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Assessing the Effectiveness of Louisiana's Freshwater Diversion Projects Using Remote Sensing

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Assessing the Effectiveness of Louisiana’s Freshwater Diversion Projects Using Remote Sensing

A Thesis

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in partial fulfillment of the
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in
Geography

by

Michael G. Metzger

B. S. Kent State University, 1978

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Abstract

Southern Louisiana is experiencing a dramatic loss of freshwater wetlands as a result of natural and man-made changes in the landscape. Multitempral remotely sensed data were used to examine the impact of the Caernarvon Freshwater Diversion Structure, built in 1991 to divert water to Breton Sound. Satellite imagery data covering the period from 1974 to 2006 were analyzed by computing several spectral indices including NDVI, VI, IR/R, Sqrt IR/R, T-NDVI, and NDWI, as well as principle component analysis. The resulting enhanced images were classified into two classes, vegetation or open water. The ratios of vegetation to open water were then calculated and the changes graphed over the 1974-2006 timeframe. The results indicated that despite the infusion of freshwater, the open water portion of the Breton Sound area continued to expand, indeed the expansion rate increased from approximately 0.25% per year before construction of Caernarvon to 0.45% per year after construction.

Keywords: Freshwater diversion, wetland, remote sensing, multitempral, spectral indices, Caernarvon

1 Introduction

Wetlands help regulate river flow, filter pollutants from freshwater, provide spawning areas for many commercially valuable species of fish, as well as necessary habitats for plants, insects, amphibians and birds. The Mississippi River wetlands in Louisiana are some of the largest and most resource rich wetlands in North America (Figure 1). In spite of the beneficial resources these coastal wetlands provide, they are disappearing at an alarming rate of 25 to 35 square miles per year. This rate of loss is an equivalent of the entire area of the state of Rhode Island disappearing every 35 years. The rate of wetland loss in Louisiana is greater than that of any other wetland habitat in the United States (Turner, 1997). Although several researchers have studied coastal wetlands and have documented the losses (Reyes et al. 2002; Morton et al. 2002; Minello and Rozas, 2002), there is a lack of focus on assessing the effectiveness of strategies to reduce or stop wetland loss.

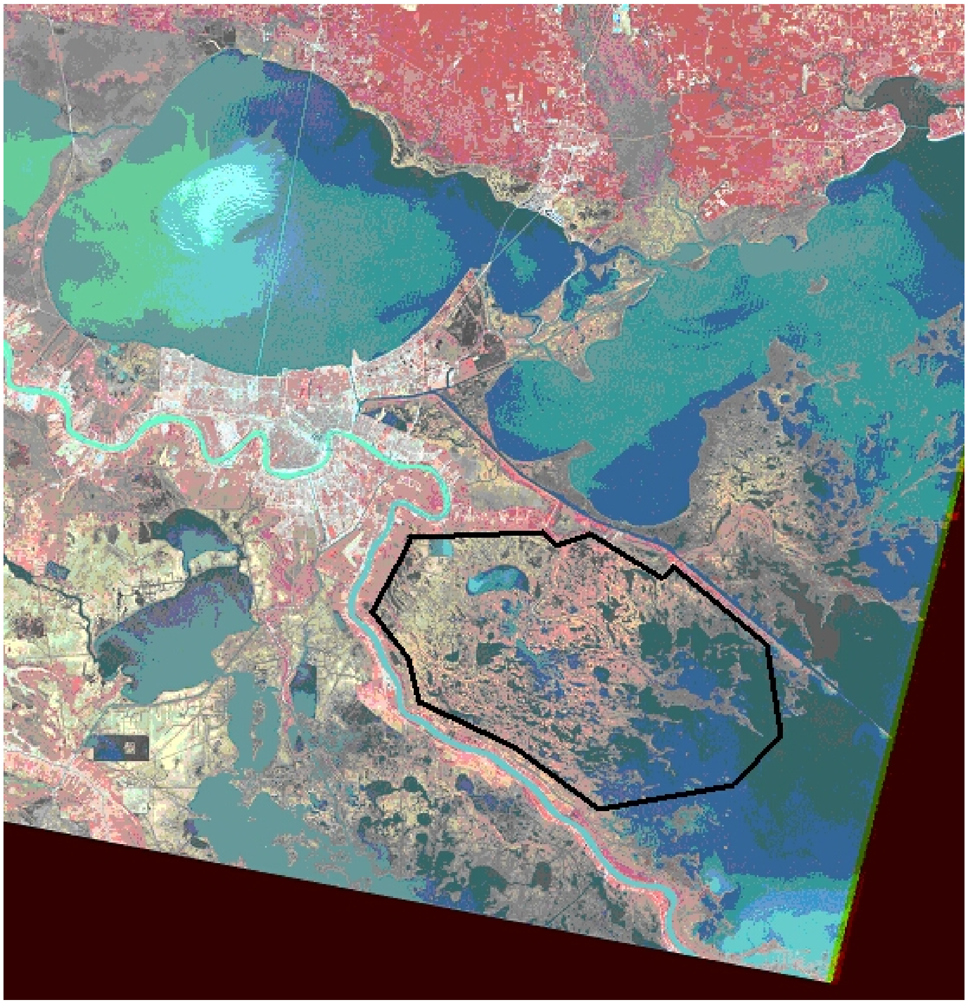

Figure 1. False-color Landsat Thematic Mapper (TM) imagery showing the study area (USGS 2002).

In 1990, the state of Louisiana in cooperation with the Federal Government initiated a program to address the issue of coastal wetlands loss in Louisiana. The Louisiana Coastal Wetlands Restoration Plan (LCWRP) also known as the “Breaux Act” in recognition of retired Senator John Breaux, the driving force behind the legislation, was passed in 1990 (LCWCRTF, 1998). The Breaux Act has a wide-ranging scope and the primary objective is to bring together several agencies both at state and federal levels, to focus their combined resources to produce effective and positive change in the deteriorating wetland situation. The LCWRP envisions a multidimensional approach to wetland restoration, including the development of a number of freshwater diversion structures to redirect freshwater from the Mississippi River in order to “recharge” the wetlands. The diversion structures are designed to mimic the periodic natural flooding of the Mississippi River prior to the construction of the present levee system. Not only is this an ambitious plan, the cost of the diversion structures is over $250 million. Considering the enormous costs associated with the construction and implementation of such diversion structures – the question needs to be asked – how effective are such strategies in restoring wetlands?

One simple method to measure the effectiveness of the diversion structures is to compare pre-and post-diversion landscape changes. Multitemporal satellite imagery can be used to quantify how much, if any, wetland restoration has been accomplished by the diversion structures.

1.1 History of the Mississippi Delta

The Mississippi delta has been building for thousands of years. Major uplift in the Rocky Mountains west of the Mississippi River Valley, in addition to the older but still substantial Adirondack Mountains to the east, has resulted in a river valley bisecting the North American continent. This natural valley feeds huge volumes of water (612,000 cfs) and sediment into the Mississippi River, resulting in the building of a substantial delta region in the Gulf of Mexico (Robinson, 1995)

The main lobes of the Mississippi Delta that are central to this study are those that comprise the present wetland region of Louisiana (Figure 2).

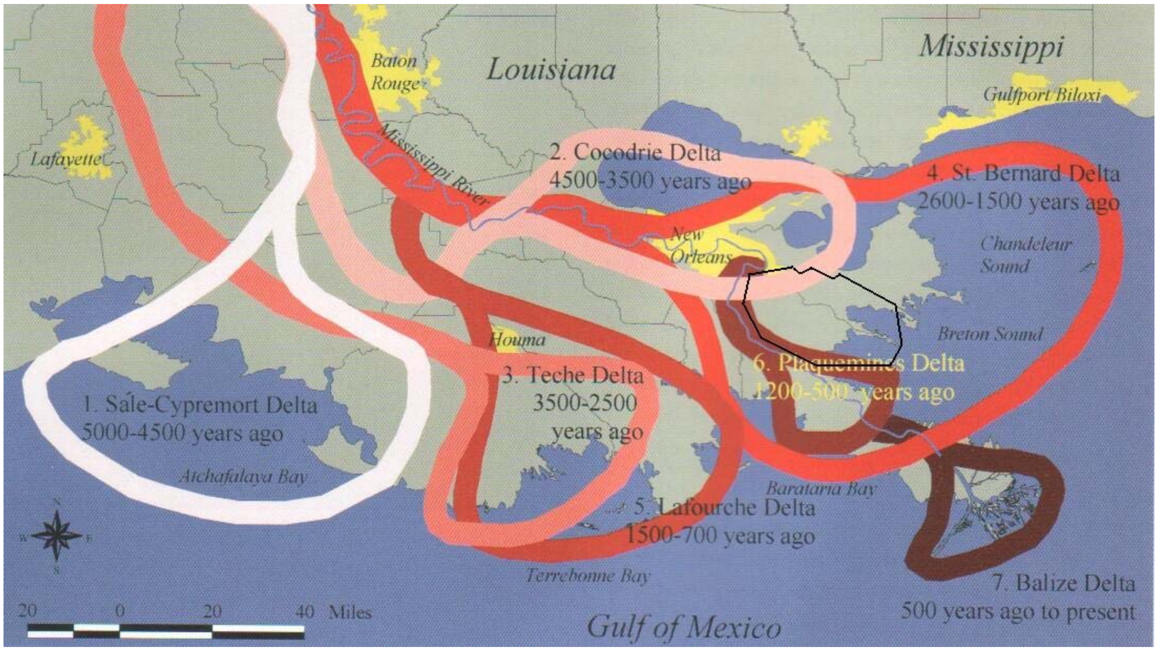

Figure 2. Main lobes of the Mississippi River Delta (Campanella 2006).

The development of each delta accompanied the deposition of enough sediment at its mouth to raise the elevation there to an unsustainable level. As the result of increased elevation, the river channel changed its course and consequently the delta-building process began again. The current delta morphology is the result of both active delta and varied features of several pre-existing Mississippi River deltas.

The Atchafalaya delta, which is a relatively recent landform, is noteworthy because it is believed to be the beginning of what may be the natural course of the Mississippi River in the centuries ahead (Meade 1995). Already the Mississippi River has deposited huge amounts of sediment in its present delta (the Balize) and it appears poised to switch channels to the Atchafalaya River Basin. Because of this, the Army Corps of Engineers built the Old River Control Structure at a point where the Mississippi River approaches the Atchafalaya River. This structure maintains 70 percent of the Mississippi water flow in its present channel, and allows only 30 percent to flow into the Atchafalaya River. (Robinson et al. 1995)

1.2 Coastal Wetland Loss

The Army Corps of Engineers defines wetlands as "…areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas." (US Army Corps of Engineers 1995) Environmental Protection Agency (1994) defines wetlands as "An area that is regularly saturated by surface water or groundwater and is characterized by a prevalence of vegetation that is adapted for life in saturated soil conditions (e.g., swamps, bogs, fens, marshes, and estuaries). The US Geological Survey defines wetlands as "…land areas which are seasonally or permanently waterlogged, including lakes, rivers, estuaries, and freshwater marshes…(or) low-lying land submerged or inundated periodically by fresh or saline water." (USGS, 1998) This definition does not mention vegetation. For the purposes of this research, wetlands will be defined as "Any area that is regularly or permanently saturated with either fresh or salt water, in which the prevailing vegetation is adapted to these conditions."

Wetlands are by nature transitory, in a sense that their sustenance depends on a constant supply of water and any interruption in that supply could cause them to shrink or even disappear. The one reason for most coastal wetland loss is saltwater intrusion. And the factors contributing to the intrusion of salt water into the coastal wetlands of Louisiana are: 1) Degradation of Barrier islands; 2) Storm surges; 3) Problems associated with oil and gas development; 4) Sea level rise; 5) Subsidence; and 6) Levee building. The role of each of these factors is described below:

1.2.1 Barrier island degradation

The degradation of Barrier islands exposes coastal wetlands to the direct impact of ocean waves and currents. The Barrier islands consist of sand beaches and vegetated sand dunes, and mudflats. The islands provide protective mechanism for coastal wetlands by not only retarding the speed of storm-generated waves but also serving as natural barrier to the devastating effects of storm waves. (USGS 2007)

At the present time, the Chandeleur Islands, on the furthermost extent of the St. Bernard delta, are experiencing serious degradation. These islands have been eroding for many years and are almost completely extinct. The total destruction of these islands is likely to have serious implications for coastal wetlands in Louisiana (Figure 3).

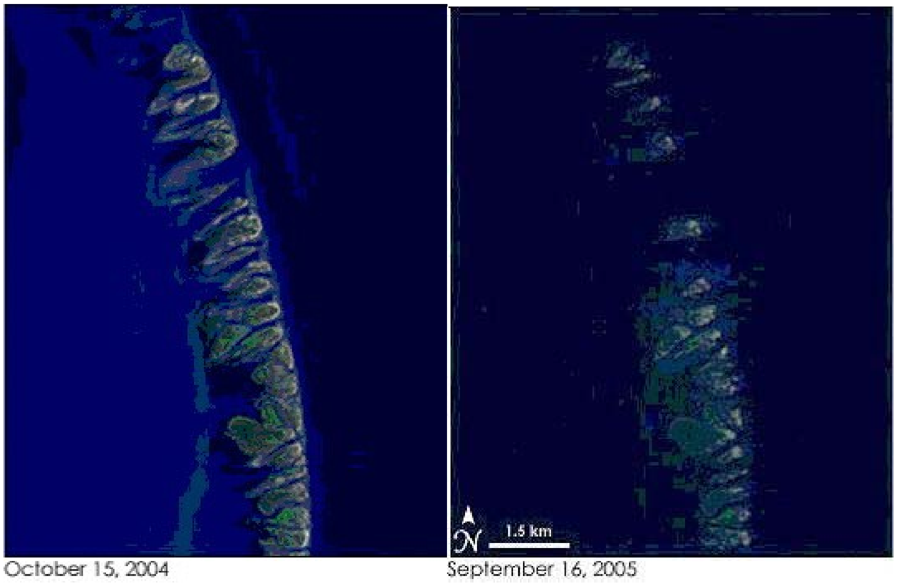

Figure 3. Barrier island degradation, left side pre-Katrina, right side post-Katrina (USGS 2007).

1.2.2 Storms

Significant loss of coastal wetlands results from wind and waves associated with major storms. Additionally, tidal surges that often accompany large storms and hurricanes cause significant salt-water intrusion into the wetlands. For instance, storm surges associated with Hurricane Katrina in 2005 brought the intrusion of huge volume of salt water into the coastal freshwater environment. This stressed the salt-sensitive vegetation, and the physical pressure from high winds downed trees and other plants that helped anchor wetland soils. While relatively rare, the widespread damage they cause make storms a powerful force for wetland destruction.

1.2.3 Problems associated with oil and gas development

Streams and channels are a natural part of coastal wetlands. Increased development activities associated with oil and gas development projects in coastal Louisiana have required the digging of numerous canals and channels in wetland areas. These canals and transportation channels are generally dug straight and deep, which facilitates more rapid intrusion of highly saline gulf water deep into the marsh. In addition, the spoil piled at the banks tends to discourage plant growth, resulting in gradual widening of the canals and exacerbation of the saline intrusion (USGS 2007). Other degradation issues associated with oil and gas development include destruction of wetland vegetation due to the transportation of drilling rigs, seismic survey vessels, production platforms, drill cuttings, and other petroleum extraction equipment and facilities. All these activities exert stress on fragile wetland environment and thus intensify the wetland loss.

1.2.4 Sea level rise

Sea level rise is a more recent concern and is potentially one of the more serious problems for wetland conservation. As global warming progresses, it is causing land-based freshwater ice to melt, which is subsequently raising ocean sea levels. In addition, the thermal expansion of water in the oceans contributes significantly to sea level rise. As the sea level rises, salt-water intrusion becomes more severe, barrier islands lose much of their protective abilities, and storm surges cause more damage. (Titus 1988)

1.2.5 Subsidence

Subsidence is the result of compaction of the underlying delta sediments beneath accumulating sediment deposited by the river. In a natural environment, this subsidence is balanced by continual addition of new sediment. However, when levees are built, replenishment stops while compaction and subsidence continue, resulting in flooding and eventual permanent loss of wetland vegetation. (USGS 2007)

Subsidence further accentuates the problems associated with rising sea levels. Salt-water intrusion, and increased storm surge damage are all amplified. (Environmental Protection Agency, 1987)

1.2.6 Levee building

Levee building is generally considered to be the single most significant threat to the Mississippi Delta region in Louisiana. (Turner, 1997) Levees were built to prevent flooding of important urban and other developed areas within the river flood plain. The levees have generally worked well for flood abatement; however, along with the freshwater flow they have also deprived wetlands of sediment. Instead, the river carried and deposited sediment well beyond the delta shelf.

1.3 Modern Remedies

In the face of the known problems stemming from the loss of delta wetlands, the Army Corps of Engineers (ACE) and the State of Louisiana have developed an approach to address wetland loss and to come up with a solution. Coast 2050 is a "strategic plan to sustain coastal resources and provide an integrated multiple use approach to ecosystem management." (Committee on the Future of Coastal Louisiana Report, 2002) The main goal of the plan is to restore wetlands and shorelines and to build sustainable, healthy wetlands in the Mississippi delta region.

1.3.1 Coast 2050 Program

The plan divides the Louisiana coastal wetlands into four regions and outlines a strategy for protecting each region. The proposals contain a wide range of engineering projects, ranging from construction of large and small freshwater diversion structures, drainage and natural stream restoration, barrier island and shoreline protection, wave break and reef zone construction, lock construction and shipping channel relocation. The following is a short description of the proposed remedies for each region.

Coast 2050 Regions	**Location**	**Planned construction projects**
Region One	Area surrounding Lake Pontchartrain	• Small diversion structures at Blind River and the Reserve Relief Canal • Natural drainage patterns restored • Small diversion structures through the Bonnet Carré Spillway, La Branche Wetlands and one near Violet • Shoreline protection projects for the Chandeleur Islands, along Lake Pontchartrain, Lake Borgne, the East New Orleans Land Bridge and the Biloxi Marshes • Special problems like the closure or modification of the Mississippi River Gulf Outlet (MRGO) slated for study
Region two	Breton Sound, Barataria Bay and Mississippi River area	• Numerous small freshwater diversions • Restore natural drainage patterns • Small diversions to convey sediment constructed at Myrtle Grove, Naomi, Bastion Bay, Benny’s Bay, American Bay and Quarantine Bay • Mississippi River navigation channel would be moved • Large conveyance channel parallel to Bayou Lafourche constructed • Wave breaks and reef zones constructed across all major bays • Fourchon headland and barrier shoreline from Sandy Point to Southwest Pass reconstructed

Table 1. Coast 2050 engineering projects.

Region three	Terrebonne, Atchafalaya and Teche/Vermilion marshes	• Improve the hydrology in the Verret subbasin • Maximize land building in Atchafalaya Bay • Increase influence of the Achafalaya River in the Terrebonne marshes • Construct conveyance channel parallel to Bayou Lafourche • Restore Isle Dernieres and the Timbalier Islands • Restore artificial reef near Point Chevreuil
Region four	Westernmost Calcasieu, Sabine and Merentau areas	• Improve drainage across Highway 82 • Constrict the Mermentau River • Maintain Atchafalaya River water and sediment input • Maintain flow from the Sabine River • Add lock at Calcasieu Ship Channel • Restore long-shore sediment flow across Calcasieu Pass and Mermentau Ship Channel • Prevent the coalescence of Grand and White Lakes

Table 1. Coast 2050 engineering projects (continued).

While all these improvements are costly, it is freshwater diversion that is the most expensive and potentially the most productive part of the plan. For that reason this research will concentrate on freshwater diversion as a method of wetland restoration.

1.3.2 Freshwater Diversion

The freshwater diversion to wetlands requires a breach in the levee system that allows river water into the surrounding wetlands. The main purpose of the diversion is to restore the balance of salinity in wetland areas that are experiencing problems associated with saltwater intrusion and to provide sediment flow to areas that are sinking due to subsidence and sea level rise (Committee on the Future of Coastal Louisiana 2002). The freshwater flow into these areas is expected to reinvigorate and enhance the marsh vegetation that is going through salinity-induced stress. The freshwater diversion is also expected to increase the commercial and recreational fishing and wildlife productivity in the area. The freshwater diversion essentially replaces the fresh water that used to flow into the wetlands before the construction of the levees. In addition, it has the added advantage that it can be regulated to allow the ACE to direct the freshwater into desired areas and in desired amounts. This allows the levees to function in their original role as flood control mechanisms as well as providing a means of wetland restoration and maintenance.

Figure 4. Freshwater Diversion Plans for the Mississippi Delta and Estuarine Areas (USACE 2003).

There are three main diversion projects in the Mississippi Delta and Estuarine areas. One is in the planning stages – the Bonnet Carré, and two have been completed – the Davis

Pond and Caernarvon diversion structures (Figure 4, Figure 6 and Figure 7). The following is a brief description of each project.

1.3.3 Bonnet Carré

The Bonnet Carré Spillway was originally designed as a flood control structure to protect the city of New Orleans. Large sluice gates built into the levee and a spillway leading into Lake Pontchartrain allow for quick diversion of flood water into the lake to lower the water level in the Mississippi river above New Orleans. The spillway was built partly in response to the Great Flood of 1937, in which parts of the levee were dynamited above New Orleans when it was concluded there was a great likelihood the city might be flooded. With the addition of new, controllable sluice gates and outflow channels, the diversion structure (Figure 5) will be able to divert freshwater to the wetlands around Lake Pontchartrain and the western Mississippi Sound. With a projected diversion capacity of 25,000 cubic feet per second (cfs), the spillway could restore 10,500 acres of wetland around Lake Pontchartrain. An estimated cost of this project is $100 million.

Figure 5. Bonnet Carré Diversion Structure Map (USACE 2003).

1.3.4 Davis Pond

The Davis Pond Freshwater Diversion Structure (Figure 6), located on the West Bank of the Mississippi, was completed in 2002. It is the larger of the two completed diversion structures and has a discharge capacity of 10,650 cfs. It diverts freshwater into the Barataria Bay Estuary, an area south of the main course of the Mississippi River. At a cost of $120 million, it is the most expensive structure to date. The cost for the Davis Pond structure is over four times that of the Caernarvon. The Davis Pond structure is expected to restore 33,000 acres of wetland and benefit 777,000 acres of wetland in Barataria Basin.

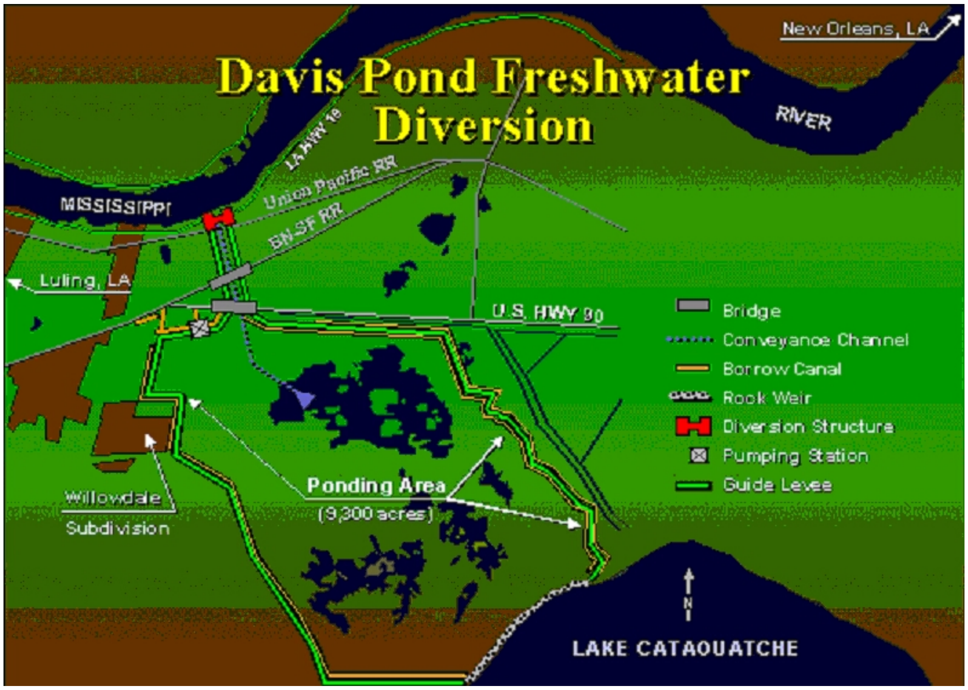

Figure 6. Davis Pond Diversion Structure Map (USACE 2003).

1.3.5 Caernarvon

The Caernarvon Freshwater Diversion Structure (Figure 7) has been in operation for over 16 years. It is located on the East Bank of the Mississippi River and it empties the diverted freshwater into the Breton Sound Basin, a large wetland area on the eastern side of the delta, southeast of the city of New Orleans. The project was completed in 1991 at a cost of $26 million and has a diversion capacity of 8,000 cfs. At the time of its implementation, it was expected to restore approximately 16,000 acres of coastal wetlands.

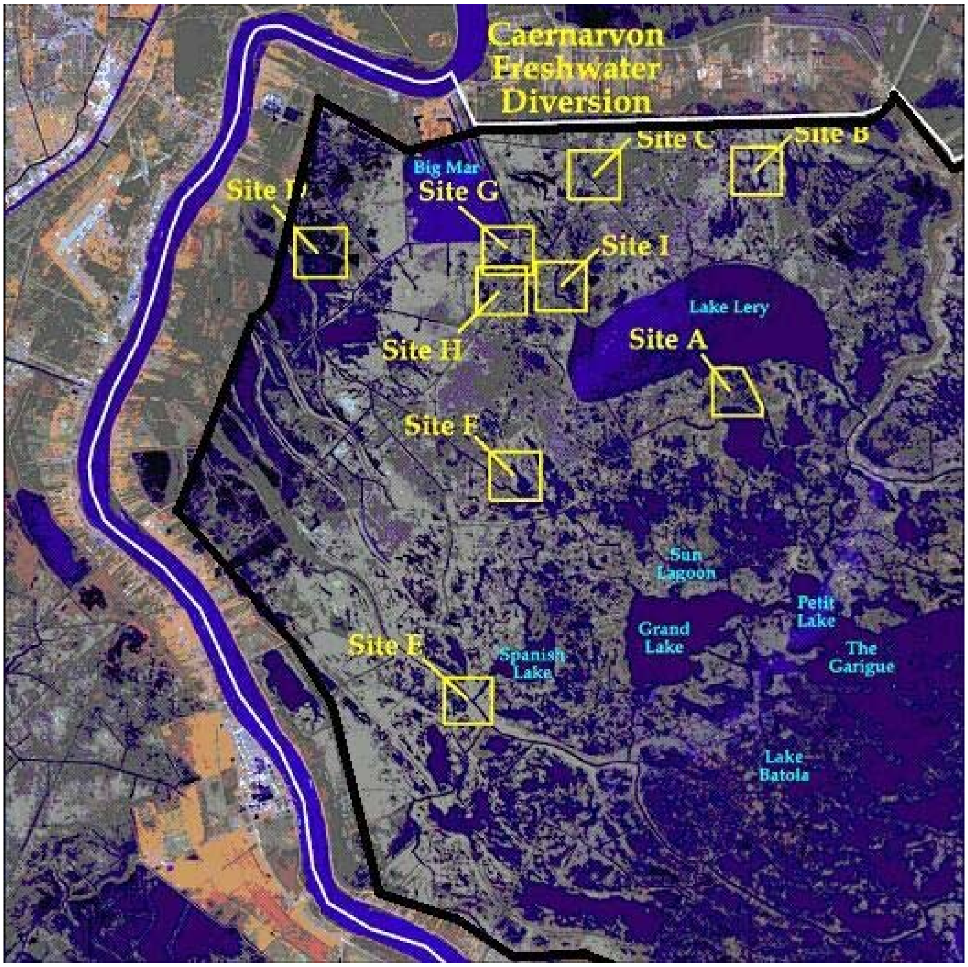

Figure 7. Caernarvon Diversion Structure Map (Lane 1999).

The Caernarvon structure is the only structure that has been in operation for several years (it opened in 1991), long enough to have provided some record of its impact on the wetlands. It is, therefore, logical to use it as an example for the analysis of the long-term effects of freshwater diversion on wetland restoration. According to the ACE, the Caernarvon structure has been a resounding success. The ACE reported that by 1996 in the Breton Sound area, the freshwater marsh has increased seven-fold, and the saline marsh has decreased by half. In addition, the ACE reported that new fresh and brackish water habitats have reappeared, oyster production has increased, and there has been a corresponding increase in wildlife and fisheries throughout the region. In addition, estuarine functions have been restored, and ecological niches previously absent have also reappeared. Overall the ACE claims a 17 percent increase in marshland, basing that on a net increase of 406 acres of marsh in an area that originally contained 2,289 acres of marsh (LaCoast 1998).

While the above numbers may sound impressive, they need to be considered in light of the projected wetland loss of 729,000 acres that is expected by the year 2050. Even if every freshwater diversion project is as successful as Caernarvon, they would only preserve 12,180 acres (17 percent) of the predicted 729,000 acres of lost wetlands. This in itself is a sobering thought when compared against the cost involved in building, implementing, and maintaining those diversion structures. Other projects, such as shoreline restoration or barrier island reinforcement would presumably protect significantly smaller percentages of the wetlands.

1.4 Research Questions and Objective

Previous studies have indicated a significant increase in freshwater marsh vegetation and a decrease in brackish marsh vegetation as the result of freshwater diversion projects (LaCoast 1998). Keeping this in mind, the research was designed to address the following two questions: i) Can remote sensing technology be used in assessing the landcover changes associated with freshwater diversion projects in coastal environments; and ii) what remote sensing methods are more effective in assessing the land cover changes associated with diversion of freshwater? The main objective of this study is to make an assessment of the impact of freshwater diversion on areas with high quantities of vegetation. This will be accomplished by determining the per year rate of change in the marshland areas, i.e., the loss or gain of wetlands within the study area.

1.5 Research Approach

The research approach is primarily focused on analyzing the multi-temporal remote sensing data to determine how much wetland has been restored since the inception of water diversion projects. Since the diversion structures are designed to target a specific area, remote sensing can be used to monitor, assess, and quantify the changes that have occurred over time. By obtaining satellite images over a number of years for the areas in question and comparing the pre- and post-diversion wetland extents, it will be possible to determine just what changes have occurred in these areas.

It is critical to determine what and how much has been accomplished as the result of these water diversion projects because of their considerable expense. Are these structures worth it or not? How much have they actually accomplished? Should we continue building them, or should we consider alternative methods of restoring and maintaining coastal wetlands?

2 Literature Review

This section examines the existing literature as it applies to remote sensing of wetlands, and reviews the current thinking on using this technique to measure wetland gain (or loss).

2.1 Using remote sensing for wetlands monitoring

2.1.1 Using MSS for wetland classification

The basics of remote sensing of wetlands have been known for over twenty years, as evidenced by M. Butera (1983). The author describes the techniques used to delineate Roseau cane in the Mississippi River Birdfoot delta region, mangrove forests on the southwest Florida coast, and wetlands in the Savannah River floodplain. The author used either LANDSAT data only or a combination of LANDSAT and aircraft Multi-Spectral Scanner (MSS) data. LANDSAT data have the distinct advantage of being available for a considerable length of time, as the first LANDSAT was launched in 1972 (originally called ERTS for Earth Resources Technology Satellite). Since that time, seven satellites have been built and launched into orbit, except for LANDSAT 6, which was lost at launch, and have returned data to provide a complete coverage of the growth or reduction in wetland extent. While the instruments mounted on the satellites have become more sophisticated over time, there is still a good continuous baseline record available for study.

In the Mississippi delta region, Butera (1983) used imagery from the MSS instrument aboard LANDSAT as well as an aircraft-mounted RS-18 scanner using the same bandwidths as the LANDSAT instrument. The satellite data, coming as they do from a stable platform in a well-known orbit, were the easier of the two to rectify, and as a result the author acquired a more accurate computation of the total area of Roseau cane. Because of typical problems with pitch and yaw for the aircraft data, in addition to continuous changes in side-lap coverage, Butera (1983) could not obtain an accurate assessment of total cane area. However, by comparing a subset of the study area with cane extents from aerial photographs, the author obtained consistent results for percent of Roseau cane coverage. Using the same basic technique of combining satellite and aircraft-mounted MSS data, Butera (1983) obtained good results for mangrove forest extents in the southwest Florida region. Again the author reports better accuracy from the satellite data even though the higher resolution of aircraft data provided more detail, it was at the expense of mapping accuracy. In the Savannah River floodplain, the author used only satellite data to measure the extent of the wetland region. What is unique here is the author used data from satellite passes in different seasons (fall and winter) and merged the two datasets. While the author does not specify what atmospheric corrections were applied, he was able to obtain good results from the multitemporal data. The author's classification accuracies were very high (82.6 percent) thus avoiding a problem inherent in using aircraft-based data.

2.1.2 More MSS wetland classification

Although studying wetland change in an area considerably smaller than the Mississippi River delta, E. J. Christensen et al. (1988) achieved good results from aircraft-mounted

MSS sensors. The authors used Daedalus Enterprises model AADS1260 and AADS1268 instruments, which can sense the same spectral bands found on the MSS sensor aboard the LANDSAT satellite. Because of the limited size of the area under investigation (9,000 acres bordering the Savannah River), the larger pixel size of a typical MSS image (80 meters) was too large to provide meaningful change data. The aircraft-mounted sensors can provide an image with a 5.6m pixel size. Unfortunately, unlike satellite imagery sensors, aircraft-mounted sensors suffer from excessive movement in three dimensions (roll, pitch, and yaw), which are difficult to correct for. The authors were unable to adequately register many of their images and thus were unable to take full advantage of the higher resolution that was available. While higher resolution of aircraft data is desirable, the added difficulty in registration effectively increases the special resolution and "smears" the data to some degree. Conversely, the superior stability of satellite-mounted sensors usually compensates for their lower resolution, even though the resolution of images used was somewhat compromised. The authors were able classify wetland vegetation with an overall accuracy of 84 percent. The study supported the idea that MSS image data can be used to accurately perform wetland classification. In the case of southern Louisiana, which is a much larger study area than that of the Savannah River site (approximately 77,000 acres), the limited resolution of MSS image data will not be a problem as it was for the researchers at the Savannah River site.

2.1.3 Wetland monitoring with AVHRR data

Using a sensor with a significantly lower pixel resolution (1.1 km), Ferguson et al. (2006) demonstrated the utility of Advanced Very High Resolution (AVHRR) data for delineating land-water interface changes. Although AVHRR is intended primarily for weather monitoring, the authors used wavelength bands centered at 580-680 nm (visible IR), and 725-1000 nm (NIR) to calculate a NDVI that could be used to differentiate the land-water interface. The main difficulty encountered by the researchers was an accurate registration of their images. They accomplished this by first developing a reference map of the land-sea boundary. Using this reference map, they were able to obtain image registration with a mean residual error (MRE) of less than one pixel. Once the images were registered, they could determine variations in the land-sea interface over time. Because of the coarse resolution of the AVHRR sensor, the smallest estuarine areas the authors could accurately track were those that were greater than or equal to 3.3 km in width. In the case of the Mississippi delta area, which is approximately 60-100 km wide, this resolution drawback would not be detrimental to tracking wetland changes.

2.1.4 Combining MSS and TM data

Measuring wetland change using a method similar to that employed in this study, Munyati (2000) examined wetland changes in the Kafue Flats area over a ten-year time frame using a combination of Landsat Multi-Spectral Scanner (MSS) and Thematic Mapper (TM) images. The images were from 1984, 1988, 1991, and 1994, and all were taken over a three-week period in September. This minimized seasonal variations in vegetation growth as well as sun angle and other physical system variables. It did however involve a comparison of images with dramatically different pixel sizes, 80 meters for the 1984 and 1988 MSS images and 30 meters for the 1991 and 1994 TM images. Though this limited the resolution of the changes that could be detected, the large area under study (approx 60x100 km) ameliorated that issue to some extent. Munyati (2000) achieved a good quality separation between open water and most of the vegetation recorded in his images. His most difficult task was to separate burnt or muddy areas of black soot or wet clay. He categorized the contents of his images as follows:

1. open water
2. dense vegetation
3. sparse vegetation
4. very sparse vegetation
5. dry grassland, woodland, and exposed soil
6. burnt or muddy areas

This categorization allowed him to detect significant variations in the wetland within the study area, and he was able to tie the temporal changes to temporal variations in the discharge rates of the irrigation dam situated upstream of Kafue Flats.

2.2 Spectral indices relevant to remote sensing of wetlands

2.2.1 Normalized Difference Vegetation Index (NDVI) for ecosystem monitoring

Large-scale monitoring of ecosystems is a critical requirement if progress is to be made in determining human impact on the environment. D. M. Stoms et al. (2000) have evaluated a predictive model using Regression Tree Analysis (RTA) to calculate land use patterns in ecoregions in California, Oregon, and Washington. They compiled a set of variables based on precipitation, temperature, and soil characteristics. Using a network of nature reserves for training data, they predicted land use characteristics based on the NDVI for the entire ecoregion and compared those results to their present land use categories. When the predicted NDVI map was subtracted from the actual NDVI map, they were left with a difference map. Their results were surprisingly accurate, given they were using a limited number of variables and were examining quite large areas. Regressive Tree Analysis accounted for 79 percent of the deviance in predicted NDVI for the training data. Most of the error occurred in urban or agricultural areas. This was expected, as urban areas generally lack significant vegetation and agricultural areas in the large Eastern Washington and Central California regions are generally irrigated, differentiating them from natural areas.

The drawback to this model was that it was developed using NDVI composites from a single year. These can vary widely from year to year, and it is this author's belief that composites from multiple years would yield more accurate results. But in general, the RTA model was moderately accurate in predicting land use classes from a minimal variable dataset. While the scale of this project was huge, encompassing three western states, it still has the potential to aid in the prediction of land-use classes in wetland areas in Southern Louisiana. Using regression analysis to predict the potential land use class for the areas affected by freshwater diversion could be useful in comparing the predicted class of the studied area with the actual class as observed in the field. Being able to predict what the land use class should be would be very valuable in seeing how close the restored areas have come to achieving the goal of returning the wetlands to a more natural state.

2.2.2 Vegetation Index (VI) performance

Baugh and Groeneveld (2006) undertook an exhaustive study of Vegetation Indices (VI), by comparing the results of fourteen published VIs for accuracy in a sparsely vegetated area in San Luis Valley in Colorado, USA. The fourteen VIs, in order of their relative performance, were:

1. Stretched Normalized Difference Vegetation Index (NDVI*)
2. Offset NDVI ($NDVI_{Offset}$)
3. Transformed SAVI (TSAVI)
4. Modified Soil Adjusted Vegetation Index (MSAVI)
5. second MSAVI ($MSAVI_2$)
6. Difference Vegetation Index (DVI)
7. Soil Adjusted Vegetation Index (SAVI)
8. Ratio Vegetation Index (RVI)
9. Enhanced Vegetation Index (EVI)
10. Normalized Difference Vegetation Index (NDVI)
11. Infrared Percentage Vegetation Index (IPVI)
12. Perpendicular Vegetation Index (PVI)
13. Atmospherically Resistant Vegetation Index (ARVI)
14. Weighted Difference Vegetation Index (WDVI)

Using Landsat TM images spanning a 17-year period (1986-2002), the authors compared images against the known effects of precipitation in the San Luis Valley, and checked their performance by using the r^2 value of the linear regression of each index. Their results showed a surprisingly low score for the standard NDVI, a widely used index and one used in this paper as well. But the area used in their research was a dry, sparsely vegetated environment, chosen because of an established relationship of vegetation with precipitation, and not at all similar to a wetland. Both of the indices that scored well, NDVI* and $\text{NDVI}_{\text{Offset}}$, are modifications of the standard NDVI designed specifically for an arid environment. Nonetheless, the authors concluded the low accuracy of the standard NDVI was most likely related to atmospheric effects, which is of serious concern when working with multi-temporal datasets. Accurate atmospheric correction is essential to any study using multitemporal images.

2.2.3 TM spectral indices model

Landsat Thematic Mapper (TM) images are probably the most utilized remote sensing product for wetland research today, due to their ready availability and long temporal baseline. Unfortunately, TM was not originally intended for water study but for terrestrial research, such as forestry and agriculture. When used in wetland applications, TM images can often return ambiguous results. A.S. Rogers et al. (2004) realized this and designed a method for analyzing TM wetland images using a simple but innovative spectral mixture model. The authors picked out three normalized spectral indices and examined them using a normalized difference transformation (NDX). The three indices were:

1. Normalized Difference Water Index (NDWI): (band 3 – band 5)/(band 3 + band 5);

2. Normalized Difference Vegetation Index (NDVI): (band 4 – band 3)/(band 4 + band 3);
3. Normalized Difference Soil Index (NDSI): (band 5 – band 4)/(band 5 + band 4).

By mapping these indices in three-dimensional space, they were able to differentiate the three major components comprising a wetland (soil, water, and vegetation) and map their changes over time. While this method was not error-free, it returned consistently reliable results.

2.2.4 Three techniques for TM analysis

Using remote sensing to measure change in a tropical forest is now a routine practice. Hayes et al. (2001) examined three techniques used in change detection analysis. Utilizing three dates of Landsat Thematic Mapper (TM) imagery, the authors applied normalized difference vegetation index (NDVI) image differencing, principle component analysis (PCA), and RGB-NDVI change detection analysis. In this way they could examine the three techniques to see which one gave the best results. Overall they found the highest accuracy from using RGB-NDVI change detection – 85 percent. The two others, NDVI and PCA, yielded accuracy rates of 82 percent and 74 percent, respectively. In addition, the RGB-NDVI technique was the simplest and easiest to interpret. While their research focused on tropical forests, their results still would have important implications for change detection in wetland areas. All three techniques are easily performed using software readily available in the lab, and it is possible that a technique other than the RGB-NDVI image differencing may return more accurate results.

However, overall accuracy and ease of use will determine which one is most useful in wetland change detection.

2.3 Chemistry and Salinity mapping

2.3.1 Mapping salinity

When studying freshwater diversion for wetland restoration, the ability to track salinity changes is of utmost importance. Glavao et al. (2003) used Airborne Visible/Infrared Imaging Spectrometer (ARIVIS) images to determine salinity levels in seven freshwater and five saltwater lakes in the Pantanal wetlands of southwestern Brazil. Using principal component analysis, they were able to differentiate freshwater from saltwater lakes by using the higher reflectivity of the saline lakes in the 400-900 nm band range, according to the first principle component. The second principal component allowed them to measure decreases in chlorophyll and increases in dissolved organic carbon, as indicated by areas of the saline lakes that graded from a greenish to bluish color.

The use of hyperspectral data was essential to this study. It allowed the researchers to more accurately characterize the variation in reflectance and also to track changes in other absorption bands that mirrored changes in water constituents. Hyperspectral data can be very useful in evaluating salinity levels in areas affected by freshwater diversion in the Mississippi delta.

2.3.2 Mapping salinity through vegetation changes

Wetland loss is often directly related to changes in salinity levels. Any remote sensing methodology that would allow for the determination of salinity could be very valuable. Using remote sensing data, an indirect method to determine salinity would be to map vegetation types that are known to be restricted to specific salinity levels. J. M. Visser et al. (2000) compiled a map of species ranges in the Chenier Plain of southwestern Louisiana that also incorporates data on salinity ranges. These mapped vegetation types were used to delineate five distinct salinity zones, following Odum et al. (1984):

- Fresh (average annual salinity < 0.5 ppt)
- Oligohaline (average annual salinity between 0.5 ppt and 5.0 ppt)
- Mesohaline (average annual salinity between 5.0 ppt and 18.0 ppt)
- Polyhaline (average annual salinity between 18.0 ppt and 30.0 ppt)
- Euhaline (average annual salinity > 30.0 ppt).

They also mapped seven specific vegetation types in the region:

- Freshwater *bulltongue*
- Freshwater *maidencane*
- Oligohaline *bullwhip*
- Oligohaline *paspalum*
- Oligohaline *wiregrass*
- Mesohaline *wiregrass*

- Mesohaline *mixture*.

Visser et al. (2000) incorporated a direct method to determine vegetation type. Using a helicopter, they flew 75 north-south transects approximately 3 km apart. The transects extended from the Gulf of Mexico to the upland boundary of the coastal zone. While the helicopter hovered over a series of stations located every 0.8 km apart, the researchers would visually survey the surrounding vegetation in an approximate 30m radius. Such rigorous examination of the vegetation provided them with a very high confidence in the accuracy of their identifications. The authors used this method to map specific wetland plant species and compared their results to previous surveys of Louisiana wetlands, including one as old as 1949. The 1949 study surveyed muskrat habitats (O'Neil, 1949) for the Louisiana Wildlife and Fisheries Commission. Visser et al. (2000) matched O'Neil's muskrat habitat maps with known muskrat habitat ranges, allowing them to create a vegetation map that could be corroborated with their own research. Using this technique they were able to map the pattern of wetland loss as well as the associated changes in salinity levels in southwestern Louisiana. Visser et al. (2000) also observed that wetland plant species found in the southwestern Chenier Plain area of Louisiana were also found in the more easterly Mississippi River Deltaic Plains (and thus could be useful as markers for wetland salinity there as well). Since one of the chief consequences of diverting large amounts of river water through the existing and proposed freshwater diversion structures will be to lower salinity levels in large areas of the wetlands, the ability to determine the extent of these "marker" species could prove valuable. If different species can be delineated using satellite remote sensing, it will provide a powerful tool in the analysis of wetland salinity levels.

2.3.3 Diverted water chemistry

Diverting freshwater into a river-isolated wetland area dramatically alters the water chemistry at the point of the diversion. R. Lane et al. (1999) examined the effect the Caernarvon Freshwater Diversion Structure has had on the water chemistry of the Breton Sound Estuary, the area directly downstream from the diversion structure and the area designated for restoration. (While wetland restoration is of principal concern today, it should be noted that Lane cites Chatry et al. (1983) to the effect that the original goal of the Caernarvon structure was to reduce salinities in order to enhance oyster production in the area. Indeed when one reads the present justification for the project on the Corps of Engineers (COE) website dated March, 1998 (http://www.mvn.usace.army.mil/prj/caernarvon/caernarvon.htm), oyster production is the first item mentioned as a reason for its construction.)

From 1988 to 1994, Lane et al. collected and analyzed water samples from Breton Sound Estuary. They measured nitrite + nitrate ($NO_2 + NO_3$), ammonium (NH_4), total Kjeldahl nitrogen (TKN), total phosphorus (TP), total suspended sediments (TSS), dissolved oxygen (DO), and salinity. These data were taken from seven monitoring stations distributed over the study area. In addition to the samples they collected and analyzed, they incorporated both Army Corps of Engineers (ACE) and Louisiana Department of Environmental Quality (LDEQ) data from 1988 to 1994. In the three years after the diversion structure was opened (1991-1994), Lane et al.'s research revealed that the nutrient and sediment levels were unchanged at any of the monitoring stations. Elevated nitrate, phosphate, sediment and dissolved oxygen (NO_2 + NO_3, NH_4, TKN, TP, TSS and DO) levels in the Mississippi River quickly reverted to background levels before the diverted water reaching the first monitoring station (< 5 km). Only salinity levels changed, and those reverted to background levels as well within 10 km of the diversion structure. These results indicate that present freshwater diversion volumes are having minimal effect, and larger volumes could be safely diverted. If the object of freshwater diversion is to build marshland, more river water is needed. However, if the main reason for the structure is to enhance oyster production, the amount of water that could be diverted is limited. Too much freshwater would disrupt oyster production, basically pushing it downstream as the salinity levels change. Overall oyster production may not be affected, but the present system of bed leasing would have to be modified.

2.4 Multi-temporal studies

2.4.1 Multi-temporal images from multiple sensors

Millward et al. (2006) used normalized multitemporal satellite imagery from three different platforms (Landsat TM, Landsat ETM Plus and SPOT 2) for assessing land cover change-detection in the coastal zone near Sanya in the Province of Hainan, China. They used brightness, greenness, and the NDVI index as input to principle component analysis (PCA). The use of PCA allowed the authors to reduce the bias caused by differences in the sensors. As the objective of this study was to map changes in urban development, efforts were made to eliminate spectral input from the ocean. When the analysis was run using masking of the radiation contribution from the water, the results were superior to those obtained when masking wasn't used. For vegetation, use of the NIR wavelength as input to the PCA provided a better contrast (and thus better discrimination) than using the NDVI. Though this was contrary to the author's expectations, in this case the NIR analysis afforded better results. (While the authors did not speculate why, it may be a consequence of the slightly different wavelength bands used by the different sensors, since the SPOT sensors use a slightly narrower band than those for the TM and ETM+). At any rate, the analysis allowed the authors to track changes in vegetation over the ten year time frame covered by the images.

2.4.2 Multi-temporal analysis with a spectral library

In Spain, as in the rest of the world, the disappearance of wetlands is of serious concern. In the La Mancha Alta region in central Spain, T. Schmid et al. (2004) measured the spectral radiance of various soils using an ASD FieldSpec Pro VNIR-SWIR spectroradiometer. Then they created a spectral library of the radiances for the various land use types of this semi-arid wetland region. Using this spectral library, they examined one set of hyperspectral airborne data from the DIAS 7915 sensor from 29 June 2000 and two sets of Landsat multispectral data – the ETM+ images from 28 June 2000 and TM images from 17 June 1987. These three image sets provided them with a 13-year image coverage in which to analyze changes in the Spanish wetlands. Using the spectral library, they were able to identify the same soil types in all three images. Numerous changes were noted in the images – in some areas the wetlands shrunk and in others they expanded, but overall the wetlands shrunk by 28.5 percent. T. Schmid et al (2004) suggested the wetland reductions were most likely due to channeling of the Cigüela River (a major river in the area) as well as a dam used for flood control.

2.4.3 Single and multi-temporal analysis compared

Although utilizing satellite images from two different dates often introduces technical problems (cloud cover changes, sunlight angle differences, changes in atmospheric transmissivity, etc), Lunetta et al. (1999) demonstrated significant benefits when using this technique for wetland identification. The authors compared the accuracies obtained from a single Landsat 5 image of the Millington, Maryland-Delaware USGS 7.5-min. quadrangle and found a significant improvement when using multi-temporal data. The best accuracy obtainable with the single-date image was 75 percent, while using multiple dates raised that accuracy to 83 percent. In this case, most of the increase in accuracy was due to the inability to identify agricultural areas in the single image, in fact no agricultural areas were identified at all. In contrast, the multi-temporal images improved the identification of agricultural areas to 75 percent. Lunetta et al (1999) clearly demonstrated that multi-temporal image analysis is a powerful tool in increasing the accuracy of overall landcover identification.

2.5 Atmospheric correction

2.5.1 Correcting atmospheric effects

Atmospheric interference is the most prevalent component of the difference in magnitude between ground radiance and at-sensor radiance. While the causes of this error are well known, it is still one of the most difficult to quantify because the atmosphere can be extremely variable. While atmospheric interference can often be measured at the time of data acquisition, it is much more difficult to resolve when analyzing time-variant images. C. Song et al. (2001) extensively examined this issue and concluded that while it is difficult to establish the exact surface radiance from historical images, it is often unnecessary if the desired result is merely to measure change over time. While there have been numerous methods devised to try to normalize satellite images to obtain true reflectance, the authors found that the simpler methods tend to do as well or better than the more advanced methods. The most straightforward method is Dark Object Subtraction (DOS), in which the reflectance values of images that are known to be dark in certain wavelengths (deep water, asphalt, etc.) are taken as a measure of the atmospheric interference. Subtracting this reflectance value from the entire image works as a simple method of atmospheric correction. Though there are a number of variations of DOS, taking into account atmospheric transmission loss and sun zenith angle, the basic methodology does not vary. Another method, the Dense Dark Vegetation (DDV) approach, uses vegetation that appears dark in the blue (TM 1) or red (TM 2) channels. The Path Radiance (PARA) approach is based on the linear correlation of the visible and mid-IR bands at the top of the atmosphere and the ground surface. The Ridge Method depends on the identification of Pseudo-Invariant Features (PIFs) and calculating the relationship between image bands over time. Despite the complexity of these three methods, C. Song et al. (2001) showed that none of them return results as accurate as the simpler DOS methods. Additionally, though the determination of true radiance is valuable, it is not necessary if one uses training data from the examined images. Only when one attempts to use training data from one time or place and tries to apply them to images taken in another time and place will errors result. As long as the training data for a class are included in the examined image, atmospheric correction is unnecessary and both land-use classification and change detection are possible. When it is compulsory to use training and image data from two different physical or temporal locations, then atmospheric correction is vital, and C. Song et al. (2001) have demonstrated that simpler is better in such cases.

2.5.2 Atmospheric correction over turbid water

Atmospheric correction of remotely sensed images is a standard procedure in the quantification of water-leaving radiance. Atmospheric correction is especially difficult when dealing with turbid waters because suspended sediments, bubbles, and bottom reflection, for example, can contribute significant radiance to the atmospheric correction bands – 0.765 μm and 0.865 μm. This can result in obtaining erroneous correction values and even negative water-leaving radiance values. In addition, chlorophyll concentration estimates suffer as well. C. Hu et al. (2000) developed a technique to reduce the errors inherent in turbid water correction values in SeaWiFS (Sea-viewing Wide Field-of-view Sensor) imagery, and obtained good results when they applied their method to Louisiana coastal environments as well as shallow areas around the Florida Keys. Their method was refreshingly straightforward. If the atmospheric correction values obtained from pixels containing turbid water were bad or suspect, the researchers would simply substitute correction values from the "nearest neighbor" pixel. In an earlier study, Gordon and Morel, (1983) demonstrated that aerosol types do not change over moderate spatial scales (100-1,000 km), so incorporating the atmospheric correction values from a nearby pixel is a practical alternative. Though this method involved significant changes in post-processing of the data, no additional data needed to be collected. The older method of calculating atmospheric correction simply assigned an atmospheric correction from a lookup table that was based on twelve aerosol models (maritime, coastal, troposphere, and oceanic aerosols, each of which were assigned various relative humidities). The values of the lookup table were calculated with the assumption that reflectance values for water at 0.765 μm and 0.865 μm are equal to zero. While this method work well for most marine images, as mentioned previously, turbid water images suffer from increased radiance in the 0.765 μm and 0.865 μm bands. Subsequently, lookup tables can lead to overestimates of aerosol values and even "atmospheric correction failure" in some areas of an image. In addition, this method overestimates chlorophyll concentrations as well. Since the "nearest neighbor" method has provided excellent results in the interpretation of images depicting turbid water conditions, it should be quite useful when applied to remotely sensed images of Louisiana wetlands, as many of those images will depict turbid water environments. Since freshwater diversion introduces large quantities of sediment into the study area, any method that improves the accuracy of water-leaving radiation values can only help improve the accuracy of vegetation classification, land-water boundary delineations, and the identification of tangential wetland characteristics.

2.5.3 TM data correction

One of the chief difficulties in working with ocean data is that water-leaving radiance values are quite low, especially in coastal areas. For TM data in the coastal areas of south Florida, M. Zhang et al. (1999) developed a noise reduction technique utilizing a two-dimensional Fourier transform to remove noise, especially banding caused by "bright-target recovery" (Barker, 1985). This banding is especially common in areas with sharp transitions between low and high reflectance areas, for example a cloud-covered ocean area. Their techniques reduced noise levels by 23-25 percent in cloudy areas. In addition, they adapted a method that is commonly used on Coastal Zone Color Scanner (CZCS) imagery to perform atmospheric correction. Marine-type aerosol effects, as well as Rayleigh scattering values were computed for each pixel of the TM image and removed from the entire scene. These corrected pixel values were then compared with typical clear-water values for the open ocean and were shown to be a good match. Finally, the researchers showcase a method to derive the vegetation fractional coverage for each pixel in shallow water areas. After correcting the digital values of each pixel for atmospheric effects, water path radiance, and attenuation, they were able to derive the vegetation fractional coverage and estimate total vegetation coverage. This method could be especially useful in examining vegetation coverage changes in shallow water deltaic environments.

2.6 Other relevant remote sensing articles

2.6.1 Monitoring ESA

J. Slater and R. Brown (2000) developed a GIS-based Map Updating System to track land cover changes in "The Broads," a wetland area on the coast of eastern England. An "Environmentally Sensitive Area" (ESA), it contains important habitats for over-wintering and nesting birds, and encloses several National Nature Reserves and "Sites of Special Scientific Interest." The authors used satellite imagery (specifically LANDSAT Thematic Mapper (TM) data) to update a digitized 1987 land cover map, which subsequently allowed them to monitor land cover changes. In addition, they used visual interpretation of aerial photographs (no specific system described) to further refine their updates. The incorporation of the GIS program into their studies facilitated their map modifications and allowed them to rigorously track changing land use trends. Due to the high cost of aerial photography and the difficulty of obtaining cloud-free satellite images, they also used radar imagery from the European Space Agency (ERS) Synthetic Aperture Radar (SAR) ERS-1 SAR satellite. This permitted them to collect all-weather data in an area not known for its clear skies. While the radar imagery was somewhat more difficult to interpret than aerial photography or TM data, over time they were able to identify land cover changes with almost the same accuracy as the more traditional methods. In addition to the above methods, the authors also obtained MSS data from as early as 1972. While of a lower resolution and containing irresolvable cloud cover issues, it gave them a 25-year baseline with which to track changes. Despite their labor-intensive visual interpretation methods, the authors were able to accurately track land use changes within their study area because of the area's relatively limited size (43,000 hectares).

2.6.2 Shallow water feasibility study

D. Durand et al. (2000) looked into various methods of correcting remote sensing images in order to accurately estimate reflectance values. They accomplished this by developing various reflective models that were mostly modifications of ocean models optimized for shallow water. They then conducted a sensitivity analysis to see if the models could handle a variety of atmospheric conditions and still return sound results. The results they obtained were very good and showed that even with significant introduced errors, the models could return reasonable values. This was good news for the authors, as it indicated their models were robust enough to provide the user with confidence the models themselves weren't generating false values, even if the user encountered unexpected results. Despite the success of these models, they were developed for and tested on shallow water environments and in mostly clear water, a condition unlikely to be encountered in the Mississippi delta wetland region. Nonetheless, it is hoped that some modifications can be made to these models to adapt them to turbid water conditions and saline waters, thus allowing for the accurate assessment of reflectance values in these environments.

2.6.3 Leaf optical property changes

E. Ramsey III, and A. Rangoonwala (2005) predicted marsh dieback in southern Louisiana (the Bayou Du Large) using remote sensing of leaf optical property changes as they apply to marsh dieback onset and progression (brown marsh). Along transects of brown marsh, they collected leaf reflectivity measurements in multiple wavelengths. They compared the blue (454-459 nm) and red (670-675 nm) reflectivity as well as two ratios of the wavelengths NIR (770-780 nm) to red. They also compared the green (545-550 nm) to red to visible marsh health determinations. These comparisons showed that while the blue and red wavelengths, as well as the NIR to red (NIRRED) ratios generally compared well with maps of visibly determined marsh dieback, they were of limited use in *predicting* dieback. Instead, it was the green to red (GRNRED) ratio that proved most useful as it allowed the authors to map marsh areas that would suffer dieback in the future, areas that under visual interpretation did not show any indication of future change. This study strongly suggests the green and red wavelength ratio is important as a predictor of future marsh dieback. Furthermore, the green and red wavelength ratio is available in most satellite imagery, including the Landsat TM imagery.

2.6.4 Dieback-created canopy reflectance changes

In a follow-up to the research described in section 2.6.3 above, E. Ramsey III, and A. Rangoonwala (2006) continued their research on reflectance changes that result from marsh dieback. They compared data derived to simulate a whole-spectral sensor, similar to the NASA Earth Observing-1 (EO-1) Hyperion satellite sensor, and broadband spectra similar to that available from the Landsat Enhanced Thematic Mapper (ETM). In addition to examining the discrete blue (454-459 nm), green (545-550 nm), red (670-675 nm), long-wavelength red (695-705 nm), and NIR (845-850 nm), the authors used band ratios of NIR/red and NIR/green. Ramsey and Rangoonwala (2006) demonstrated that while the broadband ETM spectral band ratios like NIR/green were able to differentiate healthy from stressed marsh in broad regions, the whole-spectra sensor allowed for a more accurate discrimination of dieback severity as well as its progression. While ETM spectral resolution was still useful, the whole-spectral bandwidth of the EO-1 significantly enhanced their resolution in wetland health discrimination.

2.6.5 Enhancing TM imagery

Monsef et al. (2000) applied Principle Component Analysis (PCA) to satellite images in conjunction with state's Forest Industry Analysis System (FIAS) to analyze wetland landcover. The authors achieved a significant increase in the accuracy of wetland classification. Not only were they able to more accurately classify the wetlands; they also significantly augmented their ability to discriminate between different types of wetlands. The relatively straightforward techniques of Monsef et al. (2000) could be very useful to quantify changes resulting from diversion of freshwater into the dwindling wetlands surrounding the Mississippi River in Louisiana.

2.6.6 Landcover classification methods

The determination of landcover classes is essential to the measurement of wetland change. However, assigning the correct land cover classification is often one of the most difficult aspects of remote sensing in wetland areas because classes can be spectrally inseparable, and resolution can put further limitations on landclass distinction. Ramsey et al. (2001) examined these issues in the Mermentau River Basin within the Chenier Plain of coastal southwest Louisiana. Using Landsat TM images from 1990 to 1996, along with collateral data, the authors determined landcover classes and measured their change over the six-year period. The methods they used to tease out subtle differences between classes would be invaluable in the determination of changes resulting from freshwater diversion into the lower Mississippi delta. They used three techniques to overcome classification problems. First, they separated the working area into seven broad subregions, each containing several related land cover types, such as forested uplands, cultivated uplands, and emergent wetlands. Then they evaluated each region according to its specific characteristics in order to avoid comparing disparate regions that might otherwise appear spectrally inseparable. Second, they applied masks to specific land mixtures, such as urban areas. This permitted them to avoid the comparison of spectrally similar areas like barren ground and developed urban areas. Third, they eliminated class changes that were highly unlikely, such as those between upland and wetland forests. Using these techniques, either individually or in combination, the authors obtained classification accuracies of 80 percent, 78 percent, and 86 percent for their 1990, 1993, and 1996 TM images, respectively.

In addition, they reported the majority of their classification errors were a result of confusion between the following land cover class types:

1. Cultivated land and unmanaged grasslands
2. Scrub shrub, grasslands, and forest
3. Water, unconsolidated shore, and bare land
4. Water and floating vegetation

2.6.7 Landcover modeling

Ground truth and knowing the subject of one's images is imperative to the accuracy of any assessment of wetland land cover types. In a restored wetland area in Southern California (Sweetwater Marsh, San Diego County, California), Phinn et al. (1999) developed empirical models from data gathered using a multispectral aerial digital camera and handheld radiometers. Examining data that span 1992 to 1996, they learned they could increase the accuracy of their land cover categorization by dividing the wetland area they were investigating into low, medium, and high marshland. Once the wetlands were categorized, their models returned significantly better results and more accurately assessed the variations in their indicator species, *Spartina foliosa* (Pacific cordgrass). They showed that stem and leaf length of *Spartina foliosa* were largely responsible for the differences in spectral response they observed in their images. However, since marsh height was the principle cause of stem and leaf length differences, when marsh height was factored into their model, it became much easier to assess changes due to other factors. While this study wasn't a stunning advance in scientific insight, the methodology used by Phinn et al. (1999) demonstrates a practical and straightforward approach to measuring wetland change. It employs readily available data sources in a method that is easy to understand and economical to operate, and its simplicity means errors will be easier to discover and account for.

3 Research Methodology

The first step of the process is to obtain pre- and post-diversion Landsat images to delineate the area affected by the freshwater diversion. Once the study area is defined, it can be categorized into wetlands and “other terrain,” which includes open water, developed land, or any landform type other than a wetland. By examining satellite images that were taken over a specific time interval and comparing the area of wetlands in each of them, it should be possible to determine whether the wetlands are increasing or decreasing, and by how much.

As long as there is a rigorous control baseline defined for the area under study that can be applied across all of the images, it should be possible to resolve any change the freshwater diversion is causing in the wetlands areas. Ideally, at the end of the study we will have some precise quantifiable values for wetland changes to the areas of concern. Since we know the total cost of the Caernarvon structure, we will be able to calculate the cost of wetland restoration per acre. In that manner, we will have a sound methodology to make determinations as to the efficacy of the diversion structures, and we will be able to compare that to other wetland restoration processes being used or proposed for the Mississippi Delta.

In order to determine the effectiveness of the diversion structures as a method of addressing wetland loss, this research uses satellite images to measure any gain or loss of wetlands in the areas directly impacted by these diversion structures. Only the Caernarvon diversion has been in operation in this area of the Mississippi delta long enough (16 years) to monitor its effect on wetlands, so this was used to measure what, if any, effect diversion has had on wetland loss.

Two study areas are used, one that includes the entire Breton Sound, approximately 10.5 km^2 (Figure 8), and another much smaller area directly below the diversion structure, approximately 3 km^2 (Figure 9). The two areas are used because in the course of the project it became clear that the further reaches of Breton Sound were not noticeably affected by the freshwater diversion. Reducing the area of study would hopefully measure changes that were a direct result of the diversion.

Figure 8. Main Breton Sound study area (USGS 2002).

Figure 9. Area close to freshwater discharge (USGS 2002).

Six satellite images were used, one Multispectral Scanner (MMS) image from 1974, and five Thematic Mapper (TM) images from 1983, 1988, 1991, 2002, and 2006. The images chosen were all taken during the fall/winter season in an attempt to reduce seasonal variation between images. Images with adverse atmospheric effects were avoided, and only cloud-free images were used. However, some variation in quality among the images is inevitable.

The Multispectral Scanner and the Thematic Mapper are two instruments used aboard the early NASA remote sensing satellites. The Multispectral Scanner was the older of the two, and its spectral range covered the entire spectra from green through red to infrared. The Thematic Mapper narrowed the bandwidth it received to only those spectra that experience showed were less affected by the atmosphere. This improved researcher's ability to focus on actual ground radiance and reduce atmospheric interference. The following is a list of the spectral bands used by the two satellite platforms and their wavelengths (Table 2):

Thematic Mapper			Multispectral Scanner		
Band	Wavelength	Common name	Band	Wavelength	Common name
3	0.63 – 0.69 µm	Red (R)	5	0.60 – 0.70 µm	Red (R)
4	0.76 – 0.90 µm	Near-IR (NIR)	6	0.70 – 0.80 µm	Near-IR (NIR)
5	1.55 – 1.75 µm	Mid-IR (MIR)	7	0.80 – 1.10 µm	Mid-IR (MIR)

Table 2. Satellite sensor bandwidths.

Seven spectral enhancement procedures were used (Table 3):

Index	Formula
Normalized Diff Vegetation Index (NDVI):	(Band 4 – Band 3) / (Band 4 + Band 3)
Transfomed NDVI (T-NDVI):	Sqrt((Band 4 – Band 3 / Band 4 + Band 3) + 0.5)
Vegetation Index (VI):	Band 4 – Band 3

Table 3. Spectral bands used by studied indices.

Infrared / Red (NIR/R):	Band 4 / Band 3
Square of Infrared / Red (SqrtNIR/R):	Sqrt(Band 4 / Band 3)
Normalized Diff Water Index (NDWI):	(Band 3 – Band 5) / (Band 3 + Band 5)
Principal Component Analysis (PCA)	(Bands determined by analysis)

Table 3. Spectral bands used by studied indicies (continued).

The Normalized Difference Vegetation Index (NDVI) was developed in the early days of the remote sensing satellite programs, particularly from data collected by the Earth Resources Technology Satellite (ERTS, which would eventually be renamed Landsat-1). Differences in solar zenith angle across the large swath image captured with each orbital pass were making it difficult to quantify rangeland vegetation. By taking the ratio of the differences between the red and infrared wavelengths over their sum, they were able to "normalize" these solar zenith angle effects (Rouse et al. 1973). It was an effective technique that was soon widely applied in many vegetation classification efforts. The Transformed NDVI (T-NDVI) is a slight variation on the standard NDVI. Taking the square-root variation of the difference-sum ratio will sharpen the contrast between vegetation and non-vegetation in some images.

In addition to the indices discussed above, Vegetation Index (VI), NIR/Red, and Sqrt NIR/IR (Table 3) were also used in this study. While they are very simple indices, they nonetheless were very useful when used to determine biomass by measuring green leaf area (Tucker 1979). When used to separate vegetation from water, the high reflectivity of leaf biomass in the NIR and Red wavelengths is balanced by their near total absorption by water.

The Normalized Difference Water Index (NDWI) index uses the same formula as the NDVI, but substitutes TM Band 3 (0.63 – 0.69 µm) for TM Band 4 (0.76 – 0.90 µm) and TM Band 5 (1.55 – 1.75 µm) for TM Band 3 (0.63 – 0.69 µm). This index was chosen because it has been demonstrated to be useful in the delineation of water from other landforms, including vegetation (Gao, 1996).

There are literally hundreds of indices in use today, but these six were chosen because of their potential to measure wetland change. All of the indices but one use Landsat Bands 3 and 4 (0.63 – 0.69 µm and 0.76 – 0.90 µm, respectively). These bands are ideal because they display a large contrast between water and vegetation as the result of high IR absorption of water and high NIR reflectance by the vegetation. Vegetation absorbs energy in the red wavelengths (TM Band 3), but its reflectance in the NIR wavelengths (TM Band 4) is high.

In addition to vegetation indices discussed above, Principal Component Analysis (PCA) was also used in the data analysis. PCA attempts to enhance the original data by condensing redundant components within correlated variables into a reduced set of uncorrelated variables, called principal components. These principal components are then used to differentiate between water and vegetation.

While each of the procedures returns an image in which the water and vegetation classification can be done, the images are all slightly different. It is difficult to say which procedure is more accurate, and perhaps even impossible. The images were taken under different conditions over a period of fifteen years, and some procedures return better results than others given the conditions of that particular day. While the images were chosen to reduce as many differences as possible, variation is inevitable.

By using seven different procedures to classify the images, the researcher intended that some differences between images will be averaged out and allow an overall trend to emerge. While not strictly a meta-analysis, as the different factors are not weighted according to their confidence level, the procedure does allow a trend to emerge, especially when taking the relatively long timeline (15 years) into consideration.

After obtaining the spectrally enhanced images, they were classified as water or vegetation using an unsupervised classification procedure. The amount of water and vegetation in the area of interest (AOI) of each image was determined and its percent of the total image calculated. By comparing the percentage of vegetation to open water in each image, it was possible to determine what effect the diversion structure has had on the wetland vegetation (Figure 10 and Figure 11).

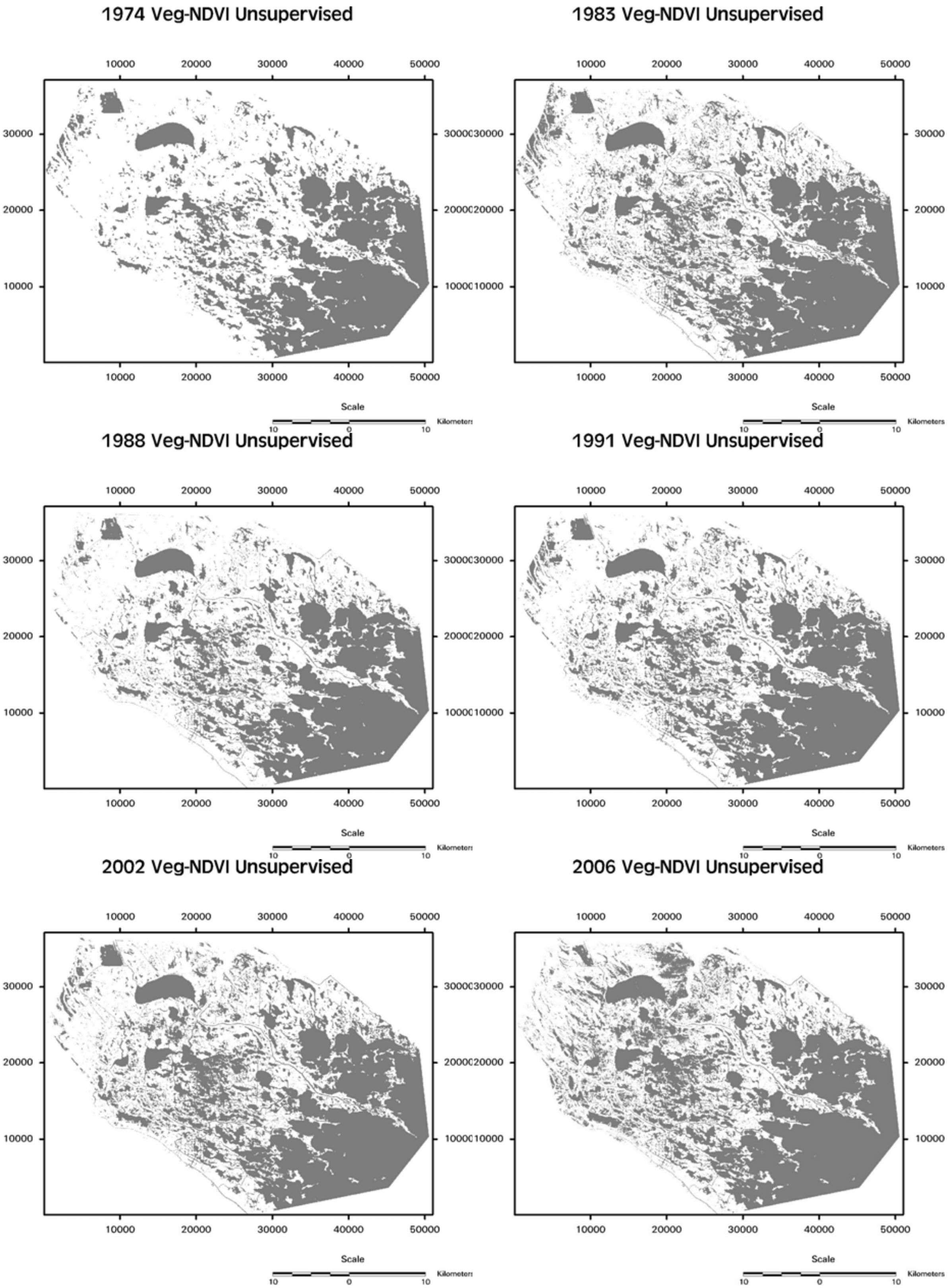

Figure 10 Wetland loss progression using NDVI.

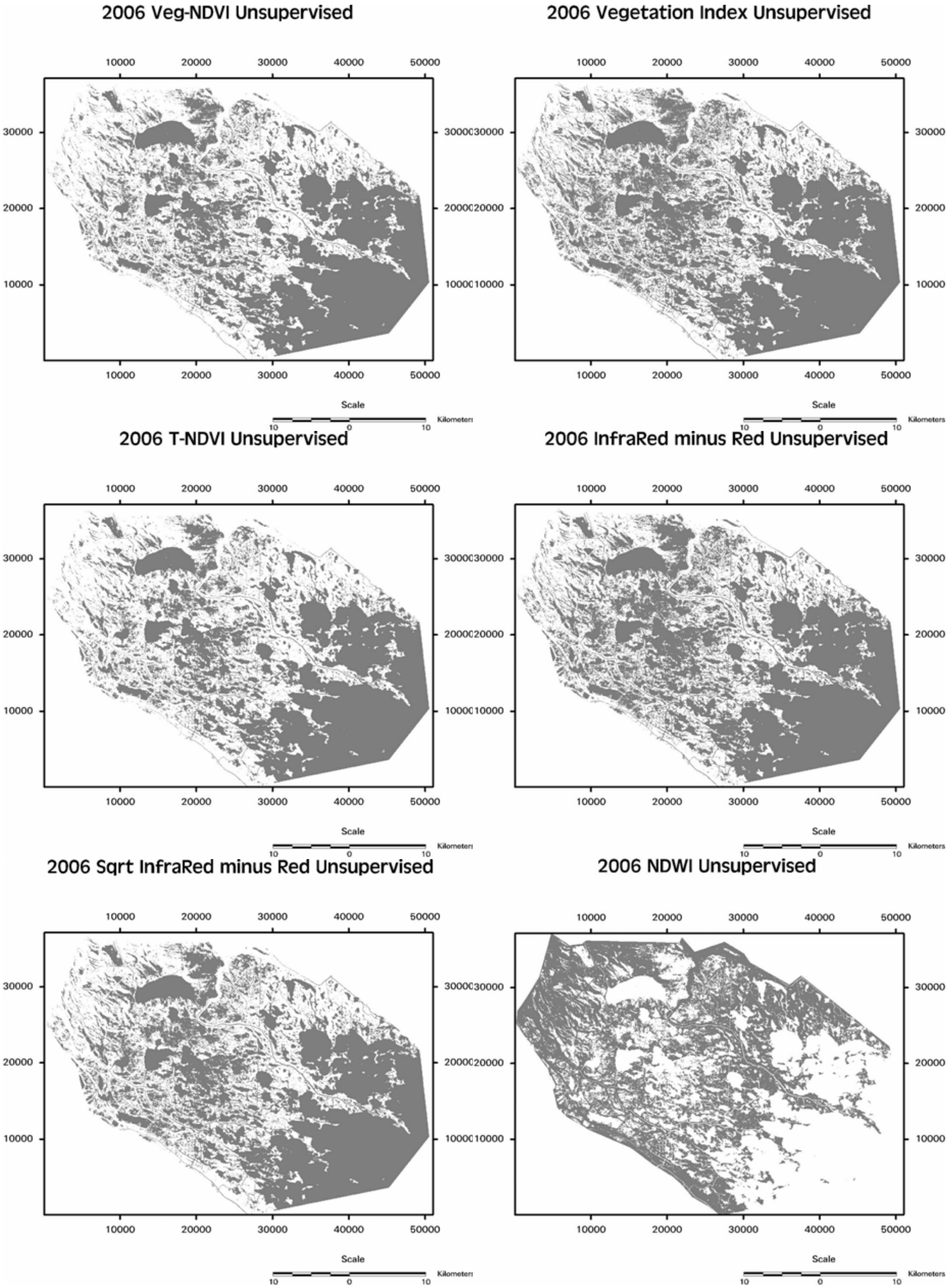

Figure 11 Comparison of all six indices using 2006 image.

Amount of vegetation compared to water is a very rough approximation of wetland extent, but will function well enough for the purposes of this research. While it would be desirable to measure many more aspects of the environment, such as specific plant species and their distribution, as well as amount of bare soil, human impacts, etc, the spatial resolution restrictions of using Thematic Mapper (30m) and Multispectral Scanner (80m) preclude such detailed investigations. On the other hand, these images have the decided advantage of being historical records of long-term changes in the wetlands, and change is exactly what this research seeks to determine.

4 Results and Conclusions

The result of the analysis shows that the wetland vegetation in the Breton Sound Basin fluctuated significantly in the years leading up to the completion of the diversion structure. Whereas the average vegetation percentage had decreased from 60 percent in 1974 to 52 percent in 1983, it increased to 57 percent in 1988. However, after 1988 it began decreasing once again. Vegetation dropped to 55 percent in 1991, 50 percent in 2002, and 45 percent in 2006 (Figure 12). This shows a significant – and accelerating – decrease in wetland extent.

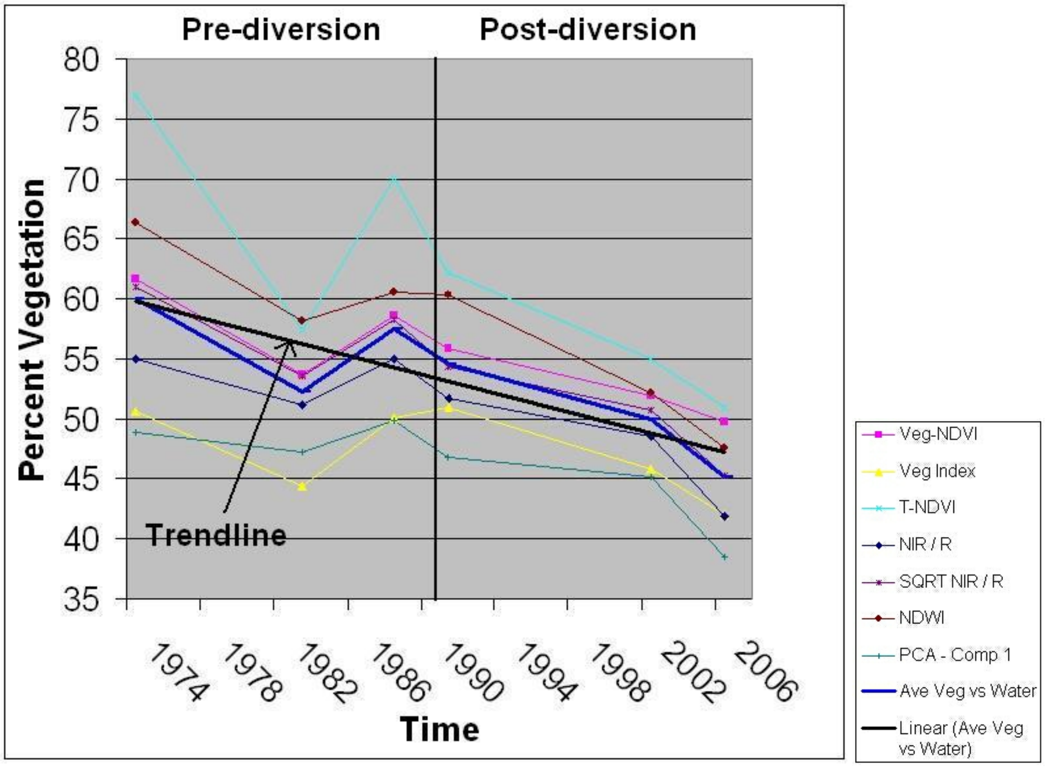

Figure 12. Breton Sound overall wetland loss.

The Caernarvon diversion structure began operating in 1991, and unfortunately there does not appear to be any change in the steady replacement of vegetation by open water in the outflow area. Indeed, there appears to be an increase in the rate of vegetation and wetland loss, as the rate of vegetation loss was only 0.17 percent per year from 1974 to 1991. The rate of loss increased to 0.67 percent per year from 1991 to 2006. Figure 13 and Figure 14 show the pre- and post-diversion wetland loss, respectively. Pre-diversion wetland loss (Figure 13) exhibits significant fluctuation over time; indeed, the VI (NIR-Red) index shows an increase in wetlands over the pre-diversion time period. However, the other indices show decreasing wetlands over time. The black trendline for the average value clearly shows a decreasing trend (Figure 13). While not a strong trend, it nevertheless indicates a gradual loss of wetland (and increase in open water). The trendline shows a pre-diversion wetland loss of 0.17 percent per year (58 percent to 55 percent from 1974 to 1991).

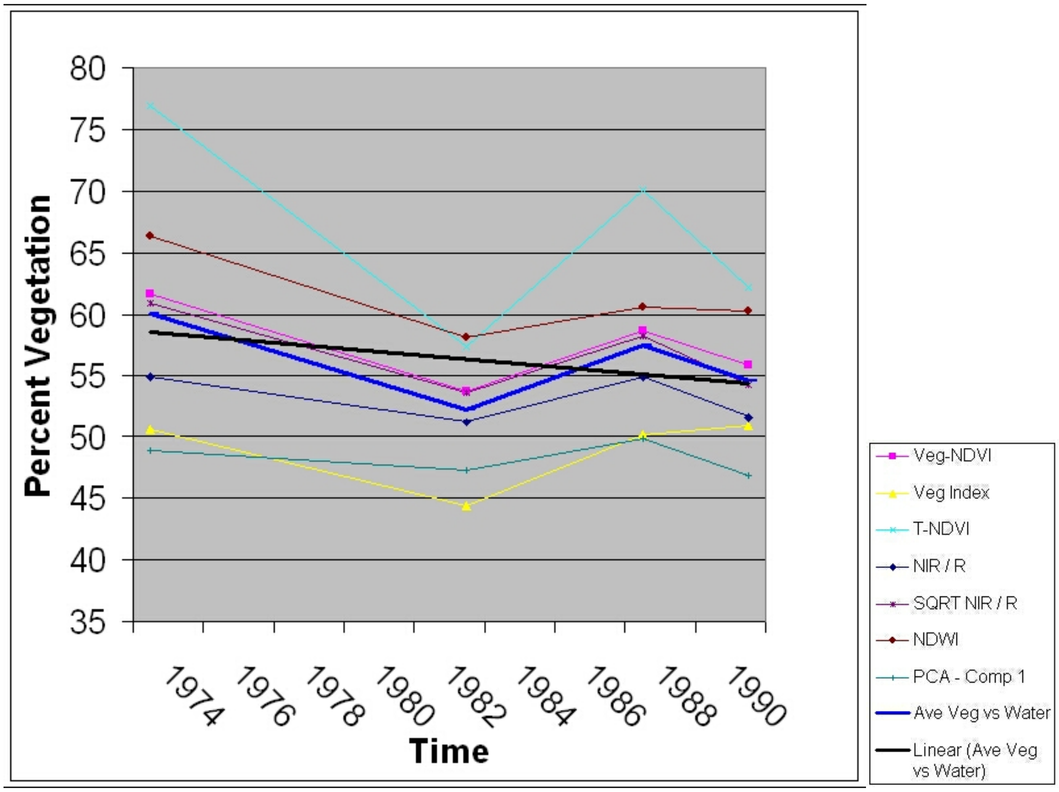

Figure 13. Breton Sound pre-diversion wetland loss and trendline.

Post-diversion wetland loss is significantly higher, 0.67 percent per year, which seems to indicate an overall increase in wetland loss. The trendline clearly shows this increase in the rate of loss, from 55 percent in 1991 to 45 percent in 2006 (Figure 14).

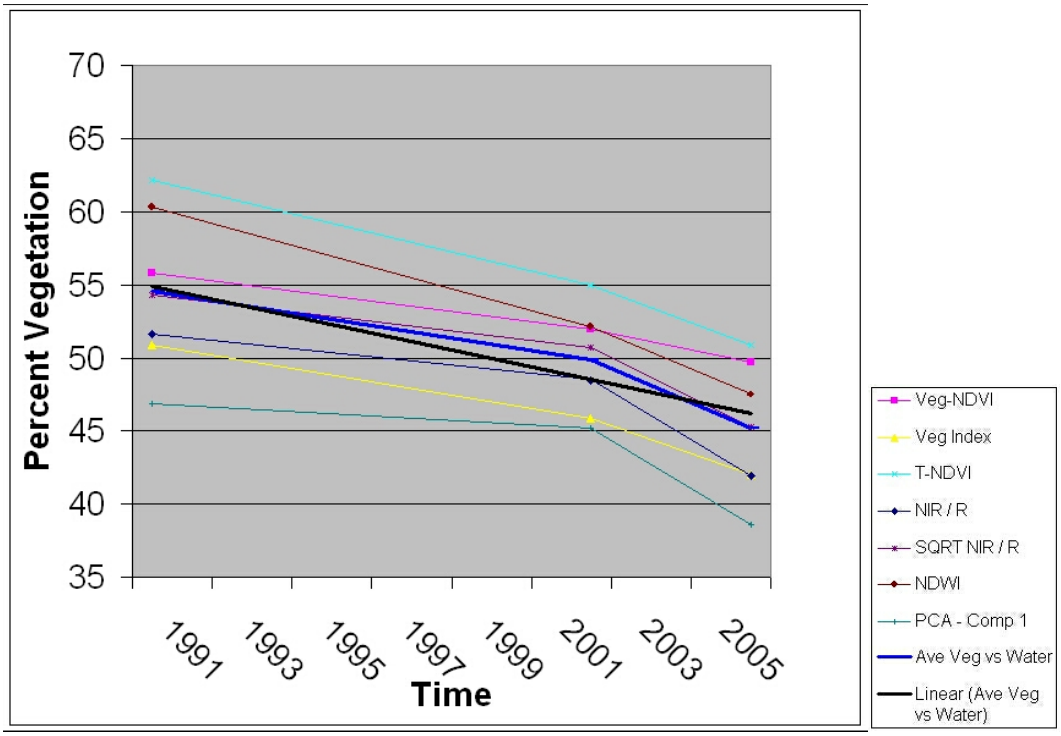

Figure 14. Breton Sound post-diversion wetland loss and trendline.

From the post-diversion increase in wetland loss, it appears that the Caernarvon freshwater structure has not been very effective in reversing the wetland loss in target areas. It is also possible that the Caernarvon structure is simply not able to affect the entire Breton Sound area, and may only be affecting wetlands much closer to its outflow channel. To determine if this is the case, an additional set of much smaller images were examined, focusing on areas closer to the outflow channel. These images cover an area approximately one-fourth the size of the Breton Sound images (3 km^2 as opposed to 10.5 km^2). The analysis of the area closer to the outflow reveals significant differences (Figure 15).

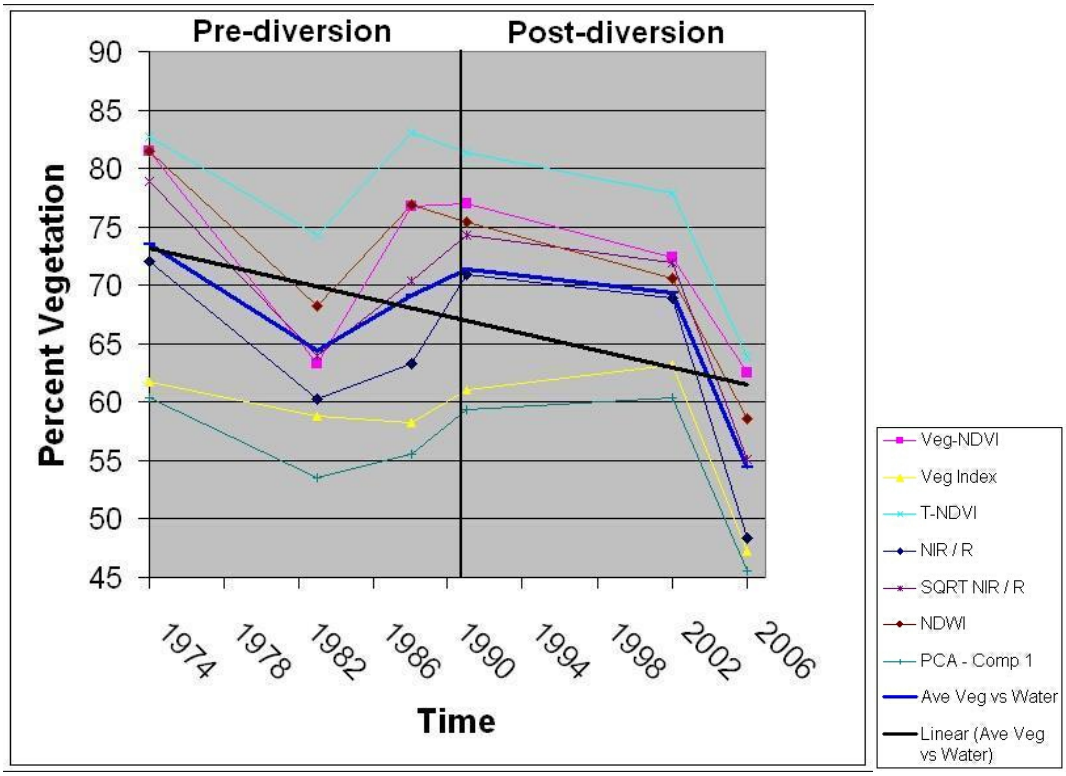

Figure 15. Overall wetland loss and trendline for area close to diversion.

Overall wetland loss for the area closer to the diversion outflow is slightly smaller, 11 percent for the new small area as opposed to 13 percent for the entire Breton Sound area. Unfortunately, wetland loss continues to occur in the new area, and does exhibit a similar trend of increasing rate of wetland loss over time even after the opening of the Caernarvon diversion structure.

In the new, smaller area, before the opening of the Caernarvon structure, wetland loss is very slow. Unfortunately, as with the larger area, there is still significant fluctuation in the rate of wetland loss, making it very difficult to have any confidence in the overall trend. Nevertheless it does indicate an overall loss of wetlands (Figure 16).

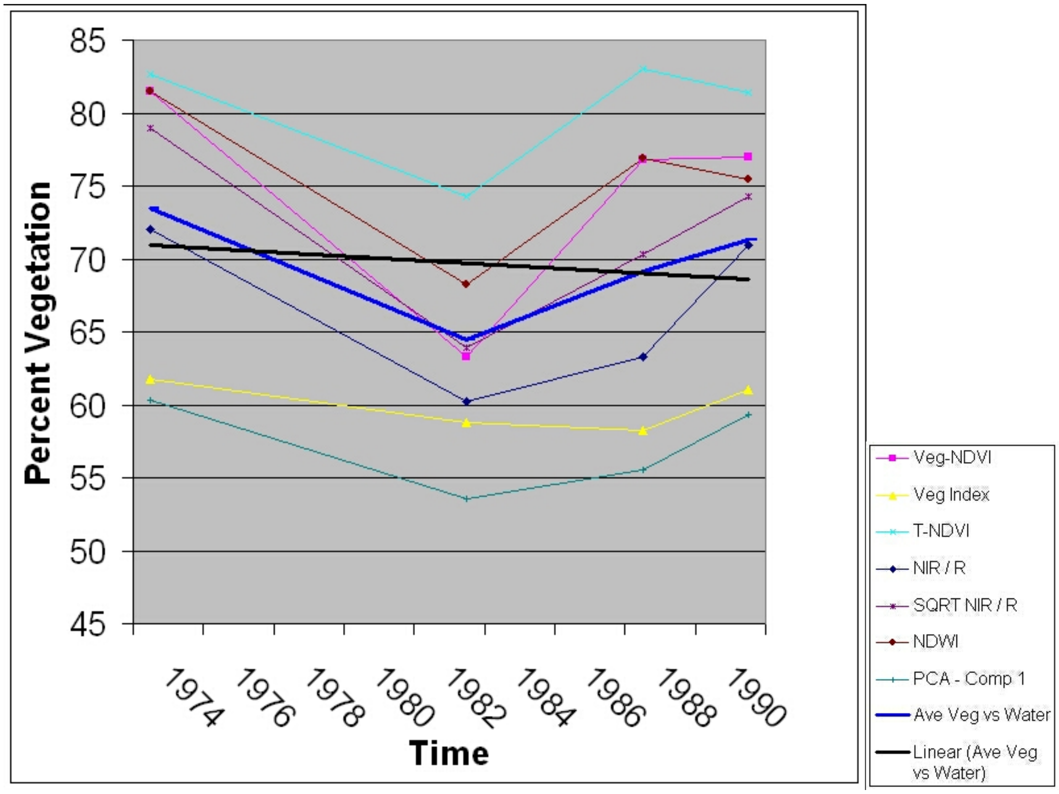

Figure 16. Pre-diversion wetland loss and trendline for area close to diversion.

By contrast, the post-diversion rate of wetlands loss is significantly higher. This is shown by the steeper trendline in Figure 17. This would indicate that despite the area being more directly affected by diversion structure, wetland loss continues to occur and indeed is accelerating.

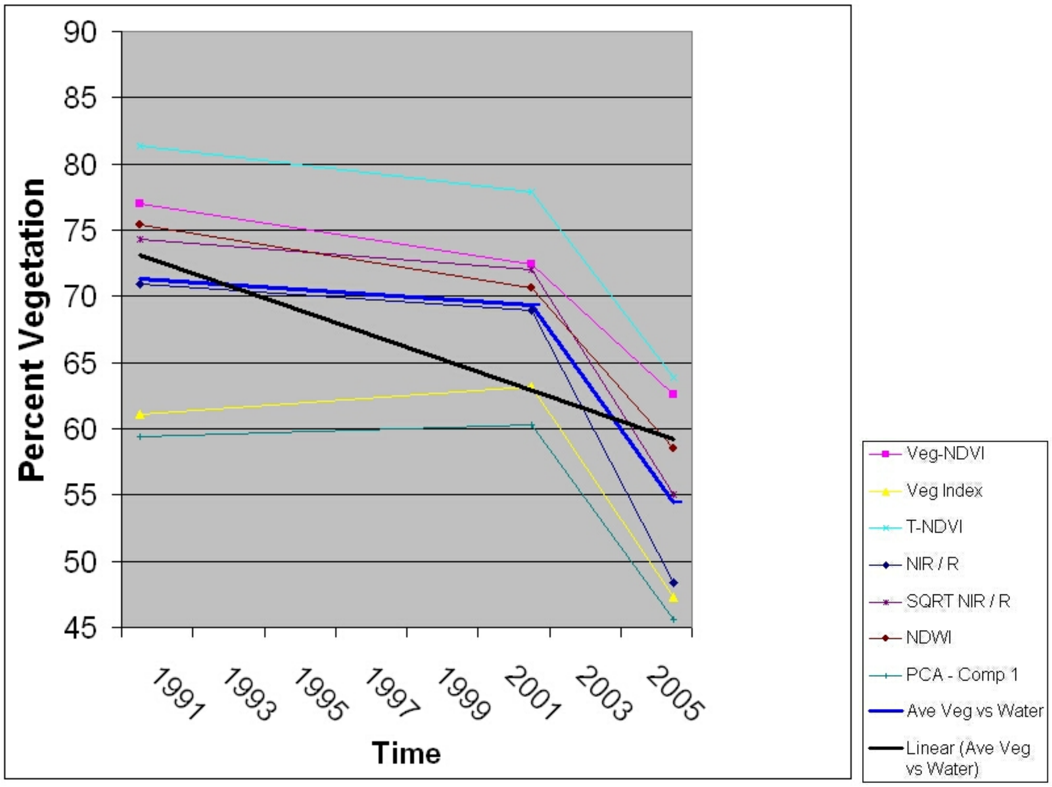

Figure 17. Post-diversion wetland loss and trendline for area close to diversion.

This research revealed a number of interesting trends. On the one hand, the overall wetland loss indicates that the Caernarvon Diversion Structure has had little or no effect on wetland loss in the Breton Sound area. There has been significant wetland loss after the opening of the diversion structure for both the complete Breton Sound area and the more compact area adjacent to the structure. Not only has there been significant wetland loss, that loss appears to be increasing.

There are of course many factors to be considered in wetland loss, and one very significant event that took place over the course of this research was the change due to Hurricane Katrina, which passed almost directly over the research area on 29 August

2005. Studies on the effects of Katrina on the wetlands are now being conducted; these studies are expected to shed light on these effects in the Breton Sound area. It is clear that there was a significant loss of vegetation in both of the study areas. Every single index shows a significant drop in vegetation in the last, post-Katrina image (taken 28 October 2006). The drop-off in vegetation is especially evident in the smaller area closer to the diversion structure. The average reduction in vegetation there is 15 percent, varying from a high of 21 percent for the NIR/IR index and a low of 9 percent for the NDVI. For the complete Breton Sound area the average drop was a somewhat smaller 5 percent. It varied from a high of 7 percent for the NIR/IR index to a low of 2 percent for the NDVI. At this point it is probably impossible to determine how much of the blame for wetland loss can be attributed to Katrina, as the wetlands in these areas continue to be impacted by the numerous factors outlined earlier in this paper, such as sea level rise, oil and gas development, etc.

While the wetland loss appears to continue unabated, the use of spectral indices to as a means of measuring that loss shows good results. All the indices were in general agreement, and while there were significant fluctuations in their results, overall they supported rather than contradicted one other. As a result, it appears that wetland loss can be measured using this relatively simple approach.

Freshwater diversion is just one of a number of strategies designed to prevent wetland loss. Following Hurricane Katrina there has been renewed interest in wetland restoration, and a subsequent increase in funding available to accomplish it. While the diversion structures area unlikely to accomplish the job by themselves, perhaps in concert with other strategies they may play a small but important part in rescuing a valuable disappearing resource.

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