.26</td>
</tr>
</tbody>
</table>

*Thermal band was excluded in the analyses.

Digital change detection in satellite images is highly affected by the seasonal change in spectral reflectance value. The reflectance values can vary seasonally which can alter the observation. To circumvent the effects of seasonality including changes in illumination conditions and phenology on surface reflectance values an effort was made to acquire near-anniversary images. The images used were temporally consistent as they presented typical fall illumination conditions.

Landsat 5 TM has seven bands covering different regions of the electromagnetic spectrum (EMS): band 1 (0.45-0.52 µm), band 2 (0.52-0.60 µm) and band 3 (0.63-0.69 µm) covering the blue, green and red portions in the visible region of the EMS. Band 4 and Band 5
are in the near infrared and the mid-infrared region, covering wavelengths of 0.76-0.94 µm and 1.55-1.75 µm, respectively. Band 6 has the wavelength of 2.08 – 2.35 µm located in the thermal region of the EMS. Band 7 is in the mid-infrared region of the EMS (2.08-2.35 µm). All the TM bands have a spatial resolution of 30 meters except for Band 6, which has a spatial resolution of 120 m by 120 m. ERDAS IMAGINE 2015 (Hexagon Geospatial) and ArcMap 10.2 were used for almost all the analyses.

3.2. Pre-processing of data

3.2.1. Geometric correction

The geometric correction or geo-referencing was performed by acquiring some ground control points, which could be identified on both imageries like roads, buildings, etc. The geometric correction is a key issue to correct the distortions caused by the factors of earth’s topography, undulation, etc. The rectification of the distortions is vital to make an image planimetric (Nguyen, 2015). Unless images are geometrically corrected the obtained raw images do not represent the accurate location of features on the ground, and cannot be used for change studies. The raw images acquired for the study from the USGS portal had significant distortions. Hence, all acquired satellite images were geometrically corrected which allowed the overlaying of different images for identifying the temporal change for a specific area. Figure 9 below is the flow chart of the geometric correction process, which illustrates the step by step process used in geometric correction.
The image-to-image rectification was used for the geo-correction using already rectified image of the study area as a reference. The polynomial model for the Ground Control Points (GCP) selection was used for the image-to-image rectification. The GCPs are specific pixels in the image that have known output coordinates. These coordinates have X, and Y pairs. The selection of GCPs was done carefully and accurately so that the Root Mean Square error (RMSE) associated with it was below one. The RMS is calculated by the formula presented in equation 1.

$$\text{Root Mean Square Error for each GCP} = R_i = \sqrt{XR_i^2 + YR_i^2} \quad \ldots \ldots \ (1)$$

Where \( R_i = \text{RMS Error per GCP}_i \)

\( XR_i = \text{X residual for GCP}_i \)

\( YR_i = \text{Y residual for GCP}_i \)
Table 4 below shows the Root Mean Square Error obtained during geometric correction of the satellite images through GCP extraction process.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>0.86</td>
<td>0.92</td>
<td>0.78</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Mostly identifiable physical infrastructures (bridges, and the intersections of the roads, etc.) were selected as GCPs in such a way that points covered the entire area for accurate rectification of the digital imagery. The proper relationship between the actual geographic coordinates in both images was established by using the geometric correction model. The polynomial model which is optimized for the global accuracy was selected for the geometric correction of the images acquired.

### 3.2.2. Radiometric correction

The atmospheric correction was also performed to remove the effects of the clouds and aerosols in the spectral radiance stored in the form of a digital number in each pixel. The main objective of the process was to obtain the true surface reflectance value by removing the atmospheric disturbances. There are a few different in-built tools such as ATCOR 1, ATCOR 2 in ERDAS IMAGINE 2015 to perform the corrections. Among them, ATCOR 2 (Atmospheric Correction for Flat Terrain) model was used for radiometric enhancement of the images. The ATCOR 2 is a two-dimensional model typically used for the radiometric enhancement of the image obtained from the flat terrain. The signals obtained in the sensor consist of the three radiance components: radiation from the neighborhood, reflected radiance and path radiance.
which is represented in Figure 10. Equation 1 is the formula to measure signals obtained in the sensor in the ATCOR model, Equation 2 is the measurement of surface reflectance.

![Diagram of solar radiation components](image)

**Figure 10:** Schematic sketch of solar radiation components in flat terrain for Atmospheric and Topographic correction (ATCOR) 2 model

Here,

\[ L = L_\text{path} + L_\text{reflected} = L_\text{path} + \tau \rho E_g/\pi = C_0 + C_1 \text{DN} \]

**Equation 1: Transmittance value in each pixel**

Source: ATCOR 2/3 user guide, version 8.3

Where \( \tau \), \( \rho \), and \( E_g \) are the ground-to-sensor atmospheric transmittance, surface reflectance, and global flux on the ground, respectively. \( L \) is radiation component.

DN is a digital number.

\( C_0 \) and \( C_1 \) are respectively the offset and gain while calibrating radiometrically with the digital numbers.
Solving for the surface reflectance $\rho$ we obtain:

$$\rho = \frac{\pi (d^2 (C_0 + C_1 DN) - L_{path})}{\tau E_g}$$

Equation 2: Surface reflectance for each pixel

Here,

- $d^2 = \text{sun to earth distance}$
- $C_0$ and $C_1$ are respectively the offset and gain while calibrating radiometrically with the digital numbers. Where $\tau$, $\rho$, and $E_g$ are the ground-to-sensor atmospheric transmittance, surface reflectance, and global flux on the ground, respectively.

3.3. Unsupervised classification

The unsupervised classification method was used in this study for the classification of the images. The unsupervised classification technique is a process by which software determines the clusters of the pixels having similar reflectance properties. The reasoning behind this classification approach is that the pixels that have nearly similar reflectance values are likely to be representing the same land cover type. The number of the clusters to be used in classification was determined by the user. Among the two different clustering methods available in ERDAS IMAGINE; ISODATA and K, ISODATA (which stands for Iterative Self-Organizing Data Analysis Technique Algorithm) were used for this study. It allows the number of clusters to adjust automatically. The ISODATA algorithm merges the clusters having similar reflectance value and splits the ones having high standard deviation automatically during iteration. A total of 50 spectral classes were produced using ISODATA algorithm for clustering options. Maximum iteration was selected to be 20 with the convergence threshold of 0.95. Thus, obtained classes were manually identified as different land cover types. The targeted study classes based on the classification scheme were coded with numbers one by one. Each of the output spectral
classes in the output raster was assigned a code corresponding to the class it falls in. Such obtained classes were identified as different groups with the help of original images, topographic map, and aerial imagery and labeled as different groups. The clusters or groups that were generated automatically through the ISODATA clustering were manually assigned informational classes consistent with different land cover classification types. Considering that the study area is only comprised of two different features--wetlands and water--each of the land cover maps that was generated had only the two informational classes.

3.4. Land Use or Land Cover Change (LULC) detection mapping

For identifying the changes in land cover during the study period, including the Hurricane Katrina year, the post classification detection method was used. The post-classification map comparison is a standard change detection method in which land cover classes generated from the unsupervised classification method are compared, and change classes are identified for two different dates. The LULC maps with two different classes (wetland and water) were produced for all the obtained images using unsupervised classification techniques. This classification approach required little prior knowledge about the study area as the pixels are clustered based on the reflectance value by the automated built-in function. The maps independently produced from unsupervised classification were comparatively analyzed for two different dates. For the quantitative assessment of the change classes, change matrix was developed which identified the way at which values in two thematic maps overlap. The change class maps were produced to identify the gain and loss of wetland.

3.5. Normalized Difference Vegetation Index (NDVI)

Another approach used to map and assess the wetlands was Normalized Difference Vegetation Index (NDVI). The NDVI is an advanced and improved form of image rationing
method to identify the vegetated area. This index was developed by Rouse et al. in 1973, and it is widely used these days in the understanding for the vegetation coverage in the given area (Valor & Caselles, 1996; Elvidge & Chen, 1995; Pettorelli et al., 2005; Jiang et al., 2006). To understand all the parameters of the electromagnetic spectrum in digital imagery can be a complicated process, that is why it simplifies multispectral measurements to the one single parameter for the targeted study of vegetation loss. The NDVI represents the combination of two bands--near infrared and red. The NDVI is measured as the ratio of the difference in reflectance of near infrared region and red region to the sum of reflectance in both NIR and red region for each pixel. Vegetation has high reflectance in NIR region whereas low in red, so it is an effective method to differentiate among the vegetated and non-vegetated area. The formula for the NDVI calculation is given below in equation 3.

\[
\text{Normalized Difference Vegetation Index} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}} \tag{4}
\]

Equation 3: Calculation of Normalized Difference Vegetation Index

The value of NDVI ranges between -1 and +1 but it remains undefined when values approach zero. Only the positive values correspond with vegetated zones. The negative values that mean higher reflectance in the red region of the electromagnetic spectrum than in the infrared region are mostly water surface values. The NDVI maps for all different years were created using multispectral processing tool in ERDAS IMAGINE. Two land cover classes were identified based on the NDVI threshold for the change detection.
4 RESULTS

4.1. Radiometric enhancement

Radiometric enhancement helped in improving the output spectral quality of the images which is important for both spectral analysis and visual aid in classification approach. Figure 11 shows the raw satellite image of the study area before applying the atmospheric correction and after being corrected, using ATCOR 2 model.

![Figure 11: An example of satellite scene (Landsat TM 5) of the study area in false color RGB (Red, Green, Blue) before and after applying ATCOR 2 model](image)

4.2. Color Composites

For a visual aid in classification purposes, different band combinations were used to identify the land cover types (land/wetland and water) in the satellite images. However, interpreting the image requires knowledge of spectral signatures and the outcome color for the different features based on the band combination used in multispectral imagery. Figure 12 is an example of the True Color Composite of a subset image of the study area produced by
masking of the Landsat TM scene for manually identifying the land cover classes. Masking was done to delineate only the high salinity wetland of southeastern Louisiana.

Figure 12: An example of True Color Composite (TCC), LANDSAT TM5 image of study area displaying Band 1 (Blue), 2 (Green) and 3 (Red)

When the natural color combinations are used, the features in the imagery appear as seen by human eye from an aerial perspective. For example, this combination displays healthy vegetation as green, affected vegetation appears light green, and the ground surface looks brown. This color combination was used to differentiate land and water while assigning the different informational class.

In addition to the TCC, another band combination, False Color Infrared was also used for visual aid in differentiating the vegetated area and water. False Color Infrared combination uses
Near Infrared (band 4) and blue (band 3). Figure 13 below shows how satellite image looks in this color combination.

Figure 13: An example of false color composite, LANDSAT TM 5 image of study area displaying band 2 (Green), 3 (Red), 4 (Near Infrared)

Band 2, 3 and 4 is assigned to the blue, green, red color gun respectively in the standard false color composite. As vegetation has high reflectance in NIR region, in this combination, healthy vegetation appears dark-red, and the intensity of the red color depends upon the density (greenness) of the vegetation. Urban features appear light blue as they reflect more in the blue region and the soils and ground appears light to dark brown. It is very significant in identifying the vegetation cover. Visual inspection of the satellite images using false color IR showed some significant differences in the land cover. This information was concurrently used for assigning the informational classes during the unsupervised classification of the images.
If a significantly larger area has undergone drastic phrenological changes during the aftermath of Hurricanes, the color composite too can visually differentiate the areas. Otherwise, the color composite systems assigned to various bands are only useful for visual aid during classification process, however, doesn’t provide any quantitative information about the land cover change. The composite color methods discussed above were used to manually assign the land cover types for each cluster generated for classification purpose.

Figure 14 shows the distribution of the reflectance value for all the pixels in the NIR and red region of the images used.

![Figure 14: Spectral scatter plot of reflectance value (Digital Number) in the Red band on the x-axis and the NIR band on the y-axis.](image_url)

The X-axis is reflectance values in red band whereas the Y-axis is the reflectance value in NIR band. A built-in tool available in ERDAS IMAGINE 2015 that allows users to select
possible band combinations was used to plot and understand the clustering of the reflectance values. In this case, the NIR (Band 4) and Red (Band 3) were selected as the research is largely focused on the vegetation density. Primarily, these scatterplots help in understanding the Digital Number (DN) clustering. The number of hotspots generated represents the possible spatial object types in the ground. Hence, it is very useful in determining the number of the informational classes to generate while performing the unsupervised classification. Only two informational classes were suggested by feature space layer in almost all the images, which is wetland and water on the ground.

4.3. Land Use/Land Cover maps

Each spectral class was carefully examined to assign the land cover types. As the current research was mainly focused on land to water change, only two classes were assigned to the spectral clusters. The classified maps have two different land cover classes; Land/wetland, and water. Figures 15, Figure 16, Figure 17, Figure 18, Figure 19 and Figure 20 below show the land cover maps generated from the unsupervised classification techniques for the years studied. Wetland/land is mapped in green color whereas water is mapped in blue color.
Figure 15: Land cover map of 2003
Figure 16: Land cover map of 2004
Figure 17: Land cover map of 2005
Figure 18: Land cover map of 2006
Figure 19: Land cover map of 1990
Figure 20: Land cover Map of 2010
4.4. Change detection map

Figure 21 below shows the change maps produced for different years. These maps help us to spatially locate the hotspots of the changes. The change map for 2003-2004 shows that few pixels have gained land. This is a common phenomenon in coastal Louisiana. The sedimentation process results in some areas gaining the land. The most significant changes (loss) observed were in the north-eastern part of the study area, near Lake Borgne which is labelled in the figure below. The coastal boundary did not show any significant changes for almost all years, the hotspots are highlighted in circles.
Figure 21: LULC change maps of the study area derived from the Landsat TM 5 images of 2003, 2004, 2005, 1990 and 2010, Circles and ovals in the maps represents the hotspots for Land/Wetland conversion to Water.
Table 5 shows the annual change matrices for three sets of data—2003-2004, 2004-2005 and 2005-2006 and decadal change from 1990-2010. The change matrix classes were further categorized into Wetland/Land to Water, Water to Wetland and Net change (loss). Among the annual changes calculated, the highest wetland loss occurred from 2005-2006. The Wetland transformed into Water, due to the both anthropogenic as well as natural change, was found to be 23.9094 km² from 2003-2004. Similarly, 22.45 km² of wetland disappeared to water from 2004-2005 during Hurricane Katrina and 44.1352 km² transformed to water from 2005-2006. Out of the total loss from 2003 to 2006, 2003-2004 accounted for 26.45%, 2004-2005 accounted for 24.80 %, and 2005-2006 accounted for 48.76% changes in the study area.

Table 5: Area/ percentage changed in the study area

<table>
<thead>
<tr>
<th></th>
<th>2003-2004 km² / [%]</th>
<th>2004-2005 km² / [%]</th>
<th>2005-2006 km² / [%]</th>
<th>1990-2010 km² / [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetland/Land to Water</td>
<td>23.90 [2.35 %]</td>
<td>22.45 [2.1 %]</td>
<td>44.13 [4.2 %]</td>
<td>85.10 [8.2 %]</td>
</tr>
<tr>
<td>Water to Wetland/Land</td>
<td>13.08 [1.21 %]</td>
<td>7.02 [0.6 %]</td>
<td>8.06 [0.7 %]</td>
<td>6.64 [0.6 %]</td>
</tr>
<tr>
<td>Net change (loss)</td>
<td>10.82 [1.05 %]</td>
<td>15.42 [1.5 %]</td>
<td>36.06 [3.5 %]</td>
<td>78.46 [7.6 %]</td>
</tr>
</tbody>
</table>
For the period analyzed, 2003-2004 showed the area loss by 1%, 2003-2005 by 1.5% whereas 2005-2006 showed the significant loss by 3.5%. The two-decadal analysis showed that the study area had lost 7.6% of its total area which is very low compared to the annual rates which indicate that Hurricane Katrina accounted for the majority of losses. Figure 22 is a change area map and Figure 23 is a pie-chart showing annual land/wetland loss rates for the periods analyzed.

![Net change (loss)%](image)

**Figure 22: Area graph of the change matrices**
Regardless of the salinity type, the study area lost significant wetland area during Hurricane Katrina. The loss identified during Hurricane Katrina accounted for more than half of the loss in a 20-year period, which is, in fact, a very high rate for a high-salinity wetland. The high salinity wetlands, in general, are expected to yield lower loss rate than those of the entire coast, as the bulk of the disappearing wetlands of the coast is the low-salinity type wetlands. Contrary to the understanding and high degree of spatial correlational between salinity regimes and the damages seen coastal aerial images, the study area of high salinity wetlands demonstrated the significant loss rate, nearly equal to that of entire coast identified by Barras et al. (2010). As the high-salinity wetlands are deeply rooted, the bulk removal of the vegetation by the erosional process is not favored. So, theoretically, they would demonstrate lower wetland loss rates. However, the loss rate calculated here is significantly higher than the theoretically anticipated loss condition. The higher loss rate calculated here suggested the possibility that the
loss might have resulted mainly from the vegetation mortality So, the images were further analyzed using NDVI approach.

4.5. NDVI

If the vegetation is considerably affected by hurricanes, the damage and even the recovery in the years after can be identified in the satellite images using NDVI. The NDVI maps were produced to identify the disturbances in the vegetation. As NDVI is a measure of greenness, the values close to the +1 represents the higher density of the vegetation on the ground. The time series enhanced vegetation mapping was performed using the NDVI. Figure 24 below shows the NDVI maps for the years studied. As the study site includes only two land cover classes—Water and Vegetation, wetlands were easily differentiated from water using NDVI. In addition to that NDVI is very useful in identifying dense and affected vegetation. In Figure 25, dark-green color is consistent with mean denser vegetation, whereas light-color means less vegetation density. In addition to the immediate disturbances visible in the vegetation after the landfall, vegetation shows the considerable disturbances as well as recovery for the several years after.
The NDVI maps above revealed the gradually decreasing trend of the greenness from 2004-2006. Data from 2006 shows the least density of the vegetation, probably accounting for the vegetation mortality post-Hurricane Katrina, whereas 2004 is the greenest year.

**4.6. Statistics of NDVI**

The NDVI maps from 2004-2006 were layer-stacked together using ArcMap 10.1. For spatially outlining the hotspots having highest differences in the vegetation indices from 2004-2006, two maps of maximum and minimum NDVI values were produced. Figure 25 respectively present the highest and lowest NDVI values for each pixel from 2004-2006. These images were later used for generating the hotspots map based on the ranges in NDVI indices for each pixel. Figure 26 is the map of the study area showing the difference in the maximum and minimum NDVI values from 2003-2006 and spatially delineates the most affected vegetation.
Figure 25: Map showing the maximum and minimum value of NDVI for each pixel from 2004-2006.
Figure 26: Map showing the difference between the highest value of NDVI and lowest value of NDVI from 2003-2006. Real-time Google Earth images of the hotspot are also displayed. Hotspots are mostly the wetlands surrounded by smaller ponds. Hence the storm surge can easily alter the ground coverage.
The areas appearing brown on Figure 26 show the hotspots for vegetation change, whereas the areas with the shades of green and light green relatively have very less change in NDVI. The pixels that experienced changes are mostly water pixels of the study area. Minor differences in NDVI of water is always possible as the images obtained for different years may not have the same value of NDVI. However, it is very insignificant for the research objective here, hence ignored during analysis. The difference between the highest and the lowest NDVI values is useful for delineating hotspots of vegetation change. The pixels inside the circle in the change map (Figure 27) have the higher range of the maximum and minimum values of NDVI among the years studied, which represents the hotspots of vegetation loss. The most noticeable change in NDVI occurred in the wetlands of northwestern area of the study site which is highlighted by a circle in Figure 28. Figure 29 is the NDVI map generated from 1990 and 2010 image.
Figure 27: NDVI maps
Figure 28: NDVI maps for 1990 and 2010

The data revealed that 2003 and 2006, had the highest upper value of NDVI, whereas 2005 and 2006 had the lowest NDVI values. The year before and after Hurricane Katrina (2004-2005) showed the high vegetation density compared to 2004 and 2005. The high upper index values during 2003 and 2006 are possibly due to the higher greenness associated with pre-Hurricane Katrina and post recovery state in the ground. The low higher index during 2004 and 2005 may be due to the destructive aftermath of the hurricane which greatly impacted the density of the vegetation. However, the ranges of the values are very small in all cases. As the images of wetlands acquired represent the similar illumination condition of a season, it resulted in the smaller range of higher and lower index values. In 2005, during Hurricane Katrina landfall, it had a very narrow range of NDVI, and the areas with the high value of NDVI (greenness) are comparatively less. The highest value of NDVI in 2005 is 0.5. Among the years studied, 2003
and 2004 were the greener years, 2004 being the greenest which significantly decreased afterward.

4.7. Z-test

The destructive nature of the hurricane causes noticeable damage to the ecosystem. For testing the statistical relationship between the sample NDVI before and after Hurricane Katrina, Z-test for two sample means was performed. Of all the pixels, 256 raw NDVI values were randomly selected from the normalized difference indices of the images before and after Katrina. Excel 2015 was used for the analysis.

The null hypotheses that there is no any statistical relationship between NDVIs before and after Hurricane Katrina landfall was established. The alternative hypotheses on the opposite would assume a positive statistical relationship between two sets of data (raw NDVI values before and after Hurricane Katrina) and would suggest that statistical correlation between NDVI before and after landfall. The hypothesis was tested using one and two-tailed Z-test. The analysis of the Z-test performed using both one-tail and two-tail tests for 2004 and 2005, and 2005 and 2006 revealed that the null hypothesis is accepted in both cases. This means the NDVI pixels obtained before and after Hurricane Katrina do not show any statistical correlation, hence belong to a different population. Here, the statistics follow the normal distribution. Table 6 and 7 below show the statistics of the Z-test performed at 95% confidence level. The first set of data is the statistical analysis of the post-Hurricane Katrina year and the second set of data is for the Hurricane Katrina year.
Table 6: Statistics of Z-test for 2005 and 2006 NDVI samples

<table>
<thead>
<tr>
<th></th>
<th>Variable 1</th>
<th>Variable 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>2006</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
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<td>0.110104133</td>
</tr>
<tr>
<td>Known Variance</td>
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<td>256</td>
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<td>Hypothesized Mean Difference</td>
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<td>z Critical one-tail</td>
</tr>
<tr>
<td>z</td>
<td>-2.482793612</td>
<td>1.644853627</td>
</tr>
<tr>
<td>P(Z&lt;=z) one-tail</td>
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<td>0.013035659</td>
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<tr>
<td>z Critical two-tail</td>
<td>1.959963985</td>
<td>1.959963985</td>
</tr>
</tbody>
</table>

Table 7: Statistics of Z-test for 2004 and 2005 NDVI samples

<table>
<thead>
<tr>
<th></th>
<th>Variable 1</th>
<th>Variable 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>2004</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.037890519</td>
<td>0.048467528</td>
</tr>
<tr>
<td>Known Variance</td>
<td>0.09758</td>
<td>0.116813</td>
</tr>
<tr>
<td>Number of samples</td>
<td>256</td>
<td>256</td>
</tr>
<tr>
<td>Hypothesized Mean Difference</td>
<td>0</td>
<td>z Critical one-tail</td>
</tr>
<tr>
<td>z</td>
<td>-0.3654917</td>
<td>1.644853627</td>
</tr>
<tr>
<td>P(Z&lt;=z) one-tail</td>
<td>0.357372195</td>
<td>0.71474439</td>
</tr>
<tr>
<td>z Critical two-tail</td>
<td>1.959963985</td>
<td>1.959963985</td>
</tr>
</tbody>
</table>

The statistical goal of the Z-test was to know if the samples belonged to the same population. Z calculated value was found to be higher than the Z critical value, which suggested the acceptance of the null hypothesis. Z calculated was found to be very less than Z critical, as Z calculated in both cases are negative, whereas Z critical are positive and are also numerically significant and large.
Furthermore, to understand the variation and dispersion among the NDVI values for the sets of images used, Standard Deviation was calculated. Table 8 below shows the statistics of the pixels.

Table 8: Statistics of Normalized Difference Vegetation Index for the study area

<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.55</td>
<td>-0.5</td>
<td>-0.47</td>
<td>-0.45</td>
</tr>
<tr>
<td>Max</td>
<td>0.74</td>
<td>0.64</td>
<td>0.58</td>
<td>0.64</td>
</tr>
<tr>
<td>Mean</td>
<td>0.06</td>
<td>0.05</td>
<td>-0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.28</td>
<td>0.25</td>
<td>0.22</td>
<td>0.25</td>
</tr>
</tbody>
</table>

There is no such difference in the standard deviation among the NDVI pixels obtained for 2003, 2004, 2005 and 2006. Also, there is no difference in the dispersion of the indices from the mean values for the years studied.

Figure 28 is the graphical representation of the statistics obtained. The NDVI indices of 2004 show the lowest variability among the population and the data sets tend to be very close to the mean, whereas 2003, 2005, 2006 indices are quite spread out. Overall results suggested that the significant area was lost to the water.

![Figure 29: NDVI statistics for whole study area](image)
5 DISCUSSION

Either by the direct removal of the wetlands/land or by the flooding of wetlands, the high-energy hurricane like Katrina could alter the land cover rapidly than compared to the slow removal by the other anthropogenic as well as ecological damages (Barras et al., 2010). One of the deadliest hurricanes in the history, Hurricane Katrina accelerated the coastal wetland removal process by converting it into open water. In addition to the intensity of the hurricane, the ease by which wetland is removed during such events is also determined by the salinity condition of the wetlands. High salinity wetlands, thus known to be less prone to the area being lost during high-intensity Hurricanes, this study was performed on a sample high salinity wetland. This thesis helped us understand the resiliency of the high salinity wetland, concerning wetland loss rate, during Hurricane Katrina. The sample area was extracted in such a way that the area is masked to predominantly high salinity wetland only. Hence, it would fairly represent the high salinity environment and their loss tendencies. The sample area was pinpointed as the high-salinity wetland based on the USGS wetland inventory.

The net loss calculated in the study area, from 2004 to 2006 (a year before Hurricane Katrina and immediately after Hurricane Katrina) was more than half (65%) of the two decadal changes between 1990 and 2000, suggesting the bulk of the loss happened during Hurricane Katrina. The net loss immediately after Hurricane Katrina (2004-2005) was found to be 19% of the total change that happened in a 20-year period, whereas, the loss one year after Hurricane Katrina was 46%. These findings suggest the enhanced mortality of the vegetation post-landfall. The percentage area loss identified in this study area during Hurricane Katrina is comparable to the area loss identified for the entire coastal Louisiana by Barras et al. (2008) during Hurricane Katrina (2004-2006). Barras et al. (2008) observed that Hurricane Katrina accounted for 70% of
the decadal loss. Barras et al. (2008), however, analyzed 26 years’ period whereas this study only analyzes the changes in 20 years (1990-2010).

The high-salinity wetlands, in general, are expected to yield lower wetland to water loss rate as they are firmly gripped by the deep-rooted vegetation and cannot be eroded easily. Contrary to the resiliency principle of the high salinity wetlands, the study area showed significant loss during the aftermath of Hurricane Katrina. This observation may, however, be peculiar to only this study area, as it was one of the hardest hit and extremely damaged wetlands. So, the loss condition here may not resemble the other major hurricanes’ effect in other high salinity wetlands and their responses. Also, Hurricane Katrina made landfall as a category three hurricane with the tremendous destructive energy with wind speeds of 131 mph so relating the loss scenario of this wetland may not be appropriate. Therefore, this study identifies the necessity of assessing the loss condition in few other similar saline wetlands to appropriately investigate if this is the case with other wetlands too. The study area, on the other hand, stood as an outlier by showing significant damages despite the high salinity environment.

Also, this study area lies on the coast which makes it vulnerable to other causes of loss such as subsidence and sea level rise. However, these observations are based on annual changes, so there is almost insignificant likelihood that sea level rise may have influenced the results obtained in annual change matrices. Nonetheless, the wetland loss calculated for a 20-year period would someway include the effects from sea level rise. However, the hotspots of the loss were located further inland, close to the Lake Borgne area and not on the shorelines. If sea level rise would have been an issue, the submerged areas should have been on the coast. Thus, sea level rise doesn’t seem to have significant contribution to the results obtained.
Lack of sufficient research on the salinity regime’s response to high-intensity storms has limited the fair comparison of loss rates in different types of wetlands as well as this study area and other wetlands. The literature available is mostly related to the entire coastal wetlands, inclusive of all salinity types. The other challenge was assessing a historic event when field observation was not possible, therefore makes it even more difficult to exactly recognize if the loss was mainly due to the vegetation mortality or the complete removal (erosion) of the wetlands by the strong energy. Lack of ample reference aerial images of the study area limited the visual documentation of the ground condition post-disaster, which would also help to identify the loss mechanism. However, results obtained by NDVI analysis indicate post-hurricane vegetation mortality as the primary mechanism.

Even though there is a lack of substantial research on the high salinity wetlands alone, abundant research is available for entire coastal Louisiana. Barras et al. (2008) assessed the land lost for the entire coast from the years 1956 to 2006 (50 years) including the Hurricane Katrina period. Their findings revealed that 70% of the cumulative loss from the 1978-2006 occurred during Hurricane Katrina, including the year of landfall and post-landfall (2004-2006). Barras et al. (2008) studied the entire coastal area which is divided into three physiographic provinces; Deltaic, Marginal Deltaic and Chenier Plain. The research (Barras et al., 2008) estimated the land lost in 2 years (2004-2006) during Hurricane Katrina in Deltaic Plain, comprising this study area, was 6.22 %. The rate they have found for the entire Deltaic Plain is lower than the rate observed for this study area during 2004-2005 and 2005-2006. Similarly, the loss rate in the Marginal Deltaic Plain was 0.22 %, and Chenier Plain was 0.91 % of total loss in 50 years from 1956 to 2006. Between 2004-2006, they have estimated the loss rates of 108.5 km²/yr in Deltaic Plain,
3.9 km²/yr in Marginal Deltaic plain and 143.8 km²/yr in Chenier Plain. For the entire area of coastal Louisiana, the rate of loss calculated was 256 km²/yr.

The significant loss of the saline wetland occurred from 2003 to 2006. The net loss of the wetland/land area from 2003-2004, 2004-2005, 2005 to 2006 were 10.81 km², 15.37 km², 36.06 km² respectively, whereas the long-term decadal change in 20 years from 1990-2010 was found to be 78.47 km². The total area studied was 1028.28 km². The percentage area lost between 2003-2004, 2004-2005 and 2005-2006 are respectively 1.05 %, 1.49 % and 3.50 % of the total area, whereas land lost from 1990-2010 was found to be 7.63 % of the total study area.

Hurricane Katrina, in fact, accelerated the loss of the high salinity wetland studied here by more than 50%. The rate estimated here may or may not be similar to the overall high salinity environment or can be substantially different than low salinity, but the lack of previous research limited the fair comparison.

The hurricane-induced effect increased the water area by 15.42 km² from 2004-2005, and 36.06 km² from 2005-2006 possibly due to the flooding caused by the storm surge and erosional tendency associated with the strong storm. Such high-intensity storms can convert the smaller ponds into permanent ones and completely erode the shallowly rooted wetlands. However, the land loss depicted in the classified image from 2004-2005, which in fact would include the damage immediately after the landfall, is 5 km² more than the previous year (2003-2004), and almost 26 km² more than the year after (2005-2006).

The loss of saline wetland during Katrina (2005 to 2006) is almost 46% of the changes that occurred from 1990 to 2010. Unexpectedly, the loss identified between 2005-2006 (post-Katrina) was higher than the loss calculated between 2004-2005 (immediately after Katrina). This indicates the damage caused by hurricane Katrina was augmented in the later year. The
A possible explanation for the observation could be that a large proportion of the loss is mainly due to the vegetation mortality post salt water intrusion, which in fact is a slow process and was identified in the images taken after a month of the disaster.

Coastal areas mainly have two major land cover classes: wetland/land and water, so the post classification images were categorized into two major classes. While doing so, the pixels of the wetlands that resulted in the loss of wetland ended up being water in post classification images. However, in reality, few pixels might have transformed into other land cover classes of similar reflectance properties which however is mostly in insignificant number in the coastal region. This could have potentially insignificantly influenced the result by adding more pixels into the water class which increases the water area in the post classification image. This is one of the demerit and challenge of using coarser resolution images in sharp boundaries.

In another hand, a huge increase of water area post-landfall may be just a short-term change produced by the storm surge. A short-term change is very likely to reflect the transitory environmental conditions rather than the permanent changes. For example, the storm surge can create smaller ponds. Hence, a short-term result of the area being converted to open water may fluctuate in the later years too. Based on the results obtained, the need for continuous assessment was realized, therefore, recommended for future considerations for the study of a similar kind. Recovery assessment should be done for several years; only one-year observation may not be enough to answer if the change post-landfall was permanent or transitory. The image for 2005 shows the ground condition immediately after the landfall before any transitory fluctuation could settle. Therefore, some of the changes found in 2005 image are also transitory. Correspondingly, the water area being converted into the wetland, which in most cases, is the recovery from the surge produced by Hurricane Katrina also shows the temporal fluctuation. Therefore, this study
further suggests the need of multi-temporal change analysis ranging from a narrow period of few months to multiple years, if the influence of the temporary changes is to be excluded from analysis and results. To minimize the influence of temporary fluctuations, monthly and seasonal tracking of the change is recommended.

The need for assessing vegetation condition was recognized. Hence, NDVI analysis was also conducted to further evaluate the status of the vegetation. All the analysis was again performed by using Landsat 5 sensor which is of 30m*30m resolution.

The disturbances mapped in the NDVI maps showed the significant disturbances in 2005, which is immediately after Hurricane Katrina. The year 2005’s NDVI had the lowest upper value than 2003, 2004 and 2006. The range of the high and low NDVI values was smaller in case of 2005 than the NDVI indices calculated for other years. The hotspot map generated based on the ranges of the NDVI values from its highest to lowest showed the northern and south western part of the study area is more vulnerable to the vegetation disturbances. These hotspots are highlighted by the circles in the hotspot map. However, outlining any rigid conclusion based on the limited NDVI analysis would not be appropriate.

This study identified the future need for a detailed study, as few questions such as why there seems to be a sudden drop in the NDVI in the Landsat image, obtained immediately after Katrina, could not be answered satisfactorily. Although it can be foreseen that increase in salinity from salt water intrusion reduces the productivity in the wetlands in 2005-2006. Killing of plants by salt intrusion is a slower process than the direct removal of the wetland. That is why post-landfall NDVI map has high vegetation disturbances than immediately after landfall. This study further demonstrates the need for continuous seasonal assessment of the wetland for few years to properly address the transitory ecological damages caused by Hurricane Katrina. This study also
points out the need for the continuous assessment of the study area to figure out if the damages have been returned. The statistical analysis of the NDVI values did not explore any significant information about the vegetation disturbance pattern. The maximum and mean NDVI values of the images were noticeably different from each other than the mean and standard deviation. This implies that the indexes were closely grouped near mean value, hence, shows no significant deviation from the mean. That is why standard deviation calculated is insignificant in all the images analyzed. There was no such huge difference between the NDVI values among the images analyzed. The NDVI maps, however, showed different coverage for each year. However, the study necessitates a detailed long-term analysis to examine the recovery status.

A similar study performed by Palaseanu- Lovejoy et al. (2013) using finer resolution satellite images (IKONOS, QuickBird, Geoeye-1) during two major Hurricanes (Rita, Katrina, and Gustav) had also suggested Hackberry, a Hurricane Rita impacted area, had lost 5.8% and the loss was even augmented by 7.9% during Hurricane Ike. In another study area, Delacroix, they estimated that the area had lost 4.9% of the land during Hurricane Katrina and 0.6% during Hurricane Gustav which is in fact very minimal. However, these rates are higher than the rates calculated in this study. The area examined here lost 5% of its total area between 2004 and 2006. However, the fact that lack of finer resolution images could potentially influence the result obtained from change detection analysis cannot be neglected.

The USGS has estimated the annual rate of loss in the entire coastal Louisiana to be 69.7 km$^2$ from 1958 to 2006. In this case, the high salinity wetland loss rate from 1990 to 2010 was found to be 3.92 km$^2$/yr in the study area. The decadal wetland loss rate yielded, in this case, was less than annual change rate calculated for the years studied. The peripheral wetlands around Lake Borgne area experienced higher loss than the shorelines of the study area. This is likely due to
the smaller ponds created near Lake Borgne, which recovered in the later years. The change detection result showed; 2003-2004 experienced the least amount of loss among the years studied and 2005-2006 (post-hurricane) experienced the highest loss of three sets of years analyzed.

Nevertheless, wetland loss rate is a matter of complex environmental process and requires an inclusive study of every ecological aspect. Proper restoration efforts are required to maintain the ecological integrity of the coastal wetlands and protect it from the possible threats and to compensate the historic loss.
6 CONCLUSIONS

Coastal wetlands are not only important ecologically but also serve as an active barrier that buffers cities from devastating hurricanes. Unfortunately, the accelerated rate of wetland loss during hurricane years identified by various researchers suggests the probable worsening of the loss condition in future events of high-intensity hurricane landfall, mostly because Louisiana has a history of being recurrently hit by destructive hurricanes. So, the reoccurring high intensity hurricanes could bring enormous damages to the coastal wetlands of both ecological and social importance.

However, among diverse ecology existing in the coast, high salinity wetlands can relatively tolerate the storms than others as they are deeply rooted and may not be removed easily and protect coastal cities from severe destruction during future hurricane occurrences. Thus, the high salinity wetland’s resistance during the destructive aftermath of Hurricane Katrina was examined using a concise change analysis method in this thesis. As a representative sample study, this thesis will help us understand the high salinity wetlands’ response to the high-intensity hurricanes. In this study area, Hurricane Katrina made landfall as a powerful category three hurricane with a wind speed of 131 mph. The study area was also selected since it lies in the path of the eyewall of the Hurricane Katrina, where the effects of the storm should be greatest. However, findings here do not support the general illustration done by various other researchers (Howes et al., 2010 and Barras et al., 2008) that high salinity wetland are a reasonably resilient environment during hurricanes, even when hit by the higher wind speeds. Despite the higher degree of spatial correlation identified in previous researches where high salinity wetlands were less affected during high-intensity hurricanes. Hurricane Katrina seems to have initiated a significant loss of wetland in this study area, regardless of the resilient ecology
and salinity type. So, the entire outcome obtained in this study can be a matter of complete chance or the damages at this particular study area is extremely high than other high salinity wetlands due to its’ critical eyewall location. On the other hand, lack of the bountiful research on specific salinity regime, either high or low somewhat limited the fair comparison and analysis.

The high salinity wetland studied here was found equally prone to the land being lost, analogous to the entire coastal region. The percentage land loss in the study area during the study period-from 2003 to 2006 was not significantly lower than the area lost on the entire coast. The entire coast and the sample area both seem to have lost the bulk of its area during Hurricane Katrina. Seeing the results obtained from the study, the area possesses the threat of losing its ground rapidly during future events of a strong storm, when the regular rate of loss is augmented by the hurricane-induced failure, especially the Louisiana coast that has the history of being recurrently hit by destructive storms.

The study area lost almost 7% in the past two decades of 1990 and 2010, if this rate is to be considered, the whole study area will be lost in less than next 300 years. The wetland removal ratio was not much lower than the comprehensive rate identified by Barras et al. (2010) for the entire coast of Louisiana. The appropriate reason behind such a higher rate of loss despite the wetland being high salinity came as an outlier. Nonetheless, the findings are supported by the fact that the study area lies at the eyewall of Hurricane Katrina and was therefore highly devastated in comparison to the wetlands in southwestern Louisiana. Also, being one of the worst hit wetlands, the destruction may have occurred through both extensive vegetation mortality and complete removal process through erosion by the 131-mph wind gust. This study further suggests the need for similar studies to be done in different salinity regimes to properly
understand the process response model of the diversified ecology existing in the coastal Louisiana.

Wetland loss by hurricanes or even gradual change is a complex phenomenon that cannot be depicted by analyzing satellite images of only a few years. The land cover change is a continuous gain and loss process at both temporal and spatial levels. These changes, occurring inherently or during hurricanes, can be both permanent and transitory and can be unique to the type of land cover regime. In this study, only one image post-landfall was analyzed that may not include the slow recovery status from the impact. Hence, this research suggests the need for change mapping analysis for multiple years to accurately assess the post-hurricane recovery process. The storm surge greatly impacts the land area mapping procedure, which importantly affects the change analysis. So, the water level fluctuation is another key component to be assessed in future research to properly address the land, which slowly regains its original condition after the flooding. Various storm surge model can be included in future studies to comprehensively integrate salt water intrusion with increased submergence.

The Landsat Thematic Mapper 5 images were proven to be reasonably useful for identifying the land cover change in the small area of just 1,000 km². However, in some cases, it was very challenging to assign the informational class, but the best possible efforts were made to make it precise. To achieve accurate results, finer resolution imagery is recommended, especially when the study area is narrowed to a smaller region. The use of coarser resolution image for the analysis might have unintentionally resulted in some pixels being classified incorrectly during classification as numerous single pixels can include both land and water when it lies on the coast. Unsupervised classification also has the disadvantage of its own kind; the algorithm used for the random clustering may separate the pixels with slightly different spectral reflectance into
different clusters, which belongs to the same group of objects in the field or vice versa. But, it cannot be completely corrected, so assigning informational class becomes very challenging in some cases. Various reference images were used to cross-check the informational classes to maintain the accuracy, which could have affected the results in unimportant scale, although the effect cannot be crucially influential enough to alter the results. Ground referencing was not possible in case of the historical event, so it was very hard to say if the bulk of the loss was due to complete removal (erosion) of the vegetation or due to the mortality of the vegetation post salt water intrusion to better justify the findings. The lack of the historical aerial images/field images in the study area during Hurricane Katrina and the lack of studies of similar kind and inadequate literature based on the high salinity marsh limited the detailed study. Still, the best possible effort was made to get some pictures of the wetland devastation during Hurricane Katrina. The lack of consistent near anniversary satellite image was another challenge for the NDVI analysis. The best achievable effort was made to make it to less than a month’s difference to represent the similar illumination condition, and furthermore, the radiometric correction was performed during processing of the raw images for fair comparison and minimizing illumination error.

Despite all the challenges and limitation, this study contributes to improving the knowledge of coastal wetland loss condition, more particularly during hurricanes. Additionally, this study can also serve as a reference for the future studies of a similar kind. The need of more focused and robust spatiotemporal analysis was realized. Additional coast wide studies and empirical data regarding the salinity regimes’ response to such high-intensity hurricanes is needed to properly address the management need of such vulnerable wetland system. While the finding from the research helps to understand the process response model of the coastal wetlands, improving the management of such wetlands always remains very crucial.
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